SKI Report 2004:26

Research

Engineered Barrier System - Manufacturing, Testing and Quality Assurance

Report from a Workshop at Bålsta Gästgivaregård, Sweden, 12-14 November 2003

Swedish Nuclear Power Inspectorate

June 2004

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Foreword

As part of preparations for review of future license applications, the Swedish Nuclear Power Inspectorate (SKI) organised a workshop on the engineered barrier system for the KBS-3 concept, with the focus on manufacturing, testing and quality assurance. The workshop was held November, 12-14, 2003 at Bålsta Gästgivaregård. The main purpose of the workshop was to identify critical issues in the demonstration of how long-term safety requirements could be fulfilled for the engineered barriers. The workshop included presentations related to engineered barrier manufacturing and testing held by external experts, and working group sessions to prepare questions to the Swedish Nuclear Fuel and Waste Management Co. (SKB). SKB presentations were followed by an informal questioning and discussion with SKB representatives. This report includes a presentation of the questions posed by the working groups, SKB's replies to these questions as well as a summary of the working group discussions. Extended abstracts for the introductory presentations are included in an appendix. The conclusions and viewpoints presented in this report are those of one or several workshop participants. They do not necessarily coincide with those of SKI.

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Contents

1 Introduction

The Swedish high-level radioactive waste repository programme has moved forward into a phase of site investigations, approaching a license application for an encapsulation plant and a license application for the construction of a deep repository. According to the Act on Nuclear Activities (1984:3) the owners of the nuclear power plants are responsible for the safe management of spent fuel. The responsibility is taken by the jointly owned Swedish Nuclear and Fuel and Waste Management Co. (SKB). The reference concept for disposal is the KBS-3 concept, presented in 1983 (SKBF, 1983) and thereafter (e.g. SKB, 2001), consisting of a repository at about 500 m depth in Swedish bedrock, with the spent fuel encapsulated in a copper canister surrounded by bentonite clay.

The long-term safety of the repository relies on the isolation of the spent fuel by several barriers, mainly the canister, the bentonite and the rock. The tool to evaluate the safety of the repository is the performance assessment (PA), which embraces the high-level strategies for safety as well as presenting the detailed description of the barriers and their evolution with time.

The barriers in the repository have different roles in the KBS-3 concept. The canister has a very basic function to completely contain the spent fuel, such that no radionuclides can escape as long as the canister is intact. The role of the bentonite is to ensure favourable mechanical properties and a suitable chemical environment for the canister. Moreover, the canister and the bentonite should provide a suitable environment for radionuclide retention once the canister has lost its integrity.

In the PA, the initial state of the system (engineered barriers, rock and biosphere) is described, followed by an analysis of the evolution of the system with time. A prerequisite for the PA is thus the description of the initial conditions for the engineered barriers. At a mature stage of a programme, generic and conceptual descriptions need to be replaced with detailed descriptions that correspond well with what has been achieved in manufacturing and testing. The proof of such correspondence will need to be documented clearly, which in turn necessitates a rigorous quality assurance/quality control programme.

According to the current SKB plans, a license application to build an encapsulation plant will be submitted in mid 2006 and a license application for detailed site investigations, i.e. the start of the construction of the repository, will be due in late 2008. To focus the research resources available and as a part of the preparation for the upcoming reviews, SKI is arranging workshops on different topics. The purpose of these workshops is to gather information and identify problems and outstanding issues. The format of rather small workshops gives the opportunity for a dialogue between the researchers and consultants active in the SKI research programme, as well as invited international experts. The workshops also provide the opportunity to discuss the issues identified informally with SKB representatives.

This series of workshops was started in November 2001 with a workshop on radionuclide transport (SKI, 2002). In November 2002 a second workshop was held with the focus on the long-term integrity of the engineered barrier system of KBS-3 (SKI, 2003). The starting point for the discussions in the second workshop was SKB's most recent performance assessment SR 97 (SKB, 1999), and the description of the evolution of the barriers with time.

To further explore the details of the initial state of the engineered barriers, a third workshop was held on November 12-14, 2003, with the title "The Engineered Barrier System - Manufacturing, Testing and Quality Assurance". This report summarises the discussions and conclusions from that workshop. Chapter 2 gives the objectives and a description of the format for the workshop. In Chapter 3, the results from the working groups are reported, followed by a discussion in Chapter 4. Conclusions for further work, representing important issues for SKB as well as SKI to address, are summarised in Chapter 5.

2 Workshop structure

2.1 Objectives

The main objective of the workshop was to gain an overview of the status of knowledge in the area of concern, as well as to identify critical issues. The focus of the workshop was on SKB's research and development, but international perspectives were also sought for balance and insight.

The more detailed aims of the workshop were formulated as:
- identify critical issues in the demonstration of how the requirements for long-term safety will be fulfilled (operational safety requirements may need similar consideration in the future)
- bring together experts from the canister and bentonite area, to obtain a comprehensive understanding of the issues;
- review and discuss SKB's recently completed, ongoing and planned research activities; and
- suggest activities that would be appropriate for SKI to carry out as a preparation for reviewing the license application for an encapsulation plant.

At the 2002 workshop on long-term integrity of engineered barriers it was found to be very fruitful to discuss both the canister and the bentonite buffer at the same time. Although there are many differences, in manufacturing as well in how safety requirements are set, the canister and the bentonite are both part of each other's environment, and thus discussions of the two barriers inevitably overlap. For this reason the workshop covered canisters as well as bentonite in the aspect of:
- choice of material and material properties;
- manufacturing and treatment including sealing of the canister and full scale pilot manufacturing;
- control and testing;
- interim storage, transport and handling;
- deposition; and
- quality assurance.

The workshop included discussion of repository backfill, because the backfill would be emplaced close to the bentonite buffer and may, to some extent, contain the same material as the buffer. However, the backfill was not the main focus of the workshop. The concept of horizontal canister deposition was also considered, mainly with the primary aim of identifying the different requirements on manufacturing and testing.

To ensure that the workshop remained focused on the canister and buffer, issues relating to the tunnels, shafts, plugs, rock reinforcements and repository layout were not discussed, but these issues will be considered on future occasions.

2.2 Format

The “Engineered Barrier System – Manufacturing, Testing and Quality Assurance” workshop was held on November 12-14, 2003 at Bålsta Gästgivaregård near Stockholm in Sweden.

The participants were mainly SKI staff and SKI researchers and consultants. Representatives from SSI (the Swedish Radiation Protection Agency), STUK (the Radiation and Nuclear Safety Authority of Finland) and NRC (the U.S. Nuclear Regulatory Commission) were also invited. SKB staff participated during the second day. For a complete list of participants, see Appendix 1.

The first day of the workshop involved discussions and preparation of questions for SKB in working groups. On the second day, SKB gave presentations and answered the questions prepared by the working groups. The final half day was devoted to group discussions on the results of the questions posed to SKB and summing up. The agenda is enclosed in Appendix 2.

In preparation for the workshop and to facilitate the discussions a list of important issues was distributed to the workshop participants (see Appendix 3). The issues were divided into a general list and two separate lists for the canister, and the buffer and backfill respectively. The issues list is rather general, and some of the important issues raised were:

- the interpretation and transfer of data between test manufacturing and the performance assessment;
- specifications of requirements, including verification (testing) of material properties;
- handling and temporal storage;
- alternatives and availability of suppliers;
- necessary level of test serial manufacturing; and
- implications on engineered barriers for horizontal deposition.

As further preparation, on the first morning, participants presented their views on the workshop issues. The presentations are documented as extended abstracts in Appendix 4.

The main part of the workshop discussion was the preparation of questions to SKB. The workshop participants were organised into two groups, the Canister Working Group and the Buffer and Backfill Working Group. The working groups were free to discuss topics within their area, using earlier presentations and the issues list as guidelines, and were asked to develop a list of questions that could be posed to SKB on the second day. There was a recommendation for each group to select ten questions regarded to be the most important that could be used as the focus of the discussions with SKB. This prioritisation was done slightly different in the two groups. The resulting lists of questions are presented in Appendix 5.

The second day started with presentations from SKB, which gave an overview and updated input for the discussions. The presentations covered:

- current plans and ongoing activities (Tommy Hedman);
- recent developments in copper corrosion studies (Lars Werme);
- status in the bentonite development program (Lars-Erik Johannesson);
- the concept of KBS-3H (Stig Pettersson);
- canister manufacturing (Claes-Göran Andersson); and
- encapsulation (Håkan Rydén).

In the afternoon, the working groups presented their question to SKB. Finally, the third (half) day was devoted to summarising the results of the discussions with SKB.

3 Working group results

3.1 Report format

It must be emphasised that descriptions in this report of SKB responses to the participants' questions do not necessarily include all of the details that SKB provided. They should be regarded as the participants' interpretation of SKB's answers. It should also be noted that SKB might have given more comprehensive responses if they had had access to all of their experts. For instance, in responding to bentonite questions, SKB did not have a complete coverage of all technical areas.

The "hearing session" during the workshop were informal in nature. Due to time constraints, all questions were not addressed. However, the questions were sorted in order of priority, although this was done slightly differently by each working group. The Canister Working Group identified question areas that contained related questions, while the Buffer and Backfill Working Group divided the questions into groups and then selected the most important ones as shown in Appendix 5. It should also be noted that the questions to SKB to some extent are influenced by the SKI experts' own disciplines.

3.2 Canister issues

3.2.1 Functional requirements and acceptance criteria for the canister

A canister consists of two main components, the outer copper shell and the inner cast iron insert. The safety function of the copper shell is to act as a corrosion barrier, while the cast iron insert should provide sufficient mechanical support. A few functional requirements of the canister are (SKB, 2002):

- The thickness of the copper shell should be sufficient to withstand known corrosion processes.
- The canister should resist the swelling pressure of the buffer and in particular the uneven stress which might be encountered in connection with the resaturation of the buffer.
- The canister should resist the pressure increase that may result from an ice-sheet formed during an ice-age.
- It should be possible to ensure that a criticality excursion does not occur even if the canister becomes filled with groundwater.

SKB has recently published an acceptance criterion for the seal weld on the 50 mm thick copper shell (SKB, 2003a). This criterion states that there should be at least 15 mm of "intact ligament". This means that an undetected discontinuity of up to 35 mm would be permissible. In addition, the maximum probability for the occurrence of larger defects should be shown to be less than 0.1% (i.e. 99.9% of the canisters should have at least 15 mm of intact ligament).

The members of the Canister Working Group were not convinced that this value represents an appropriate acceptance criterion. The possible acceptance of a number of canisters with large discontinuities in relation to the total canister thickness would most probably be controversial and could be widely questioned. However, a proper evaluation of the criterion could not be carried out during the workshop, because the corrosion evaluation (Werme, 1998; King et al., 2001) which provides a basis for the criterion had not been reviewed in any detail prior to the workshop. Furthermore, SKB may have other reasons for selecting the criterion that must be presented and included in such an evaluation.

SKB presented a series of corrosion experiments during the workshop, which showed that dents or scratches on the surface of a canister did not have any significant effects on its corrosion properties. For this reason, SKB suggested that no criterion related to the surface properties of a canister would be needed.

