Designed Buffer Components for Finnish KBS-3V Concept – 14285

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ABSTRACT

The geotechnical design of a repository for spent nuclear fuel and high level waste disposal in Finland is based on the KBS-3V method. In the KBS-3V method, single canisters containing spent nuclear fuel are emplaced in individual vertical boreholes drilled in the floor of deposition tunnels in bedrock at about 420 m depth below ground level. Disk type bentonite blocks are installed at the bottom of the hole and on the top of the disposal canister. Ring type bentonite blocks surround the canisters. The outer gap between the bentonite blocks and the deposition hole rock surface is filled at emplacement time with bentonite pellets. The final saturation and swelling of the bentonite buffer derives from inflowing water leaking from the rock over time. The saturated density of the buffer is the key parameter related to nearly all performance targets of the buffer. In estimation of the saturated density range obtainable in buffer, different sources of variability and uncertainty have been taken into account. However it is only the bulk density of the blocks and pellets and their volume with which the saturated density of the buffer is possible to control. Final properties of the different buffer components are determined iteratively, taking into account the requirements set for the buffer, the properties of the deposition hole (which in turn are partly determined by the buffer) and the manufacturing and installation processes of the buffer components.

INTRODUCTION

The design of the disposal facility is based on the KBS-3V concept. The barrier closest to the spent nuclear fuel, the canister, is placed in a vertical hole bored in competent bedrock. The long-term safety concept is based on the multi-barrier principle, i.e. several engineered, radionuclide-release-resistant, “defense-in-depth”, barriers supplement one another so that insufficiency in the performance of one barrier does not jeopardize long-term safety of the disposal system. The primary near-field engineered barriers are the canister, the bentonite buffer and the deposition and access tunnel backfill. They are supplemented by the natural barriers provided by the host rock around the repository. The canisters are installed into the deposition holes, which are bored into the floor of the deposition tunnels. The canisters are enveloped with compacted bentonite blocks that swell after absorbing water. The surrounding bedrock and the central and access tunnel backfill provide additional retardation, retention, and dilution of any migrating radionuclides, if needed.

The natural and engineered barriers of the KBS-3V system are described in more detail in Figure 1 and in the following text. The roles of the primary barriers in safe spent nuclear fuel disposal are called safety functions.

DESCRIPTIONS

The spent nuclear fuel assemblies are inserted and sealed in the cast iron insert of the copper canister. The copper canister’s lid is sealed tightly by welding so that groundwater flowing in the bedrock cannot come into contact with the cast iron insert or the spent nuclear fuel. This will ensure isolation and prevent radionuclides from escaping into the groundwater and further into the geosphere and biosphere. Individual copper canisters are placed inside vertical deposition holes bored from the floor of the deposition tunnels, into the bedrock to a depth of approximately

420 meters at locations meeting the required rock suitability criteria. Each deposition hole is then lined with compressed bentonite blocks, a natural clay material with an expanding lattice. The bentonite acts as a buffer between the bedrock and the canister. Bentonite blocks are then placed on top of the canister located inside the bentonite lined deposition hole to an even level with the deposition tunnel floor. The bedrock immediately surrounding the deposition hole protects the canister by maintaining the conditions around the canister favorable in the long-term. The bedrock also slows down and dilutes any potential radionuclide leakage from the canister as the ultimate barrier. The purpose of the deposition tunnel backfill [1] is to ensure that the bentonite buffer stays in the deposition hole when the bentonite expands and that no new flow paths for water are formed into the deposition tunnels. At the same time, the tunnel backfill prevents any inadvertent or willful unauthorized entry into the repository.

Final closure of the facility refers to other structures than those used for backfilling and sealing off the deposition tunnels, such as the backfill and closure structures of the access tunnel, central tunnels and shafts. They are required for construction engineering or operational safety reasons, but, in some cases, also for reasons related to safety functions.

The functional principles and requirements of different barriers are described below in greater detail.

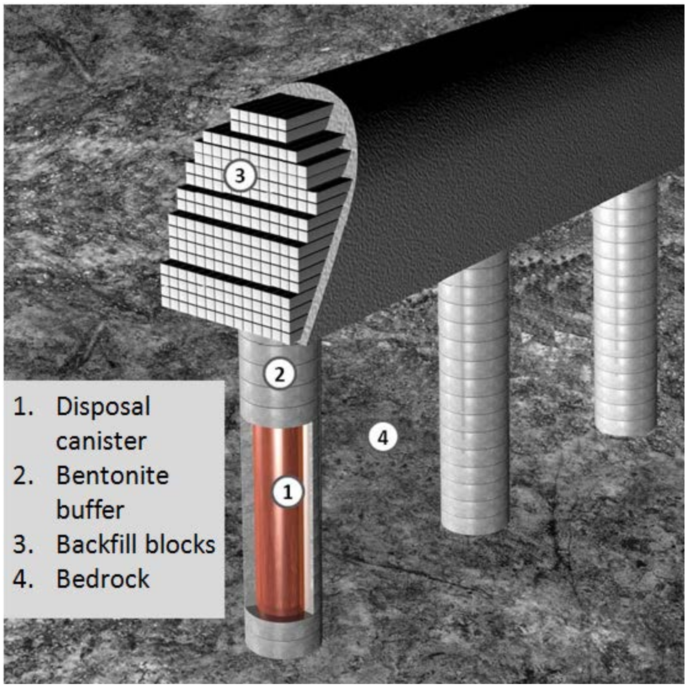

Fig. 1. Multi-barrier system for final disposal. Different barriers back up each other.

The safety functions assigned to the engineered barrier system (EBS) components and the host rock in Posiva’s KBS-3V repository are given in Table I. In this presentation the buffer is dealt with in more details.

