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Foreign Materials in the Repository – Update of Estimated Quantities

Annika Hagros

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POSIVA OY
FI-27160 OLKILUOTO, FINLAND
Tel +358-2-8372 31
Fax +358-2-8372 3709

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Saanio & Riekkola Oy

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ABSTRACT

In a repository for spent nuclear fuel, a variety of materials are used during the construction process and during the operation of the repository. In addition to materials necessary for the construction and operation, some materials may be transported into the repository through the ventilation air, as emissions from vehicles, as waste produced by the staff etc. Both of these two types of materials are considered here and their quantities – both the introduced quantities and the quantities that remain after closure – in the repository constructed at Olkiluoto in Eurajoki, Finland are estimated here based on new information. This work is intended to update the estimations that have been made previously, and it takes advantage of the experience collected during the construction of the underground rock characterisation facility ONKALO at Olkiluoto. During this construction process, the quantities of the different construction materials introduced into the underground openings have been monitored and they form a basis for estimating the quantities to be used in the future.

The estimations made in this report are specific to a KBS-3V type repository and to the Olkiluoto site, although in some cases more generic information has been used, particularly when the relevant quantities have not been monitored in the ONKALO. The estimations are based on the new repository layout produced in 2006 and consider the latest plans for grouting and rock support. As these plans are generally not final yet, several different alternative plans are assumed when necessary. Also two different strategies for the backfilling of the tunnels are considered.

The most significant differences with respect to the results of an earlier estimation are related to the materials used in grouting, shotcreting and in support bolts. In the cases where a mixture of bentonite and crushed rock is the used backfill alternative, gypsum and cement are the materials with the largest quantities remaining in the repository. The materials with the next largest quantities are carbonates and organic materials. If the chosen tunnel backfill alternative is Friedland clay, the material with the largest quantity is gypsum, followed by pyrite, organic materials and cement. The selection of the backfill alternative has a significant impact on the quantities of several important foreign materials and their relative abundance, whereas the differences between the grouting and shotcreting alternatives are minor in terms of total material quantities.

Keywords: Foreign materials, construction materials, Olkiluoto, nuclear waste, disposal, repository, KBS-3V

VIERAAT AINEET LOPPUSIJOITUSTILOISSA – PÄIVITETYT MÄÄRÄ-ARVIOT

TIIVISTELMÄ

Käytetyn ydinpolttoaineen loppusijoitustiloissa käytetään lukuisia materiaaleja sekä rakentamisen aikana että tilojen käyttövaiheessa. Joidenkin aineiden käyttö on välttämätöntä tilojen rakentamisen ja käytön kannalta, kun taas osa aineista voi kulkeutua tiloihin ilmanvaihdon kautta, ajoneuvojen päästöinä, työntekijöiden tuottamien jätteiden muodossa jne. Tässä työssä on huomioitu molempiin ryhmiin kuuluvia aineita, ja niiden määrät – sekä tiloihin tuodut että sulkemisen jälkeen tiloihin jäävät määrät – Eurajoen Olkiluodon loppusijoitustiloissa on laskettu uuden tiedon perusteella. Työn tarkoituksena on päivittää aikaisemmin tehdyt arviot materiaalimääristä käyttäen hyödyksi Olkiluotoon rakennettavan maanalaisen tutkimustilan, ONKALOn, louhinnan aikana kertynyttä tietoa materiaalien käytöstä. Louhintaprosessin aikana on monitoroitu tiloihin tuotujen erilaisten rakennusmateriaalien määriä, ja niiden perusteella voidaan arvioida myös tulevia käyttömääriä.

Raportissa tehdyt arviot koskevat Olkiluotoon rakennettavaa, KBS-3V-konseptin mukaista loppusijoitustilaa, vaikka joissain tilanteissa on käytetty hyväksi myös yleispätevämpää tietoa, etenkin sellaisten aineiden kohdalla, joiden käyttöä ei ole monitoroitu ONKALOssa. Arviot perustuvat uuteen, vuoden 2006 suunnitelmaan loppusijoitustilojen layoutista sekä uusimpiin injektointi- ja lujitussuunnitelmiin. Koska nämä suunnitelmat eivät yleisesti ottaen ole vielä lopullisia, useita vaihtoehtoisia suunnitelmia on tilanteen mukaan huomioitu. Lisäksi on huomioitu kaksi vaihtoehtoista strategiaa tunneleiden täyttämiseksi.

Tulokset eroavat aikaisemmista arvioista etenkin injektointiin, ruiskubetonointiin ja lujituspultteihin liittyvien materiaalien osalta. Niissä tapauksissa, joissa bentoniitin ja murskeen seosta on oletettu käytettävän tunnelien täytössä, tiloihin jäävistä vieraista aineista kipsi ja sementti ovat suurimmat yksittäiset aineet. Niiden jälkeen suurimmat määrät ovat karbonaateilla ja orgaanisilla aineilla. Jos tunneleiden täyttöön käytetään Friedland-savea, suurin materiaalimäärä on kipsillä ja sen jälkeen pyriitillä, orgaanisilla aineilla ja sementillä. Täyttövaihtoehdon valinta vaikuttaa merkittävästi useiden tärkeiden aineiden määriin ja suhteellisiin osuuksiin, kun taas eri injektointi- ja ruiskubetonointivaihtoehtojen erot ovat vähäisiä aineiden kokonaismäärien kannalta.

Avainsanat: Vieraat aineet, rakennusmateriaalit, Olkiluoto, ydinjäte, loppusijoitus, loppusijoitustilat, KBS-3V

TABLE OF CONTENTS

1 INTRODUCTION

The quantities of foreign materials (i.e. engineering and stray materials) that remain in the repository to be constructed at Olkiluoto, Finland, were initially estimated by Hjerpe (2004). The foreign materials discussed in this report refer to all materials introduced (either intentionally or unintentionally) into the repository except for the nuclear waste, the materials that belong to the multi-barrier system (engineered barriers and the backfilling material), the rock material and the groundwater. In addition to foreign materials, Hjerpe (2004) also estimated the quantities of the bentonite used in the deposition holes and the tunnel backfill material. Although these are – by definition – not foreign materials, they may contain foreign materials as impurities.

The purpose of this report is to update the work of Hjerpe (2004) based on any new information on the type and quantities of materials that remain in the repository after its backfilling. The repository is assumed to be constructed according to the KBS-3V disposal concept. The main emphasis is on identifying issues that may result in significant changes in the type or quantity of the foreign materials that are expected to remain in the repository. The following changes were identified and considered in this work:

- the changes made to the design of the repository layout (mainly due to a new geological site model)
- the changed plans for grouting and rock support
- the information on the type and quantities of materials that have been introduced into the ONKALO by September 2006
- new canister type and deposition hole dimensions for OL3 waste.

These sources of information indicated a need to change several assumptions used in the estimation of remaining quantities of foreign materials. In contrast to the assumptions used by Hjerpe (2004), it was assumed here that

- the repository will be constructed in one layer only (at the depth of 420 m)
- several alternative grouting plans will have to be considered, resulting in several alternative quantities of materials related to grouting
- regarding the shotcrete used in the repository, the possibility to use low-pH cement needs also to be considered.

The removal efficiencies will be assumed to be the same as those estimated by Hjerpe (2004), unless otherwise stated in the text.

The changes in the assumptions related to individual materials will be discussed below in Section 4.

2 LIMITATIONS

As stated in Chapter 1, the following materials are not considered to be foreign materials and their quantities will not be estimated in this report:

- nuclear waste
- the engineered barrier system, including the canister, the bentonite buffer and the tunnel backfill materials (the buffer and the backfill are, however, considered to include foreign materials as impurities)
- the natural barrier, i.e. the bedrock (including groundwater and its constituents).

It will also be assumed that any materials introduced into the repository related to the following activities will be totally removed and will not be discussed here in more detail:

- investigation and measurement activities
- installed electrical systems, as well as systems related to ventilation, water supply, drainage (except for the drainage pipes in the shotcrete), heating, monitoring and transport (except for the floors).

There are also materials that will not be totally removed from the repository but will not be considered here due to a lack of suitable information or because it is assumed that the quantities of these would be negligible as compared with the other material sources. These include

- microbes and decomposition products of microbes (see Hjerpe 2004)
- secondary materials created in processes acting on the introduced material, such as corrosion products and decomposition of additives of cement, e.g., superplasticisers
- materials produced by events such as major accidents, fires, natural disasters or sabotage
- materials used in the plugging of investigation boreholes
- chemicals used in different investigations and tests.

The types and quantities of some of these materials may need to be estimated later based on more extensive studies than what was possible here. It should be noted that although the quantities of microbes introduced into the repository are not estimated here, the quantities of several nutrients that affect the abundance of microbes are included in the estimations. Regarding the plugging of boreholes, it is, for example, known that in the plugging experiments in boreholes OL-KR24 and OL-KR38, some 3,000 kg of foreign materials (mainly cement) were used, but these are expected to be totally removed during the raising of the two shafts at the locations of the boreholes (Vuorio 2006). The cement used in the plugging of the shafts will also not be considered here, because they will be located near the ground surface and because the cement quantities in question are minor in comparison to the quantities used in the concrete plugs at the beginning of all deposition tunnels.

3 ASSUMPTIONS RELATED TO THE DIMENSIONS OF THE REPOSITORY

Because the layout of the repository has changed since 2003, the following values for the dimensions of the repository were updated based on Kirkkomäki (2006) and the updated values were used in this work:

- ONKALO: The total volume of the ONKALO is 365,166 m^3 in the new layout
- Repository: The total volume of the repository (incl. ONKALO) is 1,364,818 m^3 in the new layout, assuming that the number of bored deposition holes is 10 % larger than the number of canisters (the volume of the actual repository is, therefore, 999,652 m^3)
- Deposition hole dimensions and number: The only changed dimension is the height of the deposition hole for OL3 canisters, which is 8.2 m. The radius of all holes was assumed to be 0.875 m. The number of canisters has changed and it was 1,210 for OL1-2 canisters, 698 for OL3 canisters and 932 for LO canisters (the number of bored deposition holes is assumed to be 10 % larger). The total volume of bored deposition holes is 58,272 m^3.
- Deposition tunnel dimensions: The dimensions of the deposition tunnels to be used for LO canisters have changed; their height has decreased from 4.4 m to 4.0 m. The (curved) part of the deposition tunnel profile that belongs to the vault was assumed to be 5.5 m long for both type of deposition tunnels. Other dimensions have not changed.
- Deposition tunnel lengths and number: Values based on the new layout adaption were used. The total length of deposition tunnels is 41,166 m, which is distributed between tunnels with OL canisters and tunnels with LO canisters so that the total length of the OL tunnels is 32,560 m and the total length of the LO tunnels is 8,606 m. These values include an additional 20 % caused by the expected proportion of rock mass unsuitable for disposal (including both deposition holes that have been bored and then rejected, and tunnel sections that will be rejected before even boring the holes). The number of deposition tunnels is 137. The total volume of deposition tunnels is 546,008 m^3 if the widenings at the central tunnel junctions are not taken into account, and 578,574 m^3 if they are taken into account. The latter value will be used in this report.
- Central tunnel lengths: According to the new layout, the total length of all central tunnels (excluding ONKALO) is 6,854 m. It should be noted that the new layout is based on the so-called concurrent central tunnel concept (see, e.g., Malmlund et al. 2004), and the above-mentioned total length includes both tubes of the double tunnel, as well as the connecting tunnels between them. It might be more appropriate to consider only half of this total length when the quantities of certain traffic etc. are considered, but for the reason of conservativeness, this total length is always used in this report. The total volume of central tunnels (excluding ONKALO) is 264,364 m^3.

