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KBS-3H design description 2005

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Abstract

SKB and Posiva are performing an R&D program over the period of 2002–2007 with the overall aim to develop the KBS-3H to an alternative to the KBS-3V concept for disposal of spent nuclear fuel. A feasibility study of the KBS-3H concept was carried out in 2002, followed by the setting up of basic design in 2003. Several problems related to the behavior of the design and scope of future research and development work were addressed. Therefore the design basis was developed further and two candidate designs were developed: 1) previous Basic Design (BD) was developed more robust and tolerable to inflows. Parallel to that a novel modified 2) DAWE design with Drainage, Air evacuation and Watering and was developed to function robustly at various inflow situations. The candidate designs presented in this report include several novel components, such as fixing rings and steel plugs which have been designed without support of applicable design guidelines, regulations or standards available. The design basis and performance of these components include uncertainties, which should be studied and verified. It is possible that a feasible site specific design can be based on using both alternatives.

Preface

The work described in this report has been coordinated and managed by Jorma Autio/Saanio & Riekkola Oy who has written the report. The members of the design team have been Paul-Erik Rönnqvist/Fortum Nuclear Services Ltd, Esko Hämäläinen/Esko Hämäläinen Oy and Matti Kokko/Saanio & Riekkola Oy who have worked with steel design, pipe design and underground design respectively. Jari Gerlander/Saanio & Riekkola Oy has carried out the rockmeachanical modelling. Valuable information concerning the behavior of bentonite have been provided by Lennart Börgesson and Torbjörn Sandén/Clay Technology Lund Ab who have also carried out the buffer tests.

Contents

1 General

Several problems related to the behaviour of KBS-3H design and scope of future research and development work were addressed in the seminar in Stockholm 9th Feb. 2005. The designs were reviewed and assessed to contain significant uncertainties and problems. The most significant functional uncertainties and problems were related to:

1) **Piping.** Piping of water flows in buffer may cause detrimental erosion and transport of bentonite. It has been observed in scale experiments (1:10 and 1:2) that present KBS-3H designs (both TDB and OT alternatives) are not likely to behave in deposition drifts as planned under predicted inflow conditions at repository sites. The results are indicative and include significant uncertainties (e.g. scaling).

2) **Lack of adequate groundwater controlling techniques.** There is no proven existing technique for sealing the deposition drifts reliably to prevent detrimental inflows. The rock cannot be sealed to the required level by using present grouting techniques because the hydraulic apertures of the fractures, which exceed the present inflow limits (0.1 l/min per supercontainer unit) are clearly under 50 microns.

3) **Uneven saturation.** Saturation of buffer between supercontainer sections takes place unevenly. Therefore large variations in saturation degree and hydraulic head between container sections could cause significant flow and transport of bentonite (related to problem 1).

4) **Rupture of distance blocks.** Hydraulic pressure differences in deposition drifts may cause displacement or rupture of distance blocks during saturation phase and enhance the piping. The displacement of block was previously planned to be eliminated by using massive steel fixing rings between container sections, which however increase the amount of steel in drifts significantly. The fixing rings used to eliminate the movement of blocks were evaluated as a "show stopper" to be solved and verified in order to prove the feasibility of the design.

As a consequence of the seminar the functional requirements of the concept were revised and new modified designs to resolve the most significant problems were developed as described in this document.

2 Development strategy

The following approach was developed to produce new candidate designs. The problems related to unsatisfactory behaviour of buffer during saturation phase, caused mainly by piping and possible distance block displacement or rupture, are solved by:

- Utilizing the knowledge of site conditions to divide the deposition drifts into compartments and adapting the drift lay out in rock to utilize the rock heterogeneity in design by using suitable sections for deposition and by plugging the unsuitable sections.
- Reduction of operational time dependent problems by reducing the operation time by dividing the drifts is compartments.
- Increasing the robustness of the buffer and plug design by allowing local technical optimization and by controlling, if necessary, the initial state of saturation by using drainage, artificial watering and air evacuation.
- Using several different groundwater control techniques in different phases.
- Developing a research and development plan to verify the feasibility of the designs. Research is a significant part of the development of new designs because all the design solutions and alternatives are novel in a sense that there are practically no applicable standards or design quidelines. Therefore research and development should be evaluated parallel to design work and should be focused on the reduction of several significant uncertainties in the engineering design.

The present understanding of the inflow limits is indicative and may include significant uncertainties caused by e.g. scale effects and therefore important part of the development strategy is to specify the tolerance of the design for inflows more accurately.

The development in these areas is aimed at improving the feasibility of the concept so that most of the deposition drifts can be used fully for deposition and most of the few drifts with larger original inflows can be used to some degree.

2.1 Division of the deposition drift into compartments

The site data is utilized to divide the deposition drifts to compartments between major water leaking fractures where the water inflows inside the compartments are below the limits. According to the recent evaluation of geohydrological data of Olkiluoto site the bedrock may be composed of long relatively tight section between major hydraulic fracture zones (RH-zones by /Vaittinen et al. 2003, Hellä et al. 2006/). These less water leaking section would be intersected by few water leaking fractures or hydraulic features /Vaittinen et al. 2003, Hellä et al. 2006/.

At Olkiluoto the deposition drift is likely to be divided into 2–3 compartments as illustrated in Figure 2-1. It is possible that some of the deposition drifts could be used in principle as one compartment. There is as well a possibility that some of the drifts have to be rejected.

The development of ground water controlling techniques and buffer design will probably increase the compartment lengths, utilization degree of the site and feasibility of the designs significantly.

The bentonite buffer will swell because of air humidity, crack and fill the open gap between buffer and rock. The estimated time for filling the gap has been evaluated to be roughly in the in the range of 90 days. The cracking will, however, take place in a shorter time. Therefore the shortening of operation time (canister emplacement campaigns) by dividing the drift in compartments will reduce the problems related humidity induced swelling and cracking during operation.

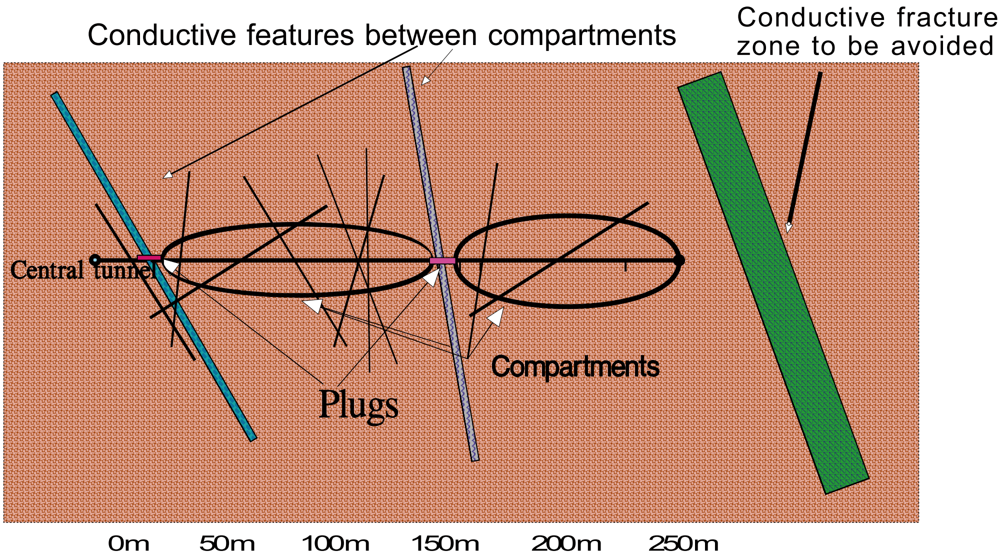


Figure 2-1. Illustrative example of division of deposition drift into compartments. Plugs are emplaced between the compartments in positions of significant water leaking fractures.

Some of the most significant questions related to the division of drifts into suitable compartments are:

- Is the length and number of suitable deposition sections large enough to allow high degree of site utilization?
- What is the realistic inflow limit for suitability of supercontainer emplacement?

2.2 Improvement of the robustness and performance of the KBS-3H design

Two candidate designs were developed. The 1) previous basic design (BD) is developed more robust and tolerable to inflows. Parallel to that a new modified 2) DAWE design with Drainage, Artificial Watering and Air evacuation was developed to function robustly at various inflow situations.

1) Features of BD-alternative:

- The original tight distance block concept is used in “dry” compartments. What “dry” means in practice remains to be defined.
- The sealing efficiency of clearly longer distance blocks is studied in case these could be used in selected sections on the basis of inflow conditions.
- The dimensioning principles of the basic design are specified and the function of e.g. longer distance blocks is evaluated.
- A compartment plug/bulkhead is developed and designed to isolate significant water leaking fractures from the compartments. The plugs should stand full hydrostatic pressure. Use of steel in the design is studied to reduce the amount of concrete (preferably of low pH type), however massive steel structures and large quantities of steel should be avoided. The installation time of plugs should be short to enable rapid sealing.
- Systematic massive fixing rings are not used within the deposition drift. Lightweight fixing rings can be used sporadically and the buffer-distance block contact is designed to minimize the design pressure.
- The end of distance block and container are coupled to minimize the hydraulic force against distance block (and possible fixing rings).

2) Features of DAWE alternative:

- A compartment end plug/bulkhead is developed as in the previous alternative.
- The distance blocks between supercontainers are assumed to swell rapidly after the compartment is plugged.
- The swelling is accelerated and homogenized by using rapid artificial wetting.
- The gap between distance blocks and rock surface remains sufficiently open for removal of pipes until the compartment is plugged.
- The development is focused on improving the initial saturation by wetting and evacuating the air by using watering/drainage and air evacuation pipes, respectively, in compartments where the basic design is not predicted to function properly.
- The pipes are removed after saturation and air evacuation.
- In dry drift compartments where the groundwater situations are such that drainage, artificial wetting and air evacuation is not required to eliminate possible piping and erosion of bentonite, the corresponding systems can be left out as an option.

It is possible that the development of the design shows that it is feasible to use only one design. However different alternatives are developed until the behavior of buffer is known more thoroughly and the water inflow limits can be defined more accurately.

Some of the most significant questions related to the development of the robustness of the design are:

- Will the original type tight distance block design function properly in “dry” sections?
- What are the inflow limits of the original real-size design (e.g. when using real 5 m long distance blocks in realistic conditions)?
- How significant is the benefit of using initial watering/air evacuation pipes (only surface of buffer is saturated)?
- Acceptance and function of lightweight fixing rings?
- The positioning pipes or selection of pipe material in such manner, that will not form a detrimental continuous pathway between rock-buffer interface?
- Is it possible to plug the compartments rapidly (e.g. use of steel or low pH concrete in the design and development of applicable design requirements)?
- Is it possible to develop the coupling of supercontainer and distance block so that the estimated pressure exerted on the block can be reduced?
- How should one operate the watering/air evacuation pipes in optimal way?
- Should the pipes be filled with bentonite paste/slurry?
- What type of water (or slurry) should be used?

2.3 Development of proper techniques to control groundwater inflows

A stepwise sealing approach based on different techniques should be developed for controlling of inflows in the KBS-3H drift. These techniques will probably not seal the inflows totally but will improve the utilization degree of deposition drifts (number of canisters which can be emplaced in one deposition drift). The stepwise technique should be based on e.g.:

Pregrouting before and during the boring of holes:

- Pregrouting using investigation holes.
- Pregrouting using pilot hole.
- Pregrouting from the deposition drift at a proper distance from the water leaking fracture.
- Use of low pH grouting material and minimization of grout volume in the holes for all techniques used.

It has been observed in many cases that the inflows have a tendency to decrease by time. That feature should be utilized in the design and postgrouting should be carried out after the leakages have been investigated:

- Conventional postgrouting using fan of holes.
- Megapacker type postgrouting.
- Dynamic and static grouting principle.

The use of structural seals in carefully selected positions could also be kept as an option. It is likely that it is feasible to use this type of seals only sparcely and therefore they will not affect the feasibility of concept significantly since the main objective is to place plugs in position of significant leakages.

Freezing could also be used as one method to control groundwater leakages in selected positions or in a systematic manner. Freezing is usually carried out by using external cooling holes and by circulating 40°C cold brine in the holes. Freezing can in principle be carried out by using external holes bored adjacent to the deposition drift or from inside of the drift. If the freezing is carried out from the inside, the rock around the drift has to be frozen to proper depth to sustain sealing for sufficient time after emplacement of canisters. There are several uncertainties related to freezing (e.g. rock deformation and fracturing, plugging of freezing holes) and therefore the use of technique should be assessed from both the technical and near-field behavior point of view. Some of the most significant questions to be resolved are:

- what is the primary benefit of freezing,
- acceptability of out of perimeter holes,
- significance of disturbance in near filed rock caused by freezing.

Some of the most significant questions related to the development of proper techniques to control groundwater inflows:

- To what degree can the inflows be reduced by groundwater control?
- How much development of grouting materials and techniques is required to obtain significant improvement?
- Is freezing technically feasible (use of brine, straightness of holes etc)?
- What is the water flow velocity limit for freezing (large flows are not possible to freeze)?
- Can we freeze the holes from inside without additional holes?

3 Specification of design basis

3.1 General

One main objective of the KBS-3H candidate design work is to produce a design, which fulfils the functional requirements and technical prerequisites under the specified environmental boundary conditions. The requirements are part of underground design premises of the deep repository, which has been presented by SKB in /SKB 2004/.

The basis for design is divided to following:

- **The functional requirements** specify what the buffer system must be able to do.
- **Environmental boundary conditions** describe the properties of the bedrock where the system has to function according to functional requirements.
- **Technical prerequisites** specify the parts of the technical design, which have been fixed and cannot be changed (e.g. diameter of the deposition drift).
- **Design guidelines** are advice, instructions, opinions and proposals specified by experts to be followed in order to fulfil the functional requirements.

3.2 Functional requirements

A functional requirement is specified as what the system must be able to do, in terms that are meaningful to its users. The functional requirements of EBS system surrounding the canister are in principle the same as in the KBS-3V repository alternative. The relevant functional requirements and other basis for developing buffer design in KBS-3H repository concept have been summarized in Appendix. A condensed description is also given in /Vieno and Ikonen 2005/.

The primary objective of the functional requirements is to ensure long term safety of the disposal. In KBS-3 concept the long term safety rest first and foremost on the long term isolation and containement of radionuclides inside the copper canisters /Vieno and Ikonen 2005/.

The isolation and containement is based on a multiple barrier principle, where all the barriers promote to the function of each other. Therefore the most important functional requirements of these barriers from long term safety point of view are protection and isolation of spent fuel. The repository design has to fullfill the functional requirements for long periods of time robustly and in a predictable manner.

Robustness and predictability in short and long term behavior implies:

- well known material properties,
- proven technical quality,
- well known and favorable bedrock conditions.

One important functional requirement, which differs from many ordinary design projects, is that the design shall undergo a significant evolution process from the implemented ”design” state to the predicted final deformed state.

Evolution of Engineered Barrier Systems

The engineered barrier systems evolve from the implemented initial state to the final state. The final state is a prediction, which depends on several factors. Therefore one of the most important functional requirements is that the EBS must evolve from the initial state to the desired final state in a robust and predictable manner.

The key **functional requirements** for different barriers are presented below in hierarhical form and the most detailed level requirement of engineered barrier system is in bold font. Requirements specified Appendix are in *italic* font.

Bedrock

- Protects the engineered barrier systems and canister against above ground processes.
  - Chemical and biological processes.
  - Rock stresses.
  - Earthquakes.
- Protect the engineered barrier systems in order to maintain favorable environment for EBS systems.
  - The state of stress shall be maintained at stable deformation level.
  - Salinity should.
- Isolates the spent fuel from biosphere including human habitat.
  - Limit and retard transport from the repository.
  - Limit and retard transport to the repository.
- Conduct heat (dissipate) from the buffer into the geosphere.

Buffer

- Isolates the canister from geosphere.
  - Limit and retard transport from the geosphere.
    - *The buffer shall prevent groundwater and corrosive substances from reaching the canister.*
      - *The buffer's hydraulic conductivity (**density**) shall be so low that any transport of corrosive substances takes place solely by diffusion.*
      - *The **density** of the buffer shall be sufficiently high so that no colloid transport through the buffer will be possible.*
      - *The **density** of the buffer shall be sufficiently high so that microbial activity in the buffer will not be possible.*
  - Limit and retard transport to the geosphere.
    - *The buffer shall retard the release of radionuclides if the canister should be damaged.*
      - *The buffer's hydraulic conductivity (**density**) shall be so low that any transport of radionuclides takes place solely by diffusion*.
- Enable escape of corrosion gases.
  - The buffer's *gas permeability (**density**) shall be sufficient to allow for gas release of the possible large quantities of gas that may be formed in a damaged canister. This gas passage shall not form persistent gas-permeable channels or cavities in the buffer.*
- Retard the transport along the deposition drift and EDZ around it from becoming a significant transport route.
  - The *buffer's* swelling *pressure (**density**) shall be sufficiently high to provide good contact with the host rock and the canister, but not higher than what the canister and host rock can withstand.*

- Protect the canister from detrimental processes in geosphere.
  - The buffer's *deformability (**function of density**) shall be sufficiently high to absorb rock movements without the canisters being damaged, but small enough to hold the canisters in position.*
    - *The buffer shall protect the canister mechanically in the event of decimetre-sized rock movements.* Deformability is evidently function of buffer **density**.
- Conduct heat (dissipate) from the canister into the geosphere. Heat conduction of buffer is a function of state of saturation and **density**.

It should be noted that in most requirements the density is also related to buffer thickness.

Backfill and sealing structures in the drift

- Prevent the deposition drift and EDZ around it from becoming a significant transport route (see Figure 3-1).
  - *The buffer's swelling pressure (dependent on **density**) shall be sufficiently high to provide good contact with the host but not larger than what the host rock can stand.*
  - *The hydraulic conductivity of permanent sealing structures in the direction parallel to deposition drift has to be sufficiently low so that any transport of radionuclides takes place solely by diffusion.* Permanent structures are composed of bentonite (concrete and steel are temporary and may cause local deviations) and the conductivity is a function of **density**.

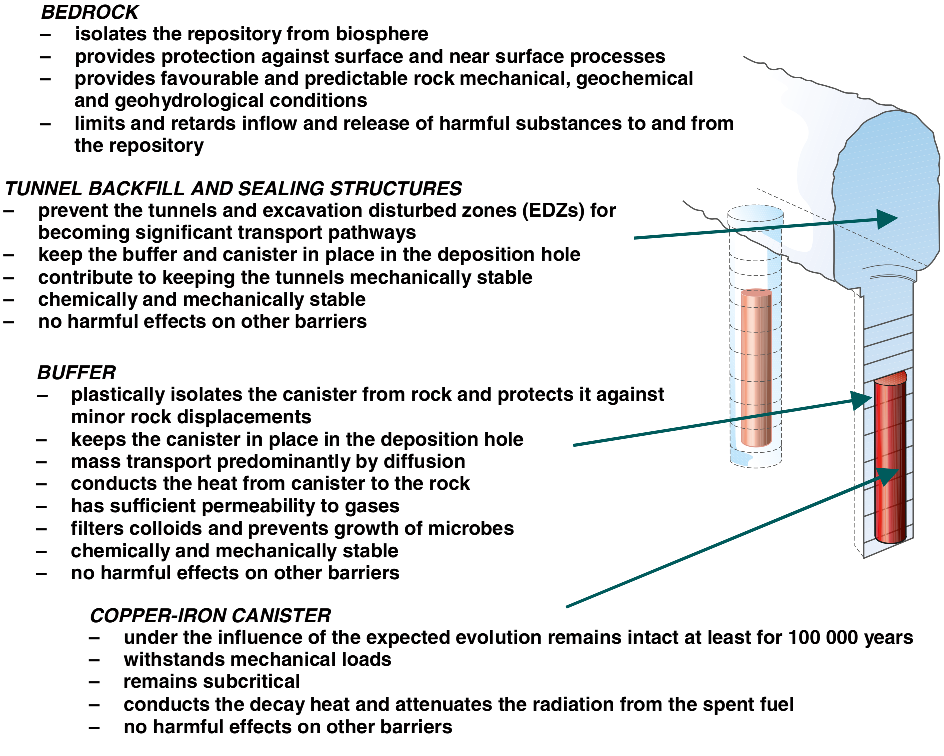


Figure 3-1. *Functions of the bedrock and engineered barrier systems in the KBS-3 disposal concept /Vieno and Ikonen 2005/. Fundamental functions are essentially the same for both KBS-3V and KBS-3H concepts.*

3.3 Environmental constraints

3.3.1 Groundwater

According to recent evaluation of the Olkiluoto site data there is likely to occur long relatively dry sections in a 250 m long deposition drift, several point inflows less than 0.4 l/min, 2–3 fracture intersections with inflow from 0.4 to 4 l/min and intersection of one or two fracture zones with inflows larger than 4 l/min. The total leakage into a deposition drift may be up to 10 l/min. Leakages into an open drift are difficult to predict accurately, as the outcome of the predictions depend, for example, on orientation, skin effect and the influence radius or gradient used in the calculations. A KBS-3H deposition drift at Olkiluoto may intersect several fractures and fracture zones with a transmissivity of the order of 10^{-8} m^2/s. An example of a possible situation is shown in Figure 3-2.

The salinities are determined by the expected site conditions at Olkiluoto, but also salinities expected at Swedish sites should be considered. The salinity of the groundwater is important parameter e.g. for bentonite erosion. Salinity of the groundwater at depths of 400 and 500 m at Olkiluoto ranges from 10 to 25 g/l of Total Dissolved Solids (TDS). Groundwater flow simulations indicate that locally the salinity may rise up to 25–45 g/l in the vicinity of excavations. Accordingly the expected salinity should be 35 g/l with a proper range.

3.3.2 Air humidity

It is expected that the air humidity in the empty drift in the initial state shall be 100%. Water flows from the rock through different size of fractures into the rock surface in the drift. Some of the water is spread on a wider area via the capillary microfractures in the EDZ. Air humidity is not purely a environmental factor because it depends on several factors, one being the water absorption capacity of buffer and another being the drainage system in the drift.

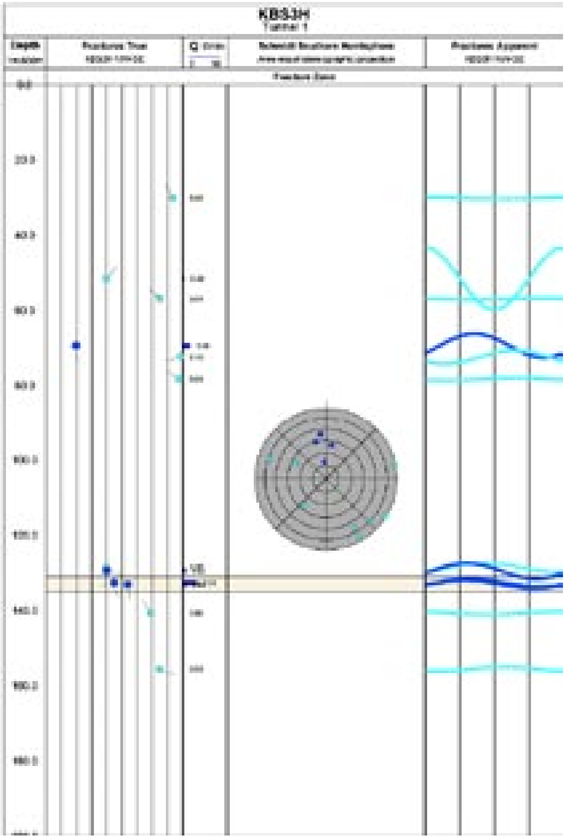


Figure 3-2. Preliminary illustrative estimate of the transmissive fractures intersected by a deposition drift at Olkiluoto and corresponding flow rates /Hellä et al. 2006/.

3.3.3 Rock stress

The rock stress at Olkiluoto has been presented in /Johansson et al. 2002/ and /Malmlund and Johansson 2002/.

Based on the stress measurement data, two different stress tensors as shown in Table 3-1 were specified. The orientation of the principal stresses was mostly based on the overcoring stress measurement data (Figure 3-3).

3.4 System constraints

3.4.1 Fixed part of design

The compilation of system parameters is described in /Johnson et al. 2005/. In principle the dimensions of supercontainer, diameter of the deposition drift and minimum length of distance block has been fixed as well as the properties of bentonite. The most important parts of the system, which are used as input for design are:

1) The buffer shall be designed as in SR 97 /SKB 1999/, i.e. with the same demands, composition and density. The density of the buffer shall be from 1,950 to 2,050 kg/m^3, with average of 2,000 kg/m^3.
2) The super container design is defined by /Thorsager and Lindgren 2004/ and in parameter description in /Johnson et al. 2005/.
3) An end plug is positioned at the drift entrance. It shall keep the buffer in place, stand the combined swelling pressure and hydraulic pressure from buffer (totalling 15 MPa) and it shall seal the drift so that properties of bentonite buffer will be maintained and no detrimental transport of bentonite occurs.

Table 3-1. The stress state at the depth level of 400 m and 500 m at Olkiluoto (based on /Posiva 2005/).

Depth (m)	Dip/DD of σ_1 (°)	Dip/DD of σ_2 (°)	Dip/DD of σ_3 (°)	Magnitude of σ_1 (MPa)	Magnitude of σ_2 (MPa)	Magnitude of σ_3 (MPa)
400 m	30/120	10/220	55/320	20	12	9
500 m	30/120	10/220	55/320	25	15	11

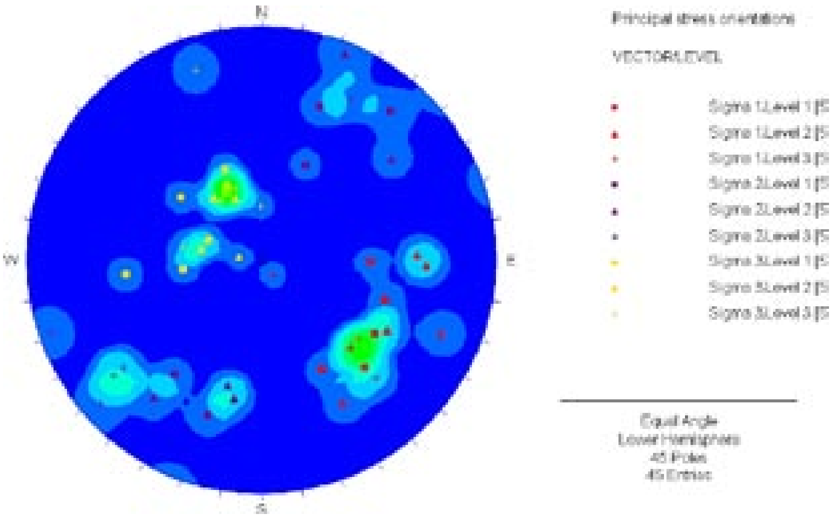


Figure 3-3. *The orientation of the principal stress vectors (σ_1, σ_2, σ_3) based on the overcoring method, plotted on a lower-hemisphere projection (based on /Malmlund and Johansson 2002/).*

3.4.2 Operation

The operation of the drift is based on emplacing supercontainers and distance blocks (deposition units) in campaigns. All deposition units are emplaced in one compartment in one campaign in continuous operating shifts. After all deposition units have been emplaced in the drift compartment, the entrance to the compartment or drift is sealed rapidly by using a plug.