TABLE I. Safety functions assigned to the barriers (EBS components and host rock) in Posiva's KBS-3V repository.

Barrier	Safety functions
Canister	Ensure a prolonged period of containment of the spent fuel. This safety function rests first and foremost on the mechanical strength of the canister's cast iron insert and the corrosion resistance of the copper surrounding it.
Buffer	Contribute to mechanical, geochemical and hydrogeological conditions that are predictable and favorable to the canister. Protect canisters from external processes that could compromise the safety function of complete containment of the spent nuclear fuel and associated radionuclides. Limit and retard radionuclide releases in the event of canister failure.
Deposition tunnel backfill	Contribute to favorable and predictable mechanical, geochemical and hydrogeological conditions for the buffer and canisters. Limit and retard radionuclide releases in the possible event of canister failure. Contribute to the mechanical stability of the rock adjacent to the deposition tunnels.
Host rock	Isolate the spent nuclear fuel repository from the surface environment and normal habitats for humans, plants and animals and limit the possibility of human intrusion, and isolate the repository from changing conditions at the ground surface. Provide favorable and predictable mechanical, geochemical and hydrogeological conditions for the engineered barriers. Limit the transport and retard the migration of harmful substances that could be released from the repository.
Closure	Prevent the underground openings from compromising the long-term isolation of the repository from the surface environment and normal habitats for humans, plants and animals. Contribute to favorable and predictable geochemical and hydrogeological conditions for the other engineered barriers by preventing the formation of significant water conductive flow paths through the openings. Limit and retard inflow to and release of harmful substances from the repository.

The Buffer

The buffer material to be used is compacted bentonite, installed as blocks to surround the canister in the deposition hole and as pellets between the blocks and the hole surface. Bentonite is a natural clay type with the following characteristics: it is plastic, swelling, and slippery when wet. The use of bentonite in the repository is based on its ability to swell when exposed to water.

The buffer must fill the entire empty space between the canister and the bedrock, and it must be

- Plastic enough to dampen the impact of minor bedrock movements on the canister.
- Stiff enough to support the weight of the canister and prevent it from moving,
- Dense enough to prevent microbial activity in the buffer that might result in unfavorable conditions for the canister, and
- Impermeable enough to limit the movement of water to insignificant quantities so that diffusion is the primary migration mechanism for both the groundwater components causing canister corrosion and for the radionuclides released from the canister.

The buffer material must display a sufficient swelling pressure and self-healing capability, which means that any potential flow or travel channel created — for example, as a result of channeling and erosion, rapid bedrock movements or gas emissions from a broken canister — is quickly closed. The impermeability of the buffer must restrict and slow down the release of radionuclides possibly escaping from a broken canister. In addition, the buffer must have a fine porous structure to stop the movement of microbes and colloids (they are filtered) and any microbe- or colloid-assisted migration of radionuclides. [2].

In line with the safety concept, the properties of the buffer material to be deployed must be known so that it is possible to ensure the capability of the buffer to fulfill the set requirements and to restrict the migration of radionuclides in case an individual canister fails to comply with the requirements. The reference material chosen for the buffer in the 2012 plans is MX-80 bentonite, or any clay material with equivalent properties.

Performance Targets for the Buffer

The performance targets (subsystem requirements) are given in Posiva's *Design Basis report* [3].

Definition

Buffer is the component that surrounds the canister and fills the void spaces between the canister and the rock. The purpose of the buffer is to protect the canister from detrimental thermal, hydraulic, mechanical and chemical, including microbiological (THMC) processes that could compromise the safety function of complete containment, to maintain favorable conditions for the canister and to slow down the transport of radionuclides if the canister starts leaking.

Performance

The amount of substances in the buffer that could adversely affect the canister, backfill or rock shall be limited.

Unless otherwise stated, the buffer shall fulfill the requirements listed over hundreds of thousands of years in the expected repository conditions except for incidental deviations.

The performance expectations are:

- The buffer shall transfer heat from the canister efficiently enough to keep the buffer temperature < 100 °C.
- The buffer shall allow gases to pass through it without causing damage to the repository system.
- The buffer shall limit microbial activity.
- The buffer shall mitigate the impact of rock shear on the canister.
- The buffer shall be impermeable enough to limit the transport of radionuclides from the canisters into the bedrock.
- The buffer shall be impermeable enough to limit the transport of corroding substances from the rock onto the canister surface.
- The buffer shall limit the transport of radio colloids to the rock.

Support to the Other Systems

The buffer shall provide support to the deposition hole walls to mitigate potential effects of rock damage. The buffer shall also be able to keep the canister in the correct position (to prevent sinking and tilting).

Design Requirements for the Buffer

Design requirements are ultimately defined so as to enable the achievement of the performance targets in the expected scenarios. The design requirements are given in Posiva's *Design Basis report* [3].

Definition

The main component of the buffer material shall consist of natural swelling clays.

Performance

The buffer shall be designed to be self-sealing after initial installation and self-healing after any hydraulic and mechanical disturbances:

- The buffer shall be so designed that the possibility of corrosion of a canister by sulphide and other corrodants including microbially-induced processes will be limited.
- The buffer material shall be selected so as to limit the contents of harmful substances (organics, oxidizing compounds, sulphur and nitrogen compounds) and microbial activity).
- The buffer shall be so designed that it will mitigate the mechanical impact of the postulated rock shear displacements on the canister to the level that the canister integrity is preserved.
- The buffer shall be designed in such a way as to make diffusion the dominant transport mechanism for solutes.
- The buffer material must be selected in a way that favors the retardation of the transport of radionuclides by sorption (e.g. cation exchange) at the clay and other mineral surfaces.
- The buffer shall have a sufficiently fine pore structure so that transport of colloids formed within or around the canister is limited.
- The gaps between the canister and buffer and buffer blocks and rock should be made as narrow as possible without compromising the future performance of the buffer.