Other assumptions were identical to those used by Hjerpe (2004). In general, values were not updated if it was apparent that they have changed by less than 10 % and the updating would have required laborious calculations. With respect to the other uncertainties in this work, a difference of less than 10 % was considered to be insignificant. For example, the dimensions of the different parts of the ONKALO were not updated, because the total volume of ONKALO has changed by less than 8 % since the calculations by Hjerpe (2004). As the deposition tunnels and central tunnels have a significantly greater volume than the ONKALO, it was considered sufficient to focus on updating any values related to their dimensions. However, when the total volume of the ONKALO was required, the volume based on the new layout (365,166 m^3) was used.

All volumes presented here are theoretical volumes, whereas the actual volumes are probably slightly (some 10 %) larger due to over break. The theoretical volumes will be used, because the difference is minor with respect to other uncertainties involved in the work, and because the data on the excavations carried out so far are also based on theoretical volumes. However, since the excavated volume is very significant for the estimation of the quantities of the tunnel backfill materials, the volumes (except for those of the deposition holes) will be multiplied by 1.1 when the backfill materials are considered.

4 ASSUMPTIONS RELATED TO INDIVIDUAL MATERIALS

4.1 Explosives

The type and required quantities of explosives were calculated by Hjerpe (2004) by scaling the results from a Swedish work (Jones et al. 1999) to the dimensions of the repository planned at Olkiluoto. In this work the calculations are based on the explosives used in the ONKALO so far (by 1 Sep 2006) and those planned to be used in the ONKALO in the future. No detailed plans on the type of explosives to be used in the actual repository were available.

Nitrogen oxides included in the explosion gases were considered here. Other types of emissions were not considered, i.e. any solid or liquid emissions are assumed to be totally removed with the muck and the drainage water (foreign materials in the crushed rock used for backfilling will be discussed separately below). The total amount of nitrogen oxides produced so far by the use of explosives is some 660 kg (0.003 kg per kg of explosives). In the future, it is planned to use mainly emulsion explosives, and it has been calculated here that this will result in a decrease in the amount of nitrogen oxides produced per kg of explosives, so that for the whole ONKALO and the repository, some 0.0006 kg NO_x per kg of explosives is assumed to be produced on average.

Another potentially harmful material included in the explosion gases is the SO_2 gas, but it could not be considered here, as the manufacturers have not reported any SO_2 emissions for any of the explosives considered in this work.

It will be assumed that 3 kg of explosives will be used for each excavated cubic metre, based on the used quantities in the access tunnel by 1st Sep 2006 and a slightly conservative estimate of future consumption. This consumption is assumed for all other openings except for the deposition holes, which will be bored.

4.2 Blasting caps and cords

Based on the experience from the access tunnel to the ONKALO, some 0.6 blasting caps on average will be used per one excavated cubic metre. The amount of aluminium in one cap has not been specified by the manufacturer, so the assumption used by Hjerpe (2004), i.e. that each cap includes 3 g of aluminium, will be used here.

So far, some 0.4 m of cord per one excavated cubic metre has been used in the access tunnel. All cords used so far have a plastic cover, but the amount of plastic has not been specified by the manufacturers, so the assumption used by Hjerpe (2004), i.e. 5.5 g of plastic per m cord, will be used here as well.

According to the manufacturer, the combustion of the cords produces “small amounts” of NO_x gases. The amounts were not specified and, therefore, could not be estimated quantitatively. Instead, it is assumed here that these amounts are minor with respect to the amounts of NO_x produced by the explosives.

4.3 Support bolts

The total number of bolts used for rock support in the access tunnel by 1 Sep 2006 is 1,315. This corresponds to 0.02 support bolts per one excavated cubic metre and approximately 1 bolt per 1 m of tunnel. In the calculations by Hjerpe (2004), the total support bolt density in the access tunnel was approximately 3 bolts per 1 m of tunnel. Accordingly, the used quantities of bolts are clearly (some 70 %) smaller than estimated by Hjerpe (2004). In this work it is assumed that in all other parts of the repository except for the remaining part of the access tunnel, the number of support bolts used per excavated cubic metre is 70 % smaller than that estimated by Hjerpe (2004). In the remaining part of the access tunnel (from tunnel chainage 1360 m onwards) it has been estimated that a maximum of 10 bolts will be needed on average per 100 m of tunnel, and here it will be, accordingly, assumed that 0.1 bolts per 1 m tunnel is used in the access tunnel in the future. This is an estimate of the *average* bolt density and in reality the bolts will be unevenly distributed, e.g., at fracture zone intersections the bolt density may be locally high. The bolt lengths assumed for the access tunnel are based on the average length used so far, and for all other parts of the repository, the same bolt lengths as suggested by Hjerpe (2004) are assumed.

The composition of the bolts used in the ONKALO have not been specified by the manufacturers and the assumptions by Hjerpe (2004) regarding the amount of steel and zinc in the bolts will be used here. It will also be assumed that cement will be used to grout the bolts in all other parts of the repository except for the deposition tunnels. Similarly to Hjerpe (2004), no bolts will be assumed for the deposition holes.

In the grouting of the support and anchor bolts, 5 kg of cement on average has been used per bolt by the end of 2005 (Vuorio 2006). This corresponds roughly to 1.5 kg of cement per one metre of bolt. This value will be used in the estimations of future use of cement for the grouting of bolts.

4.4 Anchor bolts

Anchor bolts are used for different kind of installations. As the installations usually lag behind the construction of tunnels and shafts, the experience on using anchor bolts in the ONKALO is probably not sufficient to cause a modification to the estimations by Hjerpe (2004). It should also be noted that the quantities of steel and cement in the anchor bolts are minor with respect to other sources of steel and cement. The same assumptions as used by Hjerpe (2004) are, accordingly, used here and the quantities will only be updated based on the new length of the deposition and central tunnels.

4.5 Shotcrete

By 1st Sep 2006, the total quantity of cement in the shotcrete used in the ONKALO was 386,430 kg or 6.1 kg per excavated m^3. This is very close to the average value (6.23 kg/m^3) estimated by Hjerpe (2004). Accordingly, it will be assumed here that the need for shotcreting in the ONKALO will be the same as that estimated by Hjerpe (2004). The cement will be assumed to be ordinary cement. With reference to the actual repository, two different alternatives will be considered:

A. Shotcrete with ordinary cement will be used in other parts than the deposition tunnels (in the deposition tunnels, no shotcrete will be used but steel mesh may be used).
B. Shotcrere with low-pH cement will be used in other parts than the deposition tunnels (in the deposition tunnels, no shotcrete will be used but steel mesh may be used).

In those parts where shotcrete can be used, it is assumed that the consumption of shotcrete is the same as that estimated by Hjerpe (in his support alternative A), but the quantities will be updated based on the new total length of the central tunnels (Chapter 3) and the following updated assumptions: Based on the use of aluminium-bearing additives in the shotcreting of the ONKALO so far, it is assumed that 0.003 kg of aluminium is used per kg of cement in the shotcrete. Similarly, it is assumed that 0.007 kg of organic materials, 0.04 kg of amorphous silica (SiO_2), 0.0007 kg of iron (Fe(III)), and 0.00005 kg of chloride (Cl^-) is used per kg of cement in the shotcrete. The listed values refer to the mass of the dry materials. The cement content in the shotcrete is assumed to be 430 kg/m^3, based on the reported value of one cement type that has been used in the ONKALO.

In alternative B, a low-pH shotcrete "recipe" was used where normal shotcrete (similar to that in alternative A) was modified by replacing 40 % of the dry materials (cement and additives) with silica (SiO_2). This is only an approximation of the main components of a low-pH shotcrete and it is used here to estimate roughly the quantities of materials related to low-pH shotcreting. Accordingly, the low-pH shotcrete is assumed to include 0.77 kg of silica (SiO_2) per kg of cement. The proportions of aluminium, organic materials, iron (Fe(III)) and chloride (Cl^-) to cement are identical to those in alternative A, although their concentration in the total mass has naturally decreased due to the addition of new silica.

It is assumed here that the shotcrete will be removed before backfilling the repository. A removal efficiency of 95 % is used here for both the ONKALO and the actual repository (in both alternatives A and B).

Fibre-reinforced shotcrete has been used only once in the ONKALO, the total quantity of used fibres being 90 kg. It is not known whether fibres will be used later. Due to the very small quantity used so far, fibres will not be considered in this work. If fibres will be used, the quantities will probably be smaller than those estimated by Hjerpe (2004) for the 1-level layout.

4.6 Steel mesh

It is assumed that steel mesh will be used to support the deposition tunnels, when necessary. As it is possible to remove all steel mesh (and most of the related bolts) before backfilling the tunnels, the quantities of steel mesh introduced into the repository were estimated only roughly. It was assumed that steel mesh will be used in 50 % of the deposition tunnels but not in any other part of the repository. When calculating the required quantity of steel mesh, the dimensions of the deposition tunnels were assumed as presented in Chapter 3. Other assumptions, for example regarding the use and removal efficiency of anchor bolts, were based directly on Hjerpe (2004).

4.7 Grouting materials

The estimated type and quantities of grouting materials will be different from those of Hjerpe (2004), who assumed that only ordinary cementitious grouts would be used.

By 1st Sep 2006, the total amount of cement used in the grouting of the access tunnel is 6.2 kg per excavated m^3, which is 60 % of what was assumed by Hjerpe (2004). It should also be noted that in the future, even less cement will probably be required for grouting, as the excavations proceed deeper (Vuorio 2006). The type and quantity of grouting materials needed in the future is estimated here separately based on the experience gained so far and based on the plans to use other grouts than ordinary cement, although this has not been decided yet. Regarding the type of grouting materials to be used in the future (after 1st Sep 2006), it will be assumed that until the tunnel chainage 1500 m, ordinary cement will be used. From 1500 m onwards, the following three grouting alternatives will be assumed in this work:

1) ordinary cement, both in the remaining parts of the ONKALO and the actual repository
2) 50 % low-pH cement and 50 % ordinary cement in the remaining parts of the ONKALO; 100 % low-pH cement in the actual repository
3) 50 % colloidal silica and 50 % low-pH cement in the remaining parts of the ONKALO; 100 % colloidal silica in the actual repository.

The assumptions on the quantity of grouts to be used are listed in Table 1. It is expected that the required quantity of grouts is significantly smaller in the deeper parts of the bedrock than in the excavations so far (tunnel chainages 0−1360 m). Based on the average grout composition so far, one cubic metre of grouting mass was considered to contain 776 kg of cement. As this ratio has been decreasing from 2004 to 2006, the use of this average was considered to be slightly conservative. The quantities of organic additives used in ordinary cement grouting is assumed to be proportional to the used quantity of cement and based on the experience so far, it is assumed that 0.01 kg of organic material is used per 1 kg of grouting cement. All quantities discussed here refer to the mass of the dry materials. The composition of the different additives is assumed here as reported by the manufacturers. If a value range was given, the average was used. If the content of some material was reported to be less than something (e.g., < 1 %) and no lower limit of the range was given, the content was assumed to be equal to the upper limit (e.g., 1 %).