Regarding the mechanical properties of the insert, the participants of the Canister Working Group pointed out that the estimated critical pressure of 81 MPa (Werme, 1998) is based on ideal "handbook values" of material properties. The Canister Working Group noted the importance of using properties of "as cast material" rather than ideal properties of the selected material. Implications of a less favourable mechanical performance must be evaluated, because canisters with relatively low ductility may be produced. SKB responded that there are plans to complete crush tests on canisters and insert assemblies that have already been fabricated. Moreover, finite element calculations are being carried out to analyse stress concentration effects. The tests and modelling work should address the above-mentioned concern.

3.2.2 Material selection for the canister

SKB has proposed an oxygen-free copper with approximately 50 ppm phosphorus as the preferred material for the shell. The main reason for using a phosphorus alloyed copper is that the pure copper has less favourable creep ductility. The proposed reference material for the insert is nodular cast iron (SS 0717-00), which has been chosen for its ductility and good castability.

The Canister Working Group asked if SKB is considering alternatives to the cast iron insert. According to SKB, only the cast iron insert is currently under consideration and no work is underway on previously discussed alternatives (e.g. steel).

3.2.3 Manufacturing of canisters

SKB is currently developing manufacturing methods for the copper shell and the cast insert. A series of about 11 full scale units have been produced and assembled (by November 2003). Individual non-assembled parts of the canister have been produced in larger numbers. SKB has focused on methods yielding seamless copper tubes. Ongoing work addresses the usefulness of the extrusion, pierce-and-draw, as well as the forging method. Before 1998, roll-forming was also tested in full scale. An advantage of the pierce-and-draw method is that units are produced with an integrated bottom, which would limit the welding requirements for the canister to the sealing of the top lid. A single reference method for manufacturing canisters has not been selected, because SKB wishes to retain the possibility of using more than one method.

Regarding the cast iron insert, SKB is also in the development stage of testing the production of full-scale units. At present about 27 inserts have been produced. Different casting methods and foundries have been compared. Furthermore, the influences of variations in the corner radius of the square steel tubes in the insert have been examined. There are two versions of the insert, one for BWR elements (12 elements in each canister) and one for the larger PWR elements (4 elements in each canister). However, almost all manufacturing efforts have been focused on the slightly weaker BWR version.

3.2.4 Sealing (welding) of canisters

The sealing of a canister is achieved by welding a copper lid on the edge of the shell. The final closure weld can be regarded as the most sensitive step from a quality assurance perspective, since the radiation field of the fuel elements necessitates remote handling. Two welding methods are being investigated: electron beam welding (EBW) and friction stir welding (FSW). Both methods will be further investigated in parallel during 2004 with the aim of demonstrating robustness and process quality controll. It is essential that SKB can show that an assembly-line production can meet the required quality standards and the production performance criteria. During 2005, SKB will select one of the methods to be used as the reference in the licence application for the encapsulation plant (2006).

The Canister Working Group noted that SKB has significantly less experience with defect formation in FSW. The group suggested a need for metallographic evaluation of a number of friction stir welds and an evaluation of the weight loss for the weld tool.

The group also asked about the potential failures of welding and whether or not a rejected weld could be repaired. SKB mentioned that a production failure rate of 1% could be acceptable as an upper bound. Repair of a friction stir weld has been attempted once by rewelding, but a main concern is the possibility of oxides being drawn into the material during the repair, although an inert gas could be used. SKB will address the effectiveness of weld repair once the method for making the closure seal has been selected. However, SKB noted that re-welding of canisters with flaws greater than the specified acceptance level might not be worthwhile. The fuel in such a canister would instead be repackaged in a new canister.

3.2.5 Non-destructive testing and quality control of canisters

Non-destructive testing (NDT) methods have been developed to test both the copper shell, in particular the welded parts, and the cast iron insert. Methods that are considered include digital radiography (X-ray), ultrasonic testing, eddy current testing and dye penetrant testing. Tensile tests and destructive testing will be necessary in order to evaluate the efficiency of these non-destructive testing methods. A quantitative measure of this efficiency is needed for PA and will be expressed as a probability of detection (POD) curve. SKB suggested that NDT should be regarded as an extra control process in relation to the primary quality control, which is achieved by managing the welding process with control equipment. The acceptable welding process parameter ranges need to be established by verification studies.

The Canister Working Group asked SKB to specify NDT development for the two welding methods. For EBW, SKB has developed in digital radiography and ultrasonic techniques for detecting volumetric defects. Less is know about detection of defects in friction stir welds. SKB is currently working, in parallel to the welding development, by mapping what types of defects that can occur in the friction stir welding process and how to detect them. Ultrasonic and radiographic techniques are used here as well. SKB is also developing Eddy current technique for detection of surface defects.

Members of the Canister Working Group asked about the NDT methods that will be used for the cast insert. According to SKB, plans are underway to compare the effectiveness of x-ray and ultrasonic NDT techniques on the evaluation of the cast iron insert.

3.2.6 Transportation and handling of canisters

The Canister Working Group asked if SKB had specified an acceptable level of damage to the copper canister as a result of e.g. handling and mishaps during transportation. SKB noted that the KBS-3 canister with its soft copper shell could probably not withstand any drops. Deformation of the canister could for instance preclude a proper emplacement in a deposition hole. The fuel elements in such a canister would have to be retrieved and placed in a new canister. However, SKB suggested that a scratch or other surface defect on a canister may be acceptable.

3.2.7 Quality assurance and control measures for the canister

A necessary part of the canister programme is the development of a Quality Assurance/Quality Control programme, which includes all aspects of the canister such as testing of raw materials, manufacturing, sealing, NDT, storage, transportation, and finally canister deposition.

When asked by the Canister Working Group about how the human error factor would be considered, SKB suggested that a QA/QC programme should include a comprehensive compilation of all possible types of human errors and their expected consequences. Such a list has not yet been developed. The participants of the Canister Working Group agreed that such a list would be an essential element in reducing the probability of human errors, but suggested such a programme could not eliminate the risk of human error. A reduced but still non trivial human error probability may therefore have to be explicitly evaluated using performance assessment.

3.2.8 Analysis of coupled processes after canister emplacement

After being placed in its deposition hole, a canister will be subjected to a dynamic environment with a radiation field, an initially increasing temperature, evolving geochemical conditions and initially a humid unsaturated environment, etc. The Canister Working Group noted that coupled effects, or the influence of coupled processes, may be important in such an environment (e.g. couplings between radiolysis, microbially-induced corrosion, stress corrosion cracking, long-term corrosion effects). In such a situation, the analysis of each process sequentially and independently may not be a reliable approach. SKB was consequently advised to incorporate coupled processes in performance assessment because these processes may be very informative. SKB responded that coupling effects could be revealed implicitly during long-term experiments (e.g. those underway at the Äspö Hard Rock Laboratory), but that not much relevant modelling work had been carried out or was currently planned.

3.3 Buffer issues

3.3.1 Functional requirements and acceptance criteria for the buffer

In relation to the canister, it is easy to underestimate the importance of the buffer as a component of the KBS-3 concept, since the canister has a much more explicit role in containing the spent fuel. However, the buffer separates the canister from the host rock and must in this role fulfil a range of rather diverse functional requirements. A few of the most critical ones are (SKB, 2002):

- To mitigate groundwater flow (transport of radionuclides and corrosive agents should only be possible through diffusion).
- To remain stable for extensive time periods in the repository environment.
- To protect the canister mechanically by a sufficiently large deformability, such that a small shear movement of rock near the deposition hole would not harm the canister.
- The deformability should not be so large that a canister would sink to the bottom of its deposition hole.

Members of the Buffer and Backfill Working Group asked SKB about the required properties to achieve the functional requirements. In particular, SKB stressed the importance of a suitable density for compacted bentonite blocks and the need for a smectite content of at least 85%. These two features have large influences on, for example, the development of the swelling pressure, the deformability of the buffer and buffer diffusivity and hydraulic conductivity.

The functional requirements of the buffer must be fulfilled simultaneously. For example, a sufficient deformability of the buffer to mitigate shear movement of the rock could be unfavourable with respect to transport properties and the support needed to avoid canister sinking. The Buffer and Backfill Working Group regarded the balance between the two latter requirements (in the list above) as particularly sensitive. In order to fulfil both criteria an optimisation of the buffer properties would be required. SKB has proposed a range for the final bentonite density from 1950 to 2050 kg/m^3, but the group was uncertain about the difficulty in achieving an optimum density in serial production. There are questions related to the tolerances, the variability in conditions during manufacturing and material properties as well as implications of possible human errors.

The Canister Working Group also stressed the importance of the swelling of the bentonite for the mechanical load on the canister. Two cases of particular interest are the development of an uneven swelling of the buffer and the design basis case for the canister with a maximum hydrostatic pressure in addition to the swelling pressure (due to the added weight of a 3 km thick ice sheet). The group noted that SKB have no plans to refine the analysis of canister load due to uneven swelling (Werme, 1998), and regarded this as a shortcoming of the present SKB programme. There was an interest in knowing the worst-case scenario for non-uniform bentonite swelling and the pressure gradients that result from these conditions.

Another concern of this group was that SKB is relying solely on the reference swelling pressure of 7 MPa and static load calculations with maximum values. The group recommended that SKB also use a range of swelling pressures defined by its associated uncertainty and potential variability. These ranges (as well as those of other key parameters) need to be captured in PA analyses.

A major long-term safety issue for the bentonite buffer is the influence of future groundwater with different compositions. This groundwater may either contain very low concentration of dissolved solids (e.g. glacial meltwaters) or very high concentrations (brines or saline groundwater). In response to questions on this issue, SKB stated that high salinity would not be a problem for the buffer due to the high compaction densities that will be achieved. However, SKB agreed that variation in groundwater composition could be a problem for the backfill (see Section 3.4.2). One workshop participant suggested that there could be different responses if the buffer were subjected to high-salinity water for long-time scales. In addition, the dilute water case would have to be addressed, as well as an alternation between these two cases.

3.3.2 Material selection for the buffer

The Wyoming bentonite, termed MX-80, is one of the most well-known commercially available bentonites. Almost all tests that have been conducted within the SKB programme have been based on this material. However, SKB wishes to avoid dependence on a single supplier and will therefore consider bentonite from other parts of the world (e.g. Milos bentonite from Greece). Costs and availability must be considered in addition to quality. At present, MX-80 is SKB’s reference material.

While MX-80 bentonite is of Na-type, several other suppliers offer Ca-bentonite. A comparison between the two types suggest that the lower swelling pressure of Ca-bentonite when using identical densities could be a problem. It may not be possible to compensate for this lower pressure by using a higher density material. A Ca-bentonite would therefore probably have to be artificially transformed to a Na-bentonite, before being used as raw material for buffer manufacturing.

Members of the Buffer and Backfill Working Group expressed some concern about leaving the buffer material selection as an open issue. The group's advice was not to take materials selection lightly. Given the crucial role of the buffer in the KBS-3 concept and the various requirements on its properties, SKB needs to make sure that there is a comprehensive experimental basis (especially for any new material that would substitute MX-80) and sufficient time for long-term testing. Considering the complexity of the material it would be insufficient to base material selection on simple criteria, such as confirmation of the required smecitite content.