Support of Other System Components

The buffer shall initially provide a good contact with the host rock.

Design Specifications

In addition to the performance targets and design requirements presented above, detailed specifications for the buffer have been presented at Posiva's requirement management system level 5. Design specifications are derived from the safety functions, performance targets and design requirements. Design specifications are quantitative specifications determined for the design based on the safety functions, the performance targets and the design requirements. These are given in Table II. These numerical values are based on the long development work with the KBS-3V disposal concept and iterating work with the buffer design.

TABLE II. Buffer design specifications.

1 Definitions
The buffer material being considered is MX 80 type bentonite, containing mainly mineral Montmorillonite.
The thickness of bentonite buffer from canister bottom to the bottom of deposition hole shall be at least 500 mm.
The target thickness of bentonite buffer on top of the canister shall be 2500 mm.
The thickness of saturated bentonite buffer between canister wall and rock shall be 350 mm ± 25 mm.
2 Material specifications
The montmorillonite content of the dry buffer material shall be 75–90% by weight
The water content of the buffer material shall be at least 15 wt.%
The target density of buffer at saturation shall be 2000 kg/m^3 with tolerances defined in [2].
The total sulphur content shall be less than 1 wt. %, with sulphides making, at most, half of this.
The organics content in the bentonite shall be lower than 1 wt.%
3 Support of other system components
The gap between buffer block and deposition hole shall be filled with bentonite.

Material Composition and Grading

The buffer material is bentonite clay with the material composition specified in Table III. Examples of commercial bentonites with this material composition are high grade sodium bentonite from Wyoming (MX-80) and high grade calcium bentonite from Milos (Ibeco RWC, also often called Deponit CaN). The results of analysis of these materials are presented for example in SR-Can [4], [5] and in [6], [7] and [8].

High grade sodium bentonite from Wyoming (MX-80) is the reference material for both the buffer blocks (disks and rings) and the pellets. MX-80 is the commercial name of a Wyoming sodium bentonite with montmorillonite content above 75%. It is, however, acceptable that as long as any other bentonite type containing montmorillonite 75–90% fulfills the performance targets of the buffer, the alternative bentonite can be considered as a suitable candidate in the future. However, because Ibeco RWC has higher swelling pressure, the density limits for the saturated density of the buffer and the designed bulk densities for the blocks and pellets are only valid for MX-80.

TABLE III. The reference buffer material.

Design parameter	**Nominal design, wt.-%**	**Accepted variation/ upper limit, wt.-%**
Montmorillonite content	80–85	75–90
Total sulphur content (including the sulphide)	< 1	< 1
Sulphide content	< 0.5	< 0.5
Organic carbon content	< 1	< 1

The capability of the buffer to maintain the safety functions will depend on its swelling pressure (density and porosity), hydraulic conductivity, stiffness and content of substances that may be harmful for the other barriers. According to the design basis, the montmorillonite content in the buffer material must be sufficient for the buffer to provide the required performance in the disposal system.

The swelling mineral of bentonite clays is usually montmorillonite. High-quality commercial bentonites normally contain over 75% of montmorillonite. The swelling properties and stiffness are also dependent on the magnitude and the position of the layer charge and on the type of charge compensating cation. In the repository the cation may be exchanged. However, the swelling pressure, hydraulic conductivity and stiffness must be preserved at the required level. The montmorillonite content is chosen to specify the bentonite clay since it is the most important material property influencing swelling pressure and hydraulic conductivity.

The amount of organic carbon, the sulphide and total sulphur are chosen to specify the quality of the bentonite clay since these substances may impact the radionuclide transport or cause canister corrosion. A high amount of iron might favor bentonite transformation and to some extent affect the swelling pressure of the buffer and its hydraulic and radionuclide retention properties (SKB 2010, p. 26).

These before mentioned material parameters are measured to control the quality of the purchased material.

Material Grading

The production of the buffer blocks and pellets shall be reliable and the raw material has to be in such form that it allows compaction. Furthermore, the produced blocks shall be homogenous and free from cracks and damages to allow the installation. Among other things this has resulted in the used water content for the block and pellets. The density and homogeneity of the produced blocks and pellets will depend on the grain size distribution and water content of the material to be compacted and on the compression pressure and method. To achieve high reliability in the production, the grain size distribution and water content must be specified. Figure 2 presents the nominal granular distribution of the material and the acceptable upper (Max) and lower limits (Min) for the grading. The grain size distribution is based on the laboratory test done by Ritola and Pyy [9].

The water content of the reference processed bentonite material used for the compression of the disk blocks, for the ring shaped blocks and for the pellets is 17%. The acceptable variation of the water content is ±1%. The specifications will depend on the chosen bentonite material. The specifications of grain size distribution in Figure 2 and water content 17% are valid for MX-80.

In order to conform to the density interval given in all sections of the deposition hole, the ring shaped blocks surrounding the canister and the solid blocks must be compacted to different densities. Furthermore, the gap between the blocks and the rock surface must be filled with pellets with the specified density of loose filling.

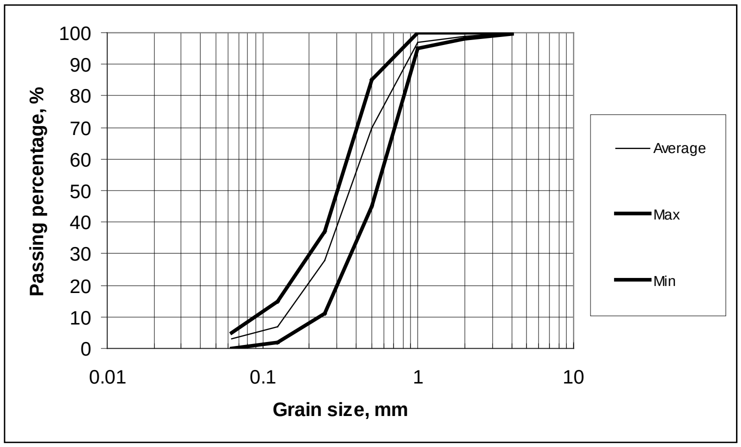

Fig. 2. Nominal grain size distribution of MX-80 used in blocks and the allowed distribution limits.