Similarly, it is assumed that 0.1 kg of silica (SiO_2) and 0.001 kg of chloride (Cl^-) is used per 1 kg of grouting cement (dry materials), based on used quantities in the access tunnel. Superplasticiser Mighty 150 includes natrium salts, but the exact composition of the superplasticiser has not been reported by the manufacturer, which is why these salts are not taken into account here. Additive Cementa Set Control II includes calcium nitrate, but this additive will only be used in the ONKALO. When the ordinary cement groutings in the ONKALO were considered, it was assumed that based on the used quantities so far, 0.002 kg of nitrate would be used per 1 kg of grouting cement.

Table 1. *The assumed consumption of grouts to be used after 1 Sep 2006 in the ONKALO and in the repository.*

Tunnel section (chainage) [m]	**Proportion of tunnel to be grouted**	**Grout take per 20 m fan [m^3]**
1360−1500	30 %	3
1500−3000	20 %	6
3000−4000	10 %	2
Other parts of ONKALO	10 %	2
Actual repository	10 %	1−2*

* The grout take depends on the dimensions of the opening; tunnels with a smaller radius have a smaller grout take. Grout takes have been scaled by assuming a 5 m thickness of grouted zone around the opening.

In the calculations it was assumed that after 1 Sep 2006, 40 m^3 of rock would be excavated per 1 m tunnel in the ONKALO (based on a rough estimate of the average cross-sectional area of the ONKALO openings). When calculating the quantities for the actual repository, the average size of the different type of openings was taken into account and the grout takes were scaled from the value of 2 m^3 per fan (based on the cross-sectional area of the ONKALO) to values of some 1−2 m^3 for the different parts of the repository, depending on their radius and the resulting total thickness of the grouted zone, which was assumed to extend 5 m beyond the boundary of the opening. No grouting was assumed for the deposition holes.

In low-pH cement grouting (grouting alternatives 2 and 3), the assumed grout recipe was P308B (see, e.g., Ahokas et al. 2006). The quantity of cement is 335 kg/m^3 in the low-pH grouting mass and the consumption of organic material (included in the Grout Aid and the superplasticiser) is 0.04 kg of organic material per 1 kg of cement. Based on the low-pH cement grout recipe and the contents of the different materials, it is assumed that 0.62 kg of silica (SiO_2) and 0.001 kg of chloride (Cl^-) is used per 1 kg of grouting cement in low-pH cement grouting. These values all refer to dry materials, as mentioned above.

In the grouting alternative 3, the most significant chemical components in colloidal silica are amorphous silicon dioxide (SiO_2), salt (NaCl or $CaCl_2$) that is used as an accelerator and aluminium (Al). The grout recipe assumed here is MEYCO MP320 (Axelsson & Nilsson 2002), which includes 33.3 wt-% of amorphous SiO_2 and 1.7 wt-% of salt (NaCl) (dry materials). Unlike some silica grouts, the considered grout does not include any aluminium. If some other type of silica grout is used in the future, the quantities of aluminium may need to be estimated as well. No other additives are assumed to be used. It should be noted that NaCl is assumed as the salt here and the resulting quantities are not directly applicable to $CaCl_2$. When using NaCl the chloride concentration is some four times higher than if calcium chloride is used (Bodén & Sievänen 2005).

Based on the density of the grout (1.25 kg/l) as reported by the manufacturer, one cubic metre of silica grout includes 416 kg of amorphous SiO_2. It was also calculated that the grout includes approximately 0.05 kg of NaCl per kg of amorphous SiO_2. The quantity of chloride would, accordingly, be 0.03 kg per kg of SiO_2. All values refer to dry materials.

It is estimated that some 20−25 % of the pre-grouting materials are removed during the excavation process (cf. Ahokas et al. 2006). Accordingly, the total removal efficiency assumed here will be 20 % instead of 0 % assumed by Hjerpe (2004).

4.8 Floors and miscellaneous constructions

According to the new repository design report (Saanio et al. 2006), the design of the structures used in the repository have not changed since 2003, and the assumptions used by Hjerpe (2004) can, therefore, be considered still valid. As structures such as floors are designed so that they are easy to remove (Saanio et al. 2006), the removal efficiencies of 98...99 % assumed by Hjerpe (2004) are also probably valid. The remaining quantities are so low with respect to other sources of cement, steel, aluminum and zinc that it is not considered necessary to update the quantities based on the new layout of the repository and the quantities calculated by Hjerpe (2004) for the 1-level layout will be used here directly.

4.9 Drainage pipes

The drainage pipes discussed here refer to the pipes between the rock surface and the shotcrete, and Hjerpe (2004) conservatively assumed that they would not be removed. Here it is assumed that they will be removed, as it is also planned to remove the shotcrete. A removal efficiency of 95 % is assumed (similar to the shotcrete). All drainage pipes in the deposition tunnels were excluded, because there is no shotcrete in the deposition tunnels (Section 4.5). Some minor updating based on the new dimensions of the repository was also made. Otherwise the same assumptions were used as by Hjerpe (2004).

4.10 Emissions from vehicles and maintenance work

Hjerpe (2004) estimated the quantities of several different foreign materials related to underground traffic and construction and maintenance work, using the following categories based on origin:

1) wear to tyres
2) exhaust fumes from diesel engines
3) diesel oil
4) battery acid
5) hydraulic and lubricating oils
6) degreasing agents and detergents
7) hard metals and metal fragments.

These include mainly organic materials, as well as metals and rubber (see Hjerpe 2004). Since the quantities of these introduced into the ONKALO so far have not been monitored or estimated, the same assumptions as those used by Hjerpe (2004) will be used here and the quantities will only be updated based on new estimates of the dimensions of the different parts of the repository.

4.11 Paints

By the end of 2005, 332 litres of AT-marking paint has been used in the ONKALO (Vuorio 2006), corresponding to some 300 kg of paint. According to the manufacturer, hydrocarbons make up some 80 % of the paint. The consumption of hydrocarbons in marking paints has been, therefore, some 0.0054 kg per one excavated cubic metre. It was assumed here that the consumption will be similar in the future, except for the deposition holes, where a consumption of 0 kg per one excavated cubic metre was assumed. A removal efficiency of 0 % was assumed.

4.12 Urine and other human waste

The same assumptions as those used by Hjerpe (2004) will be used here, updated based on the new dimensions (volume) of the different parts of the repository.

4.13 Impurities in ventilation air

Organic materials introduced by the ventilation air have not been monitored in the ONKALO. The tunnel walls are washed systematically, which should prevent some build up of organics (Vuorio 2006). The same assumptions as those used by Hjerpe (2004) will be used here. Also, the same average open times for the different parts of the repository will be used, since their possible changes – due to minor changes in the construction schedule – are thought to be insignificant with respect to other uncertainties involved in the evaluation of the quantities of organic materials.

The introduced and remaining quantities of organic materials in the ventilation air estimated by Hjerpe (2004) were almost identical in the 1-level and 2-level layouts, implying that the quantities are not sensitive to changes in the layout. The quantities will, therefore, not be updated here based on the new layout and, instead, the quantity calculated by Hjerpe (2004) for the 1-level layout will be used here directly.

4.14 Concrete plugs

According to the new design of the repository (Saanio et al. 2006), the concrete plugs that are used for the sealing of the deposition tunnels are assumed to be of similar type as assumed by Hjerpe (2004). The quantities related to these concrete plugs are, therefore, updated here only based on the total number of deposition tunnels in the new repository layout. Other assumptions are identical to those used by Hjerpe (2004).

4.15 Impurities in the deposition hole buffer material

Hjerpe (2004) estimated the total quantities of buffer and backfill materials used in the repository, but not the individual quantities of the actual foreign materials related to them, i.e. the impurities of the buffer and backfill materials. These will be estimated here. The reference material assumed to be used as the bentonite buffer in the deposition holes is MX-80 type bentonite. The studied impurities and their content (weight-%) according to SKB (2006a) are organic carbon (0.2 %), pyrite (0.07 %), gypsum (0.7 %) and carbonates, i.e. calcite and siderite (0−1 %; 0.5 % is assumed here). Other bentonite impurities will not be considered here.

The assumptions related to the total quantity of the bentonite buffer and its dry density (1,700 kg/m^3) will be used according to Hjerpe (2004), updated with the number and dimensions of the deposition holes based on the new layout. The volume of the bentonite buffer is assumed to equal the volume of the deposition hole minus the combined volume of the canister, the air gap, the water gap and the bottom plate (Chapter 4.17). This volume is assumed when deposition holes that are used for disposal are considered. Unused holes (their number is some 10 % of the used holes) are assumed to be completely filled with bentonite. The removal efficiency for the impurities in the buffer is 0 %.

4.16 Impurities in the tunnel backfill materials

The quantities of the impurities in the tunnel backfill materials will be studied using two alternative backfill concepts:

a) 30 wt-% bentonite (MX-80) and 70 wt-% crushed rock
b) 100 % Friedland clay.

These alternatives are assumed to be used in all repository openings (except for the deposition holes), which may be a conservative assumption. The backfilling is assumed to be done with pre-compacted blocks. The assumed *average* dry density for the backfill with 30/70 mixture is 2,150 kg/m^3 and the corresponding value for the Friedland clay alternative is 1,950 kg/m^3. In both alternatives it is, however, assumed that 7 % of the volume is backfilled with a mixture of 15 wt-% bentonite (MX-80) and 85 wt-% crushed rock, which will be used in the backfilling of the floors (Keto & Rönnqvist 2006). The assumed dry density of the 15/85 mixture is 1,950 kg/m^3. The volumes of all openings to be backfilled are assumed to be 1.1 times the theoretical volumes that are based on the new layout.

It is not known, whether the crushed rock to be used as tunnel backfill is originated from the construction of the repository or from some other source. It is simply assumed here that it does not include any significant amounts of impurities that should be considered here, implying that the rock material is either cleaned and sieved effectively before its use as the tunnel backfill material or that the quantities are small in the first place in comparison to other sources of foreign materials in the repository. If the bentonite/crushed rock alternative is chosen instead of some clay-based alternative (such as the one with Friedland clay), the occurrence of different kind of impurities in the crushed rock should be investigated and aspects such as the average time of storage (accumulation of organic and air-borne impurities) and the cleaning process should be paid attention to.

The impurities of the MX-80 bentonite will be considered as presented in Chapter 4.15. The impurities of the Friedland clay that are considered and their content (weight-%) according to SKB (2006a) are organic carbon (0.6 %), pyrite (0.62 %) and gypsum (0.8 %). The removal efficiency for the impurities in the backfill is 0 %.

4.17 Bottom plates in the deposition holes

According to current plans (Saanio et al. 2006), a thin bottom plate will be installed at the bottom of each deposition hole that is used for disposal. The plate is planned to be made of low-pH concrete. It is assumed here that the dimensions and composition of the plate are as presented by SKB (2006b) with the exception that the superplasticiser SP 40 is replaced by Mighty 150. No separate copper plate is taken into account here; if copper is used, it is similar to that of the canister material (SKB 2006b). The volume of the concrete bottom plate is assumed to be 0.2 m^3 (SKB 2006b) and the total number of plates is 2840 (the number of canisters). Each plate includes 50 kg of cement, 34 kg of silica (SiO_2) and 1.3 kg of superplasticiser, which is assumed to include 30 % of (dry) organic material and 0.1 % of chloride.

5 RESULTS FOR THE WHOLE REPOSITORY

5.1 Results with all design alternatives

The estimated quantities of foreign materials that remain in the repository after closure are presented in Table 2. In addition to the *remaining* quantities, the table also shows the estimated total quantities of materials *introduced* into the repository, presented separately for their most relevant chemical components. Similarly to the approach used by Hjerpe (2004), the following components of the materials are not considered here:

- water (H_2O)
- oxygen (O_2)
- nitrogen gas (N_2)
- carbon dioxide (CO_2)
- carbon monoxide (CO)
- rock minerals
- some other substances which are considered to be of minor relevance for the long-term safety of the repository or which could not be calculated due to a lack of data.