3.3.3 Manufacturing of bentonite blocks

Bentonite blocks (or more appropriately bentonite rings) have been manufactured either by uniaxial or isostatic compaction techniques. Advantages of the uniaxial method are that equipment for full-scale manufacturing is available and precise dimensions can be achieved without any need to machine the blocks. Blocks used for Äspö full-scale experiments have been produced with this method. The isostatic technique, on the other hand, produces more homogenous blocks and is quicker. Even if dimensions of isostatic blocks are not precise they can easily be adjusted without much difficulty after the compaction stage. The isostatic compaction method is currently SKB's reference option.

Before the raw material is put in the mould, its water content (weight fraction of H_2O) must be adjusted. The commercial bentonite product contains 9-13% water, while a water content of about 17% is needed in order to produce blocks with a degree of saturation (volume fraction of H_2O relative volume fraction at full saturation) of 85%. SKB has also produced blocks with 95% saturation for special cases. This would require the use of a raw material with a larger proportion of added water (about 26% water content). It has not been determined if almost saturated blocks would be a more attractive option, since less water from the bedrock would be needed to achieve full saturation. However, there are also disadvantages and SKB has not decided on the optimum initial relative degree of saturation for the bentonite blocks.

The Buffer and Backfill Working Group considered that SKB's selection of a reference alternative is inappropriate, given the practical limitations with the isostatic compaction method at this point in time. A reference alternative should generally be one that can be implemented without restrictions, rather than a method which may be the most promising in a distant future. Although this is not likely to become a critical issue until the start of repository operations, the group recommended that SKB should take steps for the full-scale implementation of the isostatic method if this method is to remain as SKB's reference method.

The uniaxial method requires use of oil lubricants on mould surfaces. Participants asked about the long-term significance of such lubricants. SKB ensured that all traces of lubricant would be removed from the blocks prior to their emplacement.

One participant was curious about the maximum size of bentonite blocks that can be produced using current technology. SKB has so far been able to produce blocks with a maximum height of 0.5 m, but claimed that the height may have little relevance with respect to long-term safety. However, from a practical handling point of view it might be advantageous to be able to produce larger blocks.

3.3.4 Handling, storage and installation of bentonite

Handling begins when bentonite is mined from a natural deposit and ends when manufactured blocks are emplaced in a deposition hole. The supplier will complete homogenisation, grinding and any other treatment (such as adjustment of the water content) of the material such that it fulfils the quality specifications of the commercial product. The supplier should also confirm the condition of the material in accordance with a quality assurance and control programme. In addition, SKB will need to ensure that the supplier's quality specification is consistent with the functional requirements and acceptance criteria discussed above. The supplier's specification will most probably not be comprehensive enough, so SKB will have to rely on its own testing and quality programme.

The Buffer and Backfill Working Group asked about storage time for the materials and whether or not production of blocks would be based on a "just in time" approach. SKB is currently planning to use about 5000 tons of (buffer) bentonite per year. The materials will be divided into 2-3 shipments per year resulting in an average storage time of a few months. This time could be used for testing of the materials to ensure compliance with the technical specifications. The bentonite blocks, on the other hand, would be manufactured regularly and stored for a much shorter duration of about one week. Even for this short duration, a controlled environment would be needed to maintain the initial water content.

Some workshop participants asked for a specification of "good enough emplacement" and the criteria for rejection of an emplacement. A few quality deviations that could be anticipated are:

- gaps between blocks,
- cracks,
- missing pieces, and
- contamination (e.g. with oil).

SKB plans to test the density of the blocks by frequently checking that no weight loss has occurred and by visual examination of the blocks to detect any missing pieces, gaps between blocks, etc. SKB believes it should not be a problem to inspect the blocks in their deposition hole after emplacement and to remove defective or damaged blocks if needed, even if the canister is also present. Retrieval and replacement of bentonite blocks would naturally be more difficult if the canister had been lowered into the hole. However, all operations should in principle be reversible according to SKB.

SKB's view is that cracks in a block would not be a problem, since the final density of the buffer would not be affected, but that missing pieces of significant size could be a problem. Assurance were made by SKB that a sufficient final swelling pressure would be achieved by filling the void spaces with bentonite pellets. Calculations would be needed to estimate the overall density by considering the volume of void space, and properties of bentonite blocks and pellets. However, pellets might not be needed if the tolerances can be reduced.

On the whole, workshop participants recommended that SKB should plan for individual examination and documentation of each stage of the deposition process. In particular, visual examination of rock surfaces prior to emplacement and the bentonite surfaces after buffer emplacement would be needed. Assurance that bentonite pieces of significant size do not fall down to the bottom of the hole, either during installation of the buffer or during deposition of a canister, would be needed. Problems could be encountered if bentonite was redistributed or if a canister would not sit evenly at the bottom of a deposition hole.

3.3.5 Testing of bentonite blocks

The testing of bentonite blocks involves confirmation that the density of individual blocks is sufficiently close to specified values. Direct measurement of the water content of the blocks would also be needed. These tests are planned to be a routine part of repository operations. Another simple test that was discussed, is the determination of the grain size distribution of the bentonite. Tests to confirm the development of the swelling pressure would also be required, but these tests will require several weeks to complete.

The need to confirm the chemical reducing capacity of the bentonite blocks, and whether traces from oxidation of pyrite could be seen during a visual inspection after storage were discussed. SKB indicated that traces from pyrite oxidation are not always detectable.

3.3.6 Resaturation of buffer after emplacement

The resaturation of the bentonite blocks could start very soon after buffer emplacement. In order to avoid early swelling and to retain the dimension of the buffer before canister deposition, there are plans to protect the outer surfaces of the buffer with a plastic film. This film would be removed after the canister is deposited.

Qualitative criteria that could be used to judge the suitability of a deposition hole for waste emplacement include water inflow rate, number of intersecting fractures, etc. However, quantitative criteria have not been developed yet. An upper limit of the inflow rate (less than 10 l/min) has been suggested (Andersson et al., 2000), but there is no information about the necessity or relevance of a lower limit.

The possibility of very dry deposition holes and potentially very long periods of time to achieve full saturation of the buffer could be a major concern. Participants asked about plans for artificial wetting with the addition of water from the deposition tunnel to speed up resaturation. SKB replied that there are no plans for artificial wetting, because a significant quantity of water would not be required to wet the buffer material. However, modelling studies of the resaturation phase are being conducted, which will investigate the issue of deposition holes with very low inflow rates.

3.4 Backfill issues

3.4.1 Functional requirements and acceptance criteria for the backfill

Some functional requirements of the backfill are (SKB, 2002):

- Sufficiently low hydraulic conductivity to avoid formation of preferential flow paths in the tunnels (i.e. similar to surrounding bedrock).
- Low compressibility such that expansion of the swelling buffer is small enough to prevent significant loss of buffer density.
- Long-term stability of the above mentioned characteristics.

Workshop participants were concerned about the backfill performance under the influence of brines or highly saline groundwater, especially a diminished capability of the backfill to prevent groundwater flow due to reduction of the swelling pressure of the bentonite component. SKB has a similar view and suggested that saline groundwater could be more problematic for the backfill compared to the buffer. Different options to mitigate this problem are being investigated by SKB.

According to recent plans (SKB, 2003a), modelling efforts will be undertaken to investigate the hydraulic consequences of a backfill having generally poor backfilling properties ($K>10^{-8}$ m/s) or a non-swelling backfill with highly conductive gaps. One participant asked whether these efforts are connected to a reconsideration of the backfill's functional requirements, e.g. the introduction of a less strict criterion for the hydraulic conductivity. SKB indicated that functional requirements are preliminary and are pending further test results.

Members of the Buffer and Backfill Working Group had the general opinion that for all of the different components of the EBS, backfill issues are those that are at the most preliminary stage. The backfill issues are particularly important from a resource perspective (in addition to the long-term safety perspective), since very large volumes of material would be required. However, a possible future introduction of the horizontal version of the KBS-3 concept (see Section 3.5) would to a large extent obviate the need for backfilling.

3.4.2 Material selection for the backfill

SKB's reference material for the backfill is a mixture of crushed rock and bentonite in the proportions 85:15. For the coastal sites under consideration, a mixture of 70:30 has previously been suggested to compensate for possible interactions with high salinity groundwater. However, it is not clear that even this higher proportion of bentonite would be sufficient to maintain swelling pressure in the long-term. MX-80 is the reference bentonite, but other materials will be considered as well. For backfilling, the use of a Ca-bentonite could possibly even be preferable, since test results suggest that the swelling pressure of a Ca-bentonite is less sensitive to high salinity levels than a Na-bentonite (at moderate compaction densities). As an alternative to the bentonite and crushed rock mixtures, SKB is also considering the use of swelling clay without any crushed rock, such as Friedland clay.

3.4.3 Storage and installation of the backfill

Crushed rock from the excavation of deposition tunnels would be stored at the surface before being used as a component of backfill. Due to the long time periods for repository construction and operation, such storage could last several decades. Members of the Buffer and Backfill Working Group asked how much organic material could be formed during such storage as a result of mostly microbial activity, and whether or not this organic fraction could affect repository performance.

SKB has, in addition to a homogenous mixture of crushed rock and bentonite (as implemented in e.g. the backfill and plug test, see Section 3.6), suggested that sandwiched layers of bentonite and crushed rock might be used (SKB, 2003a). The working group members wished to better understand the rationale for focusing on this alternative and to obtain details about how it would be implemented in practice.

For the homogenous mixture alternative, one participant was concerned that mixing could be insufficient and asked about methods to ensure homogeneity of the backfill.

3.5 The horizontal KBS-3 concept

The horizontal variant of the KBS-3 concept (KBS-3H) has recently evolved from being a peripheral alternative, to a now much more realistic option to replace the KBS-3 vertical variant (KBS-3V) as SKB's main emplacement option. However, there are a number of practical problems which must be resolved, and long-term safety aspects of this emplacement concept must be further evaluated. A demonstration site is currently being set-up at the Äspö Hard Rock Laboratory. The practical tests that will be executed within the next couple of years should be evaluated by 2006. A safety case for the horizontal variant is scheduled for completion by mid 2007, and will include a description of processes for KBS-3H, process level modelling and radionuclide transport analyses.

One workshop participant asked if the canister would be identical for the two emplacement alternatives. SKB confirmed that no plans exist for modifying the copper canister design if the horizontal variant were selected. However, a significant difference between the two alternatives is that the horizontal version also includes an outer steel cylinder, which would contain the bentonite rings. The main purpose of the cylinder is to protect the bentonite rings during emplacement. Nevertheless, the cylinder would not have any long-term safety function.

SKB was asked to identify primary issues that need to be reconsidered if the horizontal design were selected. In particular, the influence of rock movement due to an earthquake will be affected by the change in geometry. An updated evaluation of such consequences would be needed. In addition, there could be differences in how a hydrogen gas cushion might develop within the interior of a canister due to a supply of groundwater through a pinhole (Bond et al., 1997). The position of the pinhole in relation to the air cushion would be more difficult to assess. The development of a hydrogen air cushion may have a significant impact on the canister's exchange of groundwater with the surroundings and consequently on radionuclide releases. Finally, the criticality issue may need to be reconsidered.