Although human manual operation in the drift would be possible according to dose rates, the operation is based on automated emplacement of supercontainers and adjacent section of distance block. It is assumed that same vehicle is used for both deposition of supercontainer and distance block.

The minimum average transport speeds of operational equipment are:

- Supercontainer transport 20 mm/s.
- Distance block transport 30 mm/s.
- Outward transfer 100 mm/s.

The preparatory and supporting work is assumed to take 210 minutes per supercontainer distance block unit based on Basic Design Study using two different machines for transport of Super Containers and Distance Blocks:

- Preparation of supercontainer deposition vehicle, transfer and loading 150 minutes.
- Loading of distance block 60 min.

The transport time (only transport excluding preparatory work and transfer of equipment) for one supercontainer unit (containing one supercontainer and one distance block) with respect to distance in the drift are:

- 300 m, 7.1 hours.
- 200 m, 4.7 hours.
- 100 m, 2.4 hours.

The times including the transfer of the machine back to the niche for supercontainer and distance blocks are respectively:

Super Container

- 300 m, 5 hours.
- 200 m, 3.3 hours.
- 100 m, 1.7 hours.

Distance Blocks

- 300 m, 3.6 hours.
- 200 m, 2.4 hours.
- 100 m, 1.2 hours.

The expected longest emplacement time of one supercontainer unit to a depth in the drift of about 290 m is about 12 hours compromising of: a) supercontainer emplacement: the transport time is only 4.2 hours, return of machine to niche 0.83 hours, handling time in niche 2 hours, totally 7 hours and b) distance block emplacement: the transport time is 2.7 hours, return of machine 0.82 hours, handling time in niche 1.5 hours, totaling 5 hours.

The time required for preparatory work and transport of eighteen deposition units from the drift entrance to a distance from 10 to 190 m is about 120 hours (average in that compartment for one deposition unit is 6.3 hours), equal to about five days, which the same as the time required to transport deposition units to the rest of the drift from 190 to 300 m length (average in that compartment for one deposition unit is 9.3 hours), see Figure 3-4. An estimate of equal transport time is therefore five days, which corresponds to drift division at length of 190 m (assuming that the length of deposition unit is about 10 m). The estimates of transport times are rough and should be regarded to represent merely the right order of magnitude because the development of design of equipment is ongoing.

The total transport time depends on the length of the deposition unit, which depends on the chosen length of distance blocks. The time depends also on the length of plug system (plug and filling), which will reduce the operation time. The operating time should also include some reserve time for possible malfunction, failure and reparation of equipment.

The deposition time for one supercontainer unit has been estimated to be one unit per one day (Appendix). If the estimated equal time for one compartment is about four and half days, it seems evidently possible to increase operation efficiency so that one compartment could be operated and plugged in one week.

3.4.3 Drift quality and gap between rock surface and supercontainer

The gap between rock surface and supercontainer at final state depends on the geometrical tolerances (e.g. straightness and surface roughness) of the drift and the size of the supercontainer. The present nominal gap width is 45 mm. During operation the canister is lifted and lowered at steps and therefore the free gap during operation becomes clearly smaller (Figures 3-6 and 3-7).

The drift geometry and specified quality requirement applied in the boring of demonstration drifts at Äspö are shown in Figure 3-5. According to the specification the drift diameter is allowed to become 10 mm smaller than the nominal diameter at length of 95 m as a consequence of the expected wear of cutter in the cutter head of the boring machine.

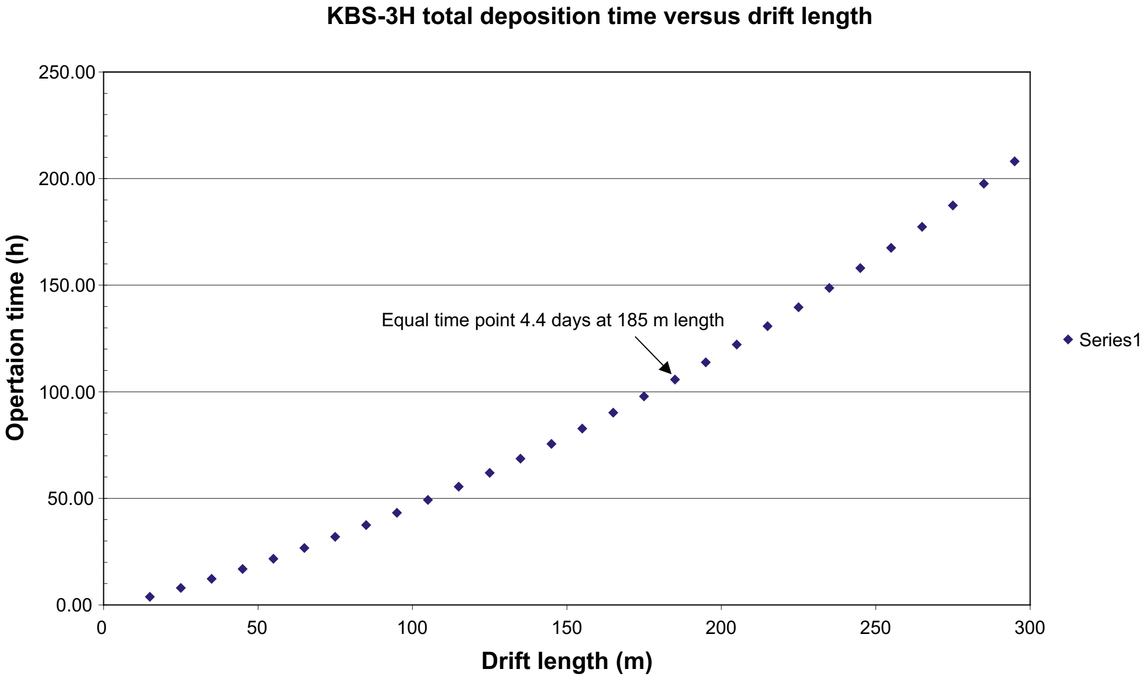


Figure 3-4. Total operation time versus drift length. The time is calculated for a supercontainer unit (supercontainer and distance block of approximated length of 10 m. The time required operate half of the 300 m long drift is roughly 5 days if the operation is based on three shifts utilizing 24 hours a day operation.

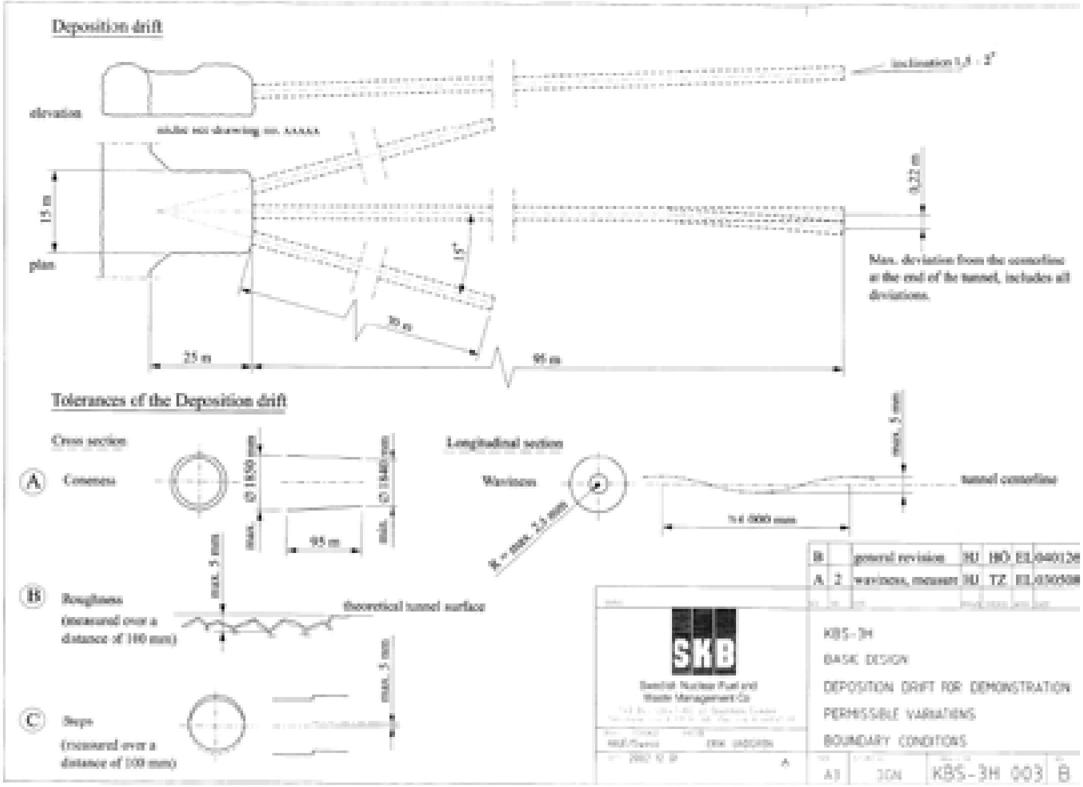


***Figure 3-5.** The requirements of drift quality applied in the demonstration boring at Äspö Hard Rock Laboratory.*

The 10 mm reduction in diameter is the largest estimated reduction in boring of a 300 m long hole. Additional reduction in effective diameter is caused by waviness, the maximum allowable deviation being 2.5 mm in all directions at wavelength of 6 m or more (see Figure 3-5). A stepwise deviation of 5 mm was defined in vertical direction. This would result in a situation where the largest effective diameter reduction in vertical direction at the length of 300 m would be 20 mm, consisting of 10 mm diameter reduction, 5 mm waviness reduction and 5 mm stepwise deviation. The corresponding reduction of diameter in horizontal direction would be 15 mm, assuming that the stepwise deviation is excluded. The diameter of the supercontainer has a tolerance of ± 5 mm.

The corresponding smallest width of the free gap would therefore be 20 mm above supercontainer assuming that the feet under the supercontainer keep the gap below it to constant 45 mm. The gap on the sides would be reduced to 35 mm. The gap above the canister will become smaller during operation when the canister is lifted 10 mm upwards. The width of the gap on the sides will however remain.

The present technology and treatment of the surface of the holes will, however enable to achieve better results and therefore the tolerances shown in Figure 3-6 are assumed to be valid with a good margin for 300 m long holes.

3.4.4 Retrieval and reversed operation

The canisters have to emplaced in one campaign in a row of successive operations. If some operation fails and the sealing and plugging of the drift cannot be carried out in suitable time period, the canister have to be retrieved or some other corrective measures should be taken (e.g. installation of "emergency plug").

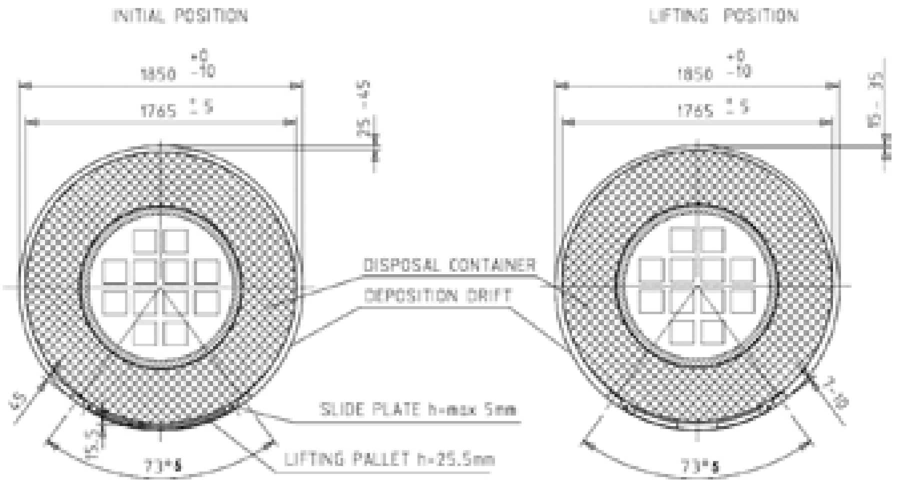


Figure 3-6. *Cross section of the deposition drift and supercontainer with diameters and tolerances in lifting position during operation (on right) and in initial and final position (on left). The diameter of the drift has been assumed to become at most 10 mm smaller than the nominal size. The 5 mm stepwise unevenness of the surface would reduce the minimum free gap on top of the canister to 20 mm. (The figure has been made by P-E Rönnqvist at Fortum Nuclear Services Ltd).*

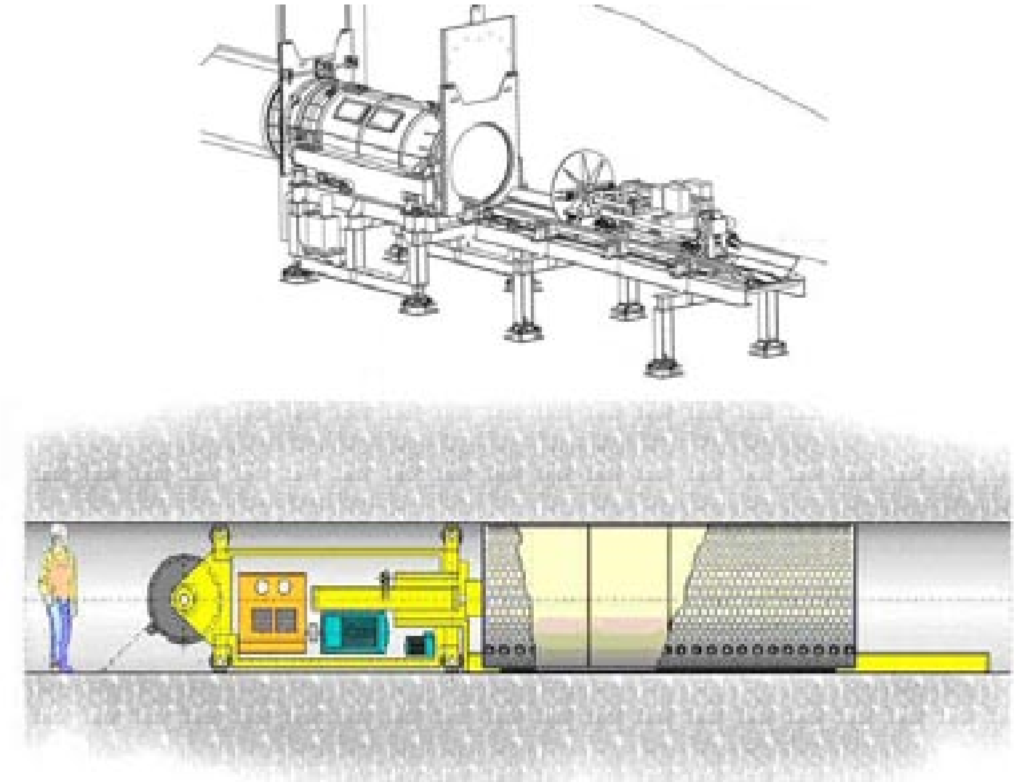


Figure 3-7. *The movement of deposition vehicle requires extra clearance on drift roof (above). Note that design has changed and the vehicle is not in contact with the roof and sides of the drift (top). /Thorsager and Lindgren 2004/.*

It has been assumed that the operation can be always reversed because that has been one design requirement for the deposition vehicle. Reverse operation is specified as operation to remove the deposited components of the repository system out from the deposition drift before the buffer is deformed (by e.g. saturation). If the buffer has already saturated, the reverse operation may not function properly and the canister should be retrieved from the deposition drift. Retrieval is specified as removal of the canister after plugging and sealing when the buffer is in deformed (saturated) state.

There is a time period just after plugging and sealing a compartment when the buffer is partly deformed but evidently still removable more easily than expected in retrievability but with more difficulty than in reverse operation.

It has been estimated that the retrievability of the canister is feasible /Kalbantner and Sjöblom 2000/ and can be based on present existing techniques (Figure 3-8). The technique has not been designed and therefore research and development is required to produce a feasible design.

It seems evident that the supercontainers and other components can be removed after intermission of operation by using other more feasible techniques than retrievability and it might even be possible perhaps to use the deposition type vehicle on some conditions with flushing based removal of softened bentonite. The development of proper equipment would require better understanding of the state of buffer after emplacement.

3.4.5 Dose rates during operation

Estimate of the radiation dose rate for the KBS-3H supercontainer was made at the Technical Research Center of Finland (VTT) in May 2003 (by Mr. Markku Anttila). A real 3D-geometry of VVER 440 canister with 12 bundles of fuel was modeled with MCNP4C computer program. The radiation dose rate at the canister lid surface was about 100 mSv/h. The 35 cm layer of bentonite in the end of the supercontainer decreases the gamma dose rate to 1:200. That means that the doserate on the end surface of the supercontainer is some 0.5 mSv/h.

If the distance block (bentonite thickness is a few metres) is installed adjacent to the supercontainer, the dose rate through the plug in the drift is negligible. The dose rate through the gap of 50 mm between rock and bentonite distance block is evidently less than the dose rate through the distance block and therefore the dose rates in the KBS-3H deposition drift behind a supercontainer and a distance block are insignificant.

If the doserate at surface of the supercontainer is of the order of 0.5 mSv/h, a person can work in such place temporarily for a few hours. Annual acceptable dose for personnel is during one year 50 mSv (equal to 100 h) and the cumulative dose of successive 5 years can be 100 mSv (200 hours).

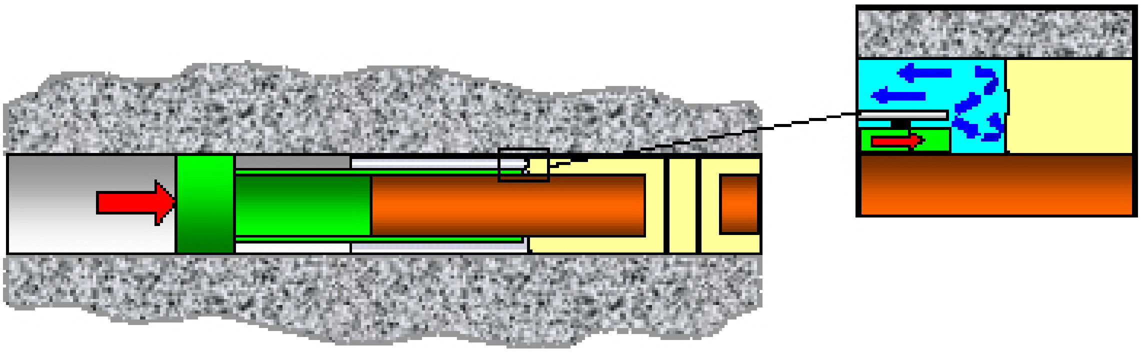


Figure 3-8. Suggested method for removal of buffer by using highly saline water circulation /Kalbantner and Sjöblom 2000/.

3.5 State-of-art specification

The hydraulic description of the bedrock at Olkiluoto has been given by /Hellä et al. 2006/ and /Johnson et al. 2005/. The description presented by /Hellä et al. 2006/ is focused on defining number of fracture intersections in a KBS-3H deposition drift and leakage rates. Some of the requirements have been specified in Appendix.

The quality of deposition drift has been addressed in the basic design phase and contract documents concerning the boring demonstration at Äspö. The boring of the demonstration holes has been reported and the drift quality has been described in the report by /Bäckblom and Lindgren 2005/ on the basis of measurements.

Buffer design and behavior has been presented in /Börgesson et al. 2005/. The report gives several significant estimates, such as e.g. preliminary water absorption of buffer rates 0.01 l/min and estimates of humidity induced swelling.

Several erosion experiments have been carried out in BACLO project and the THMG processes has been studied by /Johnson et al. 2005/.

3.6 Procedure for minimizing uncertainties in design basis

3.6.1 Functional requirements

Functional requirements contain uncertainties and ambiguousness, which evidently are difficult to manage in design work. The fulfilling of these requirements is evaluated as total after design is complete in safety assessment. However, proper integration of design and functional analysis during the design, e.g. as shown in Figure 3-9, will provide insight in the possible uncertainties during design development and is therefore the proposed approach to manage these uncertainties.

3.6.2 Environmental constraints

The uncertainties in environmental constraints, which may have significant impact on the design are related to following issues:

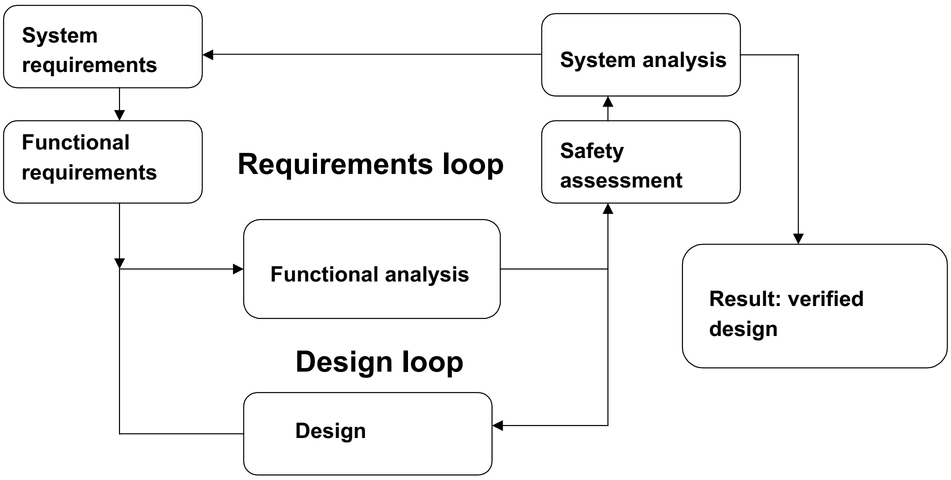


Figure 3-9. Engineering Design, functional analysis and system analysis.

Groundwater control and inflows

Groundwater control techniques and inflows have effect on several different processes and event such as piping, saturation homogeneity and movement of distance blocks. In general the groundwater issues can be regarded as economic feasibility issue by assuming that the deposition drifts can always be divided to sufficient number of compartments where the required conditions are met. However this is not fully true and therefore some of the uncertainties are discussed below. The groundwater control techniques are not part of this design description although they have significant role in improving the feasibility of the design.

Most significant uncertainties in groundwater constraints:

- distribution of higher than 0.1 l/min inflow points and rates for the length of supercontainer unit (approximately 10 m),
- number of significant water leaking fractures or zones (1 l/min or more),
- pressure increase rates,
- occurrence of very dry sections with little inflow.

Procedure for minimizing uncertainties:

- definition of reliable inflow limits (more evidence),
- more detailed characterization of bedrock with regard to transmissive fractures,
- adaptation of lay out with special emphasis on significant transmissive features,
- determination of pressure increase rates,
- development of groundwater controlling techniques to reduce inflows.

Procedure to minimize the consequences of uncertainties:

- division of drift to compartments with acceptable inflow,
- development of a design which is tolerable to inflows,
- development of design which is tolerable to dry sections,
- conservative assumptions of pressure increase rates and inflows in design.

Transport of water from bedrock as humidity

Part of water flow from bedrock is transported as humidity in the buffer. The absorption of water from humidity causes the bentonite to crack intensively in relative short periods of time. Cracked bentonite behaves evidently quite differently from solid bentonite. The rate of transported humidity depends on bedrock factors (water flux from rock) and buffer factors (e.g. heat, absorption rate).

Most significant uncertainties in humidity

- humidity transfer rates in emplacement situation (buffer, temperature etc).

Procedure for minimizing uncertainties

- the relevance of humidity should be studied (maybe irrelevant?),
- the humidity transfer rates at different operating phases should be defined,
- determination of pressure increase rates.

Procedure to minimize the consequences of uncertainties

- it assumed that RH100% is maintained unless contradicting evidence is given,
- short term feasibility of possible humidity shields is evaluated in realistic conditions,
- division of drift into “dryer” compartments,
- development of a design which is tolerable to humidity.

3.6.3 System constraints

Some factors which include uncertainties and have significant effect on the design and should be evaluated more thoroughly.

Operation time has very high importance on early behavior of buffer and the present estimates may have significant uncertainties. Therefore the operation procedure should be studied and optimized with that respect. The study should include evaluation of different means to reduce the uncertainties. That should also be included as one issue in demonstration tests carried out at Äspö. It seems that the possibilities to reduce the effect of longer than expected operation times are quite limited. In certain situation a backup system based on installing rapidly filling blocks could be evaluated. The possibility to reduce the emplacement time of distance and filling blocks should be evaluated. The emplacement of distance and filling blocks has not yet been addressed thoroughly and therefore that should be of most importance.

The free gap between rock, supercontainer and distance blocks contains uncertainties and has significant impact on the operation. Some of these uncertainties have most likely been resolved in the boring demonstration at Äspö. The remaining uncertainties could be reduced by post-excavation quality assurance procedures and use of a special tool to improve the quality if necessary. Since the width of the free gap is critical, the operation should not be allowed until the drift fulfills the quality criteria.

The minimum length of distance blocks based on thermal effect has been defined. It is likely that the emplacement of distance blocks will include some tolerances. A tolerance of e.g. 10 mm per supercontainer cell can sum up to a total length of 140 mm, which may require adjustments to position of e.g. fixing rings. The emplacement accuracy and uncertainties should be addressed and it is proposed that the distance block design is developed to include possibility to adjustments in length. The position of critical components should include the proper tolerances to be defined.

Retrievability and reverse operation after emplacement has not been addressed in detail although it has been stated that there is enough evidence to assume that it can be implemented based prevailing techniques. The operation of KBS-3H repository has certain characteristics, which may results in possible deviations from expected behavior as discussed in Sections 4.7 and 5.5 and therefore reverse operation and retrievability should be incorporated in the operation and the possible uncertainties should be evaluated thoroughly.

3.7 Procedure to take into account the uncertainties in design basis

The significant uncertainties in the design basis can be taken into account in the design by using a stepwise approach from possible overdesign (covering uncertainties) to more adjusted design. The stepwise approach in design is feasible only if the development and testing proceeds parallel to it. Functional analysis is part of the design loop and therefore many of the uncertainties in state-of-art understanding are part of the stepwise approach.

The design includes evaluation of alternatives, selection alternatives and consequent optimization. The uncertainty related factors which should be taken into account in the evaluation are:

- Minimum uncertainty – selection of components with little uncertainties.
- Simplicity – selection of simple designs over complex ones.
- Robustness – the system should function with a clear marginal.
- Redundancy – systems which can be made redundant are favored.
- Comprehensive rigorous evaluation of designs.
- State of the art principle.
- Possibility for retrieval.