As water is not taken into account, all values presented in the following tables refer to the quantities of the dry materials.

More detailed results for the main categories of construction materials (#1 to #7 in Table 2) are presented in Appendix 1, where the quantities are generally shown per excavated cubic metre, particularly when openings of different shape and size are considered jointly. Even though this approach has been used for almost all materials for consistency, it should be noted that in several materials the quantities were assumed to be proportional rather to the length of tunnels that to their volume (see Chapter 4 above and Hjerpe (2004) for detailed assumptions). Also the quantities per excavated cubic metre may be slightly different for different parts of the repository and not all of them have been separated in Appendix 1, which shows only the average quantities. Appendix 1 also includes the total quantities of the construction materials used, in addition to their components listed in Table 2. In this way the monitoring results obtained in the repository can be directly compared with the results of this work, even if the composition of the construction materials is not known.

Table 2. *The estimated quantities of foreign materials in the repository (including ONKALO), listed by origin. Table continues on the next page.*

Origin of the foreign materials	**Chemical components considered**	**Total introduced quantity [kg]**	**Removal efficiency [%]**	**Remaining quantity [kg]**
1 Explosives	Nitrogen oxides (NO_x)	2,400	99 %	20
2 Blasting caps and cords	Aluminium	2,500	90 %	300
	Plastic	2,600	90 %	300
3 Support bolts	Steel	450,000	0 %	450,000
	Zinc	8,600	0 %	8,600
	Cement	61,000	0 %	61,000
4 Anchor bolts	Steel	140,000	40 %	85,000
	Cement	18,000	0 %	18,000
5 Shotcrete				
5A Shotcrete alternative A	Cement	4,800,000	95 %	240,000
	Aluminium	14,000	95 %	700
	Organic materials	34,000	95 %	1,700
	Silica (SiO_2)	190,000	95 %	10,000
	Iron (Fe(III))	3,400	95 %	170
	Chloride	200	95 %	10
5B Shotcrete alternative B	Cement	3,900,000	95 %	190,000
	Aluminium	12,000	95 %	600
	Organic materials	27,000	95 %	1,400
	Silica (SiO_2)	1,200,000	95 %	61,000
	Iron (Fe(III))	2,700	95 %	140
	Chloride	190	95 %	10
6 Steel mesh	Steel	200,000	99.8 %	400
7 Grouting materials				
7.1 Grouting alternative 1	Cement	810,000	20 %	650,000
	Organic materials	8,100	20 %	6,500
	Silica (SiO_2)	81,000	20 %	65,000
	Chloride	800	20 %	600
	Nitrate	1,000	20 %	800
7.2 Grouting alternative 2	Cement	610,000	20 %	490,000
	Organic materials	11,000	20 %	8,600
	Silica (SiO_2)	140,000	20 %	110,000
	Chloride	600	20 %	500
	Nitrate	900	20 %	700
7.3 Grouting alternative 3	Cement	420,000	20 %	340,000
	Organic materials	5,000	20 %	4,000
	Silica (SiO_2)	250,000	20 %	200,000
	Chloride	6,200	20 %	4,000
	Nitrate	800	20 %	600
8 Floors	Cement	6,900,000	98 %	140,000
	Steel	540,000	99 %	5,400

9 Miscellaneous constructions	Cement	4,400,000	98 %	88,000
	Steel	710,000	98 %	14,000
	Aluminum	100,000	98 %	2,000
	Zinc	4,400	98 %	90
10 Drainage pipes	Steel	4,700	95 %	200
	Polyethylene (PE)	2,800	95 %	140
	Polystyrene (EPS)	1,100	95 %	60
11 Wear to tyres	Rubber	150,000	90 %	15,000
12 Exhaust fumes from diesel engines	Nitrogen oxide	1,300,000	99 %	13,000
	Soot and ash	77,000	93 %	5,400
13 Diesel oil	Hydrocarbons	210,000	95 %	10,000
14 Battery acid	Sulphuric acid	3,000	90 %	300
15 Hydraulic and lubricating oils	Hydrocarbons	82,000	90 %	8,200
16 Degreasing agents and detergents	Hydrocarbons + other organic materials	100,000	95 %	5,200
17 Hard metals and metal fragments	Steel	330,000	98 %	6,500
	Tungsten and cobalt	3,800	99 %	40
18 Paints	Hydrocarbons	7,100	0 %	7,100
19 Urine	Carbamide	1,100,000	95 %	55,000
20 Miscellaneous human waste	Organic materials	690,000	98 %	14,000
21 Impurities in ventilation air	Organic materials	10,000,000	99 %	100,000
22 Concrete plugs	Cement	4,700,000	0 %	4,700,000
	Steel	950,000	0 %	950,000
	Zinc	130,000	0 %	130,000
	Organic materials	16,000	0 %	16,000
	Copper	12,000	0 %	12,000
23 Impurities in buffer material	Organic carbon	140,000	0 %	140,000
	Pyrite	49,000	0 %	49,000
	Gypsum	490,000	0 %	490,000
	Carbonates (calcite + siderite)	350,000	0 %	350,000
24 *Impurities in backfill material*				
24a Backfill alternative a (bentonite/crushed rock)	Organic carbon	1,700,000	0 %	1,700,000
	Pyrite	600,000	0 %	600,000
	Gypsum	6,000,000	0 %	6,000,000
	Carbonates (calcite + siderite)	4,300,000	0 %	4,300,000
24b Backfill alternative b (Friedland clay)	Organic carbon	15,000,000	0 %	15,000,000
	Pyrite	15,000,000	0 %	15,000,000
	Gypsum	20,000,000	0 %	20,000,000
	Carbonates (calcite + siderite)	140,000	0 %	140,000
25 Bottom plates in deposition holes	Cement	140,000	0 %	140,000
	Silica (SiO_2)	97,000	0 %	97,000
	Organic materials	1,100	0 %	1,100
	Chloride	4	0 %	4

5.2 Results for the alternatives with ordinary cement only

The results are presented in Tables 3 and 4 for two different combinations of tunnel support, grouting and backfill alternatives (design alternatives A1a and A1b).[1] Ordinary cement is assumed to be exclusively used in both shotcreting (support alternative A) and grouting (grouting alternative 1). In Table 3, the backfill plan is based on bentonite/crushed rock mixture (backfill alternative a) and in Table 4 on Friedland clay (backfill alternative b).

In these Tables the results are categorised by the studied chemical components. It should be mentioned that depending on the availability of data, some components have been considered in more detail than others and the classes are, therefore, not necessarily mutually exclusive. For example, the quantity of iron (Fe(III)) has been calculated separately for shotcrete (some shotcrete additives contain Fe_2O_3) but iron is also present in other categories, most notably in steel (metallic iron) but also as Fe(II) in pyrite and siderite that occur as impurities in bentonite. Iron is also a constituent of cement, but the chemical constituents of cement have not been separated in the Table.

[1] Design alternative "A1a" means that the selected support alternate is A, the grouting alternative is 1 and the backfill alternative is a. The support (shotcrete) alternatives are explained in Section 4.5, the grouting alternatives in Section 4.7 and the backfill alternatives in Section 4.16.

Table 3. *The estimated total quantities of the chemical components included in the foreign materials in the repository (including ONKALO), design alternative A1a (= support alternative A, grouting alternative 1, backfill alternative a), sorted by the remaining quantity.*

Chemical components	Origin (reference to Table 2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	23, 24a	6,500,000	0 %	6,500,000
Cement	3, 4, 5A, 7.1, 8, 9, 22, 25	22,000,000	72 %	6,100,000
Carbonates (calcite + siderite)	23, 24a	4,600,000	0 %	4,600,000
Organic materials (incl. organic carbon and hydrocarbons)	5A, 7.1, 13, 15, 16, 18, 20, 21, 22, 23, 24a, 25	13,000,000	85 %	2,000,000
Steel	3, 4, 6, 8, 9, 10, 17, 22	3,300,000	54 %	1,500,000
Pyrite	23, 24a	650,000	0 %	650,000
Silica (SiO_2)	5A, 7.1, 25	370,000	54 %	170,000
Zinc	3, 9, 22	150,000	3 %	140,000
Carbamide	19	1,100,000	95 %	55,000
Rubber	11	150,000	90 %	15,000
Nitrogen oxides (NO_x)	1, 12	1,300,000	99 %	13,000
Copper	22	12,000	0 %	12,000
Soot and ash	12	77,000	93 %	5,400
Aluminium	2, 5A, 9	120,000	97 %	3,000
Nitrate	7.1	1,000	20 %	800
Chloride	5A, 7.1, 25	1,100	37 %	700
Sulphuric acid	14	3,000	90 %	300
Plastic	2	2,600	90 %	300
Iron (Fe(III))	5A	3,400	95 %	170
Polyethylene (PE)	10	2,800	95 %	140
Polystyrene (EPS)	10	1,100	95 %	60
Tungsten and cobalt	17	3,800	99 %	40

__Table 4.__ The estimated total quantities of the chemical components included in the foreign materials in the repository (including ONKALO), design alternative A1b (= support alternative A, grouting alternative 1, backfill alternative b).

Chemical components	Origin (reference to Table 2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	23, 24b	21,000,000	0 %	21,000,000
Cement	3, 4, 5A, 7.1, 8, 9, 22, 25	22,000,000	72 %	6,100,000
Carbonates (calcite + siderite)	23, 24b	490,000	0 %	490,000
Organic materials (incl. organic carbon and hydrocarbons)	5A, 7.1, 13, 15, 16, 18, 20, 21, 22, 23, 24b, 25	27,000,000	43 %	15,000,000
Steel	3, 4, 6, 8, 9, 10, 17, 22	3,300,000	54 %	1,500,000
Pyrite	23, 24b	16,000,000	0 %	16,000,000
Silica (SiO_2)	5A, 7.1, 25	370,000	54 %	170,000
Zinc	3, 9, 22	150,000	3 %	140,000
Carbamide	19	1,100,000	95 %	55,000
Rubber	11	150,000	90 %	15,000
Nitrogen oxides (NO_x)	1, 12	1,300,000	99 %	13,000
Copper	22	12,000	0 %	12,000
Soot and ash	12	77,000	93 %	5,400
Aluminium	2, 5A, 9	120,000	97 %	3,000
Nitrate	7.1	1,000	20 %	800
Chloride	5A, 7.1, 25	1,100	37 %	700
Sulphuric acid	14	3,000	90 %	300
Plastic	2	2,600	90 %	300
Iron (Fe(III))	5A	3,400	95 %	170
Polyethylene (PE)	10	2,800	95 %	140
Polystyrene (EPS)	10	1,100	95 %	60
Tungsten and cobalt	17	3,800	99 %	40

5.3 Results for the alternatives with low-pH cement and silica grouts

In Tables 5−8, the results are presented for four combinations of tunnel support, grouting and backfill alternatives that include the use of low-pH cement. In all of these tables the shotcrete used in the repository is assumed to be based on low-pH cement (alternative B). Grouting is carried out mainly by low-pH cement grouts (Tables 5 and 6) or by silica grouts (Tables 7 and 8).