3.6 Long-term experiments

The relevant long-term experiments which were mentioned during the workshop are the prototype repository, the backfill and plug test and the LOT experiment (long-term test of buffer materials), see e.g. SKB (2003b). The prototype repository is intended to demonstrate the technical feasibility of deposition and handling in full scale as well as give information about the early evolution of the EBS components after deposition. One part of the prototype repository will be dismantled after 4-5 years, whereas the other part will be dismantled after about 20 years. The purpose of the backfill and plug test is to test various backfill emplacement alternatives and different mixtures of bentonite and crushed rock (10, 20, and 30% bentonite). The test has been running since 1996 and will continue until at least 2005. The LOT experiment is intended for studying various processes within a bentonite buffer during several years, such as diffusion, microbial activity, evolution of buffer characteristics, copper corrosion etc. The experiments are being conducted at a reduced physical scale and at two temperatures (90°C and 130°C).

Workshop participants asked if the timing of the long-term experiments had been planned such that information could be used to support the planned licence applications. According to SKB, some but not all results would be available from the prototype repository and LOT experiment before the estimated time of SKB's application for repository operation (year 2017). SKB added that information would not only be available from their own experiments but also from other similar experiments elsewhere, e.g. the FEBEX experiment, operated at the Grimsel site in Switzerland by the Spanish waste management company ENRESA (ENRESA, 2000). Participants were of the opinion that a compilation of all expected information sources and schedules would be valuable in order to judge the sufficiency of such data in the context of future licensing.

A key concern, according to some workshop participants, is the ultimate objectives of the long-term experiments and in particular the prototype repository. Could the experiments provide a basis for performance confirmation and if so which particular aspects of long-term safety or system evolution could be supported? Are there aspects of the EBS component evolution for which long-term experiments could most probably not be of any help? Are there any criteria concerning what a successful experiment should demonstrate? SKB gave a rather general response to these questions and suggested that an objective of the long-term experiments is to fulfil the need to compare model predictions with real world data.

Within a repository in granitic bedrock, significant variability can be expected, e.g. in terms of groundwater flow distribution and groundwater chemistry. Moreover, there would most probably be certain amounts of randomness in EBS component quality, influence of the installation, etc. For this reason, participants asked about the statistical significance of the experiments and recommended SKB to consider if some type of additional long-term experiments or monitoring would be needed in order to improve statistical significance. In any case, if there are ranges of realistic conditions which deviate significantly from those encountered in the experiments, these ranges will limit the representativeness of the results from the ongoing experiments.

4 Discussion on workshop results

In the final discussion during the workshop, participants had the general view that SKB has a firm grip on canister issues and that good progress has been made in the canister programme. Even if there are several major issues which have not been fully addressed (e.g. formulating suitable acceptance criteria, how to detect and describe flaws, analysing human errors, sensitivity to rock movements, investigation and evaluation of coupled processes, feedback to performance assessment), they could most probably be resolved. SKB has made rapid progress in the areas of manufacturing and sealing, while the programme for non-destructive testing is slightly less clear.

On the other hand, participants judged that the remaining issues in the buffer programme will be more difficult to deal with. This is mostly an intrinsic problem, since bentonite is a material that will develop slowly for a long-time in the repository environment before it reaches its intended long-term state (e.g. establishment of reducing conditions, development of swelling pressure, resaturation, thermal evolution). Nonetheless, a contributing factor might also be that SKB has, in recent years, devoted fewer resources to resolving the buffer issues in comparison with the canister issues. The most difficult issues are related to the long time periods that are needed to conduct meaningful large-scale tests, since such tests would have to be planned so far in advance. There is thus a need to evaluate the sufficiency of the ongoing experiments. Another issue is the selection of buffer materials, which the participants possibly seemed to regard as more important than did SKB. The material selection should be considered in conjunction with the selection of a compaction density and a water ratio, which adds up to a rather complex optimisation. In addition, the selection of a reference method for compaction of bentonite blocks caused some confusion as SKB had not and could not use the reference technique for manufacturing full scale blocks.

The final major EBS topic, which was only briefly dealt with at the workshop, is backfilling. The current concept, which is tested at the Äspö Hard Rock Laboratory, may to be too vulnerable to high salinity groundwater. For his reason SKI is considering entirely new options. This new development caused the participants to regard the backfill issues to be at a very preliminary stage. It was suggested that SKI should devote more effort to follow SKB's work in this area. It is possible that previously made assumptions about the performance of the backfill have been too optimistic. It will therefore be interesting to follow SKB's planned modelling work for evaluating the implications of a less efficient backfill. If SKB wishes to seriously consider alternative backfilling concepts ("sandwiched layers", Friedland clay etc), the feasibility of such concepts need to be demonstrated. In addition, large-scale and long-term tests will be needed to support future safety assessment work.

Several times the participants discussed the need to arrive at reasonable expectations of achievements that should support the license application for the encapsulation plant in 2006. For this reason, the participants suggested that SKB should be more explicit in their definition of what they regard as a necessary basis for the application. When has enough data been gathered? Which are the most critical issues to resolve? Which issues do not have to be resolved prior to the construction application and why? SKB noted that it would always take too long and be too costly to acquire all data that may be needed and that the ultimate judgement of sufficiency would be up to the regulator. These are valid points, but even so, participants expressed the view that SKB would in the first instance be responsible for establishing an expectation level before the time of application. If such an expectation level has been proposed and discussed, the likelihood of encountering major deficiencies in the application will be much smaller.

The newly tested format with working groups to formulate questions to be posed to SKB turned out very well. It provides an opportunity for a good dialogue between SKB and the experts who are assisting SKI. This specific format is though more demanding for SKB and it is important that SKB has access to the “right” experts. For future workshops this will require an early dialogue between SKI and SKB about the workshop purpose and content.

5 Conclusions

During the workshop many issues regarding manufacturing, testing and quality assurance of the engineered barriers were discussed. The central themes in the questions and discussions are summarised as follows:

- There is a need to specify how the functional requirements for the buffer and backfill will be achieved in practise. Issues of particular interest are material selection, compaction density, initial water content and manufacturing methods for bentonite blocks. A major problem that must be addressed is the long period required to obtain relevant results from large-scale testing.

- The uncertainties relating to the wetting and subsequent swelling processes of the bentonite buffer have implications for analysis of the canister. It is necessary to know how non-uniform the bentonite swelling pressure could be in a worst case pressure differential, in order to evaluate the sufficiency of “as tested” canister performance.

- Regarding the copper shell of the canister, the requirements on the surface need further discussions. The criterion for acceptable defects in the weld is an obvious issue, but all criteria specifying the surface, including requirements from the handling and transportation, need to be compiled in a logical and comprehensive manner.

- The backfill is a more uncertain area than the bentonite buffer, and alternative backfilling concepts were discussed. To demonstrate the feasibility of the backfill, criteria need to be derived from e.g. functional requirements, and modelling and experiments are needed to confirm the appropriateness of the criteria.

- There is a need to specify more clearly how the results from the long-term experiments at Äspö should be used. Evaluation criteria need to be set up, including timing with respect to licence applications.

- The concept of horizontal deposition of the canisters in a KBS-3H repository must be regarded as a separate case, and should be given appropriate attention. At this stage it is important to identify which analyses, modelling and experiments (especially long-term experiments) should be repeated or revisited if a change of reference concept to KBS-3H is considered.

6 References

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APPENDIX 1: PARTICIPANTS

Randy Arthur	Monitor Scientific, US
Tamara Bloomer	NRC, US
Bill Bowyer	Consultant, UK
Daniel Bullen	Iowa State University, US
Tim Hicks	Galson Sciences, UK
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Dave Savage	Quintessa, UK
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Additional participants the second day (Thursday, Nov 13.)

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APPENDIX 2: AGENDA

SKi

Workshop on

Engineered Barrier System – Manufacturing, Testing and Quality Assurance

November 12-14, 2003, Bålsta Gästgivaregård

Agenda

Wednesday, November 12

9.00 – 9.30	Welcome and introductory remarks (Christina Lilja)
	Purpose of the workshop (Christina Lilja)
9.30 – 9.45	Engineered Barrier System – Manufacturing, Testing and Quality Assurance, Issues of Interest to Consider (Rolf Sjöblom)
9.45 – 10.00	Early Waste Package Failure (Tamara Bloomer)
10.00 – 10.30	Coffee break
10.30 – 10.40	PA Context of Manufacturing, Testing and Quality Assurance Issues Related to the Bentonite Buffer (Randy Arthur)
10.50 – 11.00	Issues Relating to the Manufacturing and Emplacement of Compacted Bentonite upon the Performance of the KBS-3 Design (David Savage)
11.00 – 11.10	Manufacturing, Testing and QA (Dan Bullen)
11.10 – 11.20	Short break
11.20 – 11.30	Status of the Canister Development Programme (Bill Bowyer)
11.30 – 11.40	Manufacturing of Copper Canisters (Mats Lundin)
11.40 – 11.50	Statistics of Canister Defects (Tim Hicks)
12.00 – 13.00	Lunch

13.00	– 13.15	Introduction to work in groups (Christina Lilja)
13.15	– 13.30	Conclusions from the Krägga workshop (Bo Strömberg)
13.30	– 15.00	Canister and bentonite working groups to start prepare questions to SKB (working group leaders, rapporteur)
15.00	– 15.20	Coffee break
15.20	– 17.00	Working groups cont'd
17.00	– 17.30	Presentation and general discussion on questions
17.30	– 18.00	Coordination and preparation of questions to SKB (Rolf, working group leaders, Christina, Öivind, Bo)
19.00		Dinner

Thursday, November 13

9.00	– 9.15	Introduction (Öivind Toverud)
9.15	– 10.00	SKB presentation on canister and bentonite
10.00	– 10.30	Coffee break
10.30	– 12.00	SKB presentation cont'd
12.00	– 13.00	Lunch
13.00	– 15.00	Questions to SKB from working groups (moderator: Rolf Sjöblom)
15.00	– 15.30	Coffee break
15.30	– 16.30	Questioning cont'd
16.30	– 17.00	Summation – outstanding issues (Rolf Sjöblom)
19.00		Dinner

Friday, November 14

9.00 – 10.00	Working group summarizes on the answers from SKB (working group leaders)
10.00 – 10.30	Coffee break
10.30 – 11.15	Discussion of results from questioning of SKB (moderator: Rolf Sjöblom)
11.15 – 11.45	Discussion on implications for SKI work (Bo Strömberg)
11.45 – 12.00	Conclusions (Christina Lilja)
12.00 – 13.00	Lunch

Appendix 3: Prepared questions to working groups

The superior question for the workshop is:

How is SKB going to show that they can produce/manufacture the engineered barriers with the properties they assume in their safety assessment ?

Such a general question is not easy to answer, but the outcome of the workshop should be a better understanding of the critical issues that remains for SKB to show.

To structure the discussions in the working groups several questions are presented below. First there are some general questions, and in chapter 2 and 3 respectively more specific questions for canister and bentonite are gathered.

General questions to both the canister and bentonite groups

SKI many times has pointed out the importance of the coupling between performance assessment and experiences from experiments and manufacturing tests etc. Is it as important as SKI claims ? For which areas is it most important ? Are there areas where this is less important ?

How does SKB ascertain that the experiences from experiments and manufacturing tests are used as the basis for assumptions for the performance assessment ?

How does SKB ascertain that the necessary assumptions in the performance assessment are used as requirements for the manufacturing and testing ?