Minimum uncertainty of design is improved e.g. by bedrock adaptation and use of compartments (uncertainty is transferred to utilization degree of drift).

The robustness is improved by developing sealing techniques and allowing flexibility in the EBS system (e.g. several distance blocks).

Simplicity is taken into account by e.g. favoring alternatives with minimum number of functional components. If one component can fulfill several functions it is favored unless it reduces the redundancy. Simplicity is also followed in material selection – no new materials are used in the design if possible.

State of the art principle is followed by improving the present knowledge and by evaluating new results and possible consequences in design.

4 Specification of Basic design

4.1 Specification of the functional structure

It is assumed in the specification that groundwater inflow has been reduced by applying proper techniques and therefore sealing is not included in functional structure below. The function of deposition drift, canister, supercontainer, backfilling and sealing are not described here more than necessary because they are considered to be fixed part of the design.

The functional structure of the design is composed of following elements:

1. **Prevention of surface erosion by spray and drip shields.** Direct water flow (see Figure 4-5) on buffer surface will cause surface erosion. Spraying, squirting and significant dripping of groundwater on supercontainers and distance blocks is prevented by using shields.
2. **Isolation of compartment from water bearing fracture zones by plugs – compartment formation.** Isolation of deposition compartments by using plugs from water bearing fracture zones, which may have detrimental effect on the distance blocks and supercontainer during saturation.
3. **Sealing of the drift entrance by plugs.** The deposition drift is sealed and plugged after emplacement of canisters. The plug will enable maintaining of adequate hydrostatic pressure in the drift after operation and keep the supercontainers and other components in position. The plug will be exposed to both hydrostatic pressure and swelling pressure from the buffer. The plug is positioned so that flow from the drift into the surrounding open tunnels is small enough to eliminate possible erosion.
4. **Intermission of operation by plugs.** The emplacement of supercontainers can be stopped temporarily if the drift is plugged rapidly before the distance blocks start to swell into the open tunnel.
5. **Hydraulic isolation of successive supercontainer by distance blocks.** Hydraulic isolation of successive supercontainer sections from each other during saturation phase by using seals (distance blocks) so that each supercontainer section is saturated by groundwater inflow from bedrock without flow from one supercontainer section to another through.
6. **Thermal spacing of canisters by distance blocks.** Thermal spacing between successive canisters is obtained by using a distance block of required length.
7. **Prevention of displacement of distance and filling blocks by fixing rings.** Large hydraulic pressure induced forces may cause displacement of distance and filling blocks. This is prevented by using a fixing ring type supporting structure.
8. **Sealing of unsuitable sections by filling blocks.** Positions which are not suitable for emplacement of a supercontainer because of larger than accepted water inflow or other reasons are filled with filling blocks. The objective of the blocks is to provide extra sealing against neighbouring distance blocks and to reduce the hydraulic pressure induced force exerted on distance blocks.
9. **Compensation of local density reductions by filling blocks with extra swelling potential.** The density reductions can be caused by dissolving cement from drift plug or compaction of lower density filling adjacent to compartment plugs.
10. **Drainage of major inflows in isolated plugged compartment borders by permeable low compressibility filling and swelling partially permeable filling.** Significant water leaking sections, which are not suitable for deposition are isolated from drift by plugging. See paragraph 2. The volume between compartment plugs is filled and drained during operation by using three different type of filling.

4.2 Specification of the design components

4.2.1 General

Deposition drift, supercontainer etc design components are kept fixed and are not considered in this context.

The Basic Design - Design Components (BD-DC) shown in Figure 4-1 are:

- BD-DC1 Spray and drip shield.
- BD-DC2 Distance block.
- BD-DC3 Fixing rings to support distance blocks.
- BD-DC4 Coupling between supercontainer and distance block.
- BD-DC5 Compartment plugs.
- BD-DC6 Filling blocks.
- BD-DC7 Drift end plug.
- BD-DC8 Permeable filling.
- BD-DC9 Partially permeable filling.

4.2.2 Spray shield

Spraying, dripping and squirting of water on buffer is prevented by placing spray shields on inflow points. The shields are composed of metal material, which is placed on top of the inflow point. In single inflow points the shielding can be implemented using stud type nipples. On roof of the deposition drift the inflow has to be redirected towards the lower half periphery of the drift.

Material alternatives for the shields are copper or steel. Steel is preferred because the structures are thin (in mm range), the number of them is small and the steel can be assumed to corrode and disappear in relatively short time period when compared to supercontainer. The shields are dimensioned to withstand their own weight and facilitate mechanical attachment to rock surface.

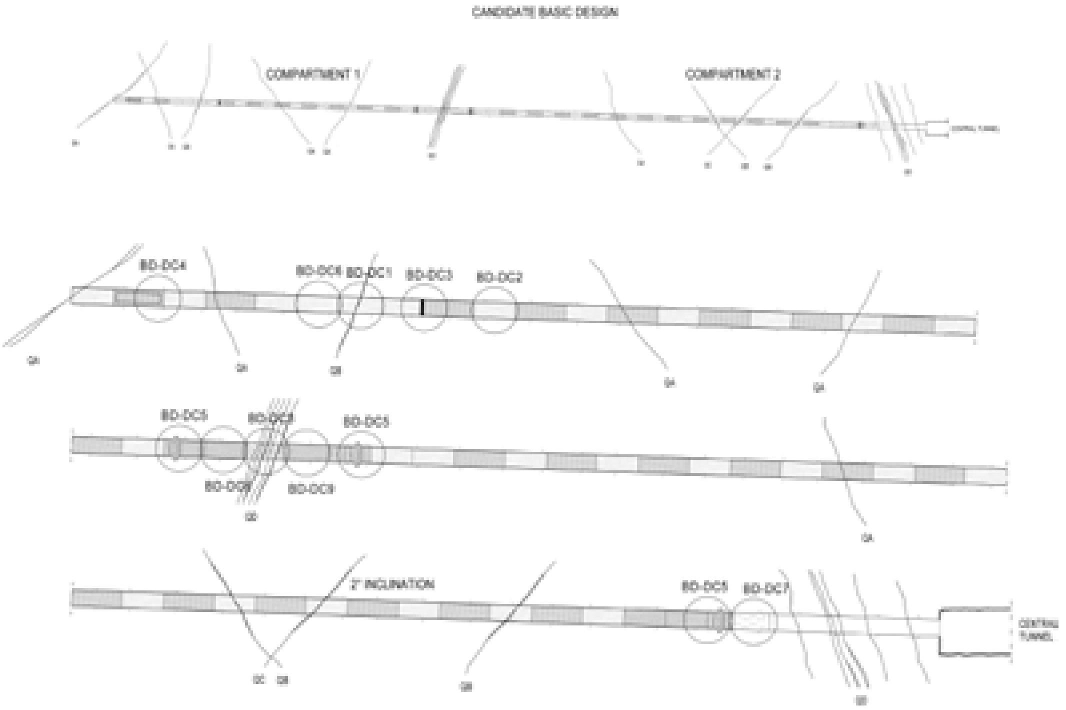


Figure 4-1. The design components of Basic Design alternative. The identifiers in fractures refer to different types of water leaking fractures.

Key design issues:

- geometry,
- thickness,
- attachment,
- installation,
- material quantities which remain in the drift after closure.

4.2.3 Distance block

A distance block is positioned between the supercontainers. The objective of the distance block is to provide sufficient thermal minimum spacing between supercontainers and to isolate the supercontainers hydraulically during saturation.

The distance block will swell faster than buffer in supercontainer. Therefore the distance block will prevent flow along the drift and on the bottom of the drift. Therefore the buffer in supercontainers will swell in more controlled state.

In order the distance blocks to swell faster than supercontainers, the distance block will have larger open buffer surface per unit area than supercontainer and the gap between block surface and rock will be made smaller or filled with higher density material than that between supercontainer and rock.

There are two alternative ways to reduce the effective gap in order to obtain sufficient sealing: a) a larger gap filled with pellets and bentonite powder or b) a smaller gap.

The largest length of the distance blocks is adapted to local water inflows within accepted range. Longer distance blocks can be used in unfavorable positions to obtain required degree of sealing.

Key design issues:

- structure (use of segments),
- gap between rock and buffer,
- length of block.

4.2.4 Fixing rings to support distance blocks

It is likely that there shall be supercontainer sections, which will stay dry relative long periods of time next to sections which will saturate and rapidly to full hydrostatic pressure. The difference in time can be two orders of magnitude or larger, e.g. empty volume in one supercontainer section can fill and the bentonite swell to fill the open gap in 10 days whereas the neighboring section in tight rock may fill and the buffer swell in 200 days or more.

Therefore the distance blocks have to maintain the sealing ability under large hydrostatic pressure differences. If there is full hydrostatic pressure on other side of the distance block and no pressure on other side, the force acting on the pressure side may move the plug and cause detrimental displacement. This can also result in piping of water flow through the distance block, erosion and transport of bentonite.

Displacement of plug is counteracted by the friction of plug against rock surface and support from next supercontainer sections. Possible movement of distance blocks in unfavorable situations is prevented by using supporting structure which will fix the distance block mechanically in desired position. The supporting structure will be positioned on one side of the distance block to prevent one-way movement.

Key design issues:

- shape,
- dimensioning pressure,
- amount of steel,
- installation.

4.2.5 Contact between supercontainer and distance block

The massive steel rings required to eliminate the movement of distance blocks when full hydrostatic pressure has been exerted on the whole top surface area have been assessed as being technically and economically unfeasible. The amount of steel in the fixing rings can be reduced significantly and the rings can be made lightweight if the dimensioning pressure is not full hydrostatic pressure exerted on whole top area of the distance block.

Test have indicated that if the coupling of distance block and supercontainer is tight (gap of the order 7 mm), the pressure is exerted on a limited circular surface area between the rock surface and outer surface of supercontainer and about 10 cm radially inwards from that.

The contact between supercontainer and distance block is designed to ensure that the distance blocks will be exposed to only partial hydrostatic pressure (see Figure 4-3). A good contact may be ensured by e.g. measuring the drift and supercontainer top surface geometry after installation and modifying the first section of distance block to fit in the position tightly.

Key design issues:

- gap size,
- implementation.

4.2.6 Plugs

There are in principal three different purposes for the use of plugs: a) sealing and plugging of drift – designated as a drift end plug, b) isolation of suitable sections and division of drift to compartments – designated as a compatment plug and c) possible management of possible operational intermissions – not addressed further in this document.

All the plugs are in principle temporary structures with respect to long-term function. However the plugs positioned inside the deposition drift are required to function only during the saturation phase whereas the plug which seals the drift has to maintain the function during the period from operation to plugging and sealing the repository.

The plugs can be composed of steel, low-pH concrete, or both. Steel plugs can be installed in relatively short time whereas concrete structures will evidently require a minimum hardening time of two weeks until the structure can be loaded. Steel is favored over concrete as material because short plugging and sealing time is favorable to the behavior of buffer under saturation and increases the efficiency. Concrete plugs will need a drainage pipe lead-through and valve in order to eliminate build-up of pressure behind the plug during curing. Different design alternatives of concrete plugs have been presented earlier and are currently being tested (shotcrete alternative) at Äspö.

With long terms behavior point of view there are some significant differences.

Steel:

- steel will expand as it corrodes,
- corrosion will produce hydrogen gas,
- after a long period of time the steel has transformed to impermeable magnetite and other corrosion products,
- expected lifetime of a steel structure is shorter than that of concrete.

Concrete:

- directly applicable low pH-concrete may not be available today, however it most likely will be available in the near future,
- concrete will dissolve in groundwater after along period of time. The rock aggregate will remain in the position of the former structure and therefore the volume will shrink,
- after dissolving the hydraulic conductivity of the reduced volume will increase,
- expected lifetime of concrete structure is longer than that of steel structure.

From operational and long term safety point of view an integrated plug with a short term steel component and long term concrete component (as illustrated in Figure 4-2) may be feasible.

The present experiences of plugs imply that in order to obtain good sealing function, the structural plug should be accompanied by a massive sealing element such as the distance blocks or similar. In this case the main function of the component giving the structural strength is therefore to reduce the flow and hydraulic gradient in the massive seal to a tolerable level in order to eliminate piping and possible transport of bentonite through the plug.

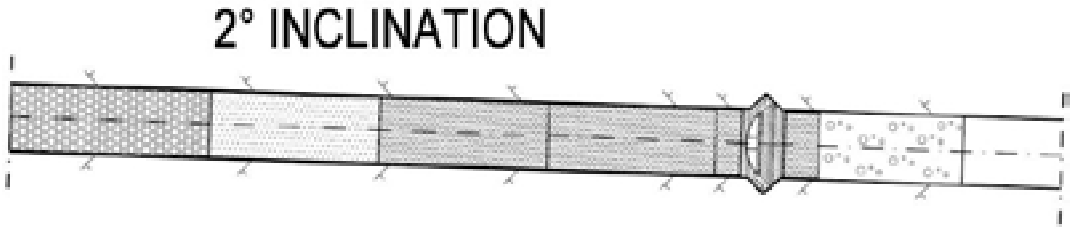


Figure 4-2. *The drift end plug arrangement based on a rapidly installed steel plug and a final concrete plug. Extra filling blocks are installed adjacent to plugs to compensate the possible density reduction in future.*

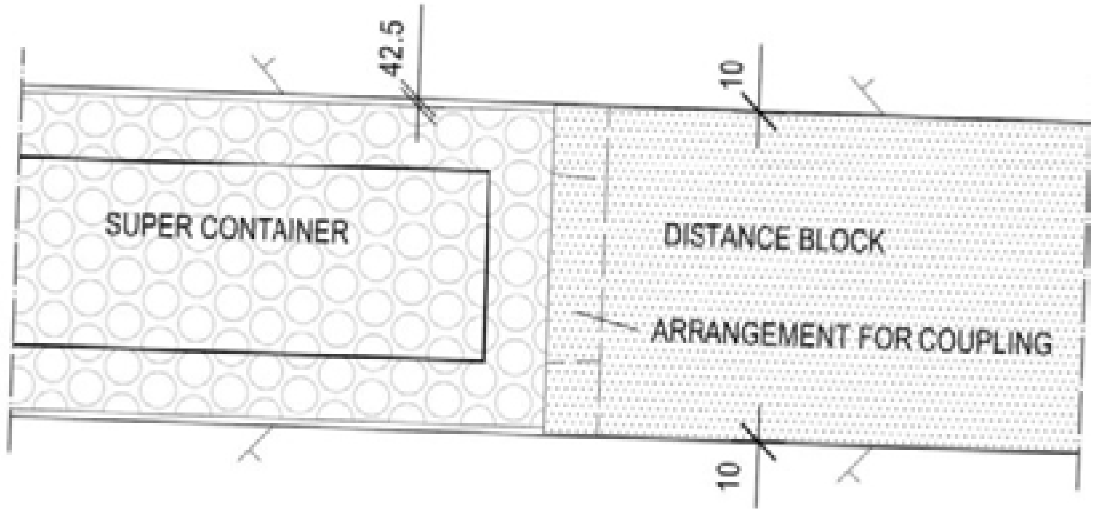


Figure 4-3. *The coupling between distance block (the gap between rock and block has not been fixed, here it has been assumed to be 10 mm) and supercontainer can be arranged in several ways all having the same objective to minimize the gap in order to prevent exposure to full hydrostatic pressure on whole surface area.*

In all alternatives the plug must be accompanied by a filling element which has swelling capacity to compensate the possible local future density reduction in filling.

Key design issues:

- geometry and size,
- installation,
- amount of steel or concrete.

4.2.7 Filling blocks, permeable blocks, partially permeable blocks

Filling blocks (see Figure 4-4) are used next to plugs as massive sealing elements (see Section 4.2.6), to compensate the reduction of buffer density caused dissolution of concrete plugs and formation of open space and to fill positions which are unsuitable for placement of supercontainer.

The filling blocks should seal the section of drift where they are positioned and should resist erosion. The properties of the blocks may possibly differ from that of distance blocks, e.g. the resistance for erosion can be increased, swelling potential decreased and hydraulic conductivity increased.

Permeable blocks and filling are installed (see Figure 4-4) in positions of significant inflows, which may erode compacted bentonite blocks. The objective is to drain the inflow section and suitable material could be e.g. crushed rock at properly graded composition.

Partially permeable blocks are used next to permeable filling to drain the gravity flow on floor of the drift. The filling is mainly composed on compacted bentonite, which will expand by swelling and compensate the compression of crushed rock.

Additional void space and density reduction is formed in the drift system e.g. by dissolution of cement from concrete drift plug, compression of permeable crushed rock filling by swelling buffer and compression of lower density filling adjacent to steel plugs. This density reduction should be compensated by additional swelling capacity and density in the filling blocks.

Key design issues:

- length,
- composition (aggregate-bentonite),
- installation density,
- compressibility modulus,
- compensation of compression.

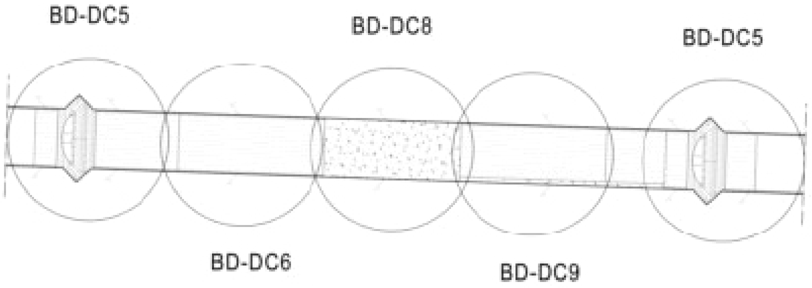


Figure 4-4. *Example of a compartment plug system and different types of filling components. Permeable filling DC-8 is positioned in the leaking fracture intersection. The leaks are conducted out from the intersection through a partially permeable filling DC-9. The upstream side of leakage is filled with impermeable filling DC-6, which will have sufficient swelling capacity with DC-9 to compensate the possible density reduction caused by compression of DC-8 when exposed to swelling pressure.*

4.3 Preliminary designs

4.3.1 General

The design and testing of drift end plugs based on using low pH shotcrete as well as development of low pH concrete is in progress in other projects and is not addressed in this document. The main issue in design is the development and applicability of low pH-concrete both for sealing and structural engineering purposes. The construction of shotcrete plug will be tested at Äspö. The applicability of concrete plugs can be evaluated in the future on the basis of the results.

The erosion of buffer blocks when exposed to water flow or sprays and effect of changes in composition and length are not understood sufficiently to modify composition of filling blocks more resistant to erosion. The development work is in progress and it is assumed for the time being that permeable and partially permeable blocks are positioned in sections with major inflows. All other filling blocks are of distance block type.

4.3.2 Spray and drip shields

There are no standards or practice for dimensioning spray or drip shields to prevent direct contact between spraying water and buffer (Figure 4-5). It is assumed in the preliminary design that 0.2 mm thick annealed steel sheet is used for drip shields. The shields are fastened mechanically by using small holes drilled in rock and screws with approximate spacing of 100 mm. Round "penny" type washers are placed in position of single flow points. The sheets are battered to follow the rock surface tightly.

4.3.3 Distance block

The effect of the length of distance block is not known and therefore it is assumed that the minimum length determined on the basis of thermal effect is used (4.65 m). The lengthening of distance blocks may have positive effect on the elimination of piping. If longer blocks are used, the spacing between deposition drifts could be reduced accordingly.

The distance block has been assumed to be transported by using same type of vehicle as for the deposition of the supercontainer. Because of the length of block, operation efficiency and requirements concerning the free gap, it may be feasible to install the block in segments by using different type of equipment.

***Figure 4-5.** Example of spraying inflow points.*

There are indications that piping tendency through the gap between distance block and rock can be reduced by two different preliminary alternatives:

- A distance block with a “larger” 42.5 mm gap between rock surface and the block, which is filled with bentonite pellets and powder.
- A distance block, which is fitted tightly with as small (e.g. 10 mm) gap as possible.

4.3.4 Fixing rings

The fixing ring design is based on the following design requirements:

- The ring shall be constructed in one shift (7 hours).
- The plug material is steel which is similar to the supercontainer.
- The ring is dimensioned to withstand one way hydrostatic pressure of 4 MPa exerted on a 10 cm circumferencial surface area at face of distance block inwards from rock. The area of this circumferencial section is 0.55 m^2 yielding a total force of 2.2 MN (220 tonnes). The basis for estimate is presented in Section 9.4 in /Börgesson et al. 2005/, which contains some uncertainties and should therefore be studied further.
- The thickness of steel in the ring is optimized with respect to thickness in order to obtain corrosion gas generation times similar to supercontainer in order to create no new significant time dependent corrosion processes. The target thickness of steel is of the same order as the thickness of supercontainer, which is 8 mm.
- The ring is composed of smaller size segments, which can be handled and transported inside the drift.
- The ring should fail in a controlled way if the strength is exceeded.

The preliminary design of the fixing ring is shown in Figures 4-6 and 4-7. The ring is composed of following elements:

- Indentation in rock which is excavated before operation starts.
- A collar attached in the rock surface before operation starts. The collar should be positioned in the required position with an tolerance of 50 mm.
- Rigid fixing ring installed during operation.

The fixing rings are installed using bolts and/or welding. The weight of the fixing ring is 600 kg if it is made of 10 mm steel plate.

4.3.5 Steel plug

Steel design

The design of hydrostatic steel plug is based on the following design requirements:

- The plug shall be constructed in one day.
- The plug material is steel which is similar to the supercontainer.
- The steel plug is dimensioned to withstand one way hydrostatic pressure of 5 MPa, which corresponds to total force of 13.4 MN.
- The thickness of steel in the plug is optimized with respect corrosion. Target thickness of steel is of the same order as the thickness of supercontainer, which is 8 mm, in order to create no new significant time dependent corrosion processes.
- The plug is composed of smaller size segments which can be handled and transported inside the drift.
- Forces on rock surface should be compressive.
- The plug should fail in a controlled way if the strength is exceeded.

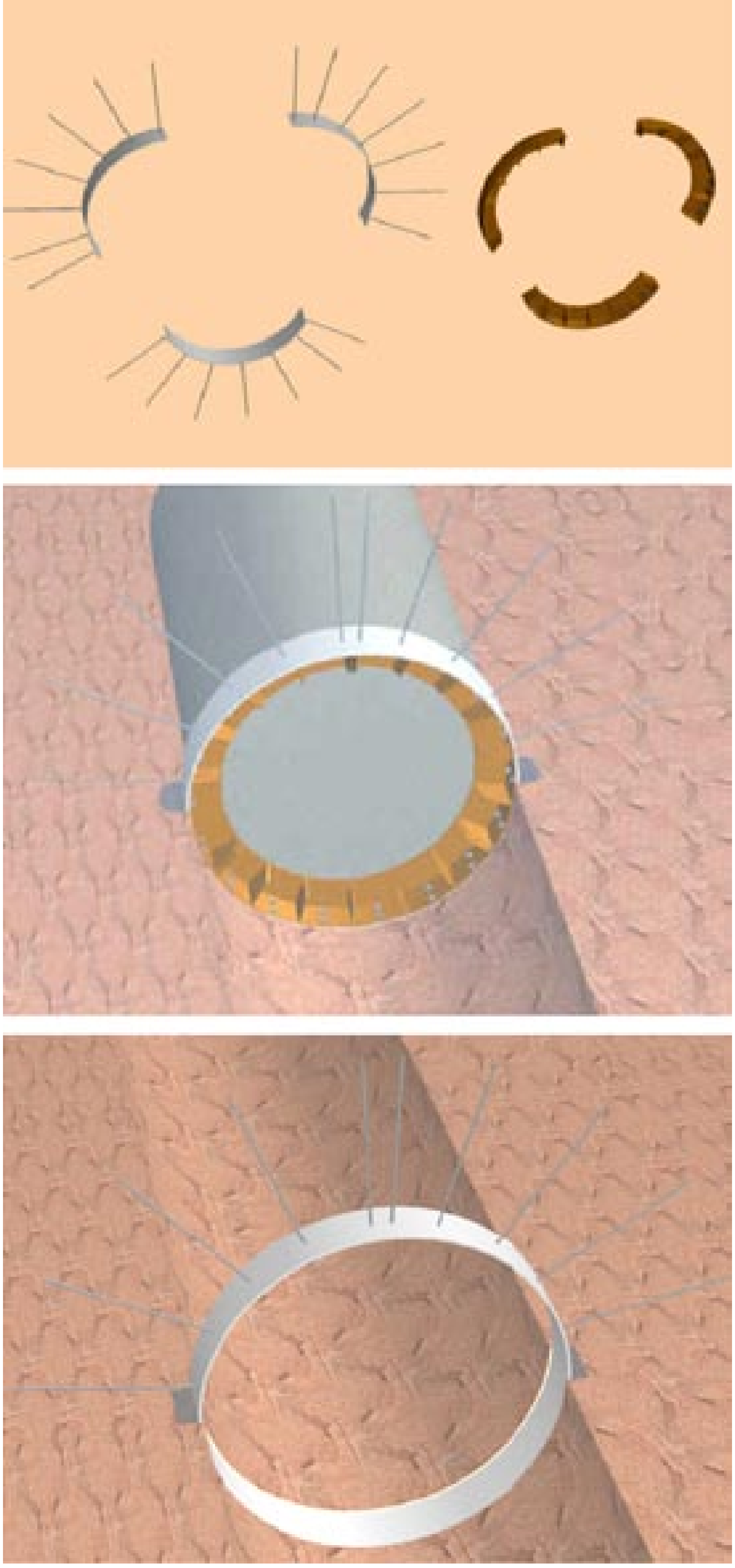


Figure 4-6. *3-D visualization of the fixing ring (middle) showing all components (top). The light gray shaded collar (above) is installed before operation starts. (The figure and design has been made by P-E Rönnqvist at Fortum Nuclear Services Ltd).*

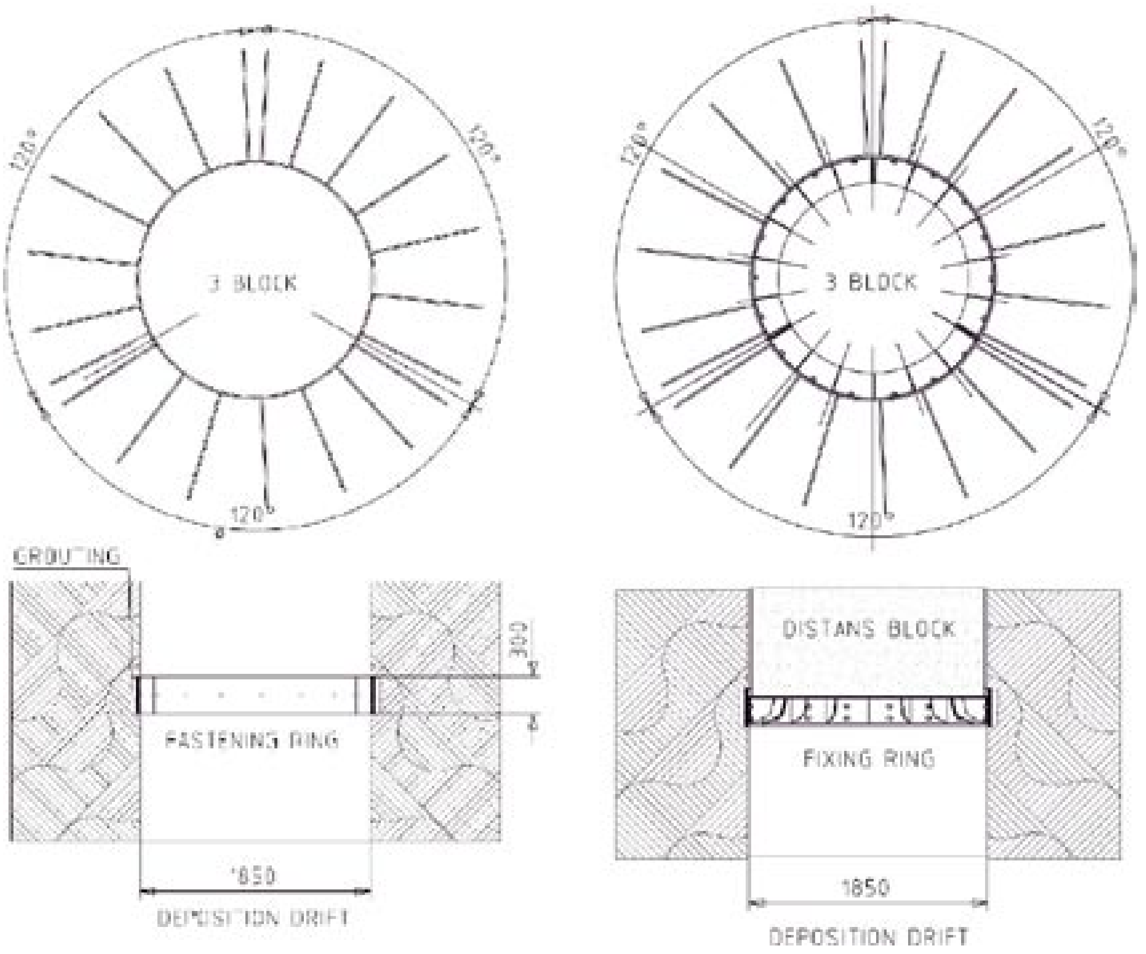


Figure 4-7. Cross-section of the fastening ring of the fixing ring (left) and the fixing ring (right). (The figure and design has been made by P-E Rönnqvist at Fortum Nuclear Services Ltd).