Table 5. *The estimated total quantities of the chemical components included in the foreign materials in the repository (including ONKALO), design alternative B2a (= support alternative B, grouting alternative 2, backfill alternative a).*

Chemical components	**Origin (reference to Table 2)**	**Total introduced quantity [kg]**	**Removal efficiency [%]**	**Remaining quantity [kg]**
Gypsum	23, 24a	6,500,000	0 %	6,500,000
Cement	3, 4, 5B, 7.2, 8, 9, 22, 25	21,000,000	72 %	5,900,000
Carbonates (calcite + siderite)	23, 24a	4,600,000	0 %	4,600,000
Organic materials (incl. organic carbon and hydrocarbons)	5B, 7.2, 13, 15, 16, 18, 20, 21, 22, 23, 24a, 25	13,000,000	85 %	2,000,000
Steel	3, 4, 6, 8, 9, 10, 17, 22	3,300,000	54 %	1,500,000
Pyrite	23, 24a	650,000	0 %	650,000
Silica (SiO_2)	5B, 7.2, 25	1,500,000	81 %	270,000
Zinc	3, 9, 22	150,000	3 %	140,000
Carbamide	19	1,100,000	95 %	55,000
Rubber	11	150,000	90 %	15,000
Nitrogen oxides (NO_x)	1, 12	1,300,000	99 %	13,000
Copper	22	12,000	0 %	12,000
Soot and ash	12	77,000	93 %	5,400
Aluminium	2, 5B, 9	110,000	98 %	2,800
Nitrate	7.2	900	20 %	700
Chloride	5B, 7.2, 25	800	38 %	500
Sulphuric acid	14	3,000	90 %	300
Plastic	2	2,600	90 %	300
Iron (Fe(III))	5B	2,700	95 %	140
Polyethylene (PE)	10	2,800	95 %	140
Polystyrene (EPS)	10	1,100	95 %	60
Tungsten and cobalt	17	3,800	99 %	40

By using Table 2, it is possible to calculate corresponding values for other combinations of alternatives. Only six combinations were presented here, but the total number of possible combinations is 12.

Table 6. *The estimated total quantities of the chemical components included in the foreign materials in the repository (including ONKALO), alternative B2b (= support alternative B, grouting alternative 2, backfill alternative b).*

Chemical components	Origin (reference to Table 2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	23, 24b	21,000,000	0 %	21,000,000
Cement	3, 4, 5B, 7.2, 8, 9, 22, 25	21,000,000	72 %	5,900,000
Carbonates (calcite + siderite)	23, 24b	490,000	0 %	490,000
Organic materials (incl. organic carbon and hydrocarbons)	5B, 7.2, 13, 15, 16, 18, 20, 21, 22, 23, 24b, 25	27,000,000	43 %	15,000,000
Steel	3, 4, 6, 8, 9, 10, 17, 22	3,300,000	54 %	1,500,000
Pyrite	23, 24b	16,000,000	0 %	16,000,000
Silica (SiO_2)	5B, 7.2, 25	1,500,000	81 %	270,000
Zinc	3, 9, 22	150,000	3 %	140,000
Carbamide	19	1,100,000	95 %	55,000
Rubber	11	150,000	90 %	15,000
Nitrogen oxides (NO_x)	1, 12	1,300,000	99 %	13,000
Copper	22	12,000	0 %	12,000
Soot and ash	12	77,000	93 %	5,400
Aluminium	2, 5B, 9	110,000	98 %	2,800
Nitrate	7.2	900	20 %	700
Chloride	5B, 7.2, 25	800	38 %	500
Sulphuric acid	14	3,000	90 %	300
Plastic	2	2,600	90 %	300
Iron (Fe(III))	5B	2,700	95 %	140
Polyethylene (PE)	10	2,800	95 %	140
Polystyrene (EPS)	10	1,100	95 %	60
Tungsten and cobalt	17	3,800	99 %	40

Table 7. *The estimated total quantities of the chemical components included in the foreign materials in the repository (including ONKALO), alternative B3a (= support alternative B, grouting alternative 3, backfill alternative a).*

Chemical components	Origin (reference to Table 2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	23, 24a	6,500,000	0 %	6,500,000
Cement	3, 4, 5B, 7.3, 8, 9, 22, 25	21,000,000	72 %	5,700,000
Carbonates (calcite + siderite)	23, 24a	4,600,000	0 %	4,600,000
Organic materials (incl. organic carbon and hydrocarbons)	5B, 7.3, 13, 15, 16, 18, 20, 21, 22, 23, 24a, 25	13,000,000	85 %	2,000,000
Steel	3, 4, 6, 8, 9, 10, 17, 22	3,300,000	54 %	1,500,000
Pyrite	23, 24a	650,000	0 %	650,000
Silica (SiO_2)	5B, 7.3, 25	1,600,000	77 %	360,000
Zinc	3, 9, 22	150,000	3 %	140,000
Carbamide	19	1,100,000	95 %	55,000
Rubber	11	150,000	90 %	15,000
Nitrogen oxides (NO_x)	1, 12	1,300,000	99 %	13,000
Copper	22	12,000	0 %	12,000
Soot and ash	12	77,000	93 %	5,400
Aluminium	2, 5B, 9	110,000	98 %	2,800
Nitrate	7.3	800	20 %	600
Chloride	5B, 7.3, 25	6,400	22 %	5,000
Sulphuric acid	14	3,000	90 %	300
Plastic	2	2,600	90 %	300
Iron (Fe(III))	5B	2,700	95 %	140
Polyethylene (PE)	10	2,800	95 %	140
Polystyrene (EPS)	10	1,100	95 %	60
Tungsten and cobalt	17	3,800	99 %	40

Table 8. *The estimated total quantities of the chemical components included in the foreign materials in the repository (including ONKALO), alternative B3b (= support alternative B, grouting alternative 3, backfill alternative b).*

Chemical components	**Origin (reference to Table 2)**	**Total introduced quantity [kg]**	**Removal efficiency [%]**	**Remaining quantity [kg]**
Gypsum	23, 24b	21,000,000	0 %	21,000,000
Cement	3, 4, 5B, 7.3, 8, 9, 22, 25	21,000,000	72 %	5,700,000
Carbonates (calcite + siderite)	23, 24b	490,000	0 %	490,000
Organic materials (incl. organic carbon and hydrocarbons)	5B, 7.3, 13, 15, 16, 18, 20, 21, 22, 23, 24b, 25	27,000,000	43 %	15,000,000
Steel	3, 4, 6, 8, 9, 10, 17, 22	3,300,000	54 %	1,500,000
Pyrite	23, 24b	16,000,000	0 %	16,000,000
Silica (SiO_2)	5B, 7.3, 25	1,600,000	77 %	360,000
Zinc	3, 9, 22	150,000	3 %	140,000
Carbamide	19	1,100,000	95 %	55,000
Rubber	11	150,000	90 %	15,000
Nitrogen oxides (NO_x)	1, 12	1,300,000	99 %	13,000
Copper	22	12,000	0 %	12,000
Soot and ash	12	77,000	93 %	5,400
Aluminium	2, 5B, 9	110,000	98 %	2,800
Nitrate	7.3	800	20 %	600
Chloride	5B, 7.3, 25	6,400	22 %	5,000
Sulphuric acid	14	3,000	90 %	300
Plastic	2	2,600	90 %	300
Iron (Fe(III))	5B	2,700	95 %	140
Polyethylene (PE)	10	2,800	95 %	140
Polystyrene (EPS)	10	1,100	95 %	60
Tungsten and cobalt	17	3,800	99 %	40

6 RESULTS FOR ONE DEPOSITION TUNNEL AND ONE DEPOSITION LOCATION

Quantities of foreign materials in one deposition tunnel are presented in Table 9 and at one deposition location in Table 10. The assumed design alternative in these tables is B2a, i.e. including low-pH cement in both shotcreting and grouting and a bentonite/crushed rock backfill alternative. The deposition tunnel (Table 9) assumed here is a 300 m long deposition tunnel for OL canisters and the quantities of materials per excavated cubic metre (or per metre of tunnel) are assumed to be average values of all deposition tunnels. It was assumed that the tunnel contains 19 deposition holes with OL1-2 canisters and two unused, bored deposition holes (based on the following assumptions: canister spacing is 11 m, 30 m of tunnel is unusable due to technical factors, 60 m is unusable due to rock mass conditions and the number of unused holes is some 10 % of the number of used holes).

The deposition location assumed in Table 10 includes 11 m of the deposition tunnel described above and a 7.8 m long deposition hole (with an OL1/OL2 canister). The materials related to the concrete plug that will be installed at the beginning of the deposition tunnel are not included here, although they could have a significant effect on the nearest deposition locations in the tunnel.

Even though the design alternative B2a includes the shotcrete alternative B (with low-pH cement), the results in Tables 9 and 10 would not change if the chosen shotcrete alternative was A, as no shotcrete is assumed to be used in the deposition tunnels or deposition holes.

***Table 9.** The estimated total quantities of the foreign materials introduced into one 300 m long deposition tunnel, design alternative B2a (= support alternative B, grouting alternative 2, backfill alternative a).*

Chemical components	Origin (reference to Table 2)	Total introduced quantity [kg]	Removal efficiency [%]	Remaining quantity [kg]
Gypsum	23, 24a	22,000	0 %	22,000
Cement	3, 4, 7.2, 8, 22, 25	57,000	36 %	37,000
Carbonates (calcite + siderite)	23, 24a	16,000	0 %	16,000
Organic materials (incl. organic carbon and hydrocarbons)	7.2, 13, 15, 16, 18, 20, 21, 22, 23, 24a, 25	13,000	49 %	6,600
Steel	3, 4, 6, 8, 17, 22	12,000	22 %	9,500
Pyrite	23, 24a	2,200	0 %	2,200
Silica (SiO_2)	7.2, 25	1,100	8 %	1,000
Zinc	3, 22	1,000	0 %	1,000
Carbamide	19	600	95 %	30
Rubber	11	40	90 %	4
Nitrogen oxides (NO_x)	1, 12	200	99 %	2
Copper	22	90	0 %	90
Soot and ash	12	11	93 %	0.8
Aluminium	2	8	90 %	0.8
Nitrate	-	0	-	0
Chloride	7.2, 25	0.7	19 %	0.6
Sulphuric acid	14	0.8	90 %	0.08
Plastic	2	9	90 %	0.9
Iron (Fe(III))	-	0	-	0
Polyethylene (PE)	-	0	-	0
Polystyrene (EPS)	-	0	-	0
Tungsten and cobalt	17	13	99 %	0.1

Table 10. *The estimated total quantities of the foreign materials introduced into one deposition location (deposition hole + 11 m of tunnel), design alternative B2a (= support alternative B, grouting alternative 2, backfill alternative a).*

Chemical components	**Origin (reference to Table 2)**	**Total introduced quantity [kg]**	**Removal efficiency [%]**	**Remaining quantity [kg]**
Gypsum	23, 24a	800	0 %	800
Cement	3, 4, 7.2, 8, 25	900	90 %	90
Carbonates (calcite + siderite)	23, 24a	600	0 %	600
Organic materials (incl. organic carbon and hydrocarbons)	7.2, 13, 15, 16, 18, 20, 21, 23, 24a, 25	500	49 %	200
Steel	3, 4, 6, 8, 17	200	51 %	90
Pyrite	23, 24a	80	0 %	80
Silica (SiO_2)	7.2, 25	50	6 %	50
Zinc	3	2	0 %	2
Carbamide	19	20	95 %	1
Rubber	11	1	90 %	0.1
Nitrogen oxides (NO_x)	1, 12	7	99 %	0.07
Copper	-	0	-	0
Soot and ash	12	0.4	93 %	0.03
Aluminium	2	0.3	90 %	0.03
Nitrate	-	0	-	0
Chloride	7.2, 25	0.03	19 %	0.02
Sulphuric acid	14	0.03	90 %	0.003
Plastic	2	0.3	90 %	0.03
Iron (Fe(III))	-	0	-	0
Polyethylene (PE)	-	0	-	0
Polystyrene (EPS)	-	0	-	0
Tungsten and cobalt	17	0.5	99 %	0.005

7 RESULTS FOR THE ACCESS TUNNEL AND THE WHOLE ONKALO

The quantities of different foreign materials, classified based on origin, that are produced in the ONKALO are presented in Table 11. The quantities for the actual repository can be obtained by comparing Tables 2 and 11.