How will handling and temporal storage influence the manufactured barriers ? What requirements do the canister and bentonite put on the handling and storage ? And the reverse: what kind of requirements do the handling and storage put on the canister and bentonite ?

How should SKB ascertain that the effect of human mistakes are properly included in requirements and routines ?

What are the implications if SKB changes into a concept with horizontal deposition ? In which areas can large new or renewed analyses (modelling, lab, pilot or full scale) be required ?

Questions to the canister group

How can or should requirements on the surface be specified ?

How can or should requirements on the weld (joint) be specified ?

Would it be acceptable with relying on a single NDT-method for inspecting the weld ?

How can or should requirements on long-term mechanical properties in copper (e.g. creep) be specified ? What tests need to be done ?

How can or should requirements on long-term mechanical properties in the cast iron be specified ? What tests need to be done ?

How is the availability of suppliers and manufacturers (for copper tube, iron insert, lids etc) ? How important is it with alternatives ?

What is a reasonable level for SKB in showing ability to serial manufacturing of canisters, at different steps (application to build encapsulation plant, application to operate it) ?

Questions to the bentonite group

What are the manufacturing alternatives of bentonite rings/blocks for the deposition holes ? Pros and cons for the alternatives ? Which other forms of bentonite are needed (pellets, blocks of other sizes etc) ?

What are the manufacturing alternatives of backfill ? Pros and cons for the alternatives ?

How is the availability of suppliers and manufacturers ? How important is it with alternatives ?

What are the most important requirements and thereby the most important properties of the bentonite ? What kind of quality control will then be most important ? For example:

How can the properties of the bentonite in general be measured ?
How can/should requirements on long-term mechanical properties be specified ?
How can/should requirements on long water uptake properties of the bentonite be specified ?
How can/should preserved internal structure of the bentonite be controlled after manufacturing ?

Are there conflicting requirements on the bentonite and the backfill ? Difficult optimising problems ?

Will the EDZ (Excavated Damaged Zone) put special requirements on the bentonite in the deposition holes but especially for the blocks in the backfill ?
Which ? For what reason ?

APPENDIX 4: EXTENDED ABSTRACTS

- **PA Context of Manufacturing, Testing and Quality Assurance Issues Related to the Bentonite Buffer**
  Randy Arthur

- **Early Waste Package Failure**
  Tamara Bloomer

- **Status of the Canister Development Programme**
  Bill Bowyer

- **Statistics of Canister Defects**
  Tim Hicks

- **Manufacturing of Copper Canisters**
  Mats Lundin

- **Issues Relating to the Manufacturing and Emplacement of Compacted Bentonite upon the Performance of the KBS-3 Design**
  David Savage

- **Engineered Barrier System – Manufacturing, Testing and Quality Assurance, Issues of Interest to Consider**
  Rolf Sjöblom

PA Context of Manufacturing, Testing and Quality-Assurance Issues Related to the Bentonite Buffer

R. Arthur
Monitor Scientific, LLC, Denver, Colorado

The functional requirements of the buffer in the KBS-3 disposal concept for spent nuclear fuel provides a useful context for consideration of manufacturing, testing and quality-assurance issues related to this component of the EBS. These requirements are briefly summarized here to help set the stage for discussions at SKI's upcoming workshop on these issues.

In SKB's view[1], the functional requirements of the buffer are:

- the *hydraulic conductivity* should be sufficiently low that transport of corrodants to the canister, and radionuclides away from the canister, is controlled by diffusion,

- the *gas permeability* must be sufficient that potentially large amounts of gas generated by corrosion of the iron insert in the canister can flow through the buffer without causing irreversible damage in the form of permeable channels or cavities,

- the *swelling pressure* must be sufficiently high to establish and sustain a good, tight contact with the canister and rock, but not so high as to deform the canister or fracture the rock,

- the buffer must be sufficiently *deformable* that any rock movements will be absorbed without damaging the canister, but not so deformable that the movements will cause the position of the canister to shift in its deposition hole.

- the *filtration properties* must be sufficient to stop the migration of colloidal-sized particles, and

- the *thermal conductivity* must be sufficient to prevent unacceptable physical, chemical or mineralogical changes in the buffer.

These requirements can be met, in SKB's opinion, if compacted bentonite is used as the buffer material, and if compaction densities are in the range 1900 – 2100 kg m^3 at full water saturation. Assuming a bentonite composition and mineralogy similar to that of commercial MX-80 bentonite, SKB have shown over this range of densities that:

[1] SKB, 1998. Detailed programme for research and development 1999 – 2004. SKB Background Report to RD&D-Programme 98, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

- the transport capacity of the buffer for diffusion is at least 10,000 times greater than its transport capacity for advection.

- the buffer vents gas without permanent alteration of its internal pore structure when the gas pressure builds up to a value equal to the swelling pressure,

- the swelling pressure (about 1 MPa under the stated conditions) is adequate to form a tight seal with the canister and host rock, but is too low to induce fracturing of the rock or deformation of the canister,

- in a worst-case scenario involving shear along a horizontal fracture located at the mid-height of the canister, the deformability of the buffer would be sufficient to protect the canister over a range of displacements predicted by a semi-empirical rheological model.

Compaction densities in the stated range will also not permit survival or reproduction of bacteria that could affect the supply of corrodants to the canister's surface. The thermal conductivity of the buffer, as well as the thermal conductivity of the host rock, will determine the spacing between deposition holes needed to keep the temperature at the canister's outer surface less than 100°C. This design constraint is intended to minimize alteration of the buffer's mineralogy.

In SKI's view[2], SKB's specification of functional requirements for the buffer should be expanded. The additional specifications should include:

- a specification of the relation between gas permeability and gas pressure build up, and

- a description of retention properties in terms of requirements on the chemical composition and mineralogy of the buffer.

[2] SKI, 2002. The Swedish Nuclear Power Inspectorate's Review Statement and Evaluation of the Swedish Nuclear Fuel and Waste Management Co's RD&D Programme 2001. SKI Report 02:33, Swedish Nuclear Power Inspectorate, Stockholm, Sweden.

Early Waste Package Failure

Tamara Bloomer
U.S. Nuclear Regulatory Commission

The Nuclear Regulatory Commission (NRC) is currently in pre-licensing consultations with the Department of Energy (DOE) on the potential high-level geologic repository at Yucca Mountain. As part of the pre-licensing consultations, the NRC reviews DOE's work to assure enough information is available for DOE to submit a license application suitable for review by the NRC. One of the documents of DOE's that the NRC has reviewed is "Analysis of Mechanisms for Early Waste Package Failure."

This presentation will focus on the NRC's review of the potential for early waste package failure. Early waste package failure is defined as "Initial or premature failures of containers due to one or more initial defects." This presentation will discuss DOE's current waste package design, potential causes for early waste package failure, comparison with known industry failures, unanticipated degradations mechanisms, and reliability of non-destructive evaluations.

While it is anticipated that general corrosion will be the main degradation mechanism that causes waste package failures, a small percentage of waste packages will be subject to early failure. Early waste package failures provide the potential for radionuclide release within the regulatory period.

Status of the canister development programme

Bill Bowyer

1. The copper corrosion barrier

1.1 Manufacture

A satisfactory process (extrusion) has been developed for production of the cylindrical shell. Processes which have been used for the manufacture of tops and bottoms are far from ideal in metallurgical terms. SKB are aware of our concern in this area and it is believed that some work has been done on a forging process which would be designed to achieve a satisfactory structure. The results of this work have not so far been disclosed.

Two welding processes are in development for joining the bases and the lids to the central cylinder, Electron beam welding and friction stir welding. Neither is yet producing reproducibly satisfactory results. The electron beam process has been under development for this application for more than 20 years and a breakthrough is required if the technique is to be successful. Friction stir welding is a relatively new process with all the desirable characteristics to meet the needs of this application. Development is incomplete but progress is rapid and the scope for improvement within the process constraints appears to be considerable.

1.2 Properties

It seems very likely that the corrosion properties of the extruded tubular will be satisfactory and that once the proper forging techniques are used the same will be true for the lids, the bases and the welds. I believe that some work on stress corrosion cracking and resistance to microbial attack is continuing.

Static mechanical properties of the OFP (oxygen-free with phosphorous added) copper do not present a problem but creep behaviour is still a matter for concern. It is believed that the high residual stresses arising during manufacture will relax to values well within the power law creep regime within a few days of completion but lower level repository stresses will be present throughout the storage period. It is known that OF (oxygen-free) copper exhibits brittle failure when it is tested in the low stress regime and that it exhibits ductile failure when it is tested in the high stress regime. OFP exhibits ductile failure in the high stress regime but no tests have been completed under representative conditions in the low stress regime. The reason for this is that OFP is a stronger material in creep and very long test durations are required for meaningful results to be achieved. Some recent work seems to demonstrate that testing under triaxial stress conditions leads to an acceleration in creep deformation without changing the deformation mode. If this is an accurate interpretation then the way may be open to carry out creep tests on OFP material in the power law regime in laboratory timescales and to use the results so obtained to predict the behaviour of OFP material under repository conditions. A complication arising from this observation is that we know that the stress regime in the repository will impose triaxial stresses on the canister and the implications of this for creep need to be thought through.

2. The cast iron liner

The cast iron liner uses a nominally ductile cast iron. The design calculations and all calculations based on the reference case for stresses have assumed that the textbook properties for this iron will be achieved. This is certainly a highly optimistic approach. The textbook properties for strength and ductility refer to specimens cast under ideal conditions which exhibit the ideal structure.

Development of the ideal structure depends on composition casting technique and conditions of cooling. The design of the liner ensures that all three of these are effectively variable throughout the casting. Calculated properties for the liner based on textbook material properties will not be achieved. We do not know what properties will be achieved in the liner as a whole or what the variability of properties will be within an individual casting or between castings. We may confidently expect that regions of any liner will have the wrong structure and that ductility will be reduced from a nominal 20% to values of 2% or less locally in regions of the liner.

3. Repository stress

Swelling pressure in the bentonite is still subject to considerable uncertainty and this impacts on considerations of canister survival. Figures from recent work (Börgesson et al 2003-SKB Technical report, to be published) indicate that a 2.5% increase in density of the bentonite above the reference value doubles the swelling pressure and a 5% increase in density results in swelling pressure being increased by a factor of 3. We do not know how easy it is to control density but if variations of this order arise then it is necessary to reconsider the calculations for the stability of the canister as a whole.

Statistics of Canister Defects

Tim Hicks, Galson Sciences Limited, UK

Background

The isolation function of the copper canister is an important feature of the KBS-3-type disposal concept. Defects in any canisters at the time of disposal may affect repository safety in the long term. The design requirement on canisters is that no more than one canister in one thousand should have a defect. This requirement has a direct implication on repository safety assessments, which have included assessment of a canister defect scenario in which no more than 0.1% of canisters are defective.

Adopting this assumption on the percentage of defective canisters places a significant reliance on manufacturing reliability and future quality checking. It is important to investigate the level of confidence with which the design objective can be achieved. This paper presents a preliminary investigation into whether statistical or other approaches could be drawn on to evaluate confidence in canister integrity.

Statistical Approaches

Sampling approaches are used to estimate the characteristics of a large population based on the measured characteristics of a subset of the population. A topical example of a sampling approach is in its application to the monitoring and inspection of waste packages during storage. Hicks and Wickham (2002) presented methods for determining the minimum sample size of waste packages based on consideration of the required reliability of the resulting population estimates for a store containing many thousands of packages.