The preliminary design of the steel plug is shown in Figures 4-8, 4-9 and 4-10. The plug is composed of following elements:

- V-shaped indentation in rock which is excavated before operation starts.
- Tight steel collar structure manufactured with high precision and attached to the rock before operation starts.
- Sealing element (annealed copper) between collars.
- Rigid collar.
- Dome shaped center part with stiffeners.

The plug is assembled in the predefined position in steps by using bolts and welding.

The mass of the steel plug dimensioned to 5 MPa pressure and made of 10 mm thick steel (excluding bolts and achoring) is about 1,400 kg. If the plug is made for 10 and 15 MPa pressure, the weight is 2,100 and 2,800 kg respectively.

The plug is equipped with an inspection hole, which can be used to fill the backside with pellet and powder and lead-throughs for possible pipes.

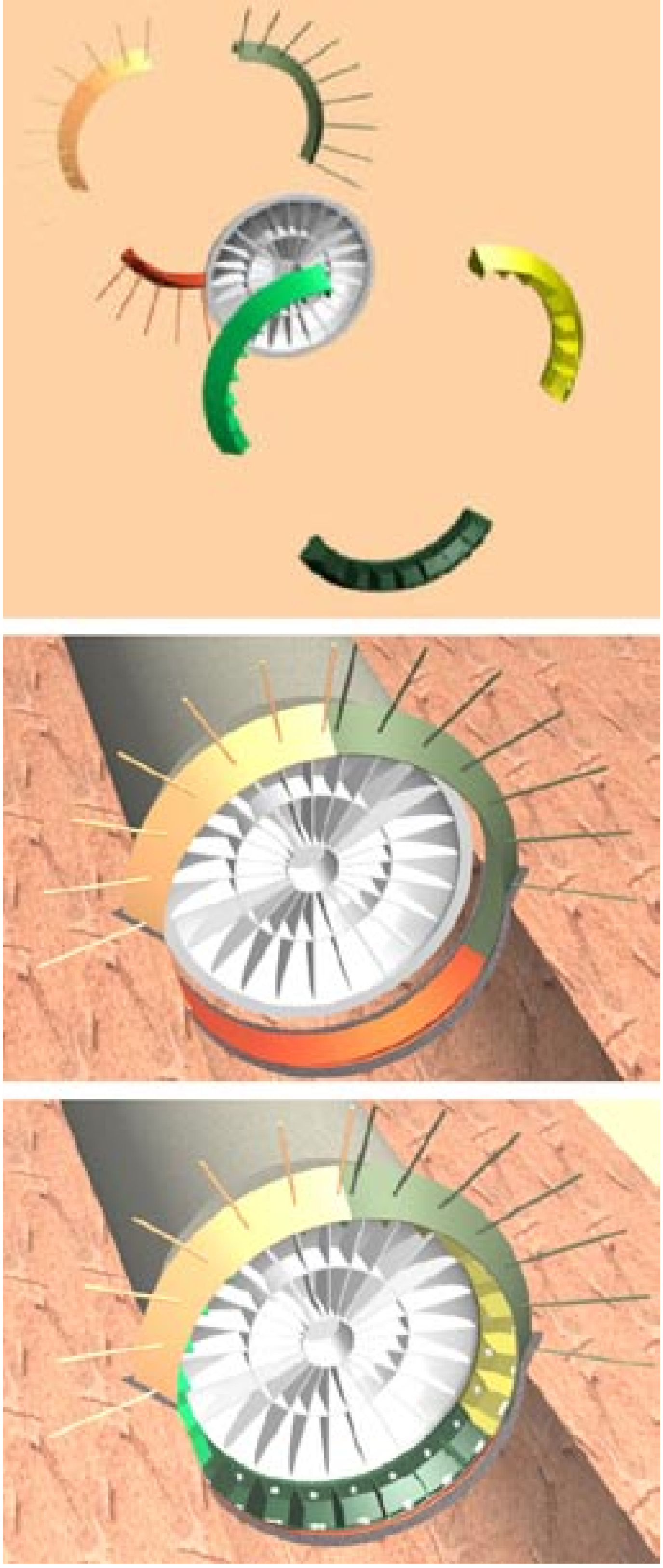


Figure 4-8. *3-D visualization of the steel plug, components from the open drift side (top), center oval detached (middle) and all components attached (above). (The figure and design has been made by P-E Rönnqvist at Fortum Nuclear Services Ltd).*

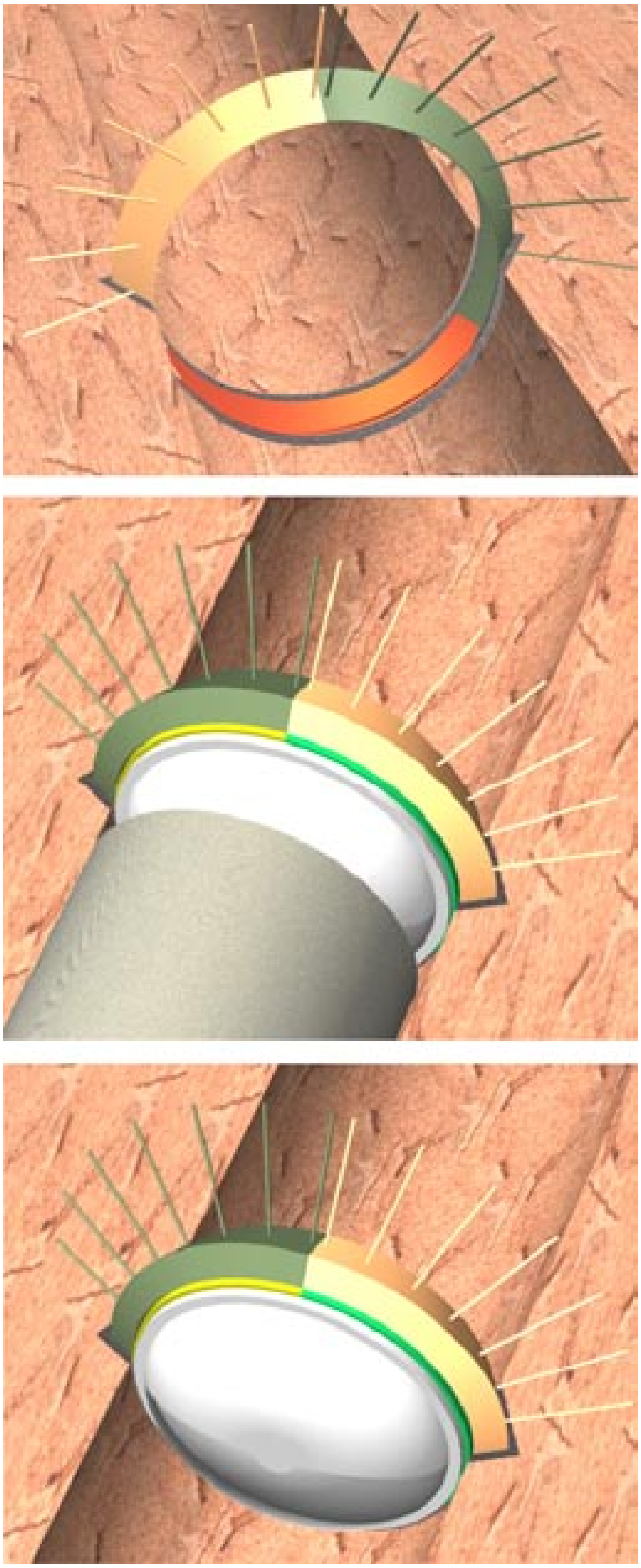


Figure 4-9. 3-D visualization of the steel plug from pressure side with filling (middle) and without it (above). The collar is attached in rock before operation starts (top). (The figure and design has been made by P-E Rönnqvist at Fortum Nuclear Services Ltd).

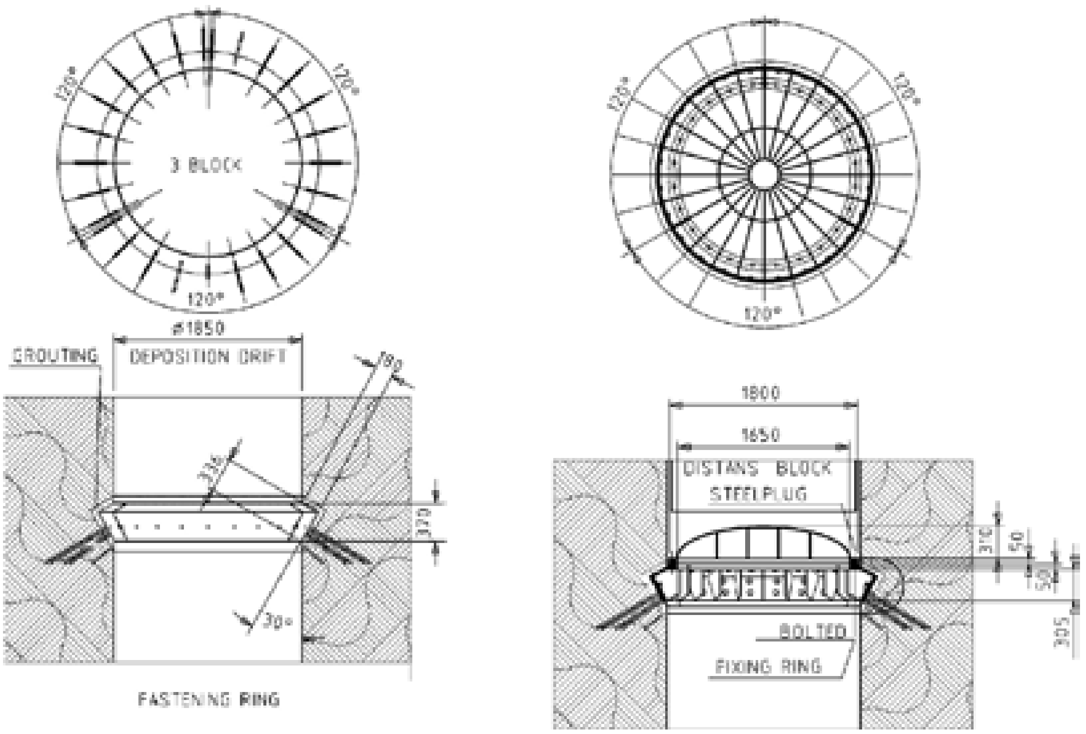


Figure 4-10. *Cross-section of the fastening ring of the steel plug (left) and the plug (right). (The figure and design has been made by P-E at Fortum Nuclear Services Ltd).*

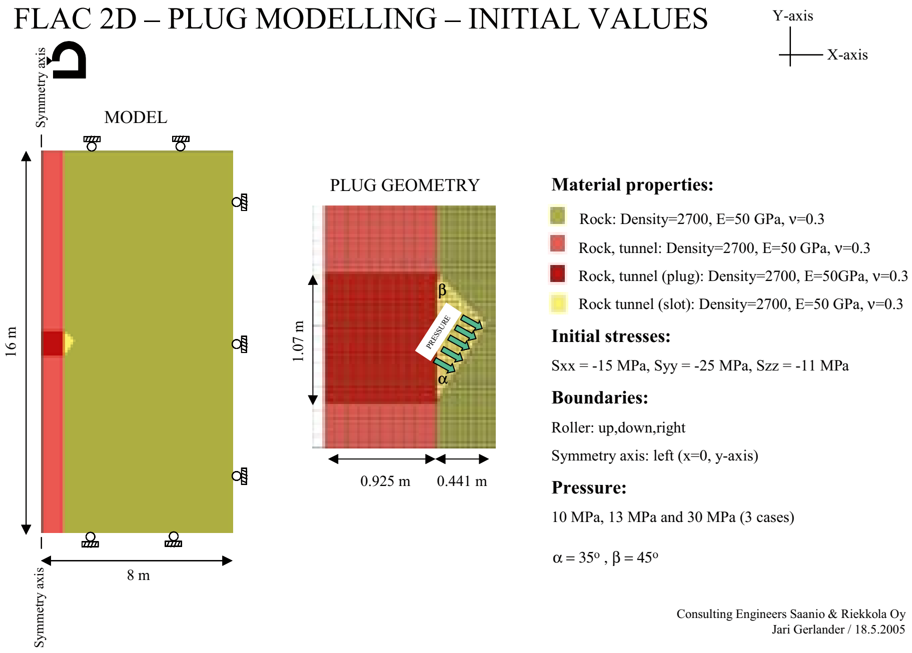
Rock behaviour in the position of the plug

The plug exerts a force on the contact surface between the steel and rock. The high force may cause the rock deformation.

In order to estimate the significance of the rock deformation an axisymmetric model of the drift and excavated notch was made and the behavior was modeled by using FLAC-2D modeling program. The force induced by 5 MPa hydraulic pressure on the whole surface of the plug was applied on the contact surface. The model and the parameter values, which represented the rock at Olkiluoto are shown in Figure 4-11.

The results show that when compared to the initial situation after excavation of the notches, the changes in state of stress caused by the contact forces of the steel plug are not significant. The most deformed rock volume is adjacent to the excavated notch and that is relatively unaffected by the contact forces. The stresses (Figure 4-12) remain well below the strength of the rock in the elastic region – assuming that the plug is positioned properly in a competent rock. The rock surface in the contact area is displaced (Figure 4-13) about 0.1 mm outwards from the axis of the drift. The initial deformation caused by excavation of drift is clearly larger that that caused by the plug because the displacement of rock is 0.4 mm inwards after excavation and the displacement after full hydrostatic pressure loading is still about 0.3 mm inwards.

It is estimated that the deformation will endanger the structural strength of the steel plug, however it should be taken into consideration when finalizing the design of the plug and sealing of the attachment ring so that the deformation will not cause leakages in contacts.



Material properties:

🟩 Rock: Density=2700, E=50 GPa, ν=0.3

🟥 Rock, tunnel: Density=2700, E=50 GPa, ν=0.3

🟥 Rock, tunnel (plug): Density=2700, E=50GPa, ν=0.3

🟨 Rock tunnel (slot): Density=2700, E=50 GPa, ν=0.3

Initial stresses:

Sxx = -15 MPa, Syy = -25 MPa, Szz = -11 MPa

Boundaries:

Roller: up,down,right

Symmetry axis: left (x=0, y-axis)

Pressure:

10 MPa, 13 MPa and 30 MPa (3 cases)

α = 35°, β = 45°

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Figure 4-11. *Flac 2-D model of the rock adjacent to the steel plug.*

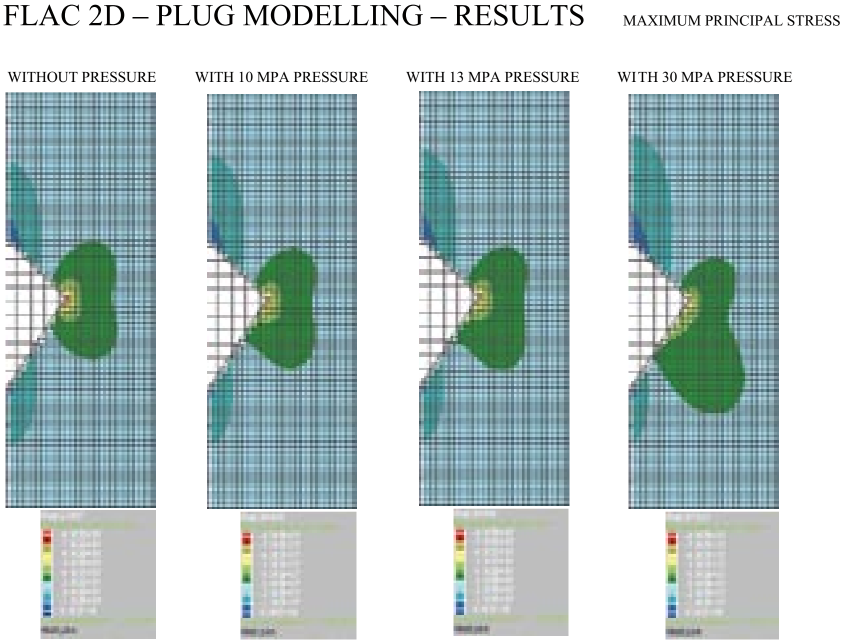
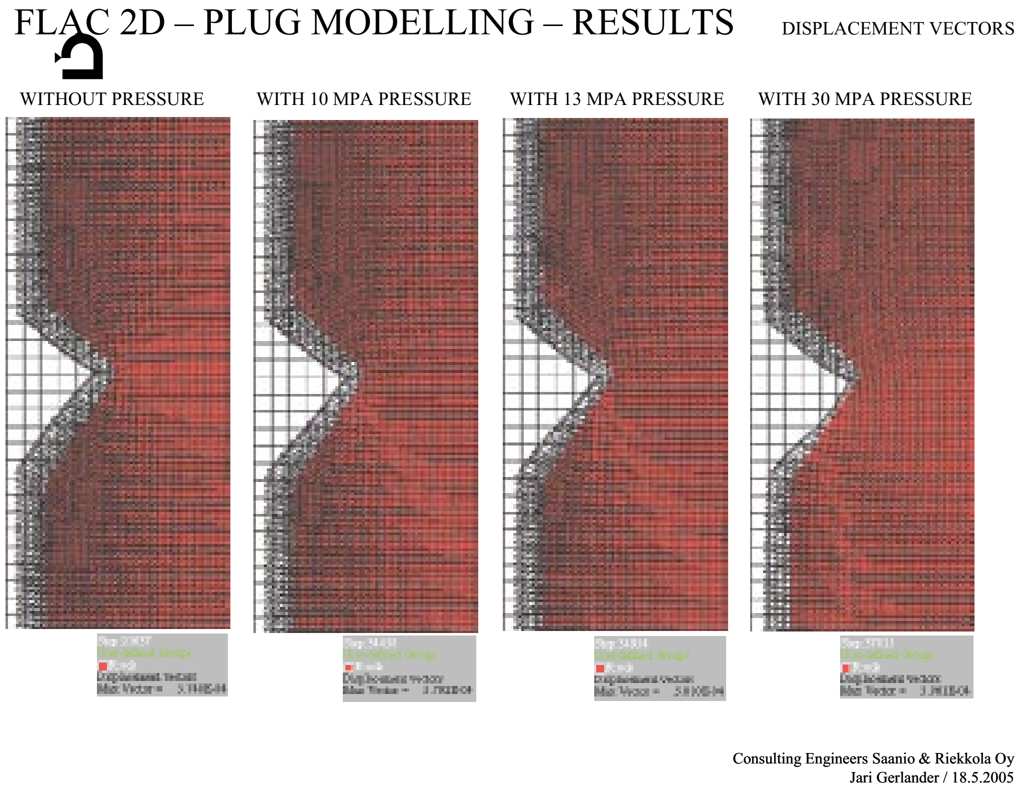


Figure 4-12. *The stresses around the steel plug modeled by using Flac 2-D. The situation after excavation is shown on left and the state of stress corresponding to 10, 13 and 30 MPa contact pressure are shown from left to righ in corresponding order. 13 MPa corresponds to hydraulic pressure of 5 MPa exerted on the whole surface of the steel plug. Lower (10 MPa) and clearly higher (30 MPa) pressures were modeled to evaluate the sensitivity of rock deformation with respect to hydraulic pressure.*



FLAC 2D – PLUG MODELLING – RESULTS

DISPLACEMENT VECTORS

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Figure 4-13. *The displacements around the steel plug modeled by using Flac 2-D. The situation after excavation is shown on left and the state of stress corresponding to 10, 13 and 30 MPa contact pressure are shown from left to righ in corresponding order. 13 MPa corresponds to hydraulic pressure of 5 MPa exerted on the whole surface of the steel plug. Lower (10 MPa) and clearly higher (30 MPa) pressures were modeled to evaluate the sensitivity of rock deformation with respect to hydraulic pressure.*

4.4 Positioning of the compartment border and plug

The compartment plug is installed in positions where rock is not suitable for deposition. The plug is installed and the position of plug is selected also on other basis which is discussed below.

One objective of the division into compartments is to reduce the time from start of operation to plugging in order to reduce the problems caused by swelling and saturation of buffer during operation. In this case it may be feasible to position the plug so that the operation time of all compartments is the same. In that case the equal operation time (as discussed in Section 3.4.2) can be calculated and is according to present estimates roughly at depth of 190 m in 300 m long drift. In that case the operation time of both compartments would be about 5 days assuming 24 hours per day operation. A time limit can probably be specified in the future which defines the maximum time the drift can be unplugged in both design alternatives.

In case of BD-alternative, the time required for the most critical supercontainer cell to fill with leaking water can be defined. In that case the plug should be positioned so that it can be installed with a good margin before the supercontainer cell becomes filled with water. It is estimated roughly that the time required to fill the open space in one supercontainer cell is of the order of 17 days if the flow is 0.1 l/min. This implies that it might be possible to plug the whole drift before any cells become filled with water.

The operation time and length of compartment has effect on the removal of piping systems. Increase in operation time increases the swelling of distance blocks, which has negative effect on removability. If the systems are removed by pulling them out, the length increases the frictional forces, which can in combination with swelling of buffer limit the length of compartment. The removability has not been studied and therefore there are not well justified estimates of the proper length.

4.5 Expected implementation and behaviour

It is assumed that the drift has been excavated according to the quality requirements, the bedrock has been sealed according to groundwater control specifications and the drift has been approved for deposition use according to specifications. It is also assumed that the drift has been equipped with temporary drainage, ventilation and lighting system and operational safety equipment and instrumentation. It is also assumed as a supporting measure, that the drift geometry has been measured and a three dimensional model of the drift is available with reference point in the drift wall.

4.5.1 Operation procedure

The planned stepwise operation procedure is:

1) Planning of drift specific implementation and definition of positions for design components (e.g. supercontainers, distance blocks, fixing rings, filling blocks, compartment plugs). The positions of deposition compartment borders and each component are determined before operation starts.

2) Preparatory rock works (e.g. installation of drip-shields, excavation of grooves and notches). Preparation of positions for steel plugs and fixing rings.

3) Installation of attachments to steel structures (mainly plugs and fixing rings) and placement of filling elements on floor in these to provide smooth surface for operation.

4) Emplacement of distance blocks, supercontainers and other design components to one compartment. The estimated longest time for this step is without attachment of fixing rings is 5 days. Installation of two fixing rings would increase the operation time to approximately 6 days.

5) The compartment plug is installed. The estimated longest time for this is one day.

6) The free space behind the plug is filled with filling material (e.g. sand and bentonite pellets).

8) The free gap and adjacent open volume is filled with water to speed up the saturation at the proximity of the plug.

9) When the drift is plugged and sealed the deposition operation of the compartment is completed and monitoring starts.

10) If the compartment border is adjacent to water leaking fracture zone, the operation continues with installation of backfilling in the fracture zone and subsequent plugging of the zone and compartment border. After that the operation starts from step 2 or 3.

The estimated time from the start of emplacement of deposition units to plugging and sealing is six days (assuming the longest length of the compartment).

4.5.2 Expected behaviour of EBS systems during operation, plugging and sealing of one compartment

a) During emplacement and plugging

Directly after emplacement, the bentonite absorbs water from air humidity in the drift. The expected longest emplacement time of one supercontainer unit (container and distance block) to a depth in the drift of about 290 m is about 12 hours, see Section 3.4.2, the corresponding time for unit at depth of 185 m is about 8 hours and for the last unit at depth of 15 m is 4 hours. The installation of a fixing ring increases the time with about 8 hours. It is however likely to be quite unfeasible to use such a section close to the end of drift for deposition and it is assumed that in such a case the end of the drift would be sealed before operation starts. Therefore it is assumed that longest emplacement time for one supercontainer unit is about 12 hours.

The operation of one compartment will take about one week if the length of compartment is 170 m at maximum. The largest possible inflow along the bottom of the drift at the border of the compartment is 1.7 l/min (assuming a supercontainer unit length of about 10 m and flow of 0.1 l/min). Right after the emplacement of the first distance block it will start absorbing water from air humidity, which is assumed to be RH100% at the initial state. The surface of the blocks will start to swell and crack. According to experiments with about 50 mm diameter buffer samples, the reference sample shown in Figure 4-14 was strongly affected after three days.

Therefore it is assumed that the emplaced distance blocks will crack during the operation time of the rest of the compartment and pieces of bentonite will fall on the bottom of drift. The flow on the bottom will erode some of the bentonite. It is assumed that after two days the gap between the distance block and drift bottom will be filled with swelling bentonite and sealed. This has not however been proven and confirming results are required.