Table 12 presents separately the quantities of materials introduced into the access tunnel. The access tunnel is a part of the ONKALO, so its quantities are included also in Table 11. The volume of the access tunnel (228,555 m^3 in the new layout) is more than 60 % of the volume of the whole ONKALO (365,166 m^3).

The materials related to shotcreting have identical values in both support alternatives A and B, because these alternatives are different only with respect to the shotcreting of the actual repository, whereas in ONKALO shotcreting with ordinary cement is assumed in both alternatives.

The majority of the materials produced in the ONKALO are produced in the access tunnel, as can be seen when comparing Tables 11 and 12. In particular, materials related to the traffic (e.g., emissions from vehicles) are predominantly produced in the access tunnel. In some cases, the access tunnel is, however, responsible for less than half of the materials introduced into the ONKALO. For example, only some 35 % of the materials related to support bolting of the ONKALO are produced in the access tunnel. This is because the need for support bolting was estimated to be very small in the remaining parts of the access tunnel, whereas the need for support is assumed to be higher in the other parts of the ONKALO, which are located mainly at the depths of 420 and 520 m, where the stresses are signifiantly higher than at shallower depths.

Table 11. *The estimated quantities of foreign materials in the ONKALO, listed by origin. Table continues on the next page.*

Origin of the foreign materials	**Chemical components considered**	**Total introduced quantity [kg]**	**Removal efficiency [%]**	**Remaining quantity [kg]**
1 Explosives	Nitrogen oxides (NO_x)	700	99 %	7
2 Blasting caps and cords	Aluminium	700	90 %	70
	Plastic	700	90 %	70
3 Support bolts	Steel	61,000	0 %	61,000
	Zinc	1,200	0 %	1,200
	Cement	24,000	0 %	24,000
4 Anchor bolts	Steel	20,000	40 %	12,000
	Cement	2,600	0 %	2,600
5 Shotcrete				
5A Shotcrete alternative A	Cement	2,400,000	95 %	120,000
	Aluminium	7,200	95 %	400
	Organic materials	17,000	95 %	800
	Silica (SiO_2)	96,000	95 %	4,800
	Iron (Fe(III))	1,700	95 %	80
	Chloride	120	95 %	6
5B Shotcrete alternative B	Cement	2,400,000	95 %	120,000
	Aluminium	7,200	95 %	400
	Organic materials	17,000	95 %	800
	Silica (SiO_2)	96,000	95 %	4,800
	Iron (Fe(III))	1,700	95 %	80
	Chloride	120	95 %	6
6 Steel mesh	Steel	0	-	0
7 Grouting materials				
7.1 Grouting alternative 1	Cement	510,000	20 %	410,000
	Organic materials	5,100	20 %	4,100
	Silica (SiO_2)	51,000	20 %	41,000
	Chloride	500	20 %	400
	Nitrate	1,000	20 %	800
7.2 Grouting alternative 2	Cement	480,000	20 %	380,000
	Organic materials	5,600	20 %	4,500
	Silica (SiO_2)	62,000	20 %	49,000
	Chloride	500	20 %	400
	Nitrate	900	20 %	700
7.3 Grouting alternative 3	Cement	420,000	20 %	340,000
	Organic materials	5,000	20 %	4,000
	Silica (SiO_2)	90,000	20 %	72,000
	Chloride	1,400	20 %	1,100
	Nitrate	800	20 %	600
8 Floors	Cement	2,100,000	98 %	42,000
	Steel	260,000	99 %	2,600

9 Miscellaneous constructions	Cement	2,600,000	98 %	51,000
	Steel	200,000	98 %	4,100
	Aluminum	73,000	98 %	1,500
	Zinc	1,500	98 %	30
10 Drainage pipes	Steel	2,400	95 %	120
	Polyethylene (PE)	1,400	95 %	70
	Polystyrene (EPS)	600	95 %	30
11 Wear to tyres	Rubber	68,000	90 %	6,800
12 Exhaust fumes from diesel engines	Nitrogen oxide	600,000	99 %	6,000
	Soot and ash	35,000	93 %	2,400
13 Diesel oil	Hydrocarbons	90,000	95 %	4,500
14 Battery acid	Sulphuric acid	1,300	90 %	130
15 Hydraulic and lubricating oils	Hydrocarbons	20,000	90 %	2,000
16 Degreasing agents and detergents	Hydrocarbons + other organic materials	29,000	95 %	1,500
17 Hard metals and metal fragments	Steel	91,000	98 %	1,800
	Tungsten and cobalt	1,000	99 %	10
18 Paints	Hydrocarbons	2,000	0 %	2,000
19 Urine	Carbamide	480,000	95 %	24,000
20 Miscellaneous human waste	Organic materials	300,000	98 %	6,000
21 Impurities in ventilation air	Organic materials	5,800,000	99 %	58,000
22 Concrete plugs	Cement	0	-	0
	Steel	0	-	0
	Zinc	0	-	0
	Organic materials	0	-	0
	Copper	0	-	0
23 Impurities in buffer material	Organic carbon	0	-	0
	Pyrite	0	-	0
	Gypsum	0	-	0
	Carbonates (calcite + siderite)	0	-	0
24 *Impurities in backfill material*				
24a Backfill alternative a (bentonite/crushed rock)	Organic carbon	450,000	0 %	450,000
	Pyrite	160,000	0 %	160,000
	Gypsum	1,600,000	0 %	1,600,000
	Carbonates (calcite + sid.)	1,100,000	0 %	1,100,000
24b Backfill alternative b (Friedland clay)	Organic carbon	4,000,000	0 %	4,000,000
	Pyrite	4,100,000	0 %	4,100,000
	Gypsum	5,400,000	0 %	5,400,000
	Carbonates (calcite + sid.)	37,000	0 %	37,000
25 Bottom plates in deposition holes	Cement	0	-	0
	Silica (SiO_2)	0	-	0
	Organic materials	0	-	0
	Chloride	0	-	0

Table 12. *The estimated quantities of foreign materials in the access tunnel, listed by origin. Table continues on the next page.*

Origin of the foreign materials	**Chemical components considered**	**Total introduced quantity [kg]**	**Removal efficiency [%]**	**Remaining quantity [kg]**
1 Explosives	Nitrogen oxides (NO_x)	400	99 %	4
2 Blasting caps and cords	Aluminium	400	90 %	40
	Plastic	500	90 %	50
3 Support bolts	Steel	21,000	0 %	21,000
	Zinc	400	0 %	400
	Cement	8,300	0 %	8,300
4 Anchor bolts	Steel	14,000	40 %	8,300
	Cement	1,800	0 %	1,800
5 Shotcrete				
5A Shotcrete alternative A	Cement	1,200,000	95 %	60,000
	Aluminium	3,600	95 %	200
	Organic materials	8,400	95 %	400
	Silica (SiO_2)	48,000	95 %	2,400
	Iron (Fe(III))	800	95 %	40
	Chloride	60	95 %	3
5B Shotcrete alternative B	Cement	1,200,000	95 %	60,000
	Aluminium	3,600	95 %	200
	Organic materials	8,400	95 %	400
	Silica (SiO_2)	48,000	95 %	2,400
	Iron (Fe(III))	800	95 %	40
	Chloride	60	95 %	3
6 Steel mesh	Steel	0	-	0
7 Grouting materials				
7.1 Grouting alternative 1	Cement	480,000	20 %	380,000
	Organic materials	4,800	20 %	3,800
	Silica (SiO_2)	48,000	20 %	38,000
	Chloride	500	20 %	400
	Nitrate	1,000	20 %	800
7.2 Grouting alternative 2	Cement	460,000	20 %	370,000
	Organic materials	5,200	20 %	4,100
	Silica (SiO_2)	56,000	20 %	45,000
	Chloride	500	20 %	400
	Nitrate	900	20 %	700
7.3 Grouting alternative 3	Cement	410,000	20 %	330,000
	Organic materials	4,100	20 %	3,300
	Silica (SiO_2)	77,000	20 %	62,000
	Chloride	1,200	20 %	900
	Nitrate	800	20 %	600
8 Floors	Cement	1,600,000	98 %	31,000
	Steel	180,000	99 %	1,800

9 Miscellaneous constructions	Cement Steel Aluminum Zinc	1,400,000 0 56,000 0	98 % - 98 % -	28,000 0 1,100 0
10 Drainage pipes	Steel Polyethylene (PE) Polystyrene (EPS)	800 500 190	95 % 95 % 95 %	40 20 10
11 Wear to tyres	Rubber	66,000	90 %	6,600
12 Exhaust fumes from diesel engines	Nitrogen oxide Soot and ash	600,000 34,000	99 % 93 %	6,000 2,400
13 Diesel oil	Hydrocarbons	87,000	95 %	4,300
14 Battery acid	Sulphuric acid	1,300	90 %	130
15 Hydraulic and lubricating oils	Hydrocarbons	9,100	90 %	900
16 Degreasing agents and detergents	Hydrocarbons + other organic materials	18,000	95 %	900
17 Hard metals and metal fragments	Steel Tungsten and cobalt	57,000 600	98 % 99 %	1,100 6
18 Paints	Hydrocarbons	1,200	0 %	1,200
19 Urine	Carbamide	460,000	95 %	23,000
20 Miscellaneous human waste	Organic materials	290,000	98 %	5,800
21 Impurities in ventilation air	Organic materials	3,500,000	99 %	35,000
22 Concrete plugs	Cement Steel Zinc Organic materials Copper	0 0 0 0 0	- - - - -	0 0 0 0 0
23 Impurities in buffer material	Organic carbon Pyrite Gypsum Carbonates (calcite + siderite)	0 0 0 0	- - - -	0 0 0 0
24 *Impurities in backfill material*				
24a Backfill alternative a (bentonite/crushed rock)	Organic carbon Pyrite Gypsum Carbonates (calcite + siderite)	280,000 99,000 990,000 710,000	0 % 0 % 0 % 0 %	280,000 99,000 990,000 710,000
24b Backfill alternative b (Friedland clay)	Organic carbon Pyrite Gypsum Carbonates (calcite + sid.)	2,500,000 2,600,000 3,300,000 23,000	0 % 0 % 0 % 0 %	2,500,000 2,600,000 3,300,000 23,000
25 Bottom plates in deposition holes	Cement Silica (SiO_2) Organic materials Chloride	0 0 0 0	- - - -	0 0 0 0

8 DISCUSSION

8.1 Comparison with earlier work

The estimates of the quantities of foreign materials in the repository have been updated in this report. With respect to previous work (Hjerpe 2004), some new materials and considerations have also been added. The most notable additions include

- the consideration of three alternative grouting strategies (low-pH cement and colloidal silica in addition to ordinary cement grouting) and two alternative shotcreting alternatives (low-pH cement in addition to ordinary cement)
- the more detailed consideration of the chemical components of the grouting and shotcrete materials (for example, the quantities of SiO_2 and chloride are also calculated)
- the inclusion of the foreign materials (impurities) in the buffer and backfill materials and the consideration of two alternative backfilling strategies (bentonite/crushed rock and Friedland clay)
- the consideration of the quantities of materials that have been used in the ONKALO (in 2004−2006)
- the calculation of the consumption of individual construction materials such as support bolts or grout additives (Appendix 1) in addition to the total quantities of the chemical components within these materials.