Application of this approach to evaluation of canister reliability under the KBS-3 concept is not immediately obvious because each canister, rather than a sample of canisters, will be inspected before emplacement in a repository. However, it is worth considering a hypothetical scenario in which only the first n packages to be manufactured are inspected, and these n packages represent a random sample of all canisters to be manufactured. This assumption requires that there are no systematic errors in the manufacturing process so that the inspected canisters form a statistically representative sample of all canisters. This approach allows the determination of the minimum value of n that will ensure, to a specified level of confidence (say 95%), that no more than 0.1% of all canisters will be defective.

Minimum sampling plans are typically used in situations where parts are limited in availability or are highly expensive or time consuming to test (Tobias and Trindade, 1994). Such plans are based on an acceptance number of zero defects for the sample. Assuming that the sample is drawn from an ongoing process, the binomial distribution applies. The binomial distribution gives the probability of exactly x failures in n trials, with probability of failure p per trial, as:

$$P(X = x) = \binom{n}{x} p^x (1-p)^{n-x}$$

where

$$\binom{n}{x} = \frac{n!}{(n-x)!\,x!}$$

With a zero acceptance number, the probability of zero failures, $P(X = 0)$, must be equal to the required risk level, β. Thus:

$$(1-p)^n = \beta$$

or, solving for n:

$$n = \frac{\ln \beta}{\ln(1-p)}$$

This is the minimum sample size necessary to ensure a maximum risk of β of accepting the sample if the fraction of the population defective is higher than p.

Applied to the process of canister manufacture and inspection, protection against a fraction of defective canisters of more than 0.001 (p = 0.1%) with 95% confidence (β = 0.05), requires a minimum sample size of about 3,000 canisters. That is, some 3,000 canisters would need to be inspected and found to be free of defects to be 95% confident that no more than that 0.1% of a population of canisters had defects. This simple analysis reinforces the need for inspection of all of the 4,500 canisters to be manufactured prior to disposal to ensure confidence in the design requirement that no more than 0.1% of all canisters are defective.

Approaches Based on Human Error Rates

Ideally, if the inspection of each canister prior to disposal revealed any potentially significant defects such that all defective canisters were discarded or repaired, then no defective canisters would be placed in the repository. However, the degree to which this ideal is achieved depends on the validity and reliability of inspection. For example, human error during inspection could result in the disposal of a defective canister. A number of studies have attempted to quantify human error rates for risk analyses. For example, Smith (1997) provides an overview of the range of quantified human error rates. Smith (1997) notes, however, that reliability on human response is governed by a number of factors, including: environmental factors, (physical, organisational, personal); intrinsic error (selection of individuals, training, experience); and stress factors (personal, circumstantial). Due attention to these factors can ensure that error rates are minimised.

Several human error rates listed by Smith (1997) are of potential relevance to canister inspection. For example, an error rate of 0.003 per task is shown for a simple visual inspection for a defined criterion. A task where more care is needed, such as reading a graph, has an error rate of 0.01 per task.

In simple terms, such error rates could be used to provide an indication of the likelihood of the disposal of defective canisters. For example, 0.1% of canisters emplaced in a repository might be defective if 10% of all manufactured canisters were defective, and the inspection of canisters had an error rate of 0.01 per task. Of course, greater confidence in achieving the design requirements can be achieved by ensuring high quality of manufacture and inspection. For example, independent inspection of canisters by more than one individual would reduce the potential for human error.

Use of Expert Judgement

Expert judgement provides an initial means of evaluating the level of confidence in canister integrity. Given the importance of manufacturing reliability and quality checking, canister inspection and testing strategies will require audit throughout the production period. Such an audit process should increase confidence in the manufacturing process and support any expert judgements on canister reliability.

It is important for the results of audits to be integrated into the expert judgement process for deriving distributions of parameters describing canister reliability. Frequency or Bayesian approaches may be used to derive distribution parameters for key features or processes. In the classical frequency approach, the distribution parameters are assumed to be fixed, and confidence bounds are derived for the parameters. In the Bayesian approach, distribution parameters are assumed to be random variables with prior distributions based on previous knowledge or judgments about the parameters. New data are used to calculate the posterior distribution.

In the context of defining canister properties, using the Bayesian approach, a prior distribution could be defined for the number of defective canisters emplaced in a repository. As the canister manufacturing and inspection process proceeds, information on canister defects could be used to improve the parameter distributions for canister integrity. Such an approach allows uncertainty in canister integrity, and reductions in uncertainty in canister integrity, to be integrated into repository performance assessments.

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Manufacturing of Copper canisters

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This abstract summarizes an evaluation made by IVF of a proposed manufacturing process for copper canisters. SKB and MABU Consulting produced the evaluated proposal during the period of 1999-2000.

1. General conclusions regarding manufacturing of copper canisters

From a technical point of view the manufacturing of copper canisters does not offer any unsolvable problems. There is however some manufacturing issues that needs special attention. Most apparent are the necessary welding operations that still will have to be further tested and evaluated.

Regarding manufacturing of the components included in the final canister assembly, no real technical problems have been identified. On the other hand there are some work left in order to find economically acceptable manufacturing solutions. These issues are mainly connected to the manufacturing of the copper cylinders, and to some extent to the manufacturing of cast iron inserts. There are also some specific operations that should be further evaluated, and in some cases replaced by more effective methods.

There are existing methods and tools available on the market, which fulfil the demands regarding quality assurance, and measuring of component properties. Once more the welding processes are most demanding, but no real problems in order to inspect the result have been identified.

1.1 Manufacturing of copper cylinder

Except for the welding operations this task is seen by IVF as the most critical. Both from technical and economical points of view, a bad choice will have a large impact on the final result. IVF has studied proposals of two different techniques to manufacture the cylinders. The pros and cons of each method are stated below. In both cases however, the low numbers of needed components indicates that the manufacturing cost will be rather high (see chapter 2).

1.1.1 Manufacturing by rolling and welding of copper plates

This method has proven to be able to produce cylinders of acceptable quality. However there are some aspects of the manufacturing process that indicates that other methods should be tested and evaluated:

1. The manufacturing chain is rather complex, with many different operations involved.
2. A lot of welding operations is needed, which increase cost and put high demands on quality inspections etc.

3. Material utilization is poor, which means that a lot of copper results in scrap at high costs
4. Machining of pure copper often produces long chips, which can disturb the cutting process.

1.1.2 Manufacturing by extrusion of copper solids

This method was slightly less established as a possible method for production of copper cylinders, at the time of the evaluation. Therefore, experience regarding pros and cons of the method were a little bit unclear. An overall judgement indicated however that this method should be a strong contender to the method described above. This since the manufacturing chain for producing cylinders will be very simple, as well as for the fact that welding operations are excluded when using extrusion. Some aspects will however still have to be investigated further, in order to give a correct verdict, concerning the methods ability to produce good cylinder parts:

- The ability to produce cylinder parts with sufficient straightness
- Material properties after extrusion
- Reliability of the method
- Cost for necessary equipment, inclusive tools etc.

1.2 Manufacturing of cast iron insert

IVF has not evaluated the actual casting process. When it comes to the machining of the cast insert to its final dimensions, no significant problems have been identified. The actual size of the inserts means that rather large machine tools will have to be used. These machines are available on the market, and the technique for machining this type of parts is standard knowledge.

One operation that can result in some difficulties is the removal of sand particles from the insert cavities. The tested method of using blasting has some drawbacks. Therefore, alternative methods should therefore be tested and evaluated, in order to find more effective solutions.

1.3 Manufacturing of insert steel lid

The manufacturing of steel lids for the cast iron insert does not include any challenging problems at all. The material itself is very easy to machine, and the specified lid geometry does not make the machining difficult in any way. Instead it could be a good idea to find a reliable sub-supplier, who most probably can manufacture these parts far more cost-effective. An internal quality inspection will certify that delivered components live up to the actual specifications.

1.4 Manufacturing of copper lid and bottom

As well as for machining of the steel lid described above the manufacturing of the copper lid and bottom for the cylinder does not include any major problems. The only thing that makes it a little bit more difficult is poor machining properties of pure copper. This will however not result in any real problems, and almost every modern workshop can handle this type of machining. Also, the component geometries do not make the machining difficult in any way. Once more it could be a good idea to find a reliable sub-supplier, who most probably can manufacture these part far more cost-effective.

1.5 Welding of canister bottom

As mentioned earlier the welding processes are regarded by IVF as the most critical, in order to manufacture the copper canisters. A very fast development is however continuously going on, which is very promising. At the time of IVF´s evaluation of the welding processes (2000), Electron Beam Welding was most established. Since then the methods of using friction stir welding or laser welding has made real progress. These methods will certainly offer alternative solutions in a near future. IVF has not recommended a specific method, due to the rapid development within this field.
In any case, the welding operations will be the most costly part of the canister manufacturing. These operations are also critical in order to create sufficient properties of the canisters. Therefore it is very likely that welding operations will be one of the core businesses of a canister manufacturing plant.

1.6 Measuring and inspection routines

IVF has not identified any major problems in order to inspect and/or measure components or the final canister assembly. There are well-tested and reliable tools and techniques for these purposes available on the market. Instead the well specified and non-changing component dimensions and properties make it possible to use more simple inspection and measuring tools, with low demands regarding flexibility etc.
Once more the inspection of welding seams, and possible changes of material properties or dimensions after welding, is most demanding. However, no real problems are identified within this application area since commercially available test equipment exists already.

1.7 Final canister assembly operations

The assembly of the cast iron insert into the copper cylinder will most probably not introduce any major problems. If the components has been manufactured and measured correctly in the earlier manufacturing stages, the final assembly is not complicated. The critical parameters are the size and weight of the components. Necessary assembly fixtures and handling equipment will therefore probably be rather costly to design and manufacture.

2. Suggestions in order to establish cost-effective manufacturing solutions

In general IVF claims that there is a good possibility to make the manufacturing of copper canisters far more cost-effective, than what the solutions up to this date has indicated. There are a number of modern manufacturing strategies that would reduce both overall investment costs, as well as the manufacturing costs per unit, drastically. Some examples are stated below.

2.1 Outsourcing of manufacturing of non-critical components

By separating the manufacturing of components with low complexity level, and non-critical properties, great savings can be made. These components can normally be manufactured by sub-suppliers to a very low cost, and then delivered just in time to the canister production unit. Examples of components can be lid and bottom of the copper canister, as well as the steel lid for the cast iron insert. This type of solution will also drastically reduce the necessary investment in manufacturing equipment for the production plant. The personnel at the plant can then concentrate on the core processes such as manufacturing of the copper cylinder, welding, activities for quality assurance and final assembly.

2.2 Inventory levels for raw material, components and assembled canisters

Copper is a relatively expensive material. This fact, in combination with the large amount of material circulating on the shop floor, will keep a significant amount of money tied up. Therefore, it is essential to reduce the material volumes as much as possible. Inventories for raw material should be kept low, and produced canisters should be produced “just-in-time” if possible. It is also recommended that components, which are manufactured by sub-suppliers, should be delivered in close connection to the final assembly of the canisters. This in order to further reduce the inventory kept at the production plant.