The buffer blocks are manufactured with the isostatic compression method [9], which is Posiva's reference method for block manufacturing. In this method, pressure is exerted evenly on the mould from all sides, which results in an even density of the bentonite block. The combination of correct water content of bentonite and suitable pressure produces the desired density for the buffer [10].

The dimensions and the shape of the pellets shall be such that they can be installed in the gap in a reliable way. The dimensions need to be specified and inspected for the production but regarding the installed density it is sufficient to specify the bulk density of loose filling. The dimensions and density of individual pellets may be altered as long as they can be poured into the gap and yield the required bulk density of loose filling. No compaction or vibration of the poured filling is used, since using compaction can result in the density being too high [11]. Pellets are poured in the outer gap without excess compaction. Gap filling test have been undertaken with several materials on a small laboratory scale and on a larger scale with test in an actual hole diameter and a height of 2 meters [11].

Posiva's reference method for manufacturing of pellets is roller compaction of small briquettes [12].

Three Types of Deposition Holes

The disposal canisters are emplaced in holes bored in the deposition tunnel floors. The deposition holes have a diameter of 1.75 m, and their depth depends on the length of the canister to be emplaced. This, in turn, varies with the type of spent fuel originating from the different NPPs. The length for Loviisa 1-2 NPP (LO1-2) canisters is 3.6 meters, for Olkiluoto 1-2 NPP (OL1-2) canisters 4.8 meters and for Olkiluoto 3 (OL3) canisters 5.25 meters. The depth of the deposition holes for the canisters of OL1-2 units is approximately 7.8 m, for the canisters of OL3 about 8.3 m and for the canisters of LO1-2 units about 6.6 m (Figure 3). The depth of the deposition holes for the canisters of OL4 will be established once the fuel type has been decided on. A protective structure for the buffer will be constructed at the mouth of each finished deposition hole. It consists of a frame structure and a watertight steel lid attached to it.

When the deposition tunnels are located 25 meters apart and when the disposal canisters are located at even intervals, the minimum distance between deposition holes is about 9.0 meters for

OL1-2 canisters, about 7.5 meters for LO1-2 canisters and about 10.5 meters for OL3 canisters [13].

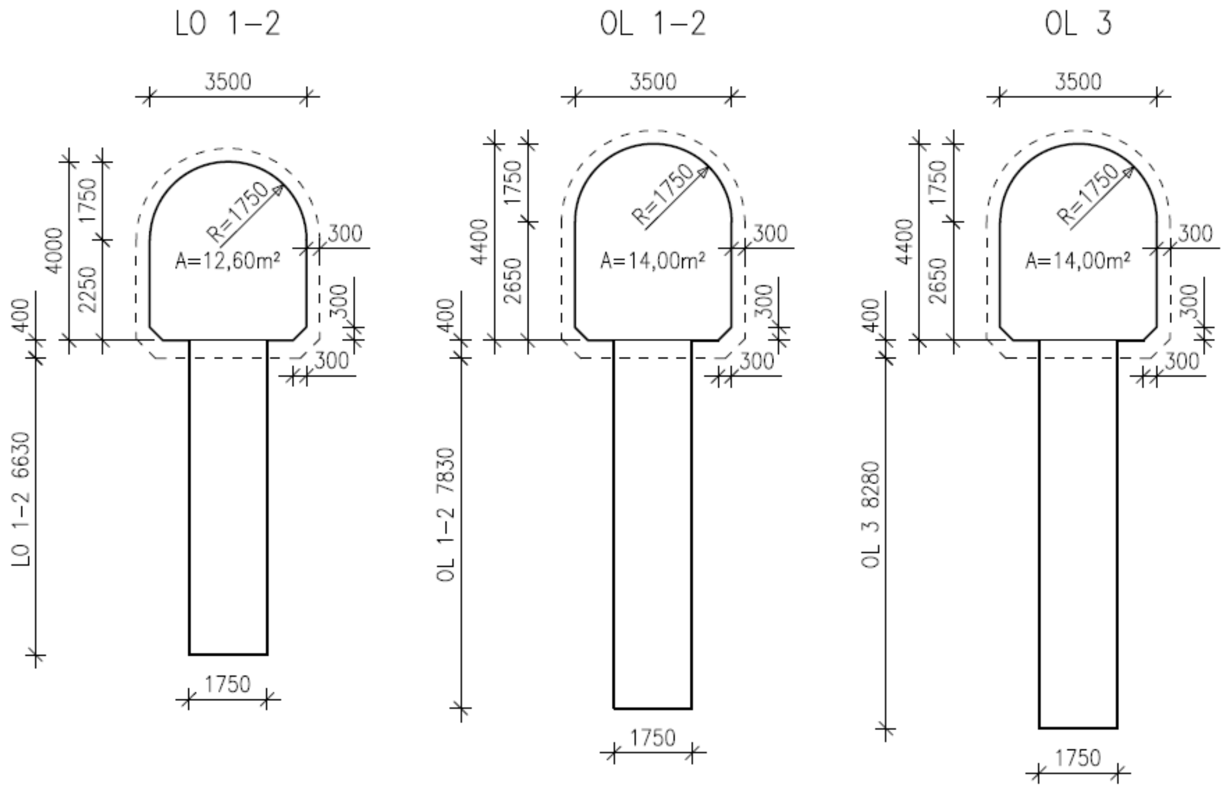

Fig. 3. Cross-sectional view of a deposition tunnel [14].