The results can be compared with those of Hjerpe (2004) only with respect to those materials that were included in both reports. Many of these are based on the same assumptions and the resulting quantities are, therefore, nearly the same. Minor differences are mainly due to the changes in the repository layout. Such materials include, for example, the concrete plugs (#22 in Table 2), the emissions from vehicles and maintenance work (#11...#17) and the organic materials in the ventilation air (#21).

The most significant differences with respect to the results of Hjerpe (2004) are related to the materials used in grouting (#7), shotcreting (#5) and in support bolts (#3). The remaining quantity of the grouting cement used in ordinary cement grouting (grouting alternative 1) is 650,000 kg, whereas Hjerpe (2004) estimated that 5,000,000 kg would remain in the repository. The quantity has, thereby, decreased by nearly 90 %. A decrease was expected due to other, more recent estimations (e.g., Ahokas et al. 2006), and it is partly caused by the assumption of a 20 % removal efficiency instead of 0 % assumed by Hjerpe (2004), but mainly it is due to the experience in the ONKALO and to the more detailed predictions on the reduction of grout take as a function of depth. These predictions can be tested in the future as the construction of the ONKALO proceeds deeper in the rock mass. In addition to cement, the quantities of organic materials related to grouting have reduced significantly, by some 95 %. This is mainly due to the above-mentioned new estimates of the need for grouting but also partly due to the fact that Hjerpe (2004) calculated the total quantities of superplasticisers, whereas in this report only the dry materials of additives have been considered, and water and some inorganic substances are not included in the quantities.

The remaining quantity of the cement used in the shotcreting (alternative A) is 240,000 kg and the introduced quantity is 4,800,000 kg (removal efficiency 95 %). In Hjerpe's (2004) estimations, a removal efficiency of 0 % was assumed and the introduced and remaining quantities were both some 11,000,000 kg. The introduced quantity has, thereby, decreased by some 55 % and the remaining quantity by 98 %. The introduced quantity has decreased because it was assumed here that no shotcrete would be used in the deposition tunnels. The significant reduction in the remaining quantity is caused by the assumption that the shotcrete (or 95 % of it) would be removed before backfilling the tunnels.

The differences in the quantities of materials in support bolts are due to the fact that based on the experience in the ONKALO, the consumption of support bolts is only some 30 % of that estimated by Hjerpe (2004), and in the remaining parts of the access tunnel it is, according to current plans, even smaller than this, i.e. only 0.1 bolts per metre of tunnel. As a result, the quantities of steel and zinc in the support bolts that remain in the repository are more than 70 % smaller and the quantity of cement is almost 80 % smaller than that estimated previously. The larger difference for cement is a result of assuming no grouting of the support bolts in the deposition tunnels in this work.

The quantities of the impurities in the buffer and backfill materials were not estimated by Hjerpe (2004) and these have caused a significant difference to the results of the total quantities of materials. In all cases where bentonite/crushed rock is the used backfill alternative (alternative a), gypsum is the material with the largest quantity remaining in the repository (6,500,000 kg), whereas in Hjerpe's (2004) results cement had the largest quantity. In this work, the total remaining quantity of cement is 5,700,000−6,100,000 kg in all bentonite/crushed rock alternatives. After gypsum and cement, carbonates (4,600,000 kg) and organic materials (2,000,000 kg) have the next largest quantities in Tables 3, 5 and 7 and steel comes only after them (1,500,000 kg), being the material with the second largest quantity in the previous estimations (Hjerpe 2004). In these calculations, gypsum and carbonates originate solely from the buffer and the backfill materials and their quantities were not estimated at all by Hjerpe (2004). The total remaining quantity of the studied components of foreign materials is some 22,000,000 kg regardless of the shotcrete and grouting alternatives.

If the chosen backfill alternative is b (Friedland clay), the difference to Hjerpe's work is even more pronounced. The material with the largest remaining quantity is gypsum (21,000,000 kg), followed by pyrite (16,000,000 kg) and organic materials (15,000,000 kg). Cement comes fourth with 5,700,000−6,100,000 kg depending on the shotcrete and grouting alternatives. Steel is fifth with 1,500,000 kg. The total remaining quantity of the studied components of foreign materials is as high as some 60,000,000 kg – and the actual quantity of foreign materials is naturally even greater than this, as only some of the chemical components of the foreign materials were studied here.

8.2 Conclusions on the different design alternatives

When using mainly low-pH cement grouting in the future (alternative 2), the total quantity of grouting cement is 25 % lower than in alternative 1 (ordinary cement), and if silica grouting is used, the cement quantity is 50 % lower than in alternative 1. However, these differences relate only to the quantities of grouting cement and when the total cement quantities are compared, the differences are smaller, even if the two shotcreting alternatives are considered at the same time. The total remaining cement quantity in alternative A1 (only ordinary cement in both shotcreting and grouting) is 6,100,000 kg and the corresponding value for the alternative B2 (mainly low-pH cement in both shotcreting and grouting) is 5,900,000 kg, i.e. only some 3 % smaller. If silica grouting is used (alternative B3), the quantity is 5,700,000 kg, i.e. 6 % smaller than in alternative 1. The differences are small because the total quantity of cement is largely dominated by the cement in the concrete plugs that will be used to seal off the deposition tunnels. To reduce the quantity of the cement in the repository, the most effective way would appear to be to reduce the quantity of cement in the concrete plugs (for example by using low-pH cement in the plugs). It is clear, however, that the total amount of cement has already been reduced significantly (by more than 70 %) since the previous estimations, mainly because of more detailed predictions on grout take and the plans to remove the shotcrete before backfilling the tunnels. If no shotcrete were removed, the total remaining cement quantities would increase by 65−80 % depending on the design alternative.

Because the quantity of buffer and backfill materials to be used are enormous and the quantities of their impurities are, thereby, also very large and will not be reduced by any removal (removal efficiency is 0 %), the selected backfill alternative has a significant impact on the remaining quantities of foreign materials. If backfill alternative b (Friedland clay) is chosen instead of alternative a (bentonite/crushed rock mixture), this will increase the total quantity of remaining foreign materials by some 180 %. It should be noted that in this work the crushed rock used in the backfill (alternative a) was not assumed to include any impurities at all, which is not exactly the case in reality and which will level off some of the differences observed here. In any case, the properties of the Friedland clay are slightly different from those of the MX 80 bentonite and it may be assumed that at least the quantities of organic carbon and, in particular, pyrite will increase significantly if Friedland clay is chosen as the backfill alternative.

9 SUMMARY

In a repository for spent nuclear fuel, a variety of materials are used during the construction process and during the operation of the repository. In addition to materials necessary for the construction and operation, other materials may be transported into the repository through the ventilation air, as emissions from vehicles, as waste produced by the staff etc. Both of these two types of materials have been considered in this report and their quantities – both the introduced quantities and the quantities that remain after closure – in the repository constructed at Olkiluoto have been estimated here based on new information, for example the new repository layout. The goal of this work was to update the estimations that have been made previously by Hjerpe (2004), and the report takes advantage of the experience collected during the construction of the ONKALO. During this construction process, the quantities of the different construction materials introduced into the underground openings have been monitored and they have formed a basis for estimating the quantities to be used in the future.

The estimations made in this report are specific to a KBS-3V type repository and to the Olkiluoto site, although in some cases more generic information has been used, particularly when the relevant quantities have not been monitored in the ONKALO. These kind of materials include, for example, the emissions from vehicles and construction equipment. The estimations are based on the new repository layout produced in 2006 and consider the latest plans for grouting and rock support. As these plans are generally not final yet, several different alternative plans have been assumed when necessary. For shotcreting, these alternatives are A) shotcreting with ordinary cement and B) shotcreting with low-pH cement in the repository. For grouting, the alternative grouting strategies are grouting with 1) ordinary cement, 2) mainly low-pH cement and 3) mainly colloidal silica. Also two different strategies for the backfilling of the tunnels were considered: backfilling with a) 30/70 mixture of bentonite and crushed rock and b) Friedland clay.

The most significant differences with respect to the results of Hjerpe (2004) are related to the materials used in grouting, shotcreting and in support bolts. The remaining quantity of the grouting cement used in ordinary cement grouting has decreased by nearly 90 % as compared with the results of Hjerpe (2004). This is mainly due to updated estimations of the reduction of grout take as a function of depth. The remaining quantity of the ordinary cement used in the shotcreting has decreased by 98 %. This is mainly due to the assumption that the shotcrete would be removed before backfilling the tunnels. The differences in the quantities of materials in support bolts are due to the fact that based on the experience in the ONKALO, the consumption of support bolts is only some 30 % of that estimated by Hjerpe (2004), and in the remaining parts of the access tunnel it is even smaller than this, according to current plans. As a result, the quantities of steel and zinc in the support bolts that remain in the repository are more than 70 % smaller and the quantity of cement is almost 80 % smaller than that estimated by Hjerpe (2004).

In the cases where a mixture of bentonite and crushed rock is the used backfill alternative, gypsum is the material with the largest quantity remaining in the repository and cement has the second largest quantity. After gypsum and cement, the materials with the next largest quantities are carbonates and organic materials. The total remaining quantity of the studied components of foreign materials is some 22,000,000 kg in this case regardless of the shotcrete and grouting alternatives. If the chosen tunnel backfill alternative is Friedland clay, the material with the largest quantity is gypsum, followed by pyrite, organic materials and cement. The total remaining quantity of the studied components of foreign materials is as high as some 60,000,000 kg.

Accordingly, the selection of the backfill alternative has a significant impact on the quantities of several important foreign materials and their relative abundance, whereas the differences between the grouting and shotcreting alternatives are minor in terms of total material quantities. The differences are small because the total quantity of cement is largely dominated by the cement in the concrete plugs that will be used to seal off the deposition tunnels. To reduce the quantity of the cement in the repository, the most effective way would be to reduce the quantity of cement in the concrete plugs. It is clear, however, that the total amount of cement has already been reduced significantly – by more than 70 % – since the previous estimations, mainly because of more detailed predictions on grout take and the plans to remove the shotcrete before backfilling the tunnels.