2.3 Organisation and manning of a canister manufacturing plant

Since the stated production volume per day is rather low, the work force has to be flexible. This since each work task often only occupies smaller parts of an eight-hour working day. Therefore machine operators should be trained to handle a number of different machine tools. (lathes, milling machines etc.) They should also be capable of performing measuring of components as well as taking care of internal transportation of material. This approach will also result in a favourable work content for each employee.

2.4 Distribution of manufacturing tasks between co-operating partners

If it is possible for a number of partners to co-operate, a significant improvement would be made concerning the cost to manufacture canisters. This is especially obvious when it comes to the manufacturing of the copper cylinders. If for example one partner invested in equipment for extrusion of copper cylinders, it could be utilized far more if the “market” was greater. Another task, which could result in a similar positive effect, is the production of cast iron inserts.

Issues Relating to the Manufacture and Emplacement of Compacted Bentonite upon the Performance of the KBS-3 Design

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In the KBS-3 concept, bentonite is used around waste packages as a 'clay overpack' (Pusch, 1983), in tunnels as a backfill, and in tunnels, boreholes and shafts as 'plugs'. Bentonite used in disposal holes as an overpack will be emplaced in disposal holes as compacted bentonite blocks. It is this latter emplacement technique/methodology which has been questioned recently (e.g. Toyota and McKinley, 1998, in consideration of the application of the technique to the Japanese and Swiss programmes). For example, it is likely that compacted bentonite blocks may start to swell in the humid underground environment, before emplacement, thus hindering the emplacement technique. Also, it may be difficult to achieve perfect fits between different blocks so that undesirably large gaps may appear in places. Techniques for manufacturing and emplacing compacted bentonite blocks need to be evaluated very carefully if such methods are not to impact upon the long-term safety behaviour of the repository. These issues have been reviewed by SKI (Savage et al., 1999).

Manufacture of compacted bentonite blocks

SKB has investigated the feasibility of producing compacted bentonite blocks on the industrial scale (Johannesson et al., 1995). These blocks were of 10-15 kg in weight. Tests for producing blocks of this size were carried out by Höganäs Bjuf AB. Tests showed that it was possible to make good quality compacted blocks, particularly with coarse ground bentonite with a water content of 20 %. Initially a number of problems were encountered, namely:

- cracks due to friction between the mold and the bentonite;
- cracks caused by air that was entrapped in the blocks during compaction;
- cracks due to the elastic swelling at unloading and removal of the block from the mold;
- cracks caused by brittle edges of the blocks;
- damage due to the sticking of the bentonite to the mold and pistons;
- desiccation of the blocks during storage;
- appearance of mould on the blocks during storage.

These problems were eliminated during the tests by:

- using coarsely ground bentonite;
- using stepwise compaction;
- using fairly large gaps between the pistons and the mold;

- making blocks with a height/diameter ratio not larger than 0.4;
- lubricating the mold with oil;
- making sure that water saturation was of the order of 20 %;
- wrapping the bentonite blocks in plastic sheeting to prevent desiccation;
- making sure the water content did not exceed 20 % to eliminate the formation of mould on the blocks.

Even after designing a technique to produce high quality bentonite blocks, the edges of the blocks were prone to fall off, even though the rest of the block remained intact.

Further work for SKB by Kalbantner et al. (2000) has shown that the isostatic pressing technique is applicable to the production of both ‘high’ and ‘medium’ size blocks, but that the uniaxially-compressed blocks require a greater degree of precision and control during manufacture.

By contrast to work carried out for SKB, ENRESA (1998) reports activities concerning the manufacture of bentonite blocks for the FEBEX experiment at the Grimsel underground research laboratory in Switzerland. For the FEBEX project, about 300 tons of Spanish bentonite were selected, homogenised and treated. At the factory, the bentonite was disaggregated and dried to a water content of 14 %, and material with particle size > 5 mm was rejected. The processed material was used to fabricate blocks both for the in situ and mock-up tests. The bentonite was characterised mineralogically by Ciemat and was found to have > 90 % montmorillonite, with roughly 40 % of the exchange sites occupied by calcium. Blocks for both the in situ and mock-up tests were manufactured using a 'crown' technique, in order to minimise void volumes. Compaction took place at 40-50 MPa, with the resulting dry density being 1.77 g cm^{-3} for the mock-up test and 1.70 g cm^{-3} for the in situ test. ENRESA report no major problems during block fabrication, although some crumbling was observed in blocks made from bentonite with higher water content. The optimum water content was determined to be 16 %, which is similar to that recommended by SKB (above). Some fracturing during storage of the blocks was observed, which was attributed to those blocks pressed with a water content higher than 16 %. Characterisation of the physical properties of the blocks revealed no dramatic differences between blocks or within block samples. ENRESA report no use of lubricating oil to ensure better removal of blocks from molds. Blocks were packaged in cardboard boxes placed on wooden pallets prior to emplacement. There was a plastic lining and plastic 'sponge' within the box. ENRESA (1998) does not refer to any problems during storage such as water absorption or growth of mould.

Emplacement of compacted bentonite blocks

SKB investigated the practicalities of borehole, shaft and tunnel sealing as part of the International Stripa Project (Pusch et al., 1987a, b, c). The borehole plugging experiment consisted of three field tests using Na-bentonite as a sealant. The emplacement technique utilised compacted blocks of bentonite contained in a perforated copper sheath. The plugging of a 100 m long, 56 mm diameter borehole demonstrated the practicality of the technique and the plugs 'matured' quickly enough that piping or distortion by high hydraulic gradients did not occur after one week. After 2.5 years, it was discovered that the clay was completely saturated.

The shaft plugging test consisted of a comparison of the sealing effect of bentonite with that of concrete. The test was conducted in a 14 x 1.3 m diameter shaft with alternately two concrete plugs or two bentonite plugs separated by a sand-filled injection chamber. This test concluded that the bentonite blocks were almost non-permeable, blocked flow passages along the rock/plug interface, the clay swelling pressure compressed fractures in the rock, and the clay expanded into fractures and shallow openings. The practical application of the bentonite blocks was deemed to be a simple and straightforward process and that the filling of gaps between the blocks and the rock with bentonite powder did not have to be especially precise.

The tunnel plugging test was aimed at determining whether the use of compacted bentonite would be a practical technique at the large scale. The test arrangement consisted of a 9 m long and 1.5 m diameter steel tube surrounded by sand cast in concrete plugs at each end. These plugs hosted bentonite blocks arranged in the form of O-ring seals at the rock-concrete interface which simulated the temporary sealing of a water-bearing rock zone penetrated by a tunnel in a repository, allowing for transports through the plug construction whilst minimising the water inflow into the tunnel. The measured water leakage through the structure was similar to that predicted from modelling (about 75 l/hour at a pressure of 3 MPa). Again, it was considered that the emplacement of the bentonite blocks was practical and that the sealing power was substantial despite strong local variations in block density.

ENRESA, the Spanish equivalent of SKB, has investigated the feasibility of emplacement techniques for compacted bentonite blocks via the 'FEBEX' project, an experiment in the underground research laboratory at Grimsel, Switzerland, designed to investigate coupling between thermal, hydraulic and mechanical processes (Huertas and Santiago, 1998; Gens et al., 1998). The FEBEX project involves both a full-scale in situ test underground in Switzerland and an almost full-scale 'mock-up' in a laboratory in Madrid. For the in situ test, a drift 70 x 2.28 m was excavated using a tunnel boring machine. 5531 blocks of compacted Ca-bentonite, manufactured with a dry density of 17 g cm^{-3} were emplaced. The average dry density of the buffer was 1.60 g cm^{-3} (assuming a 3-7 % voidage). The blocks were emplaced in 136 vertical segments. To ensure alignment, a liner was emplaced parallel with the drift axis prior to emplacing the bentonite blocks. The whole system was enclosed with a 2.7 m long concrete plug, designed and constructed to withstand the swelling pressures developed by the bentonite when fully saturated (5 MPa in this configuration). ENRESA believe that the first stage of the test, namely the fabrication, construction and handling of the dummy EBS was achieved successfully (Huertas and Santiago, 1998).

Implications for performance

Although SKB appear confident that manufacturing and emplacement of compacted bentonite blocks will be a straightforward process with little impact upon long-term performance, there are a number of issues of concern:

- the reproducibility of techniques to manufacture and store (both on the surface and underground) thousands of compacted bentonite blocks to minimise problems of block disintegration and degradation (physically or via microbial processes).
- the use of mineral oil to lubricate block production could entail the presence of large amounts of organic materials available for radionuclide complexation in the long-term.
- other agencies (e.g. ANDRA, ENRESA, Nagra) all intend to use compacted bentonite blocks in their EBS design. There is therefore merit in collaborative studies to develop manufacturing and emplacement techniques.

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Engineered barrier systems – Manufacturing, Testing and Quality Assurance; Issues of interest to consider

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Background

A number of requirements apply to a KBS-3 type of repository for spent nuclear fuel in order for it to provide the desired short and long term safety with a high degree of assurance and at a tolerable cost.

All such requirements will have to be met by the technologies applied to manufacture the technical barriers and to put them in place. Thus, we are dealing with a systems analysis, and are also faced with its various elements such as limits of the analysis, systems descriptions, identification of potentially problematic combinations of features, etc.

The approach taken in the present contribution would be similar to that of an HazOP analysis, i e identification of areas which might warrant consideration and attention. It is hoped that this approach will lead to constructive discussions, valuable contributions and a comprehensive coverage of the topic at the workshop to be held.

Thus, supposedly salient questions will be asked in what is to follow. This should not be related to the author's views, nor to those of SKI, but be regarded as just a support to the workshop. Please note also that the questions are not supposed to reflect the present stage of development at SKB, but rather issues which warrant attention and consideration.

On long time

The issue of long time warrants special attention not just to the safety analysis itself but also to the manufacturing. Important features in this regard include the following:

- The times in question are accessible to us mainly by means of extrapolation (natural analogues play a certain role as well)
- Extrapolation is usually performed by means of Arrhenius equation. It is valid only if there is one mechanism in one material
- In some cases, scaling up to longer times and larger dimensions may be justified without any large difficulties (e g diffusion related processes)
- In other cases, artefactual phenomena might invalidate prognoses made. How could such phenomena be identified, and is there a systematic approach to be applied?

Examples of manufacturing and extrapolation related issues include the following:

Issue	Relation to manufacturing
Can the ability of the canister to deform be less favourable at very slow rates of deformation?	Relates to the issue of diffusion limited creep and its relation to the design, e g the fit between the outer and inner canister and the associated constraints for the creep process.
Can diffusion or capillary flow in surface layers be more rapid than diffusion in the gas phase at high pressure and long times?	The question has to do with the mechanism for transport of water into a penetrated canister. Relates to the largest defect acceptable from manufacturing.
Is there any mechanism which can lead to growth of corrosion products on the canister in elongated structures?	Relates to anion exclusion in combination with pores in the bentonite in combination with transport of copper through copper sulphide.
Can bentonite recrystallise or otherwise restructure so that its properties change?	The handling of the bentonite involves oxidation, carbonatisation, dehydration and shearing. Will this lead to changes over time?