Reference Design of the Buffer

Concept Development

The development of the reference concepts for disposal of spent nuclear fuel in crystalline bedrock used in Sweden and Finland began in Sweden in the 1970s and early 1980s. The dimensions of the canister and deposition hole have somewhat changed during the research and development work, but very recently the material for the buffer and its major properties were defined resulting to the current design.

During the JADE project, which was initiated in 1996, the diameters of the canister and the deposition holes got the presents dimensions [15] as well as the buffer dimensions: the saturated thickness 350 mm (block thickness around the canister 290 mm); height under canister 500 m and above the canister 1500 mm [15], although the dimension of the blocks have varied after that too. The specifications for the saturated density of the buffer became also more specific.

In [16] it was stated that the desired swelling capacity and low hydraulic conductivity of the bentonite buffer will be obtained in the brackish and saline groundwaters at Hästholmen and Olkiluoto by ensuring that the density of the compacted bentonite is sufficiently high, around 2000 kg/m^3 at saturation.

The diameter of the hole was defined as the sum of the diameter of the canister, the original thickness of the bentonite blocks, and the tolerances between the canister and the blocks and between the blocks and the rock. The thickness of the bentonite buffer was in turn determined by the desired mechanical, chemical and hydraulic properties and the thermal performance of the buffer. Allowance was also made for the desired gas transport capacity [17].

The allowable temperature that can be tolerated by the canister surface was also taken into account. In view of this and the requirement of maintaining a diffusion barrier around the canister that will last for the whole lifetime of the repository, the buffer was made 350 mm thick, which led to a hole diameter of 1750 mm for the actual canister design [17].

In SR-Can [18] the buffer has also a saturated reference density of 2000 kg/m^3 with an allowed variation of density for the saturated buffer in the deposition hole ±50 kg/m^3 and also this requirement is confirmed in SKB’s buffer production [19].

Posiva’s Developments in Buffer Design

Posiva has taken the same kinds of development steps in buffer design as in Sweden.

In Saanio et al. [20] the diameter of the deposition hole was defined to be 1750 mm and the diameter of the canister 1050 mm. The diameter of the blocks was 1700 mm and the inner and the outer gaps 10 mm and 25 mm (without bentonite filling) respectively.

In TKS-2009 [21] definitions were based on the balance between competing requirements on the saturated density of the buffer, with a performance target range of about 1900 kg/m^3 to 2050 kg/m^3. The upper boundary for saturated buffer density (2050 kg/m^3) was based on the requirement that the buffer must protect the canister in the event of rock shear movements and the lower boundary of 1900 kg/m^3 was derived from the requirement on the buffer to prevent significant microbial activity. It was also assumed that in design the initial lower boundary buffer density should be 1950 kg/m^3, before backfill compression or any losses due to piping and erosion take place [21]. The basic design for the buffer [22] was done keeping this range as requirement and 2000 kg/m^3 as the target density of the saturated buffer.

In the current reference design the most essential feature compared to the basic design is that the outer gap is filled with pellets. In the reference design the target density of the saturated buffer is 2000 kg/m^3. The range for the saturated density takes into account the buffer material, canister design and the prevailing and expected conditions at Olkiluoto. The thermal dimensioning of the buffer has also been checked [13] perceiving the updated reference design.

Reference Design Features

In Posiva’s current reference design the gap width is 50 mm and the gap is filled with bentonite in the form of pellets.

The advantages of this kind of gap design are that:

- It is not as sensitive to break-outs and geometric imperfections, because all the gap width (possible varying due to boring and break out of rock) is filled with bentonite pellets
- It offers immediate contact to the rock.

The support that the filling of the outer gap offers is not so high, if it consists of only the influence of the weight of the filling itself. However the filling itself already prevents potentially breaking off parts of rock from falling into the gap [23].

The disadvantage of a design with gap filling is that it creates one additional working phase and may prolong the disposal timetable.

In the reference design the outer diameter of the block is 1650 mm and the clearance between the wall of the deposition hole and the bentonite blocks is currently assumed to be 50 mm. The initial bulk densities of the blocks and pellets are defined so that the target value for saturated density for the buffer will be reached during the expected post-closure buffer evolution.

The required saturated density of the buffer can be achieved in the reference design with different conditions, taking into account the uncertainties related to the deposition hole and its tolerances and to some uncertainties related to the buffer blocks and rings themselves.

In order to determine the density, dimensions and water content of buffer components required for the buffer to conform to the design basis for long-term safety, the geometry of the deposition holes must be known. Furthermore, both to determine the saturated density and to achieve a reliable deposition, the variation in deposition hole geometry must be limited and known.

The design basis imposed for the deposition holes by the buffer related to the determination of the saturated density of the buffer and to achieve a reliable installation are given in Table IV.

The requirements imposed for the deposition holes by the buffer presume that:

- There is enough space in the deposition hole for the canister and buffer
- The deposition hole bottom is even enough to allow the installation of the buffer blocks and the deposition of the canister and
- The variations in deposition hole geometry are acceptable with respect to the dimensions of the buffer blocks and pellet filling, in order to allow the installation of the buffer and to achieve the saturated density according to buffer specifications.

These requirements are met with the following measures and allowed deviations.

The nominal diameter of the deposition hole required for the reference design is 1750 mm. The diameter of the hole shall be between 1745 mm and 1800 mm. In the reference design the pellet filled gap width is 50 mm with a deviation of $\pm$25 mm.