The open volume around a supercontainer unit (length about 10 m and gap width of 42.5 mm between rock and buffer) is about 2.6 m^3. There is also additional open volume in the gaps between buffer distance block segments and in the porosity of bentonite, which however is not openly connected to flow in similar manner as the gaps). ***If the largest allowed flow into a supercontainer unit (supercontainer and distance block) is 0.1 l/min, it will take about 17 days before the supercontainer unit with that inflow is filled with water.***

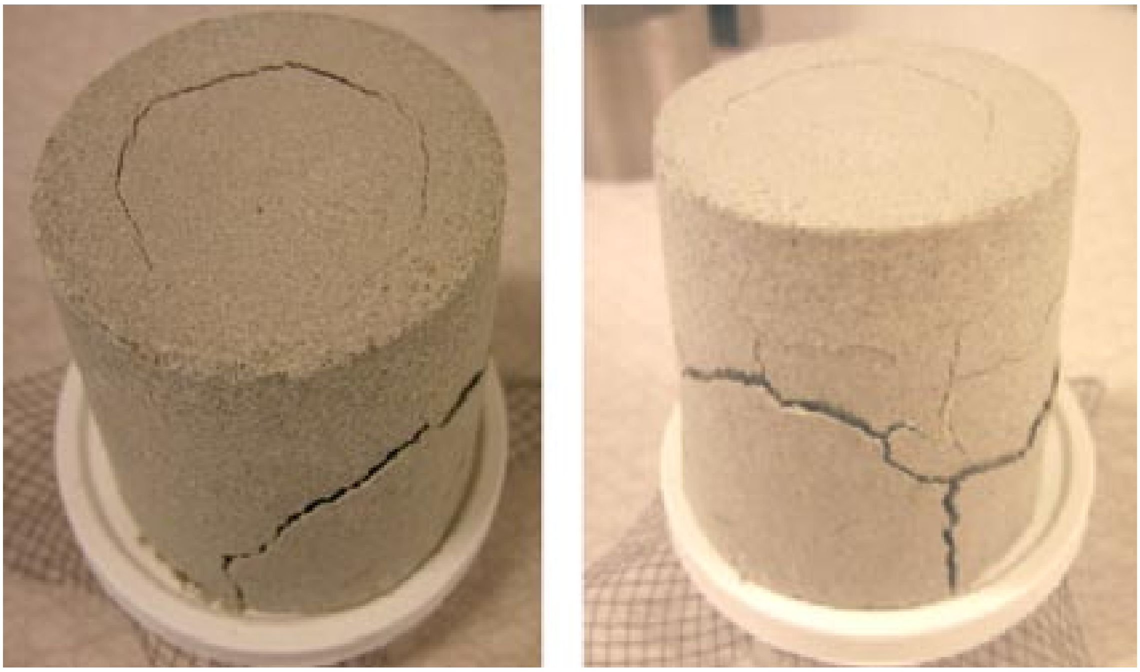

Figure 4-14. *A 50 mm diameter sample after being exposed to RH100% humidity for 3 days (left) and 9 days (right), the photo is provided by Torbjörn Sandén/Clay Technology Lund Ab.*

The operation of one compartment from the beginning of operation to the sealing is about six days. ***Therefore the open air volume in the supercontainer units have not been filled by the time when a hydrostatic steel plug is installed.***

However the buffer blocks have already started swelling and cracking by absorbing humidity from the drift air. Tests have indicated clear swelling and surface cracking after 7 days (see Figure 4-14). Therefore it is assumed that even before the drift is filled with water, the possible gaps between supercontainers and distance blocks have swollen in contact. The swelling in the proximity of the steel plug is accelerated by watering. Since the gaps have been tightened, ***it is assumed that the distance blocks cannot move after installing the plug***. It is also assumed that because the contacts between supercontainers and distance blocks have deformed by humidity to state where the surfaces are in contact. If there are water inflows available from the bedrock, this deformation and "tightening" of gap between supercontainer and distance block is enhanced. Therefore ***the hydrostatic pressure on the end surface of a distance block blocks is exposed only to a narrow ring shaped section adjacent to the outer periphery of the top of the distance block***.

There is experimental evidence, which shows that pressure is exerted only on a smaller surface area of the distance block, although the process may be fully understood. It seems that the bentonite in the gap swells – to a fluid type gel in the very early stage, but as it swells, it generates internal friction and does not behave like a fluid or gel anymore. Because of the internal friction in the deformed gap filling seals and the hydrostatic pressure does not affect the pore pressure in the deformed bentonite any longer. Therefore the water pressure in the open volume does not increase the pressure.

Fixing ring is one important design component, however, the dimensioning of it to eliminate the movement of distance blocks is not fully known.

b) After plugging and sealing the compartment before all open air volume is filled with water

As the open volume in the "wet" supercontainer units with largest leakages are filled with water, the gas escapes to other "dryer" units as long as the distance blocks have not become fully tight and there remains a small gap between the rock surface and distance block. It has been estimated roughly /Börgesson et al. 2005/ that the time required for the gap to be filled with humidity induced swelling of buffer is of the order of three months. Therefore the gap will remain open and the air will escape as long as the supercontainer unit has not been fully filled with water. As the supercontainer unit is filled with water, the gap between distance block and rock will swell almost simultaneously with the raising water level. After the supercontainer unit is totally filled with water, the pressure will raise rapidly with a rate from 100 to 200 kP/h or even more. The time required to obtain full pressure is from 25 to 50 hours, roughly from one to two days. A pressure of 1 MPa is obtained relatively fast in from 5 to 10 hours. It is likely that the highest pressure will be in range from 2 to 5 MPa.

It is assumed that no piping will take place, however the assumption is based only on small-scale tests, which may not describe the full scale behavior properly. The assumption is based on effective saturation of distance blocks via leaking rock fractures. The surfaces of distance blocks will absorb water from air humidity and crack before being in direct contact with water. The water contact will speed up the cracking and the cracks will transport water in the blocks and enhance the saturation. As the cracks become filled with water they swell, create confinement and seal. Some water may also be transported in the distance blocks along the drift surface as capillary flow. The principles of behavior of distance blocks and piping are not fully understood and there is lack of evidence to support the assumed behavior described above.

However, if some piping will take place from “wet” to “dry” supercontainer cells, it is assumed that the amount of bentonite being transported is insignificant. The open volume in a supercontainer unit is of approximately 2,600 l. This is the largest flow, which can take place from “wet” supercontainer cell to “dry” one. The maximum flow rate is defined by the allowed inflows being 0.1 l/min. If the piping occurs in an early state of saturation, there is not adequate swelling pressure to keep the piping channel closed. Therefore flow will transport some of the bentonite, which enlargens the channel, decreases the flow speeds and slows down the erosion. If the amount of total suspended solids (transported bentonite) in flow would be in the range of 1.5% (see Figure 5-14), the amount transported would be 37 kg. The total amount over fourteen cells (the maximum number of canisters between two sections) would be 525 kg, which would be transported from one distance block as suspension “mud” and deposited along the supercontainer “train”. This would reduce the mass in buffer by about 2%, which would be equal to density reduction in distance block roughly from 2,000 kg/m^3 to 1,960 kg/m^3. The erosion of bentonite buffer by piping depends on entrainment, transport and deposition (sedimentation). The entrainment depends on flow speeds, which are function of flow rates and pipe geometries, which are not known. When bentonite is entrained in the flow, it will be transported efficiently, however the amount of total suspended solids in the flow probably has a maximum value, which is to some extent dependent on the flow rate and is not known. After the bentonite is transported as suspension and the flow stops it will be deposited slowly.

It is assumed that no significant transport of bentonite takes place inside a supercontainer cell from surface of supercontainer (60% perforation) or distance blocks to drift bottom. The water inflow can be at largest 144 l/day for 17 days in one supercontainer position. The flow will be spread in filling across the whole open volume. The inflows are directed towards the bottom and walls by using drip shields. The area of the gap around the distance block is 0.25 m^2. If the flow is directed only in one way from the source, and that would be the minimum cross sectional area, the flow speed would be about 7E–6 m/s. The flow speed is very slow and it is assumed that it is not enough to cause erosion. The possible softened bentonite “mud” is assumed to be partly suspended in water, however it will be settled evenly on the drift bottom along the supercontainer. The density of suspension is assumed to be so low that it will not affect the buffer density significantly.

c) After all compartments are filled with inflowing water from bedrock

The filling of all supercontainer cells by inflowing water may take several months or even years if some sections in the drift are very dry. The water is transported to dry section in several different ways. After all the supercontainer cells have been filled with water and the buffer has swollen and filled the gap between rock and buffer, the buffer will absorb the water. It is assumed that the absorption of water into supercontainer is so slow that the additional water required to keep the buffer surface swollen and fill the gap between rock and buffer is provided from surrounding bedrock.

The pressure raises relatively rapidly (at rate of 100 kPa/h or more) to the full hydrostatic pressure. The full hydrostatic pressure is obtained in 50 hours (about two days).

Since there is no free space available in the drift to be filled with inflowing water, it is assumed that there is no significant flow from the drift to any other open tunnel section.

4.6 Possible deviations from the expected implementation and behavior

Some deviations from expected implementation and behavior are presented based on engineering judgment. It is assumed that a full comprehensive analysis shall be made later. It is assumed that thorough QA-program is applied and therefore deviations in construction are detected.

4.6.1 Deviations during operation

The possible deviations and subsequent actions are presented corresponding to the stepwise operation procedure presented in Section 4.5.1:

1) Planning of drift specific implementation.

   Deviation: the conditions in the drift change during the time from drift excavation to operation so that the plan is not valid, e.g. the inflows in some points have increased over the limits.

   Action: The drift is characterized before operation starts and remedial measures are taken. The conditions in the drift should be checked after neighboring drift has been sealed.

2) Preparatory rock works (e.g. installation of drip-shields, excavation of grooves and notches). Preparation of positions for steel plugs and fixing rings.

   Deviation: the preparatory works are carried out in wrong position. The result is that there are e.g. anchoring holes or grooves in wrong positions.

   Action: **the grooves or holes are filled with low pH-cemen**t and remedial measures are taken.

   Conclusion: additional amount of cement shall be left in the drift.

3) Installation of attachments to steel structures (plugs and fixing rings).

   Deviation: The installation fails or does not fulfill the requirements.

   Action: The installation is disassembled and repeated.

4) Emplacement of distance blocks, supercontainers, fixing rings and other design components to one compartment.

   Supercontainer

   Deviation: The installation equipment fails and is damaged and/or the supercontainer is damaged.

   Action: The equipment is repaired or replaced and continued. In severe situation (e.g. deposition vehicle burns in the drift) when long delay is expected the operation is reversed and a single or several supercontainers are removed from the drift.

   Conclusions: The installation time becomes longer. The buffer has swollen more than in the expected situation. It is assumed that the operation time can however be doubled without significant effect. In severe case the deposition timetable is delayed by the time which is needed to remove supercontainers from the drift, however the operation efficiency requirement of one canister per day, which is one third of the real operation time, allows significant flexibility in timing.

   Distance block

   Deviation: The distance block is broken during emplacement.

   Action: The distance block is transported out of the drift, the drift is cleaned and a new block is transported in the drift. In case of small failure, the block is emplaced and the drift is cleaned.

   Conclusions: The installation time becomes longer. The broken distance blocks have to be removable relatively rapidly. The criteria for acceptance of a broken distance block has to be defined.

5) The compartment plug is installed.

   Deviation: the installation takes more time than expected because of technical problems and possible replacement of steel parts.

   Action: The timetable has flexibility and no specific actions are required.

   Conclusions: The longest allowable time for installation of the steel plug has to be defined.

6) When the drift is plugged and sealed and all system parts are removed, the deposition compartment operation is completed and monitoring starts.

   Deviation:
   Hydraulic pressure does not increase behind the plug because of a) failure of plug, b) side-flow through rock into open tunnel.

   Action:
   a) The plug is repaired (by welding, grouting etc) and the pressure is released during the operation. If required a new plug is installed.

   b) The amount of side flow and flow path is estimated. If the flow is directed towards the open part of the drift, a new plug is installed if necessary. If required, the drift is retrieved.

   Conclusions: The positions of plugs have to be selected so that sideflow will not occur. The possibility of significant flows from the compartment into open tunnels or drifts has to be eliminated by proper characterization and groundwater control techniques. The operation has to be planned so that a new plug can be installed rapidly if necessary. The criterion for acceptance and largest allowable time delay has to be defined.

7) The operation continues: A) from step 4 or B) with installation of backfilling in a leaking fracture zone and subsequent plugging.

4.6.2 Deviations in behaviour of EBS systems during operation, plugging and sealing of one compartment

a) During emplacement and plugging

The emplaced distance blocks will crack during the operation time of the rest of the compartment and pieces of bentonite will fall on the bottom of the drift. The flow on the bottom erodes significant quantity of bentonite and the gap between rock and buffer is not sealed.

The distance block is not saturated and swollen as assumed and there is constant eroding flow on the drift floor. The total largest possible flow rate of 1.7 l/min corresponds to a daily flow of about 2,400 l/day. The total amount of suspended solids (see Figure 5-14) that the flow can transport is clearly larger than assumed, of the order of 5%, the transported amount of bentonite out from the drift during six days would be 750 kg. Most of this would be transported from the supercontainer units positioned further away from the compartment entrance where the units have been in humidity for the longest time (assuming an equal flow of 0.1 l/min in every supercontainer unit).

The possible gaps between supercontainers and distance blocks have not been swollen in contact. Therefore ***the hydrostatic pressure on end surface of a distance block blocks is exposed to the full top of the distance block and the distance blocks move after installing the plug. The movement is limited by the compressibility of other supercontainer units and possible fixing ring. If there is a e.g. a 5 mm gap between supercontainer and distance block, and 14 supercontainer units, the sum of all gaps is 14 cm. This would roughly be the largest possible movement of one distance block***.

A fixing ring is used to eliminate the movement of potential distance blocks. If the distance block cracks, it is possible that the fixing ring cannot support the block. If the distance block moves sufficiently, full hydrostatic pressure is exerted on the top surface of the block and the block is driven through the fixing ring until it collides with the next supercontainer unit. As a consequence of the movement the block cannot maintain sealing capacity and piping occurs.

The full hydrostatic pressure in supercontainer unit is exerted on a full top surface area of the distance block. The distance block is driven through possible fixing ring and collides with adjacent supercontainer unit.

b) After plugging and sealing the compartment before all open air volume is filled with water

After the supercontainer unit is totally filled with water, the pressure will raise at a faster rate than expected e.g. 400 kP/h. The time required to obtain full pressure is 12 hours. Fast pressure generation causes piping because the plug has not been sufficiently saturated.

Piping will take place from “wet” to “dry” supercontainer cells and the transported amount of bentonite is insignificant. The open volume in a supercontainer unit is of approximately 2,600 l. This is the largest flow, which can take place from “wet” supercontainer cell to “dry” one. The maximum flow rate is defined by the allowed inflows being 0.1 l/min. If piping occurs through bentonite with some swelling pressure, the pressure will diminish the opening of the pipe and therefore increase the flow velocity in the pipe and enhance the entrainment of bentonite particles. Therefore flow will transport significant quantities of the bentonite. If the amount of suspended solids would be in the range of 5%, the amount transported would be 120 kg. The total amount over fourteen cells (the maximum number of canisters between two sections) would be 1,680 kg, which would be transported from one distance block as suspension “mud” and deposited along the supercontainer train. This would reduce the mass in buffer by about 6% which would be equal to density reduction in distance block roughly from 2,000 kg/m^3 to 1,880 kg/m^3.

c) After all compartments are filled with inflowing water from bedrock

After all the supercontainer cells have been filled with water and the buffer has swollen and filled the gap between rock and buffer, the buffer will absorb the water. It is assumed that the absorption of water into supercontainer is such that the additional water required to keep the buffer surface swollen and fill the gap between rock and buffer is not provided. There will become pressure gradient between “wet” and “dry” supercontainer cells, which will cause piping.

The swelling of buffer will be caused by absorption of water as moisture from the air in the drift and later by absorption of water from inflows. If the hydraulic conductivity of bedrock in tight sections is of the order 1E–12 m/s, the inflow flux will be of the order 0.5 ml/(h*m^2). The humidity absorption rate of buffer is of the order 19 ml/(h*m^2) and diffuse transport from wet surface to buffer is of the order 9 ml/(h*m^2). Therefore there shall be supercontainer sections, which will stay dry relative long periods of time next to sections, which will saturate and rapidly to full hydrostatic pressure. The difference in time can be two orders of magnitude or larger, e.g. empty volume in one supercontainer section can fill and the bentonite swell to fill the open gap in 10 days whereas the neighboring section in tight rock may fill and the buffer swell in 200 days.

One possible deviation form expected behavior is that flow takes place from water filled drift at hydrostatic pressure to open neighboring drift or other tunnels. The flow is driven by pressure gradient. The flow will erode and transport buffer.

4.7 Evaluation of preliminary BD design

4.7.1 Design components

The design involves several design components, which have not been tested and verified. The most important design components and relevant uncertainties are described in Table 4-1. (Note: the level of design of components is preliminary).

4.7.2 Implementation and operation

The implementation and operation of the design is quite simple and straightforward. However some parts of the design of distance blocks (e.g. segmenting of the block, filling of gap with pellets) may require development of new type installation equipment.

Operation time from start of deposition operation to plugging the compartment is important. The movement of distance blocks could become negligible if the plugging is carried out before any of the supercontainer cells is filled with water. The operation time affects also the possible transport of bentonite by erosion. The allowed operation time has effect on the feasibility and therefore the range for the time should be defined more comprehensively.

If the critical operation time is exceeded, the long-term reverse operation or short-term retrieval should be developed.

Table 4-1. List of uncertainties related to design components.

Component	Status	Uncertainties 1 = low 3 = high
BD-DC1 Spray shield	Not demonstrated	1
BD-DC2 Distance block	– The design parameters are uncertain – The performance of distance blocks in given inflow conditions is uncertain – Uncertainties in process understanding – Significant uncertainties with respect to piping and behaviour with fixing rings	3
BD-DC3 Fixing rings to support distance blocks	– Implementation not tested – Necessity should be evaluated – Functioning not verified by tests	2
BD-DC4 Coupling between super-container and distance block	– The function is not verified at full-scale – Understanding of process may contain uncertainties	2
BD-DC5 Compartment plugs	– Implementation not tested – Positioning not investigated – Functioning not verified by tests	2
BD-DC6 Filling blocks	Same as distance blocks	3
BD-DC7 Drift plug	– Several alternatives – Design being tested	1
BD-DC8 Permeable filling	– Several alternatives – Functioning not verified by tests	1
BD-DC9 Partially permeable filling	– Several alternatives – Functioning not verified by tests	1

4.7.3 Degree of drift utilization

The average spacing between water bearing fractures depends on the transmissivity (see Figure 4-15). The distribution is evidently site specific and is in general of unsymmetric-type. The present estimate is that the largest allowed inflow to a supercontainer unit of length about 10 m is 0.1 l/min. If flow is higher, the leaking section has to be isolated by plugging, which consumes the effective drift length available for deposition. One compartment plug consumes roughly about 5–10% of the drift length. Because the correlation between fracture transmissivity and spacing is of reversed exponential-type, the reduction in largest allowed inflow increases the number of plugs exponentially and on the contrary. Therefore uncertainties in the largest allowed inflows has exponential effect on the feasibility and reduction in allowed inflows may lower the feasibility under acceptable level.

The design can be optimized with respect to inflows in lay-out design, if there is proper information available to improve degree of drift utilization if necessary. However, the design can be used as alternative to DAWE design in section with suitable sections.

4.7.4 Most significant uncertainties/Risks

Most significant uncertainties and risks in the design are:

- Distance blocks ability to seal the drift effectively and fulfill the requirements is uncertain and critical to feasibility. If the distance blocks don’t function properly, the design is unfeasible.
- The degree of site utilization is uncertain. It is possible the drift utilization degree at given inflow condition is low and therefore the design is not feasible (both economically and technically). It is possible however that by developing proper sealing techniques the utilization can be improved significantly.

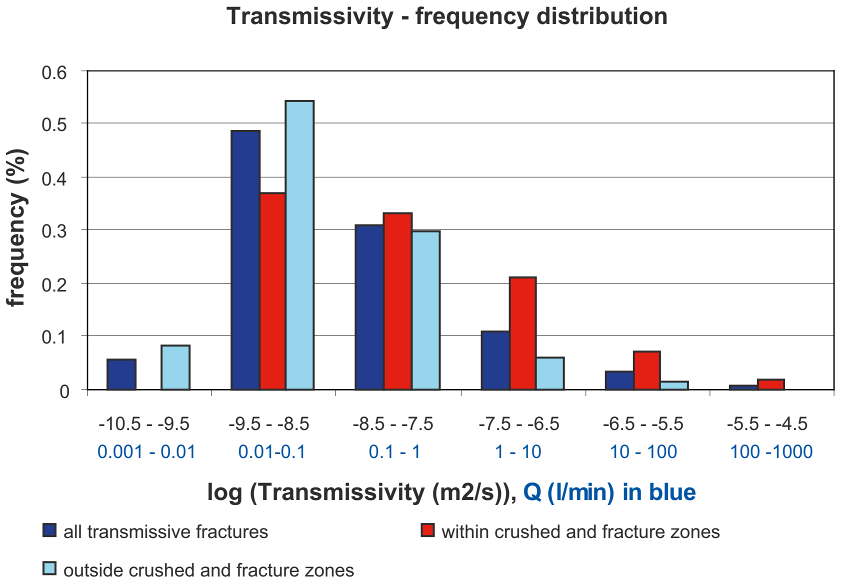

Figure 4-15. *Distribution of transmissive fractures at Olkiluoto. Note: The scale is logarithmic, therefore the inflow to drift from a fracture with log (–8.5 m^2/s) transmissivity is ten larger than from a fracture with log (–9.5 m^2/s) /Hellä et al. 2006/.*

5 Specification of DAWE design

5.1 Specification of the functional structure, concept development

It is assumed in the specification that groundwater inflow has been reduced by applying proper techniques and therefore sealing is not included in functional structure below. The function of deposition drift, canister, supercontainer, backfilling and sealing are not described here more than necessary because they are considered to be fixed part of design.

The functional structure of the design is composed of following elements:

1. **Prevention for surface erosion by spray and drip shields.** Direct water flow (see Figure 4-5) on buffer surface will cause surface erosion. Spraying, squirting and significant dripping of groundwater on supercontainers and distance blocks is prevented by using shields.
2. **Prevention of transport of moisture by drip shields.** Significant leaking wet sections on the walls of the drift are covered to prevent diffusive transport of water into the buffer, which causes cracking. All water inflows are directed to the bottom section of the drift under shield.
3. **Drainage on the bottom of the drift.** The water inflows are drained so that buffer will not be in contact with water. The drift is inclined and therefore water flows naturally towards the entrance of the drift.
4. **Negative effect of buffer cracking is reduced by metal mesh.** Transport of air humidity in the buffer will cause some swelling, which will induce surface cracking. As a consequence of cracking some particles of bentonite will drop on the floor of the drift. If there is free flow on the floor these particles will be transported along the flow. The degree of swelling is reduced and the loosened particles will be kept from falling by placing a metal net under the buffer when necessary.
5. **The plugged drift is filled with water by using artificial watering pipes.** The empty volume in the drift is filled with water to diminish possible hydraulic pressure differences between supercontainer section, which may cause e.g. piping and detrimental transport of bentonite. All supercontainer sections are filled at the same time prevent axial flow along the drift. As a consequence of filling, bentonite will swell rapidly and seal the drift. The pipes are removed from the drift after watering.
6. **Air and gas is evacuated during filling by using air evacuation pipe.** Large volumes of air and gas are trapped in the drift after plugging. Highly pressurized gas acts as an energy accumulator, which may induce unfavorable flow in the drift and cause operational problems during removal of wetting pipes.
7. **Isolation of water bearing fracture zones by plugs (same as in basic design).** Isolation of deposition compartments by using plugs from water bearing fracture zones, which may have detrimental effect on the distance blocks and supercontainer during saturation.
8. **Sealing of the drift by plugs (same as in basic design).** The deposition drift is sealed and plugged after emplacement of canisters. The plug will enable maintaining of adequate hydrostatic pressure in the drift after operation and keep the supercontainers and other components in position. The plug will be exposed to both hydrostatic pressure and swelling pressure from the buffer. The plug is positioned so that flow from the drift into the surrounding open tunnels is small enough to eliminate possible erosion.

9. **Intermission of operation by plugs (same as in basic design).** The emplacement of supercontainers can be stopped temporarily if the drift is plugged rapidly before the distance blocks start to swell into the open tunnel.
10. **Thermal spacing of canisters by distance blocks (same as in basic design).** Thermal spacing between successive canisters is obtained by using a distance block of required length.
11. **Sealing of unsuitable sections by filling blocks (same as in basic design).** Positions which are not suitable for emplacement of a supercontainer because of larger than accepted water inflow or other reasons are filled with filling blocks. The objective of the blocks is to provide extra sealing against neighboring distance blocks and to reduce the hydraulic pressure induced force exerted on distance blocks.

5.2 Specification of the design components

5.2.1 General

Deposition drift, supercontainer etc design components are kept fixed and are not considered in this context.

The design components, which are same as in basic design are described in Section 4.2.

The DAWE Design Components (DAWE-DC) shown in Figure 5-1 are:

- DAWE-DC1 Spray and drip shield.
- DAWE-DC2 Distance block.
- DAWE-DC3 Drainage system of inflowing water.
- DAWE-DC4 Air evacuation system.
- DAWE-DC5 Compartment plugs.
- DAWE-DC6 Filling blocks.
- DAWE-DC7 Artificial watering system.
- DAWE-DC8 Metal net to reduce humidity induced cracking in supercontainer.
- DAWE-DC9 Metal net to reduce humidity induced cracking in distance block.
- DAWE-DC10 Drift end plug.
- DAWE-DC11 Permeable filling.
- DAWE-DC12 Partially permeable filling.

5.2.2 Spray and moisture shields

Spraying and squirting of water on buffer is prevented by placing spray and drip shields on inflow points and significant leaking wet surfaces are covered with moisture shields. The inflow is conducted to the floor section under shields, which reduce the transport of water by moisture and other mechanisms in the air. The shields are composed of metal material.

Material alternatives for the shields are copper or steel. Steel is preferred because the structures are thin (presumably less than one mm), the number of them is small and the steel can be assumed to corrode and disappear in relatively short time period when compared to supercontainer. The shields are dimensioned to withstand their own weight and facilitate mechanical attachment to rock surface.