Manufacturing and sealing of the canister

- The quality of the copper and its relation to the various processes and properties
- The significance of fine microstructure for good mechanical properties
- The significance of fine microstructure for good inspectability
- The relation between materials properties and manufacturing methods (extrusion, rolling, forging {lid} e t c)
- The significance of this relation to need for scale in the manufacturing tests
- Methods for sealing (electron beam and friction stir welding) and properties for the seal
- What types of weld defects are to be expected
- Methods for inspecting the weld (ultrasound, x/gamma-rays)

Preparation of bentonite blocks

- What bentonite will be used and for which types of water?
- What happens if/when the water chemistry changes with the glaciation cycles?
- Methodology for manufacturing of the bentonite blocks (uniaxial or isostatic)? Advantages and disadvantages?
- What size of blocks will be used (brick-size, full diameter or {more or less}full size)?
- Do the manufacturing methods apply equally well to all types of bentonite considered?

- How to manage the internal stresses in bentonite appearing as a result of compaction (mainly for the uniaxial one) and of moisture availability variations? E g a slightly elevated moisture content in the air will lead to an expansion of the surface layer of a bentonite specimen, consequent tensile forces, and fracturing on the inside. Such fractures are not readily observed but can jeopardise the integrity of the specimen.
- How is appropriate uptake of water by the bentonite to be assured? Fracturing together with shifts in the positions of the individual blocks might conceivably lead to areas having a lower density.
- What mechanisms of uptake are expected for low and high availability of water, respectively? Do they influence the result, and if so, in what way?
- How is the quality of the bentonite powder to be ensured? How can such a quality be maintained for the time needed considering e g the natural variations in a bentonite deposit.
- How is the quality of the blocks to be ensured? How – if at all – can you determine the relevant mechanical properties of a block (with regard to e g fracturing)?
- How is the gradation of the bentonite powder to be selected with regard to the need for evacuation before compaction (little fines) and the need or advantage of a low level of variation of the density on a microscale (a certain amount of fines)?
- Or is it even desirable with a very coarse grain structure to promote an even wetting?
- How is it to be ensured that the bottom block has the appropriate load carrying capability required during long time?

Design of backfilling

- What materials are intended to be used?
- What is the appropriate gradations of the materials (with regard to clay and non-clay particles)? What is the appropriate agglomeration pattern?
- What is the reactivity of fines from excavation? Is there a case for consolidation, and if so, what microstructural changes might be foreseen, and what significance, if any, might this have?
- How is the proper mixing on the microscale of bentonite and ballast material to be achieved. Small grains form agglomerates which may not easily be disintegrated.
- How is a proper balance to be achieved between on one hand the need for the bentonite to swell and fill the space between the hard particles, and on the other hand the loss of shear load bearing capacity if the bentonite takes up more than this volume? (Shear load bearing capacity is required in order for the bentonite and canisters in the deposition holes not to partially rise into the tunnels with the consequent loss of density in the bentonite around the canisters)
- Is there a case for manufacturing of blocks for backfilling?

Operation of the repository

- How is an empty deposition hole to be characterised and what are the prerequisites for acceptance?
- Is there any technique available to see inside the walls of a deposition hole (such as radar or magnetic resonance)?
- How should the deposition hole be kept sufficiently void of water to allow the emplacement operations?
- How should the bottom surface of a deposition hole be made sufficiently planar and levelled to allow the appropriate stacking of the bentonite blocks and the canister?
- Is there any requirement on the roughness of the walls of a deposition hole to ensure appropriate friction with the bentonite
- How is the wetting of the bentonite to be carried out? Artificially or naturally?
- What would be the advantages, if any, to use fresh water for the wetting?
- What would be the advantages/disadvantages, if any, of wetting the entire surface all at once as compared to spotwise?
- Is there a case for misaligned / fractured blocks and the associated variation in density during and/or after wetting?
- What is the precise pattern of cooling at the canister surface? Is there 100 % water saturation, i e no gas phase present? In the case of a gas phase, is there a case for transport of dissolved salts by capillary action to the canister surface? If so, what is the significance, and how does this (if at all) relate to the design / emplacement?
- How are the bentonite blocks to be handled with regard to their quality assessed mechanical properties?
- Are there any particular surface conditions which are required / desired for the canister when emplaced? If so, how is the handling to be carried out to ensure that surface damage does not occur?
- How is the densification of the backfill to be carried out? Pertinent aspects include input vibration energy per unit area versus spring back properties with regard to compaction in different directions. What does the load versus compaction relation look like? How does it depend on the moisture content, the mixing and the gradations?
- How does the internal friction depend on the shapes of the grains, and how does this affect the compaction? (In concrete technology sand from crushing of rock is difficult to use because of internal friction and poor flow properties).

Other

- Monitoring after closure? If so how, if at all, does it affect the emplacement operations?
- What sort of quality system is to be applied? How is the knowledge base to be compiled, up-kept and maintained? What systems for reliability, feed-back of experience, and revision are to be applied?
- In particular, how will the hydro-thermo-chemo-mechanical development of the buffer be monitored / assured?
- Needs for independent review and control in general? It should be noted that this and other questions might not be entirely technical in nature.

APPENDIX 5: QUESTIONS FROM WORKING GROUPS TO SKB

Canister Working Group

The Canister Working group arranged their questions into 10 question areas.

1. A range of Bentonite densities from 1900 kg/m^3 to 2100 kg/m^3 has been proposed. The reference swelling pressure is 7 MPa. Within the proposed range of density, variation of swelling pressure will be considerable (from 7 MPa to 20+ MPa). How will this range of swelling pressures affect the calculated canister load cases related to uneven wetting (Werne 1998) and how will it affect the pressure on the canister for the uniform loading case? Rather than using a single value of swelling pressure, is there a range (and an associated distribution across that range) employed in the calculation? How is this uncertainty captured in the PA analyses?

2. For each sealing method (EBW and FSW), what NDT methods are proposed and why? What are the predominant types of flaws associated with the weld techniques selected? What is an acceptable weld flaw type and the associated detection limit of an appropriate NDE method? How are the flaw size distributions captured in the performance assessment?

3. The crushing pressure for the cast iron liner (81 MPa – Werme 1998) is based on ideal properties in the material. How will the variations in properties in the case of real cast iron influence the crushing pressure calculation? How will this influence the response to earthquakes (seismic displacement) as presented by Börgesson (MRS 2003)?

4. A number of analyses include evaluation of a single process or effect (radiolysis, MIC, SCC, long-term corrosion effects, etc.) Has the effect of coupling of these processes been incorporated into recent performance assessment models? Are there data to support conclusions the coupling of these processes? What long term corrosion experiments are underway for this range of conditions (humidity, surface chemistry, MIC, radiation flux, weld microstructure)?

5. If a weld is determined to be unacceptable, what are the current options for remediation (grind out, repair)? How can you assure the quality of a repair? What is the order of weld inspection (then repair)? In what order do you do post-weld machining, inspections, rework, reinspect?

6. How are human errors in fabrication, canister loading, sealing, inspection and transport considered in the overall performance assessment process? What are the likelihood and consequences of human error?

7. Are there alternative designs to the cast iron insert being considered? If so, what are they? What NDT methods are proposed for the cast insert?

What type of flaws can be detected? How can microstructure of cast insert be confirmed?

8. What are the primary canister issues associated with horizontal emplacement? (Bending moment, criticality issues, void space, stress distribution, Bentonite and ground support – iron corrosion product issues)?

9. How much data are enough? How do the data acquired in the scientific program feed back to ultimate criteria for performance of the whole repository?

10. What is the acceptable level of surface damage as a result of handling? What kind of inspections are completed upon arrival of the canister at emplacement location? Where/what is final inspection?

Buffer and Backfill Working Group

The Buffer and Backfill Working group arranged their questions into 6 different areas, and marked the prioritized questions with numbers.

Selection of materials

1. What are the functional requirements of the buffer? What are the properties of the reference buffer material needed to meet these requirements? What are the nominal values and permissible ranges of technical specifications regarding material composition (*e.g.,* mineralogy) and initial state (*e.g.,* compaction density, water content) needed to achieve these properties?
2. Will alternative buffer materials (*e.g.,* IBECO) be considered? If so, what will be the technical basis, and schedule, for making a final selection among the reference material and alternatives?
3. How will SKB address the relation between material properties and the likely range of environmental conditions (*e.g.,* groundwater chemistry, no. of fractures, groundwater inflow rate, *etc*.) in the repository?

- Is it a requirement that the buffer should have a capacity to act as a redox buffer? If so, how will this be confirmed?
- How will the long-term performance of the buffer be affected by low-saturation, high temperature alteration, *e.g.,* effects of impurities?
- What materials selection criteria will be used to ensure that canisters will not sink in the bentonite? Are there any modifications warranted to rule this out?

Fabrication

1. If uniaxial pressing is used, will the bentonite blocks come into contact with lubricants?
2. Will the blocks be made on a ‘just-in-time’ basis, or will they be stored for relatively long periods of time?

Emplacement

1. Has SKB assessed what is required to achieve 'good-enough' performance with regard to bentonite emplacement?
2. Will SKB use artificial wetting to saturate the bentonite to ensure rapid re-saturation and a desirable water chemistry? (low salinity)
   - will horizontal deposition affect the possibilities of artificial wetting?
   - will an artificial membrane be used to ensure saturation of the buffer?

- Will gaps between bentonite blocks, or the use of imperfect blocks, adversely affect swelling and long-term performance?
- Has SKB assessed the pros and cons of using different sizes and shapes of bentonite blocks?
- How will the 'toothpaste effect' (*i.e.,* differential swelling between the buffer and backfill) be managed?
- How will SKB address non-uniform saturation of the bentonite?
- Is there a minimum groundwater inflow rate to ensure bentonite saturation?

Testing

1. How will SKB demonstrate that the functional requirements of the buffer will be met? Are there potentially adverse THMC conditions (*e.g.,* leading to buffer cementation) that cannot be addressed by testing? If so, how will these conditions be handled?
2. What statistical basis is needed to interpret the results of long-term experiments?

- The prototype repository testing covers one specific set of hydrogeological conditions - will it be necessary to consider other conditions in full-scale testing, *e.g*., groundwater with higher salinity and/or lower flow rates?
- Will there be additional long-term testing other than that already being carried out?

QA

1. What are SKB's QA/QC plans for acceptance of raw bentonite material and manufactured bentonite blocks (*e.g.,* will the smectite content and composition be measured routinely)? What QA exists for the supply of raw bentonite material?
2. What are the inspection criteria for bentonite blocks prior to canister deposition?

- How will SKB's QA requirements be integrated with that of the suppliers?

Backfill-specific questions

1. What are the functional requirements of the backfill? How will it be made? How will it be emplaced?

- How will the possible occurrence of saline groundwater affect material selection and emplacement design?
- What long-term testing is planned for the various backfill alternatives?
- What requirements are there for the backfill in terms of sealing the tunnel - should the backfill completely fill the tunnel, or will plugs be considered if voids occur?

- Is TBM muck still an option for the ballast in the backfill? If so will the muck be stored prior to use in the repository?
- Are there performance aspects related to the chemical reactivity of fine grained rock mixed with bentonite?
- Are there special requirements for the backfill with regard to the EDZ?
- What is the rationale behind using ‘sandwich layers’ of bentonite within the backfill?
- What mechanical requirements are there for the backfill to keep the buffer in place?

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