The bored hole shall be situated in an area in which the minimum radius is at least 850 mm and the maximum radius under 900 mm measured from a vertical line in the center of the deposition hole. The maximum circular cross-section area in the hole shall not be larger than 5.8% compared to the nominal cross-section area of the hole at any depth. These values include all the combined effects of steps and notches, inclination and bending of the hole and spalling of the rock. The percentage, 5.8%, corresponds to the maximum allowed diameter of the deposition hole. If, for example, the spalling is supposed to happen in an elliptic area according to the maximum allowed area (nominal area +5.8%) the maximum local radius shall be less than 925 mm. If the radius of the hole around the whole circumference of hole is 900 mm already after boring, there is no reservation for spalling. Although in the case of spalling the local saturated density may fall below the lower density limit for the buffer, the average density of the cross-section fulfills the density requirement. The area assumption of elliptic form is probably over-estimating the spalling which is likely to occur in a more triangle shape.

The nominal heights of the deposition holes are for LO1-2 canisters 6.63 m, for OL1-2 canisters 7.83 m and for OL3 canister 8.28 m. The deposition holes are not allowed to be lower than these values. The evened deposition hole bottom shall not be deeper than the nominal height of the hole plus 0.05 m. These nominal heights of the holes include the thickness of the copper bottom plate. This means that the nominal heights of the buffer are 30 mm lower, i.e. 6.60 m, 7.80 m and 8.25 m.

In the heights of the deposition holes presented in Figure 3 an excavation tolerance of 400 mm is taken into account and the height of the holes are measured from the theoretical excavation line.

The nominal thickness of the buffer around of the canisters is 350 mm, below the canisters 500 mm and above the canisters 2500 mm.

The deposition hole bottom inclination shall be less than 1/1750.

TABLE IV. Design basis imposed for the deposition holes by the buffer.

Design parameter	Design value	Allowable deviation
Diameter of the hole	1750 mm	-5/+50 mm
Cross section area of the hole (nominal area according to nominal diameter)	2.4053 m^2	-0.57% / +5.8%
Depth of hole (nominal values measured from the lowest allowable level of the tunnel floor specified in the excavation design)	LO1&2 6.63 m OL1&2 7.83 m OL3 8.28 m	-0 m / +0.05 m
Inclination of the bottom of the hole		< 1 mm / 1750 mm

The buffer block emplacement scheme for each canister type is illustrated in Figure 4. The sizes of the block components to be emplaced in the deposition holes are shown in Table VI The block installed at the bottom is 0.5 m thick, and the total thickness of blocks installed at the top is 2.5 m. The number of ring shaped side blocks around the canister is 4 to 6 blocks, depending on the canister type. The height of the disk blocks varies from 400 mm to 800 mm and for ring shaped blocks from 875 mm to 960 mm. The heights of the disk blocks are dependent on the placement location (see Figure 4). The heights of the ring shaped blocks are specific for different canister heights.

In the installation phase, the blocks are first installed to the height of the canister top. After the canister disposal, the rest of the bentonite blocks are emplaced and the gap between the buffer and the bedrock is filled with bentonite pellets.

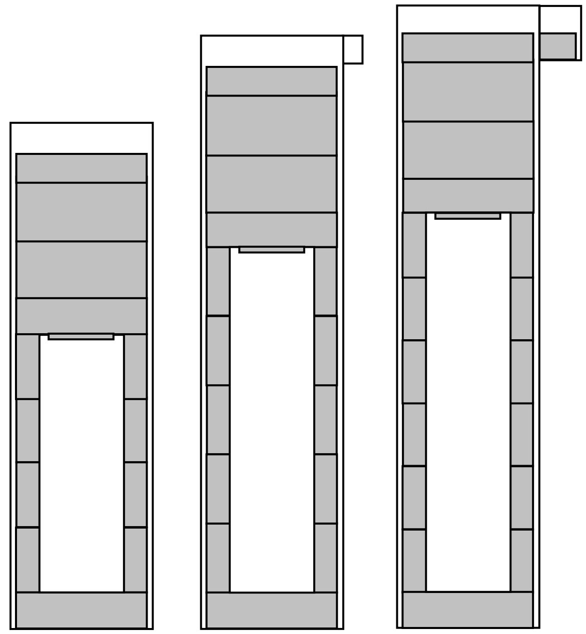

Fig. 4. Schematic illustration of the deposition holes, canisters and buffer blocks for spent fuel from the LO1-2, OL1-2 and OL3 units [2].

Variations in Deposition Hole Geometry

Due to variations in the deposition hole geometry, the density of the buffer after saturation will vary along the deposition hole. The saturated densities are calculated separately around the canister and under and above the canister.

In the following review the saturated density of the buffer is calculated as a function of outer gap width. In the calculations the blocks have their nominal dimensions, but the outer gap width, which means also, that the radius of the deposition hole, is changed.

The acceptable variations in the width of the pellet filled gap between the buffer blocks and rock wall is 25–75 mm. The causes can be a result of the placement of the blocks within a circular cross section without rock damage or a result of rock damage, or a combination of the two. The stack of buffer blocks has to be vertical straight in order to allow deposition of the canister. If the deposition hole is oblique or inclined, the stack of buffer blocks has to be placed off-centered in some sections of the deposition hole.

The results of the calculations are presented in Figure 5, where the width of the pellet filled outer gap is varied. In Figure 5 the water content of the ring shaped blocks is 17% and the block bulk density is 2050 kg/m^3. The water content of the disk blocks is 17% and the block bulk density is 1990 kg/m^3. The water content of the pellets is 17% and the loose density of pellet filling 1075 kg/m^3.

The figure shows that with the nominal deposition hole and the nominal dimensions, water content and bulk densities of the blocks, the saturated density of the buffer around the canister is 1999 kg/m^3. The saturated density of the buffer under and above the canister is 2027 kg/m^3. The nominal average saturated density of the buffer is 2012 kg/m^3. More exact values for each canister type are presented in [10].