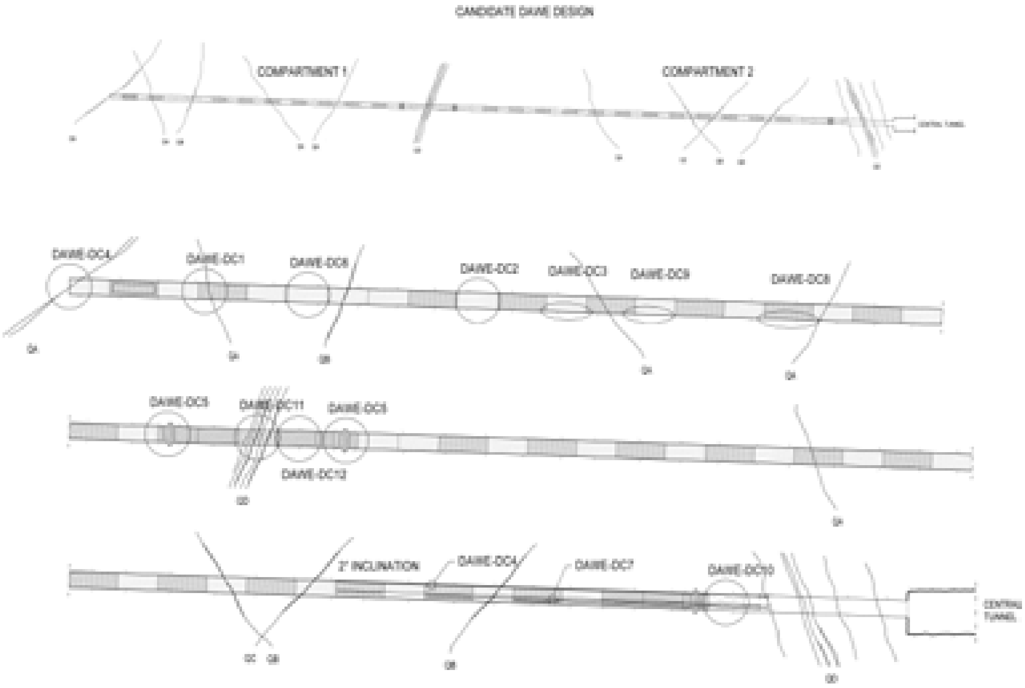

Figure 5-1. The DAWE design in an illustrative vertical section with examples of positions of design components. The identifiers in fractures refer to different types of water leaking fractures. The wetting and air evacuation pipes are shown only in the beginning of the drift.

Key design issues:

- geometry,
- thickness,
- attachment,
- installation,
- material quantities which remain in the drift after closure.

5.2.3 Drainage system of inflowing water

The objective of the drainage system is to remove 10 l/min of water out from the approximately 150 m long drift compartment. The drainage system can be based in alternative principles:

1) The primary alternative is to allow free flow.
2) If transport of humidity from the water surface cannot be allowed, the flowing surface is covered with drainage mat before operation starts. The mat is removed after operation. The operation equipment have to adapted to the design.
3) As an alternative a groove can be made on the bottom of the drift to narrow the open water surface and enlarge the gap between water surface and buffer. The groove is made only as long as necessary. The groove is covered with a shield, which reduces the transport of humidity. The shield is removed after operation and the groove is filled with bentonite if necessary.

Key design issues:

- geometry and size,
- removability,
- excavation works.

5.2.4 Metal net to reduce humidity induced cracking of buffer

The swelling and cracking of buffer (see Figures 5-2, 5-3 and 5-4) is reduced by covering the bottom part of buffer by metal mesh. The objective of net is to keep loosened particles of bentonite from falling and to reduce the cracking by giving confinement. The net is placed only on down side of buffer because the expected swelling is more rapid in that part and cracking of bentonite on upper half will not cause significant dropping of loosened particles.

The mesh is used only when necessary and it may not be required in dry sections, e.g. if there is no flow on floor. The diameter of strings in the mesh is likely less than one millimeter. The preferred metallic material is iron because it will disappear rapidly by corrosion. When the drift is filled with water, the bentonite will soften and the softened gel will swell through the mesh. At saturated state the mesh will be embedded in bentonite.

Figure 5-2. *A 50 mm diameter cylindrical sample of compacted MX-80 bentonite after being exposed to humidity RH 100% for nine days (the photo is provided by Torbjörn Sandén/Clay Technology Lund Ab).*

Figure 5-3. *Example of three50 mm diameter samples of bentonite wrapped in a mesh after being exposed to RH 100% humidity for nine days. Note: this small scale experiment does not show how distance blocks behave, however they give indications of certain processes related the interactions between mesh and bentonite (the photo is provided by Torbjörn Sandén/Clay Technology Lund Ab).*

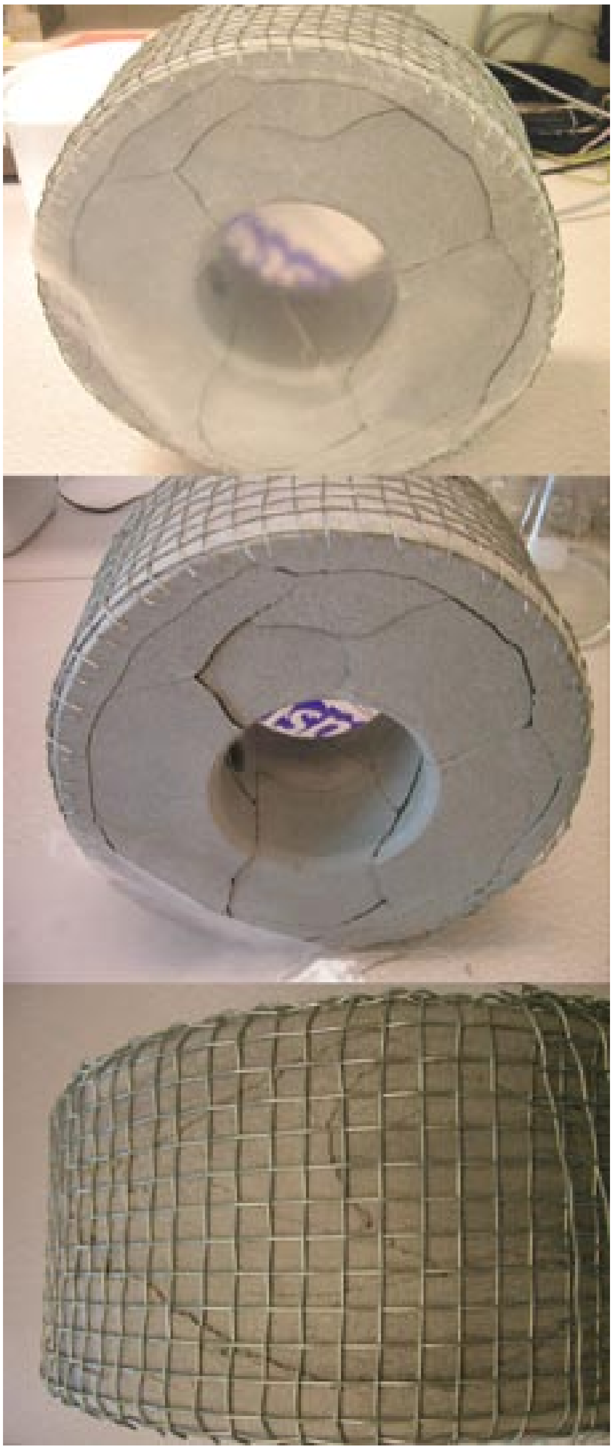

Figure 5-4. *Example of swelling of bentonite after being exposed to RH 100% humidity for 12 (top) and 28 days (middle and above). The diameter of sample is 28 cm, the diameter of the hole in the middle is 11 cm and the length of the sample is about 10 cm. The bentonite is compacted MX-80 (reference buffer in KBS-3 concept). The mesh size is 8–12 mm. Note: this small scale experiment give indications of certain processes related the interactions between mesh and bentonite (the photos are provided by Torbjörn Sandén/Clay Technology Ab).*

The method for application of the net is also very important for the function in this case. A strong net, locked to the surface, will allowed the bentonite to swell through the net and prevent it from being moved out to the rock surface. A loose net will probably be moved as the swelling is going on. A parameter, not investigated here, is the mesh size of the net. This will probably affect the behavior.

Key design issues: attachment of mesh, installation technique and procedure, geometry and amount of steel.

5.2.5 Artificial watering system

The open volume in a supercontainer section is about 1.3 m^3 (42.5 mm gap and 5.56 m length). The open volume in the distance block section of length 5.46 m is 1.3 m^3 (42.5 mm gap). The largest possible total open volume is about 2.6 m^3. Most likely the final volume will be smaller because of humidity induced swelling. In order to fill the total open volume in a 15 supercontainer compartment in 14 hours, a flow rate of 45 l/min is required. This is equal to about 3 l/min per supercontainer section. The open gap between supercontainer and rock surface under operation is 20 mm. After operation the gap is 42.5 mm. As design principle, no pipes are allowed to be left in the drift.

The positioning of pipes on top of the drift is preferred over bottom of drift to avoid possible problems with removal of pipes. However, the clearance on the sides is clearly larger during operation and therefore vulnerability for damage is smaller on sides. Therefore sides are the preferred position for pipe systems. Water is led to the drift evenly through several holes in every container section to avoid large inflows. If twenty holes are positioned in every supercontainer section, the inflow per hole is 1.3 dl/min. Water is not injected in sections where distance blocks are positioned in order to avoid possible erosion.

The pipes should have redundancy if possible in such a way that if one pipe is blocked the required flow should be conducted through other pipes.

A collar seal system is required in order to remove the pipe or pipes without loss of softened bentonite from the plugged drift. The collar system may be based on similar principle as collar systems used in underwater drilling. Another alternative is to pressure the drift for the period of removal. This would require a pressure of 0.3–0.5 bar at maximum (difference in hydraulic head between the ends of the drift) and will not prevent the leakage of groundwater at higher pressure. Bentonite mud is pumped in the drift if necessary to fill the open volume left by the pipes during removal.

Steel is the preferred pipe material because it will not introduce any new material in the drift and will corrode in case it is left in the drift as a consequence of deviation in operation.

Key design issues:

- geometry and size of pipes,
- installation and removal,
- amount of steel.

5.2.6 Air evacuation system

A pipe is installed on top of the drift or on sides before operation. The end of the pipe is attached to the highest point at the far end of the drift. The pipe is removed after air is evacuated and the filling water comes out of the pipe. A collar seal system is required in order to remove the pipe without loss of softened bentonite from the plugged drift.

Steel is the preferred pipe material because it will not introduce any new material in the drift and will corrode in case it is left in the drift as a consequence of deviation in operation.

Key design issues:

- geometry and size of pipe,
- installation and removal,
- amount of steel.

5.2.7 Plugs

The specification of compartment and drift end plugs are similar to that in Basic Design presented in Section 4.2.6.

The only difference to BD alternative is that the plugs are equipped with lead-throughs, valves and collar seals for possible drainage, wetting and air evacuation pipes.

5.2.8 Filling blocks

Filling blocks are used next to plugs as massive sealing elements and to fill positions, which are unsuitable for placement of supercontainer similar to Basic design described in Section 4.2.7.

The filling blocks should seal the section of drift where they are positioned and should resist erosion. The properties of the blocks may possibly differ from that of distance blocks, e.g. the resistance for erosion can be increased, swelling potential decreased and hydraulic conductivity increased.

5.3 Preliminary designs

5.3.1 General

It is assumed that the spray and drip shields, steel plug can be based on the same design as in case of basic design.

5.3.2 Artificial wetting system

The watering system can be implemented by following alternative designs (note that all pipes are removed after filling):

A) Several smaller diameter watering pipes positioned on the sidewalls of the drift before operation starts.

B) Installation of few larger diameter pipes stepwise during operation on the sidewalls of the drift.

C) Installation of one large watering pipe in a groove on top of the drift before operation.

D) Installation of watering pipe in a groove on bottom of the drift and filling of the groove with bentonite after water filling if necessary.

The pipe material in all alternatives is steel. In all systems the water is distributed evenly in the supercontainer sections through several (10–30) holes.

A) Installation of several smaller diameter watering pipes before operation starts

One pipe of diameter 17.2 mm is required for every supercontainer section. The number of pipes is doubled by installing pipes on both sidewalls for redundancy. The air evacuation pipes are installed on top the wetting pipes. If the deposition vehicle hits one wall and set of pipes the rest are assumed to function properly. The amount of pipes on both walls is therefore about 15, see Figure 5-5. The pipes are attached on the sidewalls of the drift in U-shaped brackets so that they can be pulled out separately. One collar seal is installed in the plug for every pipe. The water is distributed through several small holes in the pipes to supercontainer cells.

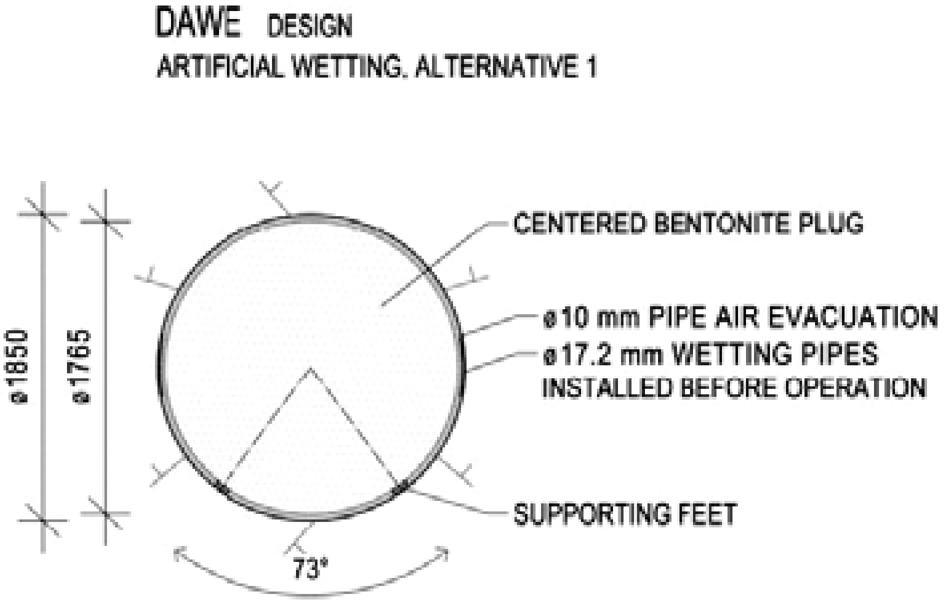

__Figure 5-5.__ The artificial watering and air evacuation pipes in the alternative based on use of several small 17 mm diameter pipes on the sides of the drift.

B) Installation of few larger diameter pipes stepwise during operation

One pipe of diameter 42 mm is required for three supercontainer sections. The total amount of pipes is therefore about 5 as shown in Figures 5-6 and 5-7. The number of pipes is doubled by installing pipes on both sidewalls for redundancy. The water is distributed through several small holes in the pipes to supercontainer cells. The air evacuation pipes are installed on top of the wetting pipes. The pipes are placed on the sidewalls in U-shaped brackets so that they can be pulled out separately. One collar seal is installed in the plug for every pipe.

The pipes are extended stepwise similar to extension of drill string in a diamond coring equipment.

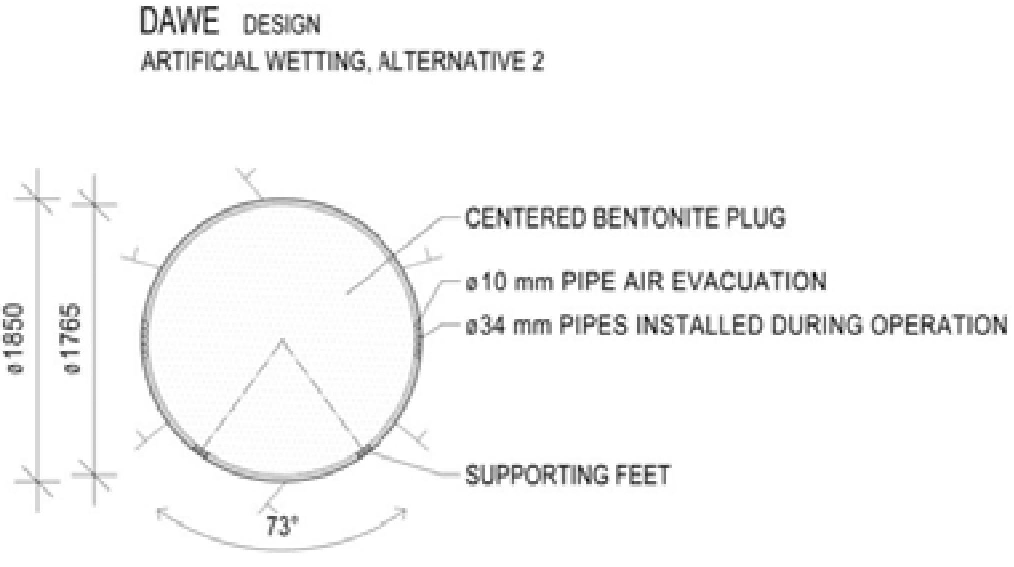

__Figure 5-6.__ The artificial watering and air evacuation pipes in the alternative based on use of few 42 mm diameter pipes on the sides of the drift.

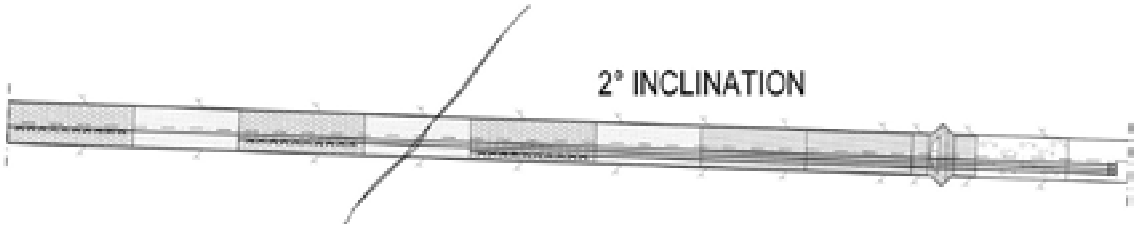

Figure 5-7. *The artificial watering and principle of water distribution in alternatives based on use of pipes on the sides of the drift.*

C) Installation of one watering pipe in a groove on top of the drift

One pipe of diameter 80 mm is required for 150 long drift (fifteen supercontainer sections). If the length of drift is shorter, the diameter can be reduced. The water is distributed through several small holes in the pipes to supercontainer cells. The pipe is placed on top of the drift before operation in an excavated groove in U-shaped brackets as shown in Figures 5-7, 5-8 and 5-9 so that it can be pulled out. One collar seal is installed in the plug for removal of the pipe. The groove is filled with bentonite pumped through the pipe during removal if necessary.

D) Installation of watering pipe on in a groove on bottom of the drift

One pipe of diameter 100 mm is installed on bottom of the 150 m long drift compartment. If the length of drift is shorter, the diameter can be reduced. The pipe is placed in a groove on the bottom of the drift before operation as shown in Figure 5-10. The pipe can be removed by pulling it out. One collar seal is installed in the plug for removal of the pipe. The groove is filled with bentonite pumped through the pipe during removal if necessary. The groove and watering pipe can be used also for drainage.

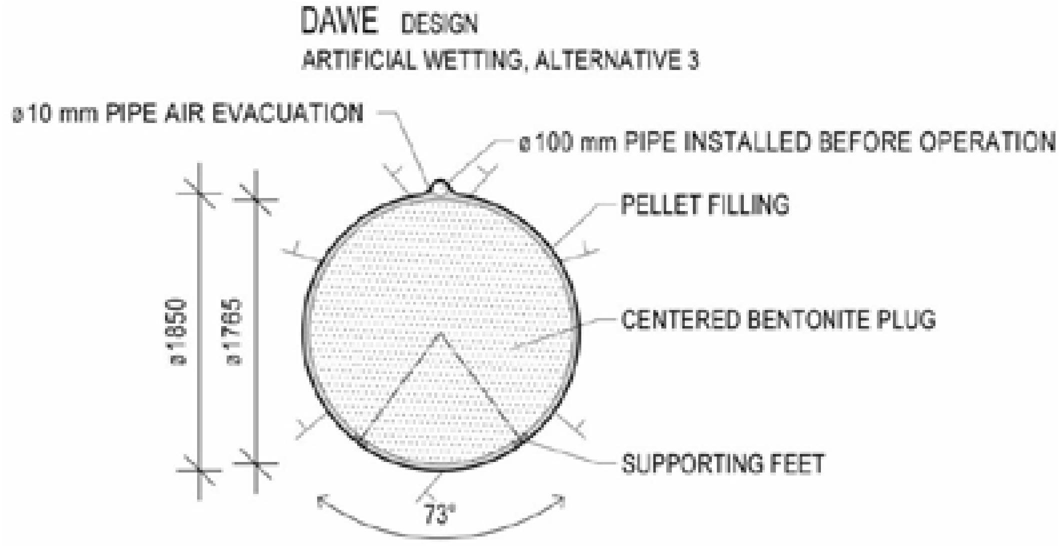

Figure 5-8. *The artificial watering and air evacuation pipes in the alternative based on use of one large 100 mm diameter pipe in excavated groove on top of the drift.*

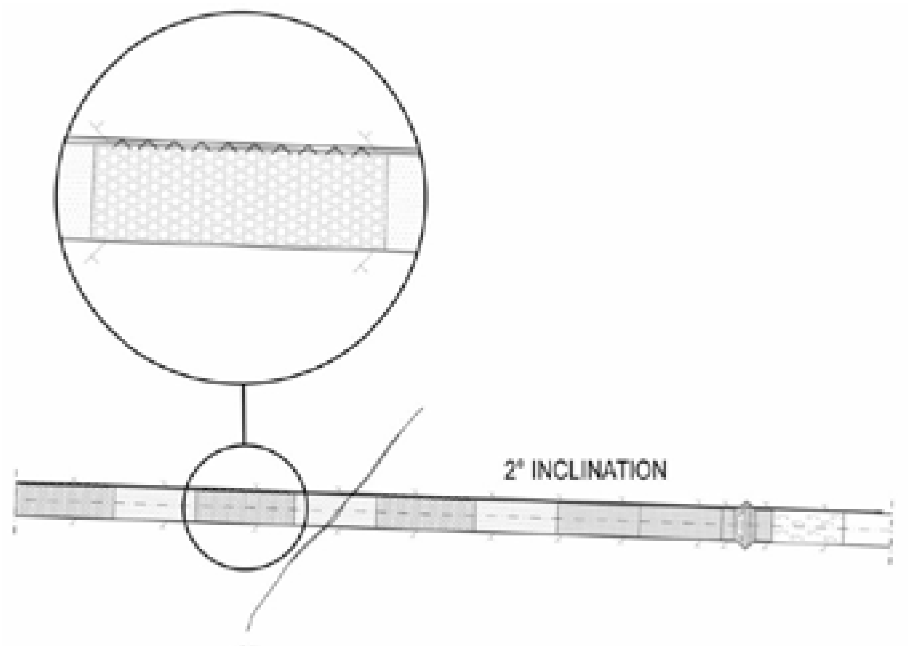

Figure 5-9. *Example of distribution of water through several holes in the 100 mm pipe to a supercontainer position.*

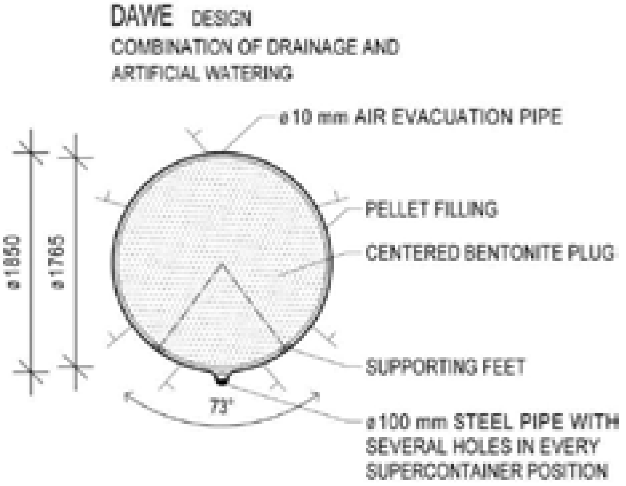

Figure 5-10. *Artificial watering and drainage alternative, a pipe installed in a groove on the bottom of the drift.*

5.3.3 Air evacuation system

The air is evacuated from the drift through one 10 mm diameter pipe. Two pipes installed for redundancy. The pipe is dimensioned to the same air flow 45 l/min as the inflow of water. The end of the pipe is positioned in the uppermost corner in the end of the drift and is equipped with a filter to eliminate possible plugging. The pipe is attached on the roof or sidewalls of the drift in U-shaped brackets so that it can be pulled out. One collar seal is installed in the plug for the removal of the pipe as shown in the figures in the previous chapter. The position of air evacuation pipe is shown in Figures 5-5 to 5-10.

5.3.4 Drainage system

The drainage system can be implemented by following three alternative designs shown in Figure 5-11 (note that all components are removed after filling):

1) Free flow along the bottom of the drift.
2) Installation of a 6 mm thick drainage mat on the bottom before operation.
3) Excavation of a drainage channel on the bottom of the drift and covering the channel with removable shield.