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APPENDIX 1: RESULTS FOR MAIN CONSTRUCTION MATERIALS

1) Explosives

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Explosives	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO+repository excl. dep. holes	1306546	3	3919638
Deposition holes	58272	0	0
		SUM	**3919638**

2) Quantities of important components

Nitrogen oxides (NO_x)	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO+repository excl. dep. holes	1306546	0.0018	2352
Deposition holes	58272	0	0
		SUM	**2352**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Nitrogen oxides (NOx)	2352	99 %	24

2) Blasting caps and cords

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Caps	Excavated volume (m^3)	Number per excavated cubic metre (pcs/m^3)	Total number (pcs)
ONKALO+repository excl. dep. holes	1306546	0.64	841416
Deposition holes	58272	0	0
		SUM	**841416**

Cords	Excavated volume (m^3)	Quantity (length) per excavated cubic metre (m/m^3)	Total quantity (m)
ONKALO+repository excl. dep. holes	1306546	0.36	470357
Deposition holes	58272	0	0
		SUM	**470357**

2) Quantities of important components

Aluminium	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO+repository excl. dep. holes	1306546	0.0019	2524
Deposition holes	58272	0	0
		SUM	**2524**

Plastic	Excavated volume (m3)	Quantity per excavated volume (kg/m^3)	Total quantity (kg)
ONKALO+repository excl. dep. holes	1306546	0.0020	2587
Deposition holes	58272	0	0
		SUM	**2587**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Aluminium	2524	90 %	252
Plastic	2587	90 %	259

3) Support bolts

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Support bolts	Excavated volume (m^3)	Number per excavated cubic metre (pcs/m^3)	Total number (pcs)
ONKALO by 1 Sep 2006	63387	0.021	1345
Access tunnel after 1 Sep 2006	160672	0.0022	349
Deposition tunnels	578574	0.053	30875
Deposition holes	58272	0	0
Other parts	503913	0.023	11715
		SUM	**44283**

2) Quantities of important components

Steel	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO by 1 Sep 2006	63387	0.27	17103
Access tunnel after 1 Sep 2006	160672	0.028	4442
Deposition tunnels	578574	0.51	297426
Deposition holes	58272	0	0
Other parts	503913	0.27	135652
		SUM	**454623**

Zinc	Excavated volume (m3)	Quantity per excavated volume (kg/m^3)	Total quantity (kg)
ONKALO by 1 Sep 2006	63387	0.0051	325
Access tunnel after 1 Sep 2006	160672	0.00052	84
Deposition tunnels	578574	0.010	5648
Deposition holes	58272	0	0
Other parts	503913	0.0051	2576
		SUM	**8634**

Cement	Excavated volume (m3)	Quantity per excavated volume (kg/m^3)	Total quantity (kg)
ONKALO by 1 Sep 2006	63387	0.11	6725
Access tunnel after 1 Sep 2006	160672	0.011	1746
Deposition tunnels	578574	0	0
Deposition holes	58272	0	0
Other parts	503913	0.10	52805
		SUM	**61277**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Steel	454623	0 %	454623
Zinc	8634	0 %	8634
Cement	61277	0 %	61277

4) Anchor bolts

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Anchor bolts	Excavated volume (m^3)	Number per excavated cubic metre (pcs/m^3)	Total number (pcs)
ONKALO+repository excl. dep. holes	1306546	0.046	60101
Deposition holes	58272	0	0
		SUM	**60101**

2) Quantities of important components

Steel	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO+repository excl. dep. holes	1306546	0.11	141090
Deposition holes	58272	0	0
		SUM	**141090**

Cement	Excavated volume (m3)	Quantity per excavated volume (kg/m^3)	Total quantity (kg)
ONKALO+repository excl. dep. holes	1306546	0.014	17966
Deposition holes	58272	0	0
		SUM	**17966**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Steel	141090	40 %	84654
Cement	17966	0 %	17966

5A) Shotcrete – Alternative A

**SUPPORT ALTERNATIVE A:
SHOTCRETE WITH ORDINARY CEMENT**

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Cement in shotcrete	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	6.6	2406454
Deposition tunnels and holes	636846	0	0
Other parts	362806	6.6	2404839
		SUM	**4811293**

Additives in shotcrete	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.61	223425
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.62	223275
		SUM	**446700**

2) Quantities of important components

Cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	6.6	2406454
Deposition tunnels and holes	636846	0	0
Other parts	362806	6.6	2404839
		SUM	**4811293**

Aluminium	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.020	7219
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.020	7215
		SUM	**14434**

Organic material	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.046	16845
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.046	16834
		SUM	**33679**

SiO_2	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.26	96258
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.27	96194
		SUM	**192452**

Iron (Fe(III))	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.0046	1685
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.0046	1683
		SUM	**3368**

Chloride	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.00033	120
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.00033	120
		SUM	**241**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Cement	4811293	95 %	240565
Aluminium	14434	95 %	722
Organic material	33679	95 %	1684
SiO2	192452	95 %	9623
Iron (Fe(III))	3368	95 %	168
Chloride	241	95 %	12

5B) Shotcrete – Alternative B

SUPPORT ALTERNATIVE B:
SHOTCRETE MAINLY WITH LOW-pH CEMENT

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Cement in shotcrete	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	6.6	2406454
Deposition tunnels and holes	636846	0	0
Other parts	362806	4.0	1454089
		SUM	**3860542**

Additives in shotcrete	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.61	223425
Deposition tunnels and holes	636846	0	0
Other parts	362806	3.3	1194398
		SUM	**1417823**

2) Quantities of important components

Cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	6.6	2406454
Deposition tunnels and holes	636846	0	0
Other parts	362806	4.0	1454089
		SUM	**3860542**

Aluminium	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.020	7219
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.012	4362
		SUM	**11582**

Organic material	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.046	16845
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.028	10179
		SUM	**27024**

SiO_2	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.26	96258
Deposition tunnels and holes	636846	0	0
Other parts	362806	3.1	1119648
		SUM	**1215906**

Iron (Fe(III))	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.0046	1685
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.0028	1018
		SUM	**2702**

Chloride	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.00033	120
Deposition tunnels and holes	636846	0	0
Other parts	362806	0.00020	73
		SUM	**193**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Cement	3860542	95 %	193027
Aluminium	11582	95 %	579
Organic material	27024	95 %	1351
SiO2	1215906	95 %	60795
Iron (Fe(III))	2702	95 %	135
Chloride	193	95 %	10

6) Steel mesh

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Steel mesh	**Excavated length of tunnel (m)**	**Quantity (area) per excavated metre of tunnel (m^2/m)**	**Total quantity (m^2)**
Deposition tunnels	41166	2.75	113207
Other parts	-	0	0
		SUM	**113207**

New anchor bolts for steel mesh	**Excavated length of tunnel (m)**	**Number per excavated metre of tunnel (pcs/m)**	**Total number (pcs)**
Deposition tunnels	41166	1	41166
Other parts	-	0	0
		SUM	**41166**

2) Quantities of important components

Steel in mesh	**Excavated volume (m^3)**	**Quantity per excavated cubic metre (kg/m^3)**	**Total quantity (kg)**
Deposition tunnels	578574	0.31	177734
Other parts	786244	0	0
		SUM	**177734**

Steel in bolts	**Excavated volume (m^3)**	**Quantity per excavated cubic metre (kg/m^3)**	**Total quantity (kg)**
Deposition tunnels	578574	0.031	17701
Other parts	786244	0	0
		SUM	**17701**

SUMMARY

	Total introduced quantity (kg)	**Removal efficiency (%)**	**Total remaining quantity (kg)**
Steel in mesh	177734	100 %	0
Steel in bolts	17701	98 %	354
Steel (total)	**195436**	**99.82 %**	**354**

7.1) Grouting materials (Alternative 1)

GROUTING ALTERNATIVE 1:
GROUTING WITH ORDINARY CEMENT

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Grouting cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	362039	1.4	506855
Actual repository	999652	0.3	299896
		SUM	**806750**

Grout additives	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	362039	0.20	73579
Actual repository	999652	0.04	43535
		SUM	**117113**

2) Quantities of important components

Cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	1.4	511232
Actual repository	999652	0.3	299896
		SUM	**811128**

Organic material	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.014	5112
Actual repository	999652	0.003	2999
		SUM	**8111**

SiO_2	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.14	51123
Actual repository	999652	0.03	29990
		SUM	**81113**

Chloride	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.0014	511
Actual repository	999652	0.0003	300
		SUM	**811**

Nitrate	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO	365166	0.0028	1022
Actual repository	999652	0	0
		SUM	**1022**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Cement	811128	20 %	648902
Organic material	8111	20 %	6489
SiO2	81113	20 %	64890
Chloride	811	20 %	649
Nitrate	1022	20 %	818

7.2) Grouting materials (Alternative 2)

GROUTING ALTERNATIVE 2:
GROUTING MAINLY WITH LOW-pH CEMENT

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Grouting cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	5.7	393226
ONKALO from PL 1500 onwards	296179	0.29	85892
Actual repository	999652	0.13	129955
		SUM	**609073**

Grout additives	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.83	57083
ONKALO from PL 1500 onwards	296179	0.096	28491
Actual repository	999652	0.098	98116
		SUM	**183690**

2) Quantities of important components

Cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	5.7	393226
ONKALO from PL 1500 onwards	296179	0.29	85892
Actual repository	999652	0.13	129955
		SUM	**609073**

Organic material	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.057	3932
ONKALO from PL 1500 onwards	296179	0.0056	1659
Actual repository	999652	0.0052	5198
		SUM	**10789**

SiO_2	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.57	39323
ONKALO from PL 1500 onwards	296179	0.075	22213
Actual repository	999652	0.081	80972
		SUM	**142508**

Chloride	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.0057	393
ONKALO from PL 1500 onwards	296179	0.0003	89
Actual repository	999652	0.00013	130
		SUM	**612**

Nitrate	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.011	786
ONKALO from PL 1500 onwards	296179	0.0004	118
Actual repository	999652	0	0
		SUM	**905**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Cement	609073	20 %	487258
Organic material	10789	20 %	8631
SiO2	142508	20 %	114006
Chloride	612	20 %	490
Nitrate	905	20 %	724

7.3) Grouting materials (Alternative 3)

GROUTING ALTERNATIVE 3:
GROUTING MAINLY WITH SILICA GROUT

QUANTITY OF MATERIALS INTRODUCED

1) Consumption of construction materials

Silica sol (40% SiO_2, 60% water)	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0	0
ONKALO from PL 1500 onwards	296179	0.28	81449
Actual repository	999652	0.40	399861
		SUM	**481310**

Accelerator to Silica sol (10% NaCl)	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0	0
ONKALO from PL 1500 onwards	296179	0.06	16632
Actual repository	999652	0.08	81653
		SUM	**98286**

Grouting cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	5.7	393226
ONKALO from PL 1500 onwards	296179	0.089	26360
Actual repository	999652	0	0
		SUM	**419586**

Additives to cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.83	57083
ONKALO from PL 1500 onwards	296179	0.067	19902
Actual repository	999652	0	0
		SUM	**76985**

2) Quantities of important components

Cement	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	5.7	393226
ONKALO from PL 1500 onwards	296179	0.089	26360
Actual repository	999652	0	0
		SUM	**419586**

Organic material	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.06	3932
ONKALO from PL 1500 onwards	296179	0.0036	1054
Actual repository	999652	0	0
		SUM	**4987**

SiO_2	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.57	39323
ONKALO from PL 1500 onwards	296179	0.17	50350
Actual repository	999652	0.16	159944
		SUM	**249617**

Chloride	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.0057	393
ONKALO from PL 1500 onwards	296179	0.0034	1007
Actual repository	999652	0.0048	4798
		SUM	**6199**

Nitrate	Excavated volume (m^3)	Quantity per excavated cubic metre (kg/m^3)	Total quantity (kg)
ONKALO PL (tunnel chainage) 0...1500	68987	0.011	786
ONKALO from PL 1500 onwards	296179	0	0
Actual repository	999652	0	0
		SUM	**786**

SUMMARY

	Total introduced quantity (kg)	Removal efficiency (%)	Total remaining quantity (kg)
Cement	419586	20 %	335669
Organic material	4987	20 %	3989
SiO2	249617	20 %	199694
Chloride	6199	20 %	4959
Nitrate	786	20 %	629