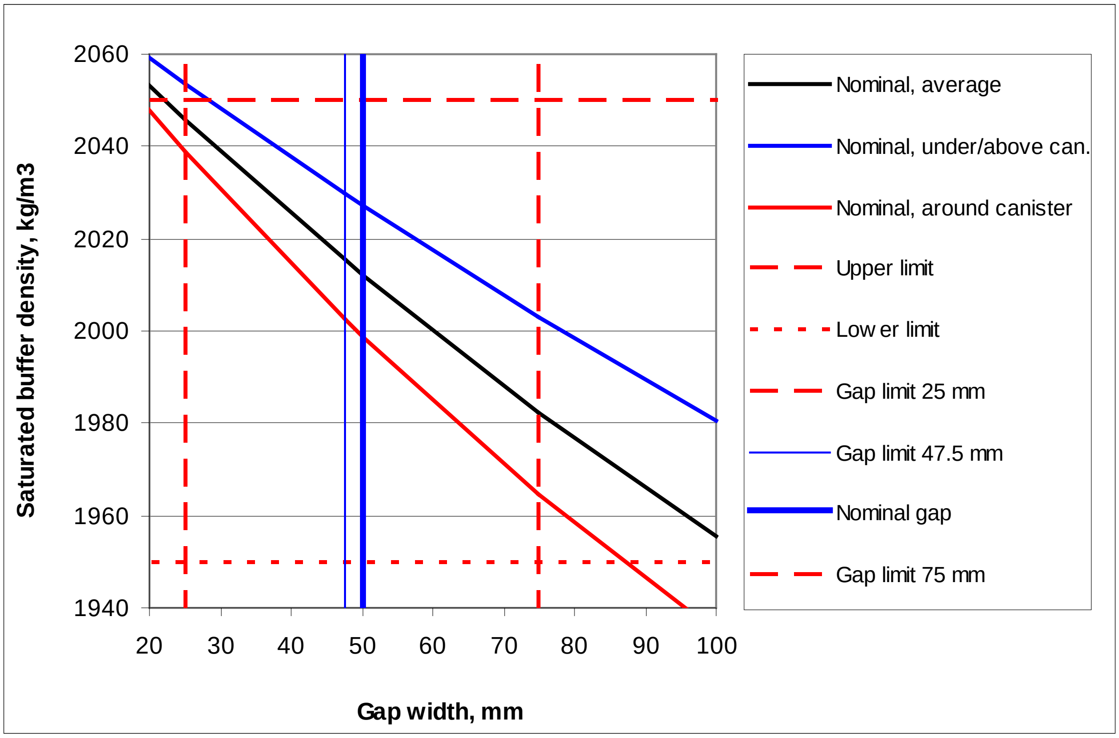

Fig. 5. The calculated saturated density of the buffer as a function of the width of the pellet filled gap between the bentonite blocks and the wall of the deposition hole.

The acceptable variations in the gap and deposition hole radii and diameter will result in a variation of the density over the cross section. The maximum variation in gap width for the nominal blocks and pellets is plotted with vertical red dash lines in Figure 5. The maximum variation in gap width results in a maximum variation of the saturated buffer density around the canister: If the water content of the ring shaped blocks is 17%, and the gap width is the smallest allowed, the saturated density is 2039 kg/m^3, which is lower than the upper limit 2050 kg/m^3. With the largest allowed gap width (75 mm) the saturated density is 1964 kg/m^3 which is larger than the lower limit 1950 kg/m^3. Under and above the canister the saturated densities just overrun the upper limit: with the smallest gap width the saturated density is 2054 kg/m^3. This density is advisedly kept a bit high, because of the risk of up swelling and erosion of the buffer. At the largest allowed gap width (75 mm) the density is larger than the lower limit, 2003 kg/m^3.

Probability Based Calculation with @RISK Program

Because it is quite rare that all the smallest gap width and the largest bulk densities of the blocks and pellets take place at the same time, statistical calculations were performed with the @Risk program. @Risk is a risk analysis and simulation add-in for Microsoft Excel® or Lotus® 1-2-3 [24].

In these calculations the assumptions and parameter distributions used are presented in Table V.

TABLE V. Input values in @Risk calculations with 50 mm nominal gap with gap fill.

Parameter	Distribution	Min	Most likely	Max
Gap width, mm	Triangle	25	50	75
Block diameter, m	Triangle	1.648	1.650	1.652
Block bulk density, kg/m^3	Triangle	2030	2050	2070
Block water content, %	Triangle	16	17	18
Pellet bulk density, kg/m^3	Triangle	1025	1075	1125
Pellet water content, %	Triangle	16	17	18
Montmorillonite content, %	Triangle	75	82.5	90
NaCl concentration, g/l “normal”	Triangle	13.5	18.5	23.5
NaCl concentration, g/l “maximum”			70	
Ring block outer diameter, mm	Triangle	1648	1650	1652

With a ring block bulk density of 2050 kg/m^3 ±20 kg/m^3 the average saturated density of the buffer around the canister is 1998 kg/m^3 and varies between 1951…2051 kg/m^3. In less than 4 deposition holes of the total 4500 holes, the saturated density is more than 2050 kg/m^3. In less than 5 deposition holes of the total 4500 holes, the saturated density is less than 1950 kg/m^3. The target density of the buffer (2000 kg/m^3) is also achieved. Using equation developed for purified and Ca^{2+}-exchanged MX-80 material by Karnland [25], the swelling pressure exceeds 15 MPa in 5 (calculation result) to 13 (lognormal fitting to calculation results) holes of the total 4500 deposition holes in fresh water. 15 MPa is the maximum swelling pressure that is used in canister design [26]. The swelling pressure is also always over 2 MPa in all calculations at up to 70 g/l NaCl groundwater concentrations, if 1950 kg/m^3 is regarded as the lower density limit. A swelling pressure of this order retards microbiological activity in the buffer.