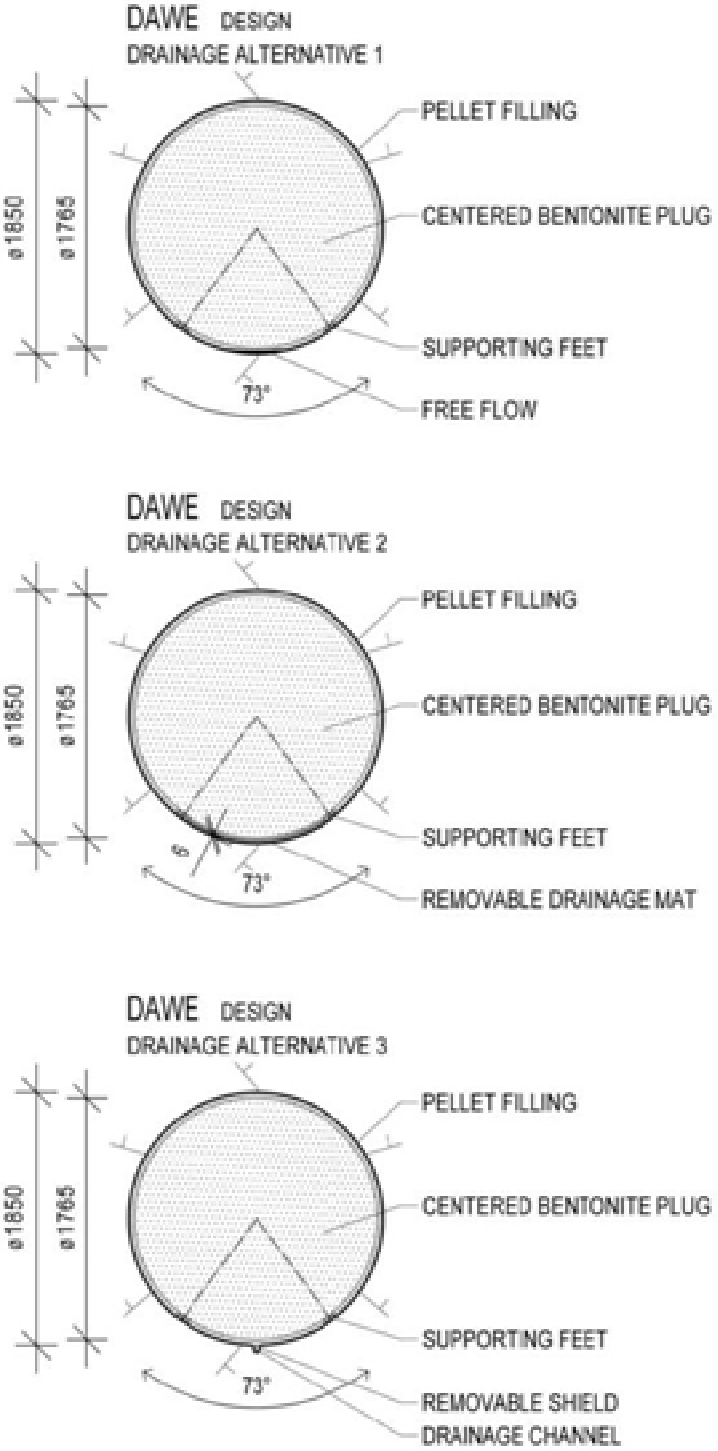

Figure 5-11. *Drainage alternatives.*

The drainage mat material used in alternative 2) is of type Enkadrain /Colbond 2005/, which is coated with an impermeable layer on the top side. The filter liner on the down side is removed. The mat is removed after operation by pulling it out. The deposition equipment will move on top of the mat. The standard type of drainage mat of type Enkadrain 5006H/T110PP (see Figure 5-12 can transport 15 l/min of water at 1.7 deg. inclination and tolerate surface pressure of 100 kPa. The mat will decrease the free space for the sliding plate and the water cushion palette of supercontainer emplacement equipment.

Figure 5-12. *Enkadrain 5006H/T110PP drainage mat (above). The mat was tested at Äspö (top) and shall be covered with impermeable upper surface layer for the proposed use.*

5.4 Expected implementation and behaviour

It is assumed that the drift has been excavated according to the quality requirements, the adjacent bedrock has been sealed according to groundwater control specifications and the drift has been approved for deposition use according to specifications. It is also assumed that the drift has been equipped with temporary drainage, ventilation and lighting system and operational safety equipment and instrumentation.

5.4.1 Operation procedure

The planned stepwise operation procedure is:

1) Planning of drift specific implementation and definition of positions for design components (e.g. supercontainers, distance blocks, plugs). The positions of deposition compartment borders and each component are determined before operation starts.
2) Preparatory rock works (e.g. installation of drip-shields, excavation of grooves and notches). Preparation of positions for steel plugs.
3) Installation of attachments to systems and steel structures (mainly steel plugs).
4) Installation of drainage, air evacuation and artificial watering systems for the deposition compartment.
5) Emplacement of distance blocks, supercontainers and other design components to one compartment. The estimated longest time for this step is 5 days.
6) When all supercontainers and other components have been installed in the drift the necessary auxiliary systems (drainage mat etc) are removed. The estimated longest time for this step is one shift (7 hours).
7) The collar of compartment steel plug with necessary cuffs and lead-throughs is inserted. The estimated longest time for this step is one shift.
8) Necessary pipes are extended through the cuffs and lead-throughs. The estimated longest time for this step is one shift.
9) The compartment plug is installed. The estimated longest time for this and Step 10 is one shift.
10) The free space behing the plug is filled with filling material (e.g. sand and bentonite pellets)
11) The air evacuation pipe and watering pipes are connected to relevant systems and the function is checked.
12) The watering and air evacuations starts. The estimated longest time for this and Step 11 is two shifts.
13) When the drift is filled (water comes from air evacuation pipe) the pipes are removed through cuffs and necessary supporting measures are taken (e.g. shutting of valves etc).
14) When the drift is plugged and sealed and all system parts are removed, the deposition compartment operation is completed and monitoring starts.
15) The operation continues: A) from step 4 or B) with installation of backfilling in a leaking fracture zone and subsequent plugging.

The estimated time from the start of emplacement of deposition units to the artificial watering, plugging and sealing is seven days (assuming the longest length of the compartment).

5.4.2 Expected behaviour of EBS systems during operation, plugging and sealing of one compartment

During emplacement

The bentonite absorbs water from air humidity in the drift. The expected longest operation time from the beginning of operation to the sealing is seven days. The experiments have indicated that the amount of water absorbed from RH100% humidity is of the order of 0.0026 g/m^2 s /Börgesson et al. 2005/ corresponding to 9.35 g/m^2 h. If the bentonite surface area of distance block is 31 m^2 and that of supercontainer (assuming 60% perforation) is 19 m^2, the total absorption of water would be about 11 l per day. The estimated time for buffer to swell and fill the gap between buffer and rock is three months /Börgesson et al. 2005/. Therefore the direct swelling will be insignificant. However, the surface of bentonite will start cracking but the net inclosing the distance blocks will keep the particles in place. Only small quantity of little particles of bentonite will fall through the net on the bottom of drift. In the test the amount of fallen particles after ten days was roughly 15 g. The downward area of the buffer surface was 0.04 m^2. The corresponding quantity for the distance distance block with downward surface area being about 350 times larger would be 5 kg, which is about 0.02% of the total mass of the saturated buffer (26,000 kg). The total mass of bentonite from 15 distance blocks would be 75 kg. If this would all be transported to one supercontainer unit, the increase in bentonite mass would be 0.2%.

The buffer in distance blocks and in supercontainers will dry the air and drift surface. Therefore the absorption is likely to slower than in RH100% humidity experiments.

During watering

The open volume in the drift is filled with water. The watering lasts at maximum about 10 hours. The fastest filling time is obtained by using several small pipes is 5 hours. The average flow to one supercontainer unit is about 3 l/min. The flow is spread on the length of the supercontainer by using several nozzles. The flow from one nozzle is about 0.5 l/min and it is directed towards the rock surface. Therefore it is assumed that no significant transport of bentonite takes place from exposed surface of supercontainer (60% perforation) to drift bottom. The possible eroded bentonite stays in the position of the supercontainer unit because the water is distributed so that insignificant amount of flow takes place from deposition unit to another along the drift. At the same rate with watering, the air is evacuated from the drift.

After watering and sealing the compartment

The bentonite buffer absorbs the water relatively rapidly. It is assumed that the buffer has swelled and the gap between rock and supercontainer has been filled with bentonite gel in few hours. It has been estimated the water absorption rate of buffer in a supercontainer is roughly 0.01 l/min /Börgesson et al. 2005/. In that case it would take months before the open void is filled with swelling bentonite, however the distance plugs will absorb water at higher rate and swell faster.

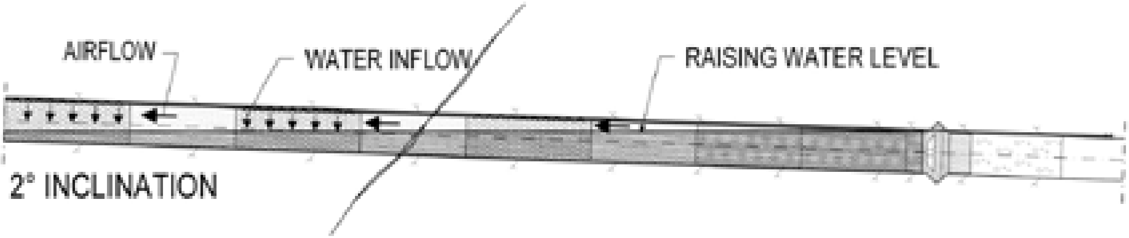

Figure 5-13. Watering phase. As the water level raises, the air escapes towards the end of drift.

The pressure raises relatively rapidly (at rate of 100 kPa/h) to the full hydrostatic pressure. The full hydrostatic pressure is obtained in 50 hours (about two days).

Since there is no free space available in the drift there is no flow in the drift. It is assumed that there is no significant flow from the drift to any other open tunnel section.

As the bentonite absorbs the water provided by initial artificial watering, more water enters the drift through the rock and is spread slowly along the EDZ.

After filling all the open void with water, the surface of the bentonite becomes soft and the bentonite starts to swell and penetrate through the perforation in the supercontainers and net around distance blocks.

The gap between the net inclosing distance blocks becomes filled with softened bentonite. The density in the gap filling equalizes gradually as the swelling pressure is generated.

After longer period of time the net inclosing distance blocks erodes. The erosion time is faster than that of supercontainer because of clearly smaller thickness of metal wire in the net and larger relative exposed area.

5.5 Possible deviations from the expected implementation and behavior

Some deviations from expected implementation and behavior are presented based on engineering judgment. It is assumed that a full comprehensive analysis shall be made later. It is assumed that thorough QA-program is applied and therefore deviations in construction are detected.

5.5.1 Deviations during operation

The possible deviations and subsequent actions are presented corresponding to the stepwise operation procedure presented in Section 5.4.1:

1) Planning of drift specific implementation.

   Deviation: the conditions in the drift change during the time from drift excavation to operation so that the plan is not valid, e.g. the inflows in some points have increased over the limits.

   Action: The drift is characterized before operation starts and remedial measures are taken.

2) Preparatory rock works (e.g. installation of drip-shields, excavation of grooves and notches). Preparation of positions for steel plugs and fixing rings.

   Deviation: the preparatory works are carried out in wrong position. The result is that there are e.g. anchoring holes or grooves in wrong positions.

   Action: **the grooves or holes are filled with low pH-cemen**t and remedial measures are taken.

   Conclusion: additional amount of cement shall be left in the drift.

3) Installation of attachments to steel structures (plugs and fixing rings).

   Deviation: The installation fails or does not fulfill the requirements.

   Action: The installation is disassembled and repeated.

4) Installation of drainage, air evacuation and artificial watering systems for the deposition compartment.

   Deviation: The systems are damaged during installation.

   Action: The installation is disassembled and re-assembled.

5) Emplacement of distance blocks, supercontainers and other design components to one compartment.

   Supercontainer

   Deviation: The installation equipment fails and is damaged and/or the supercontainer is damaged.

   Action: The equipment is repaired or replaced and continued. In severe situation (e.g. deposition vehicle burns in the drift) the operation is reversed and the supercontainer or supercontainers are removed from the drift.

   Conclusions: The installation time becomes longer. The buffer has swollen more than in the expected situation. It is assumed that the operation time can however be doubled without significant effect. In severe case the deposition timetable is delayed by the time, which is needed to remove supercontainers from the drift, however the operation efficiency requirement of one canister per day, which is one third of the real operation time, allows significant flexibility in timing.

   Pipes

   Deviation: pipes are damaged during operation.

   Actions: damaged parts of pipes are replaced by new ones. The parts of pipes that are in the position of the newly installed supercontainer or distance block cannot be replaced unless the obstacle is removed by reverse operation. There are two pipes per one supercontainer section. The volume can be filled by using only one pipe as an alternative.

6) Removal of auxiliary systems (drainage mat etc) are removed. The estimated longest time for this step is one shift (7 hours).

   Drainage pipe and mat (alternatives)

   Deviation:

   a) The drainage mat is broken during operation and parts of mat remain in the drift.

   b) The drainage pipe is stuck and break down during removal, parts of the pipe remain in the drift.

   Action:

   a) The draimage mat is removed and the operation is repeated. The supercontainers, distance blocks and other components are moved out of the drift by reverse operation.

   b) The remaining piece of pipe is removed by reverse operation.

   Conclusions: During operation the removability of the drainage mat has to be tested after emplacement of every distance block and supercontainer to ensure that reverse operation is not necessary.

7) The collar of compartment steel plug with necessary cuffs and lead-throughs is inserted.

   Deviation: The collar is damaged during installation and transport.

   Action: New identical collar is installed. A spare collar is available rapidly during installation.

8) Necessary pipes are extended through the cuffs and lead-throughs.

Deviation: Extension takes more time than expected because of technical problems.

Action: The timetable has significant flexibility and no specific actions are required.

9) The compartment plug is installed.

Deviation: the installation takes more time than expected because of technical problems and possible replacement of steel parts.

Action: The timetable has significant flexibility and no specific actions are required.

Conclusions: The longest allowable time for installation of the steel plug has to be defined.

10) The free space behind the plug is filled with filling material (e.g. sand and bentonite pellets).

Deviation: the open volume cannot be filled completely because of deformation or arching of already emplaced filling material.

Action: The filling is vibrated through the steel plug to ensure filling. The amount of filling blocks is designed to give desired average density even without filling.

Conclusions: The filling block (buffer blocks behind the steel plug) has to be designed assuming a low degree of filling.

11) The air evacuation pipe and watering pipes are connected to relevant systems and the function is checked.

Deviation: a) The coupling to systems fails b) the system does not function properly.

Action: a) Coupling is reassembled, no significant effect on timetable. b) The system is checked and repaired.

12) The watering and air evacuations starts.

Deviation: Air evacuation or watering pipes are blocked.

Actions: The number of blocked pipes is estimated and the pipes are opened by using overpressure if possible. If there is enough redundancy, the operation continues, if not, the plug is opened and the drift compartment is emptied in a reverse operation.

Conclusions: all the pipes have to be equipped with filters which eliminate the possibility for blocking. The need to double the air evacuation pipe for redundancy is evaluated. The redundancy of the watering system is evaluated.

13) When the drift is filled (water comes from air evacuation pipe) the pipes are removed through cuffs and necessary supporting measures are taken (e.g. shutting of valves etc).

Deviation:

a) A pipe is stuck and b) breaks down during removal, parts of the pipe remain in the drift,
c) the cuff or lead-through (manschett) leaks and water flows out of the drift.

Action:

a) The pipe is vibrated and rotated and pulled out while flushing it.

b) The remaining piece of pipe is removed by reverse operation.

c) The leakage is plugged and compensated by pumping more water in the drift.

Conclusions: The possibility to leave a rapidly corroding piece of pipe is investigated. The lead-through system to remove pipes has to be developed robust.

14) When the drift is plugged and sealed and all system parts are removed, the deposition compartment operation is completed and monitoring starts.

Deviation:

Hydraulic pressure does not increase behind the plug because of a) failure of plug, b) side-flow through rock into open tunnel.

Action:

a) The plug is repaired (by welding, grouting etc) and the pressure is released during the operation. If required a new plug is installed.

b) The amount of side flow and flow path is estimated. If the flow is directed towards the open part of the drift, a new plug is installed if necessary. If required, the drift is retrieved.

Conclusions: The positions of plugs have to be selected so that sideflow will not occur. The possibility of significant flows from the compartment into open tunnels or drifts has to be eliminated by proper characterization and groundwater control techniques. The operation has to be planned so that a new plug can be installed rapidly if necessary. The criterion for acceptance and largest allowable time delay has to be defined.

15) The operation continues: A) from step 4 or B) with installation of backfilling in a leaking fracture zone and subsequent plugging.

5.5.2 Deviations in behaviour of EBS systems during operation, plugging and sealing of one compartment

During emplacement

The bentonite absorbs water from air humidity in the drift and causes swelling. A deviation from expected behavior might be that swelling is much faster than evaluated or the operation time is longer. As a consequence the swollen bentonite buffer in distance blocks:

- is cracked intensively and large quantity of bentonite particles fall through the net covering the distance block on the floor of the drift,
- the net covering distance block deforms and breaks, bentonite buffer comes into contact with drift floor,
- the net is pushed by the swelling bentonite against the rock surface.

As a consequence of the above mentioned phenomena bentonite is transported out of the tunnel with drainage during operation. No large scale tests have been made to investigate the behavior of distance blocks enclosed in steel net, however smaller scale test have indicated that only a small amount of bentonite will fall through the net.

The swelling bentonite may also fill the gap between rock surface and distance blocks and press the watering and air evacuation pipes along the rock surface so that the pipes are stuck. It has been estimated roughly, however, that this will take 89 days. The estimated operation time from start of deposition to plugging and sealing is seven days.

During watering

The open volume in the drift is filled with water. The watering lasts at maximum about 10 hours. If some pipes of nozzles are blocked, the distribution of inflows changes causing flow in the drift parallel to drift axis during filling. The total flow required to fill one supercontainer section is about 1,500 liters. If the solids-water ratio of the water flowing from one section to another is 1.3% (in erosion test with MX-80 bentonite pellets, the highest total suspended solids (TSS) ratio has been approximately 1.3% – at 1% water salinity, see Figure 5-14), about 20 kg of bentonite will be transported from one section to another. The TSS ratio of flow around highly compacted buffer blocks has not been studied.

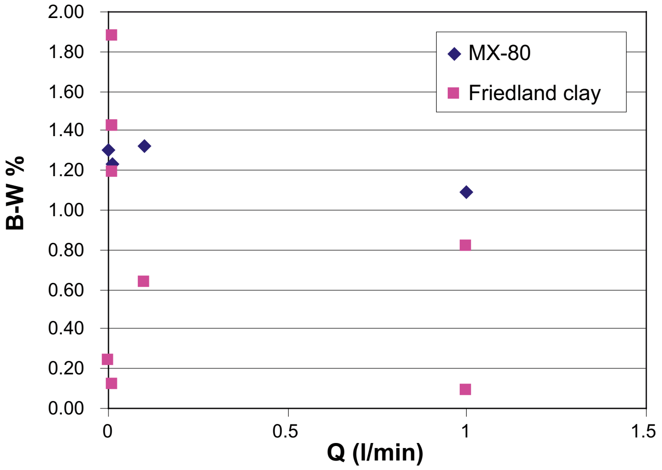

Figure 5-14. *Total transported bentonite ratios (B-W%) measured in erosion experiments (as weight% of water, similar to total suspended solids ratio) with respect to flow rates. The graph is based on information provided by T. Sandén/Clay Technology Lund AB).*

Some of the water flow may become directed towards bentonite by misalignment of the pipes. It is assumed that the bentonite suspended in the flowing water stays in the position of the supercontainer unit. If the bentonite is settled on the bottom of the drift and the softened bentonite swollen in the rock-buffer gap is not homogenized, the density may increase.

The air evacuation pipe is plugged and the drift is filled only partially with water and the bentonite will not be homogenously saturated. The air will be left in the upper part of the drift because of the drift inclination. Therefore the supercontainers behind the plug will be saturated. After the drift is sealed by the plug the pressure increases and the remaining air is compressed and some piping is likely to occur from the water filled sections to the sections with air. The piping will transport some bentonite and the amount of transported bentonite depends on the air filled volume.

After watering and sealing the compartment

It is assumed that the positions of plugs and compartments are positioned in such a way that no clearly transmissive fracture paths are formed from the drift into open rock excavations.

However, it may be possible, that water inflows from rock into the drift "leak" out from the drift through fractures or leakages in the plug to other open tunnels or drifts and the flow erodes and transports bentonite. The situation is similar to that described in previous sections and is illustrated in Figure 5-15.

It is assumed that the artificial wetting will speed up the swelling of distance blocks, buffer in supercontainer and therefore seal the hole so that resistance for flow along the drift is increased and possible hydraulic gradients, which are necessary to induce flows, are lower. It is possible that the density of bentonite in the groove (in two design options) will remain lower for some time period and therefore the resistance to flows becomes smaller and the flows are channel in the lower density groove. The flows may transport bentonite more easily than in the alternative without a groove.

It is also possible that the "sealed" saturation phase (distance blocks have swollen and sealed the supercontainer units) after wetting is temporary. The supercontainer and distance block will absorb water and the estimated rate for the buffer inside supercontainer is 0.01 l/min. The absorption of the distance block will probably be clearly higher but probably not at different order because it is related to the degree of perforation, which is 60%. Therefore a rough approximation could be that the absorption rate is doubled.

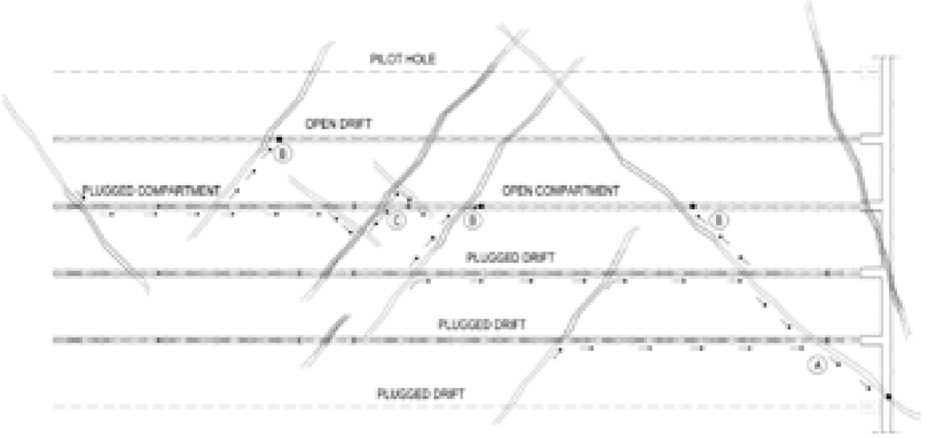

Figure 5-15. Possible flow pathways from sealed drift to open excavations. A) Flow from plugged drift to open central tunnel, B) flow from plugged drift to neighboring open drift, C) flow passing a plug from plugged compartment to open compartment.

It will take roughly three months until the water from wetting has been absorbed in buffer and buffer has swollen and filled the gap totally and generated some swelling pressure. After bentonite has absorbed the initial water, the water will be transported in the "dryer" inner parts of the buffer and the buffer will dry from the outer side. If the bentonite starts to dry from the outer surface section, the gap may form again unless additional water is flown in from the rock, see Figure 5-16.

In the case of supercontainer the swelling of buffer through perforation and drying of outer surface of buffer is evidently significantly slower process because of the thermal gradient caused by the hot canister. Therefore the gap may not form at all (assuming some water is provided from bedrock). However, in the case of distance blocks there is no heat gradient. If the sections are in very dry rock, the necessary additional water to compensate the drying induced shrinkage may not flow from rock. This could result into a situation where there is a dry section without properly functioning distance block next to a wet section with full hydrostatic pressure, Figure 5-16. This could result into a flow from wet section to dry section by piping. There are several processes, which may transport water into the distance blocks (flow from bedrock, flow from fractures in bedrock to EDZ and transport along EDZ, transport through buffer) and the issue should be evaluated further.

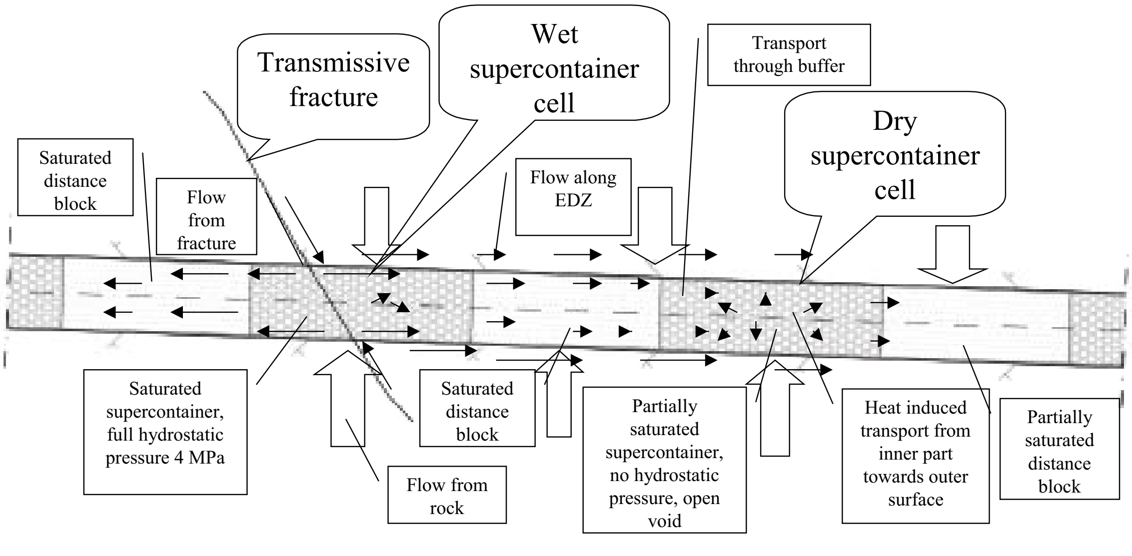

Figure 5-16. Example of a "wet" and "dry" supercontainer cell after initial saturation. Arrows indicate transport of water in different processes.

It is possible that after longer period of time the net inclosing distance blocks corrodes and forms a transmissive network type layer at the bentonite-rock interface or inside the bentonite. It is unclear whether the corrosion products will form transmissive pathways.

5.6 Evaluation of preliminary designs

5.6.1 The design components

The design involves several design components, which have not been tested and verified. The most important design components and relevant uncertainties are described in Table 5-1. (Note: the level of design of components is preliminary).

Table 5-1. List of uncertainties related to design components.

Component	Status	Uncertainties 1 = low 3 = high
DAWE-DC1 Spray and moisture shield	Not demonstrated	1
DAWE-DC2 Distance block	– Some uncertainties with respect to piping during early evolution phase	2
DAWE-DC3 Drainage system	– Three alternatives – Implementation not tested – Effect on groove on piping during early evolution is uncertain – Functioning not verified by tests – Removability of pipes not investigated – Acceptance of pipe abandonment uncertain	2
DAWE-DC4 Air evacuation system	– Not demonstrated	1
DAWE-DC5 Compartment plugs	– Implementation not tested – Positioning not investigated – Functioning not verified by tests	2
DAWE-DC6 Permeable filling blocks	– Several alternatives – Functioning not verified by tests	1
DAWE-DC7 Artificial watering system	– Three alternatives – Implementation not tested – Functioning not verified by tests – Removability of pipes not investigated – Acceptance of pipe abandonment uncertain	2
DAWE-DC8 Metal net, supercontainer	– Not demonstrated – Uncertainties in erosion during watering	1
DAWE-DC9 Metal net, distance block	– The performance during saturation is uncertain – Uncertainties related to transport properties after corrosion	3
DAWE-DC10 Drift plug	– Several alternatives – Design being tested	1
DAWE-DC11, Permeable filling	– Several alternatives – Functioning not verified by tests	1
DAWE-DC12 Partially permeable filling	– Several alternatives – Functioning not verified by tests	1

5.6.2 Drainage system alternatives

The alternatives in order of attractiveness are: 1) free flow, 2) drainage mat, 3) pipe in a groove on bottom.

The drainage based on free flow on floor is simple, does not add any new components to the system and is therefore the most attractive alternative. The performance of the alternative is uncertain but can be tested in drift conditions.

If the alternative with free flow fails there are two alternatives with pros and cons:

1. **Pipe in a groove**
+ efficient,
+ may be beneficial for operation equipment (no flow on floor),
– adds two components to the system; groove and a pipe,
– may require modification of deposition equipment,
– sealing behavior of groove uncertain, to be investigated,
– removability of pipe uncertain.

2. **Drainage mat**
+ adds only one temporary component to the system,
– removability has not been tested and verified,
– affects the operation equipment, feasibility uncertain.

The drainage mat alternative is more simple because it adds only one temporary component to the system. The feasibility of drainage mat should be tested. If found not feasible, the alternative with a pipe in the groove is the only alternative left.

5.6.3 Artificial watering alternatives

1. **Several small pipes installation before operation on the drift walls**
+ installation before operation,
+ redundancy,
+ simple water distribution,
+ flexibility in stepwise operation,
+ clearance around the pipes,
– damage and blocking of pipes because of contact with deposition equipment,
– removability of several pipes,
– number of lead-throughs and cuffs in the steel plug is large.

2. **Few large pipes installed during operation**
+ less pipes than in small pipe option,
+ redundancy if pipes are coupled,
+ the pipes are not exposed to contact with deposition vehicle during transport,
– installation of pipes is difficult during operation, reliable automation is difficult,
– removability is difficult because of small clearance,
– the tolerances of drift clearance must be reduced,
– operation time is increased by installation time,
– several lead-throughs is the steel plug.

3. **One big pipe in a groove**

+ Only one (or two) pipe, less components,
+ installed before operation,
+ removability easier,
– stepwise control of flow more difficult,
– uncertainties in flow distribution,
– adds two components to the system, the groove being permanent,
– uncertainties in sealing of the groove, to be investigated.

The most attractive main alternative is based on using several small pipes. The selection of the most attractive alternative is based on avoiding lengthening of operation time (alternative with few large pipes), automated operation procedures during operation (alternative with few large pipes) and introduction of a new permanent component, groove in the rock, in the system (big pipe alternative).

The second attractive alternative is based on excavating a groove and installing a pipe in it and the least attractive alternative is based on installing few larger pipes during operation.

5.6.4 Combination of drainage and watering

If it is found that the most feasible alternative for drainage is the groove and pipe, it is evidently more feasible to integrate the watering in the system by using the same pipes and groove.

The suggested procedure is therefore to:

- test and develop drainage systems,
- if the groove and pipe drainage is the moist feasible alternative, the possibility to integrate watering into that should be investigated and developed if possible.

5.6.5 Drift quality requirements

The installation and operation of drainage, watering and air evacuation systems benefit from good drift quality (mainly surface smoothness) because that increases the clearances around pipes during drift operation and watering phase. It is also evident that the movement of the deposition equipment along the hole is also stable if the floor quality is good. It is easier to achieve good surface quality by using a separate tool for that in which case the actual drift excavation could be carried out as high performance production boring. It is proposed to evaluate the potential of a trimming tool, which would finalize the hole after boring and ensure proper clearances and surface smoothness. The tool would be used as an option in occasions when the measured quality of the drift is not adequate after boring. The tool could be composed of a steel cylinder of size of the supercontainer and cutting tools installed on the surface of it. The toll could be operated with the same raise boring equipment as used in the drift excavation.

6 Conclusion of the preliminary design alternatives

All the presented alternatives include uncertainties at different levels, which should be resolved. The designs of alternatives are preliminary levels and need further development and more detailed design.

The BD design alternative is simple and robust to operate. However the evolution during operation and after it include significant uncertainties, which should be resolved. It is suggested that the development of BD alternative is based on determining the performance of distance blocks and determination of design parameters. If the distance blocks fail to seal the supercontainer cells and piping through the blocks may causes significant transport of bentonite, the further development of the alternative is not justified.

The DAWE design alternative is more complicated to operate than DB design and include more components. The evolution of DAWE design from start of operation to initial saturation includes fewer uncertainties than BD alternative. The most significant uncertainty is related performance of the net design to keep the cracking surface of distance blocks from falling apart. Therefore the development of the design should be focused on verifying the performance of the net. The drainage alternatives should be evaluated and tested. If the result shows that the alternative with a groove and a pipe is most feasible, the further development should be based on integrating the drainage and wetting. If drainage can be arranged by using other techniques, the use of several small pipes should be developed further.

The stepwise operation of KBS-3H repository is complicated and requires performing of several successful complicated succeeding operations. Therefore the risk for deviation in operation is significant and development of KBS-3H system should include a feasible design of reverse operation after a drift compartment has been plugged and sealed.

7 R&D needed to verify and develop the designs

The preliminary design presented in this report includes several novel components, such as fixing rings and steel plugs which have been designed without support of applicable design guidelines, regulations or standards available. The performance of these components may include significant uncertainties, which should be studied and verified. There are also several design requirements and assumptions, which are likely to contain significant uncertainties and affect the feasibility of the concept significantly. The next step in design would be the selection of reference design components out of available alternatives and detailed design of all the components.

7.1 System requirements and constraints

The following system requirements and environmental constraints have significant impact on the design and should be assessed in more detail:

7.1.1 Operation time

The operation time is important, because it is directly related to the behavior of distance blocks, buffer and saturation process during operation.

The length of compartment and largest number of supercontainers to be deposited depends on the operation efficiency. The faster the supercontainer deposition cycle, the longer the deposition compartment assuming there are no other constraints. The present assumption for the operation time has been one day per canister according, which is based on the general average deposition efficiency of KBS-3 design in Sweden.

The absorption of humidity and cracking of distance blocks is time dependent. It has been observed that significant surface cracking occurs in two weeks. The shorter the operation time, the smaller the extent of cracking.

It has been estimated that in the case of BD-design, all the void in the drift is filled with inflowing water in 10 days or more. The filling time is about 18 days with the estimated inflow criteria for supercontainer positioning of 0.1 l/min and empty volume of 2.6 m^3. The time to emplace all canisters in a 150 m long compartment is clearly longer, over two weeks (based on assumption that one deposition unit is emplaced in one day). The possibility to emplace all the deposition units in one compartment and plug the compartment in a time, which is shorter than that should be evaluated.

7.1.2 Groundwater inflow conditions, pressure, distribution of inflows

The generation of groundwater pressure and pressure increase rates seem to have significant effect on piping through distance blocks. The present increase rates and supporting evidence should be documented and tested.

It has been noted that very dry (impermeable) drift compartments could be a problem. The probability to encounter these and the smallest possible inflow to a drift compartments should be evaluated to assess the severity of the possible problem.

The quantity and distribution of groundwater inflows has significant impact on the feasibility of the design, however the impact is different depending on the design alternative.

In case of DAWE design, the limiting factor is the capability of drainage system to remove the inflows from the drift. The efficiency of drainage systems has been dimensioned to tolerate inflows in the range of 10–20 l/min (in 150 drift). It is likely that larger inflows cannot be handled on free flow basis. The drainage based on using a bottom groove will function with larger inflows and can be dimensioned easily accordingly.

The largest tolerable inflow in BD design is likely to be of the order of deciliter per minute and is clearly smaller than in DAWE design. A compartment plug is positioned in every drift section where the inflow limits are exceeded. If a significant number of the exceeding inflows are spread along the length of drift, the feasibility of design becomes very low. Seven exceeding inflows spread evenly along the drift and five compartment plug systems would fill about 140 m equal to about 50% of the drift length.

7.1.3 Drift quality

The free gap on top of the drift between the rock surface and supercontainer is of the order of 15–20 mm during operation. On the basis of the quality requirements for excavation, this includes a possibility that the diameter can become 10 mm smaller along the drift. 15–20 mm gap is very small and a decrease of 10 mm would make a significant difference.

The width of the free gap was measured with a "dummy"-test cylinder as part of the drift boring demonstration at Äspö. The preliminary result was that the average width of the free gap in final position was about 38 mm, smallest gap 29 mm and largest 48 mm. The free gap on top of the supercontainer given in Section 3.4.3 was 20–45 mm. The width of the gap on the sides is 35–45 mm.

The possibility to modify the cutter head of the boring machine and/or use of possible smoothing tool discussed in Section 5.6.5 should be studied in order to minimize the tolerance allowances of 25 mm on top of the drift. This would also be beneficial for the operation vehicles.

7.2 Processes

There are some processes governing the behavior of the system after emplacement and affecting the design, which include significant uncertainties and should be understood adequately for design purposes.

7.2.1 Humidity induced swelling and cracking of buffer

The surface of buffer will absorb water from air humidity and swell. The swelling and cracking occurs in small test samples already after a couple of days. It has been estimated /Börgesson et al. 2005/ roughly that the free gap will be filled by humidity induced swelling of bentonite in about three months. The cracking may also have effect the saturation of bentonite.

The humidity induced swelling has significant impact on the design and operation and it should be studied at different scales in representative environments.

7.2.2 Buffer erosion and transport in free flow

Some buffer material will evidently be fallen on the drift floor where it will be entrained in the flowing water which can transport it as suspension.

It is also likely that some of the flow from artificial watering can erode some of the bentonite and cause transport.

The entrainment, transport and settling of buffer should be studied in order to obtain estimates of the largest possible ratio of suspended bentonite that the flows can transport.

7.2.3 Saturation of distance blocks, transport of water

The saturation of distance blocks in different phases of evolution is affected by several different processes and is not fully understood.

One key question is, whether the artificial wetting will enable a state of saturation, which eliminates possible significant piping and transport of bentonite in combinations of "wet" and "dry" drift sections. The transport of water in the buffer from "wet" sections to dry sections is affected by several processes and factors such as:

- heat in supercontainers,
- flow through bedrock,
- flow through capillaries in EDZ,
- transport through bentonite.

One process to be studied is the drying of bentonite surface after the water provided in initial saturation has been absorbed in bentonite. The results could be formation of open space in "dry" sections and piping flow from other "wet" sections.

7.2.4 Piping through distance blocks

Piping water flow through distance blocks can erode and transport bentonite. The piping and rate of erosion may be affected by design (e.g. width of free gap, gap filling, distance block length).

The erosion by piping is composed of entrainment, transport and settling (deposition), see Figure 7-1. The key parameter is the flow velocity, which depends on the size of flow channel. Therefore the behavior of bentonite during piping has influence on flow. If the bentonite swells during erosion and maintains the channel size, the erosion is not reduced. If flow channel grows at constant flow, the flow speed is reduced and the erosion reduces. As bentonite particles are

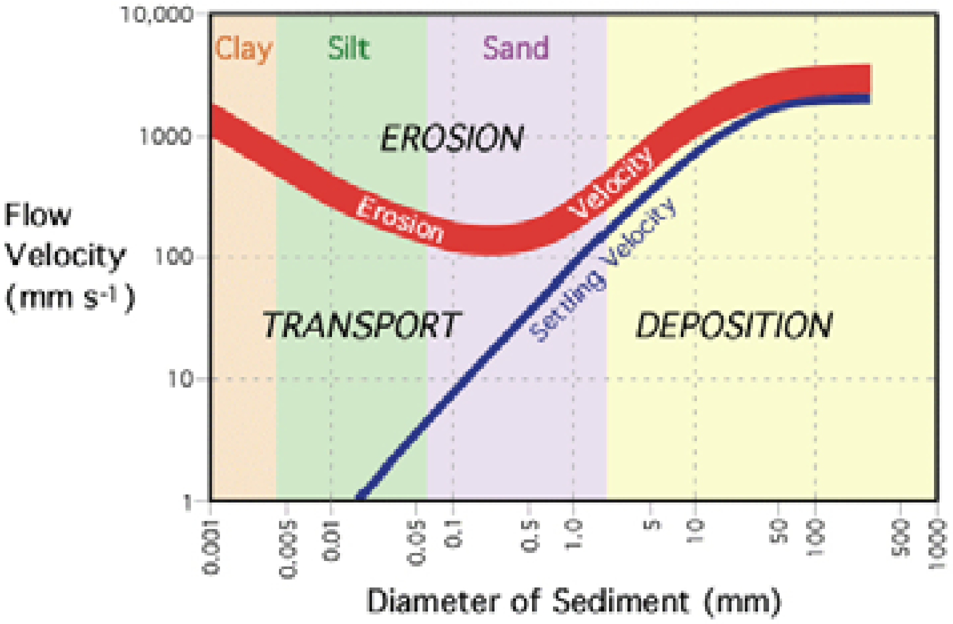

Figure 7-1. *This general graph describes the relationship between flow velocity and particle erosion, transport, and deposition (based on /Hjulström 1935/). The curved line labeled "erosion velocity" describes the velocity required to entrain particles with respect to particle size. Note that the entrainment of silt and clay needs greater velocities than larger sand particles. Clay evidently forms cohesive bounds between particles. The graph also indicates that the transport of particles requires clearly lower flow velocities than erosion.*

entrained in the flow they will easily move as suspension until flow stops and the clay particles are settled. The entrainment depends on flow velocity as well as the largest amount of suspended clay that can be transported. Therefore it is important to define the magnitude of flows, which can go through distance blocks and buffer by piping and to define the total suspended solids ratios of flows.

7.3 R&D required to develop more detailed designs

7.3.1 Selection of alternatives

There are different watering and drainage alternatives in DAWE design, which should be evaluated and tested as mentioned in Sections 5.6.2–5.6.4. The objective is to test drainage systems and select the suitable system. If the result shows that the alternative with a groove and a pipe is most feasible, the further development should be based on integrating the drainage and wetting.

7.3.2 Development of designs

Detailed designs have to made of several design components before the components can be tested:

- The net system in DAWE design, has to be dimensioned and the attachment technique has to be developed.
- The distance block design has to be developed. Few important issues are the division of blocks to segments, filling of free gap with pellets, possible reduction in gap width, effect of length on piping, coupling between distance block and supercontainer contacts.
- Development of removal systems for pipes (lead-throughs, attachment, forces).
- Development of filling design: filling blocks, permeable filling, partially permeable filling.
- Retrievability, reversed operation and "emergency" plugging techniques should be developed to manage unexpected deviations in operation.

7.4 Key design components to be tested and verified in experiments

The design is composed of several novel design components, such as fixing rings and steel plugs. These components have not been tested and therefore the performance of these includes significant uncertainties, which should be investigated in order to verify the proper functioning. The components, which are part of the EBS system, should be tested in expected drift conditions with respect emplacement, initial saturation and final stable state – if possible.

The verification of the proper function should be carrier out in steps:

1. Small scale tests with few parameters to evaluate functioning in principle.
2. Test and demonstrations to verify that the most significant components of the KBS-3H design function properly.
3. Test and demonstrations of the whole design in total to verify that the specified requirements are fulfilled robustly.

The components which are considered as being critical and should be tested thoroughly are presented below in bold:

The Basic Design Design Components (BD-DC)

- **BD-DC1 Spray shield.**
- **BD-DC2 Distance block.**
- **BD-DC3 Fixing rings to support distance blocks.**
- **BD-DC4 Coupling between supercontainer and distance block.**
- **BD-DC5 Compartment plugs.**
- BD-DC6 Filling blocks.
- BD-DC7 Drift plug.
- BD-DC8 Filling block arrangement between plugs.

The DAWE Design Components (DAWE-DC)

- **DAWE-DC1 Spray and moisture shield.**
- **DAWE-DC2 Distance block.**
- **DAWE-DC3 Drainage system of inflowing water.**
- **DAWE-DC4 Air evacuation system.**
- **DAWE-DC5 Compartment plugs.**
- DAWE-DC6 Filling blocks.
- **DAWE-DC7 Artificial watering system.**
- **DAWE-DC8 Metal net to reduce humidity induced cracking in supercontainer.**
- **DAWE-DC9 Metal net to reduce humidity induced cracking in distance block.**
- DAWE-DC10 Drift plug.
- DAWE-DC11 Permeable filling.
- DAWE-DC12 Partially permeable filling.

The important design components to be tested are summarized below:

1. Steel plug (both).
2. Fixing ring (BD).
3. Coupling between supercontainer and fixing ring (BD).
4. Net around distance blocks and buffer (DAWE).
5. Artificial watering (especially removal of pipes) (DAWE).
6. Air evacuation system (DAWE).
7. Distance blocks (e.g. humidity induced swelling) (both).
8. Drainage (DAWE).
9. Spray and moisture shield (both).

7.5 Supporting development and testing

There are several supporting techniques to be developed and tested. It has been assumed in the design that the drift has been excavated and sealed properly. However the groundwater control measures have significant impact on the feasibility of the design and should be developed and tested.

If the drainage or watering is based on excavating a groove on the surface of the drift, the excavation method has to be developed and tested.

8 Conclusions

Both designs alternatives include several uncertainties, which are different in nature.

The most significant uncertainty of BD alternative is the performance of distance blocks during operation and saturation phase until full saturation is obtained. One of the key uncertainties is the occurrence and acceptability of piping.

The most significant uncertainty of DAWE design is the performance and acceptability (from long term safety point of view) of the net system. The functioning of the net system during operation and saturation can be tested. The evaluation of corrosion and possible formation of detrimental conductive pathways is evidently a more complicated issue.

Both design alternatives are based on dividing the drift in compartments rapidly, but for different causes. In case of BD alternative the cause for division of drift is the isolation of "good" quality sections for deposition. In case of DAWE-design the main objective is to enable rapid operation. In both alternatives the compartment plug is required to achieve a favorable state for saturation of the buffer. Therefore the steel compartment plug is a critical functional component of both design alternatives.

It is possible that a feasible site specific design can be based on using both alternatives. It is also possible that the wetting of DAWE alternative can be based on much more simple solutions – direct watering through a lead-through in the plug. There is, however, not enough information at the moment to justify the selection of that system component as one design alternative. It is also possible that the DAWE alternative can function properly without artificial watering or air evacuation. This might be a feasible option in certain drift sections where inflows are small enough. However in that case the behavior during saturation after plugging the compartment would be very similar to BD alternative in problematic situations where "dry" and "wet" supercontainer cells are located next to each other. The "wet" section will attain high hydrostatic pressure rapidly and may leak by channeled flow through piping to "dry" sections. This behavior may depend significantly on the function of the net around distance blocks. It is also possible that the design can be simplified significantly by excavating the drifts in conventional way instead of blind boring, which has been one alternative. Therefore it is important to promote continuous evaluation of the results in order to simplify the design and increase the robustness if possible.

The development of the design process should also be continued to integrate functional analysis, functional requirements, testing and risk analysis in the design. It would also be beneficial for the engineering design to incorporate the functional analysis and testing closely to the design.

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Appendix

Functional requirements and other basis for developing buffer design in KBS-3H repository concept

DOKUMENTTYP	TILLHÖR/REG.NR
Functional requirements	KBS-3H
VERSION	GÄLLER TILL
2.0	2005-08-31
HANDLÄGGARE / UTARBETAD AV	DATUM
Erik Lindgren, SKB, Börje Torstenfelt, SwedPower, Lennart Börgesson, Clay Technology	2005-02-22
KOMMENTERAD AV	DATUM
Margit Snellman	2005-03-23
GODKÄND	DATUM
Erik Lindgren, SKB	2005-04-06

One main objective of the KBS-3H project is to produce a buffer design, which fulfils the following functional requirements and technical prerequisites under the specified environmental boundary conditions.

- **The functional requirements** specify what the buffer system must be able to do. **Environmental boundary conditions** describe the properties of the bedrock where the system has to function according to functional requirements.
- **Technical prerequisites** specify the parts of the technical design, which have been fixed and cannot be changed (e.g. diameter of the deposition drift).
- The **design guidelines** are advice, instructions, opinions and proposals specified by experts to be followed in order to fulfil the functional requirements.

1 Functional Requirements

The functional requirements common for KBS-3H and KBS-3V are:

- The buffer shall protect the canister mechanically in the event of decimetre-sized rock movements.
- The buffer's deformability shall be sufficiently high to absorb rock movements without the canisters being damaged, but small enough to hold the canisters in position.
- The buffer shall prevent groundwater and corrosive substances from reaching the canister.
- The buffer shall retard the release of radionuclides if the canister should be damaged.
- The buffer's hydraulic conductivity shall be so low that any transport of corrosive substances and radionuclides takes place solely by diffusion or as specified below.
- The buffer's gas permeability shall be sufficient to allow for gas release of the possible large quantities of gas that may be formed in a damaged canister. This gas passage shall not form persistent gas-permeable channels or cavities in the buffer.
- The buffer's swelling pressure shall be sufficiently high to provide good contact with the host rock and the canister, but not higher than what the canister and host rock can withstand.

- The density of the buffer shall be sufficiently high so that neither microbial activity in the buffer will be possible nor colloid transport through the buffer will be possible.
- The buffer's heat conduction properties shall be such that heat from the canisters will not lead to unacceptable physical and chemical changes in the buffer. This depends also on the thermal diffusivity in rock.
- The buffer shall not contain anything that has a negative effect on the performance of the other barriers.
- The buffer shall be chemically and mechanically stable to ensure the required functional properties for long time periods.

2 Environmental boundary conditions

The expected inflow rates of groundwater and water pressure increase rate into the deposition drift should be determined by the expected site conditions at Olkiluoto and Swedish sites.

Olkiluoto conditions will be specified within the SC project (fracture thickness, estimated water inflow, water pressure increase, water conductive sections with higher inflow, etc).

According to recent evaluation of the Olkiluoto site data there could be long relatively dry sections in a 250 m long deposition drift, some point inflows less than 0.4 l/min, 2–3 fracture intersections with inflow from 0.4 to 4 l/min and intersection of one fracture zone with inflow larger than 4 l/min.

The salinities determined by the expected site conditions at Olkiluoto, but also salinities expected at Swedish sites should be considered. The salinity of the groundwater is a very important parameter e.g. for bentonite erosion. Salinity of the groundwater at depths of 400 and 500 m at Olkiluoto ranges from 10 to 25 g/l of Total Dissolved Solids (TDS). Groundwater flow simulations indicate that locally the salinity may rise up to 25–45 g/litre in the vicinity of excavations. Accordingly the expected salinity should be 35 g/l with a proper range.

Expected water pressure increase rates will be xxx kPa/h in Olkiluoto and ca yyy kPa/h in Swedish rock (to be completed).

3 Technical prerequisites (fixed details of design)

The system is described in Appendix A List of input parameters for HMCBG analyses /Johnson 2005/. In principle the dimensions of supercontainer, diameter of the deposition drift and minimum length of distance block has been fixed as well as the properties of bentonite:

1) The buffer shall be designed as in SR 97, i.e. with the same demands, composition and density.
2) The super container design is defined in drawing M-011 B.
3) The steel used in the perforated steel container enclosing the buffer and canister package must not affect the future function of the buffer.
4) Significant dripping or spray water on the super container or distance block during emplacement is not acceptable before the end plug is in place.
5) An end plug is positioned at the drift entrance. It shall keep the buffer in place, stand the swelling pressure and hydraulic pressure from buffer (totalling 15 MPa) and it shall seal the drift so that properties of bentonite buffer will be maintained and no detrimental transport of bentonite occurs.

4 General design guidelines

- Emplacing of the drift close to major fracture zones should be avoided.
- It is important to ensure that there are no significant connective flowpaths between the drifts and those parts of the repository, which remain open for a long period.
- If found feasible, fracture leakages with higher water inflow than 1 l/min can be passed by adding extra distance blocks.
- The total water inflow for the drift can be at the highest less than 10 l/min. If the total water inflow into the drift is higher than 10 l/min the drift should be rejected.
- Use of groundwater controlling techniques are proposed to reduce inflows into the drifts.
- Leaking end with the high inflow can be filled with a combination of bentonite+low–pH concrete plug+bentonite. This enables that the other end of the deposition drift can be used for emplacement of supercontainers.
- The design should be such, that there will be no significant water pressure built up in the tunnel during super container deposition which could cause movement of supercontainer or distance block, rupture or piping and transport of bentonite through buffer until a solid permanent plug is in place (preferably the tunnel end plug, or intermediate stop plugs somewhere in the tunnel in case of too wet sections in the tunnel).
- A plastic protection cover is not acceptable.
- The time from the deposition of the first super container until the drift seal is in operation is three months for one 300 m long drift.
- It would be desirable, if the design could take, with a good safety margin, at least an inflow rate of 0.1 or 0.2 l/min into a supercontainer section.
- The design should be robust and should not “collapse”, if the inflow rate exceeds the maximum design value.
- The investigations carried out by the KBS-3H project should confirm that the buffer design is robust enough to accept these or higher values.
- Pellets in the gap between the distance block and the rock are acceptable.
- Water inflow from fractures in the rock must be stopped by the swelling and sealing ability of the buffer inside each container section or set of container sections.
- If the solution leads to water flowing past a distance block, the time until the inflow is stopped must be so short that the loss of bentonite due to piping and erosion does not affect the future function of the buffer.
- The flow of water and eroded bentonite out of the tunnel must not be so high that it affects the installation of the subsequent buffer and canister packages.
- No items are allowed to be left in the distance blocks that may cause “cross circuit” between supercontainer sections.
- The buffer system has to be robust and it has to be able to be implemented as planned with a proper margin.
- The behaviour of buffer should be predictable.

5 Candidate design specific guidelines

5.1 Basic design (BD)

- A massive supporting ring for fixation of the distance block and dimensioning to resist full water pressure is not acceptable.
- The design is adapted to bedrock and inflow conditions by dividing it into compartments suitable for emplacement and by plugging the unsuitable sections.
- Local lengthening of distance blocks is allowed if feasible.
- If temporary hydraulic pressure is assumed to accumulate behind distance blocks, evidence must be given that the design (e.g. lightweight fixing rings) is robust and the design must go through rigorous evaluation.
- It is not likely that all water inflows can be eliminated by groundwater control techniques. However, significant improvement in feasibility may be achieved by developing proper groundwater control techniques.

5.2 Design with drainage, artificial watering and air evacuation (DAWE)

- A favourable initial state of saturation is obtained by using draining, artificial water filling and air evacuation. After artificial water filling the buffer should have swollen uniformly and filled all the open space. The bentonite should have sealed the drift so that there is no flow inside the drift that could cause piping and transport of bentonite.
- A buffer wetting system shall wet all super containers at the same time (or step-wise controlled wetting during installation), thus ensuring that the bentonite will swell and seal the tunnel uniformly. This minimises the risk of bentonite piping and erosion, as well as water pressure displacement of distance blocks and/or super containers during the saturation phase after sealing of the drift.
- A drainage system shall be installed that can evacuate water from all sections of the deposition drift, preferably from each super container section. The drainage system must be possible to seal with a borehole plugging technique.
- An air evacuation system is needed if the tunnel is water drained until the final end plug is in place. The air evacuation system shall be in place because after deposition all super containers should be uniformly artificially wetted by filling the tunnel with water or bentonite sludge water.
- In case of an air ventilation tube in the ceiling of the drift, the swelling pressure shall be sufficient to flatten the vent tube after final closure of the tunnel.
- The design must ensure that water will be drained from each super container until the final end plug is in place.

Reference

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