The calculated distributions for saturated density of the buffer and for the swelling pressure are presented in Figure 6.

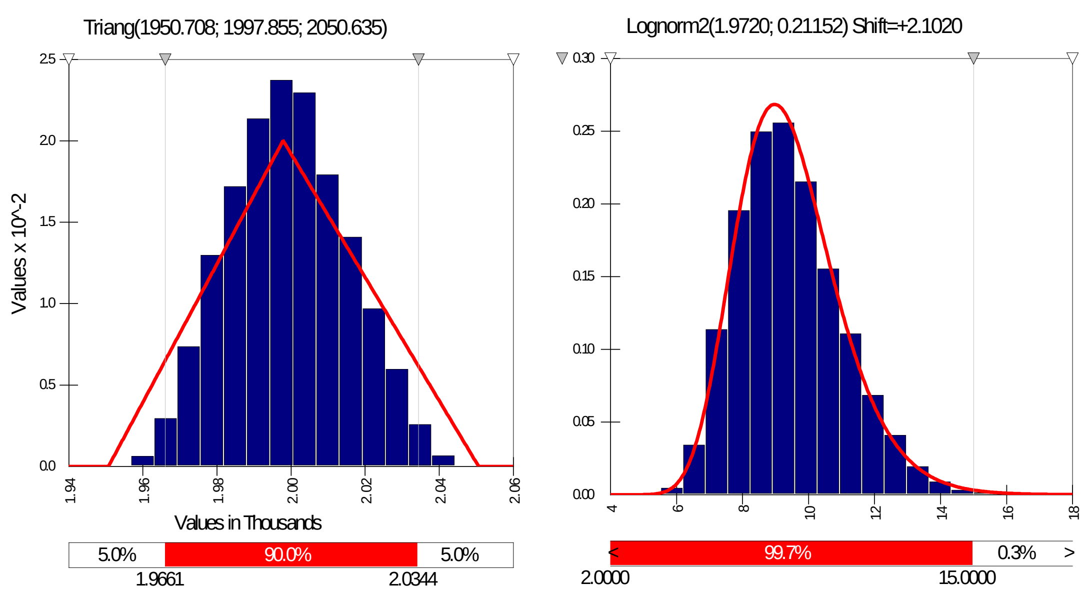

Fig. 6. Saturated density distribution of buffer and swelling pressure distribution of the buffer around the canister.

Designed Blocks and Pellets

Basic properties for the buffer blocks and pellets within Posiva's reference design are presented in Table VI. The densities are given as bulk densities since it is the bulk densities that are going to be inspected in the production and quality control program at the time of installation. In the design basis, the saturated density of the buffer is specified.

TABLE VI. Buffer blocks and pellets for the reference design.

Design parameter	Design value	Allowed deviation
Disk blocks		
Water content of disk blocks	17%	±1%-unit
Bulk density of disk blocks	1990 kg/m^3	±20 kg/m^3
Disk block outer diameter	1650 mm	±2 mm
Disk block height (see Figure 4)	400, 500, 800 mm	±1 mm
Parallelism block bottom / top		< 1 mm/1750 mm
Ring blocks		
Water content of ring blocks	17%	±1%-unit
Bulk density of ring blocks	2050 kg/m^3	±20 kg/m^3
Ring block outer diameter	1650 mm	±2 mm
Hole diameter in ring blocks	1070 mm	±1 mm
Ring block height (see Figure 4)	OL3: 875 mm; LO1,2: 900 mm; OL1,2: 960 mm	+2 mm
Pellets		
Bulk density separate pellets	1850 ±70 kg/m^3	±70 kg/m^3
Dimensions	11x11x5 mm	-
Bulk density of pellets	1075 kg/m^3	±50 kg/m^3
Water content of pellets	17%	±1%-unit

The calculated saturated densities for the buffer are given in Table VII.

TABLE VII. Total amount of bentonite in the deposition holes during the installation phase and the resulting saturated density.

	LO1-2	OL1-2	OL3
Total amount of bentonite (w = 17%), kg	23814	27215	28541
Total amount of bentonite (w = 0%), kg	20354	23261	24394
Deposition hole volume, m^3	12.715	14.566	15.288
Dry density in hole, kg/m^3	1601	1597	1596
Saturated density in hole (S_r = 100%), kg/m^3	2019	2016	2016

CONCLUSIONS

In the KBS-3V method, single canisters containing spent nuclear fuel are emplaced in individual vertical boreholes drilled in the floor of deposition tunnels. Disk type bentonite blocks are installed at the bottom of the hole and on the top of the disposal canister. Ring type bentonite blocks surround the canisters. The outer gap between the bentonite blocks and the deposition hole rock surface is filled at emplacement time with bentonite pellets. The final saturation and swelling of the bentonite buffer derives from inflowing water leaking from the rock over time.

The saturated density of the buffer is the key parameter related to nearly all performance targets of the buffer. However, it is only the bulk density of the blocks and pellets and their volume with which the saturated density of the buffer is possible to control. Final properties of the different buffer components to be installed have to be designed iteratively taking into account the requirements set for the buffer, different scenarios, other engineered barriers and the manufacturing and installation processes of the buffer components.

In estimation of the saturated density range obtainable in buffer, also different sources of variability and uncertainty of the buffer components themselves have been taken into account.

After having taken into account all of these items above, Posiva's reference design for the buffer consists of buffer components with a water content of 17% and with the bulk density of disk blocks 1990 kg/m^3, ring blocks 2050 kg/m^3 and pellets 1075 kg/m^3 at installation phase. These properties result in a saturated density of 2000 kg/m^3 ±50 kg/m^3 in the buffer.

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