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Principal organic materials in a repository for spent nuclear fuel

Lotta Hallbeck, Microbial Analytics Sweden AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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1.1 Background

The interim reports on SKB's assessment of the long-term safety of a KBS-3 repository /SKB 2004a, b/ describes several issues concerning geochemical aspects of the near field of the repository that need to be analysed. In the KBS-3V concept, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at a depth of approximately 500 m in saturated granitic rock. The chemical evolution of the buffer, backfill, and rock is ultimately governed by the composition and flow of the groundwater. During excavation and the relatively long operational period, groundwater will change substantially in composition around the repository. The effects of several disturbances introduced into the groundwater system due to the activities of repository construction and operation are relevant. In this regard, it is important to understand the chemical status of the repository system at closure in order to describe its immediate geochemical evolution after closure.

One disturbance identified in a spent fuel repository is the presence of organic material. Although it is known that such material will influence the system, there are no clear indications as to the extent of the disturbance introduced. Organic materials may be decomposed through microbiologically mediated reactions, thus adding reducing capacity to the near field of the repository. However, these materials might also be detrimental by enhancing the potential for radionuclide transport in groundwater. The possible effects of these materials in the safety assessment (SR-Site) have to be reviewed from a chemical and microbiological standpoint /SKB 2006/.

Organic compounds can play an important role in transporting radionuclides through the near and far fields of a radioactive waste repository because of their ability to form mobile complexes, participate in redox reactions, and sorb onto solid surfaces and thereby make surfaces unavailable to radionuclides. A good understanding of radionuclide behaviour is dependent on accurate predictions of radionuclide speciation and therefore must take account of complexes with organic material.

Various categories of organic material may be left in a spent fuel repository after construction is complete. There will be organic material produced by living organisms in the rock and tunnel environments, as well as material brought into the repository by constructors. Finally, the mere presence of various human activities will generate organic material that remains in the repository, unless it is removed or its deposition is prohibited in the first place. The main groups of possible residual organic materials in repository systems are:

- various types of microorganisms and small plants in the tunnels,
- organic material entering with the ventilation air,
- organic material in construction, buffer, and sealing materials,
- organic material in fuels and from vehicle emissions,
- detergents and lubricants,
- organic material from human activities,
- organic residues from blasting and/or rock-drilling operations.

Construction and stray material made of steel can by its possibility to corrode anaerobically under production of H_2 contribute to microbial growth by H_2-utilising microorganisms. One scenario is that acetogens produce acetate from H_2 and CO_2. The acetate in combination with H_2 can then be used by sulphate-reducing bacteria that produce H_2S by their metabolism.

This report focuses on the following: identifying organic material that may be present in repository systems at the time of closure (unless removed); the chemical composition, structure, and main organic degradation products of the identified material; and the microbial processes that will affect this material. H_2S produced from H_2 produced from anaerobic corrosion of steel will be addressed. The report ends with a summary including recommended actions to deal with the different types of organic material.

1.2 Aerobic degradation of organic material

Biodegradation is a redox process by which organic material is oxidised. In complete oxidation, all organic carbon is converted into carbon dioxide. In aerobic degradation, the organic molecules are oxidised by oxygen and converted into carbon dioxide and water:

$CH_2O + O_2 \rightarrow CO_2 + H_2O$ Eq. 1-1

Polymeric molecules will be split into monomers by the action of exoenzymes produced by micro organisms. Molecules such as proteins and nucleic acids, which contain nitrogen, sulphur, and phosphate, are degraded as shown in Figure 1-1. Some of the nitrogen, sulphur, and phosphate groups are separated and expelled from the cell. As long as there is degradable organic material available, most of these nutrients will immediately be assimilated by the degrading microorganism and used in biosynthesis, and will not be released to the environment. Chemo-autotrophic microorganisms will use available nutrients in their biosynthesis as well.

1.3 Anaerobic degradation of organic material

There are two types of anaerobic degradation: fermentation and anaerobic respiration. A general schematic of microbial degradation is shown in Figure 1-2, which shows the order in which the different microbial processes occur in an anaerobic environment. All biodegradation starts with the hydrolysis of polymers to oligo- and monomers. The monomers are then oxidised to other compounds or optimally to carbon dioxide by the different groups of microorganisms, depending on the electron acceptors available in the environment.

1.3.1 Fermentation

In anaerobic systems containing great amounts of organic material, fermenting microorganisms will thrive. Fermentations are degradation pathways that do not require external electron acceptors. Instead, electrons are shuffled around within the degraded molecule that has been split into two or more compounds. The degradation products consist of both more reduced and oxidised organic molecules, such as organic acids, ketones, and alcohols. Fermentation of sugar commonly yields carbon dioxide and ethanol.

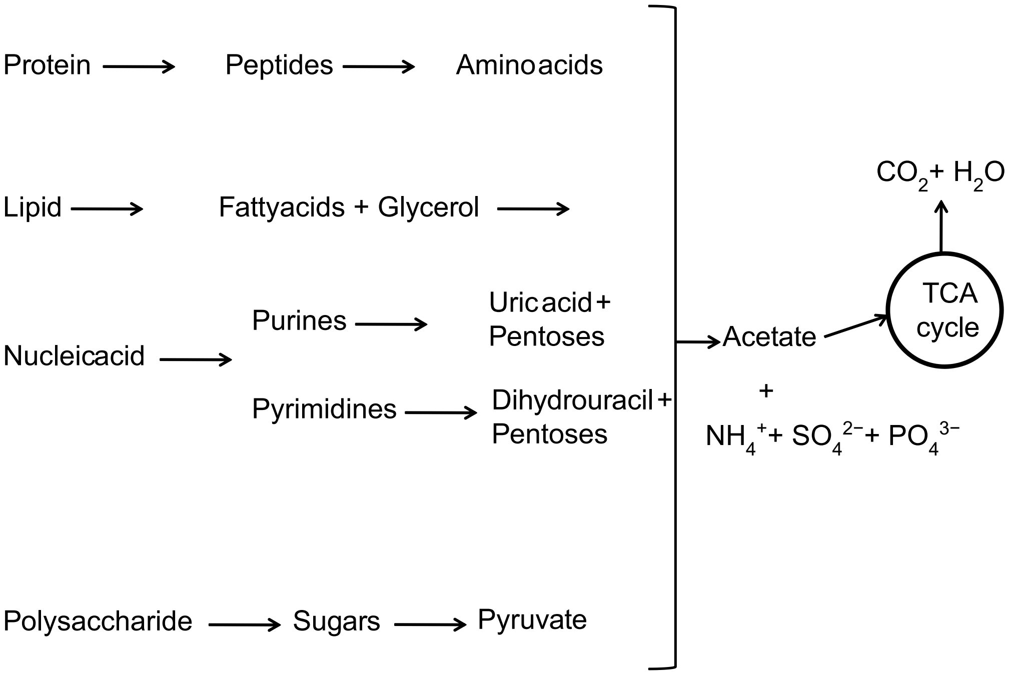

Figure 1-1. Aerobic degradation of major cell components. The tricarboxylic acid (TCA) cycle is one of the key pathways in many degradation systems.

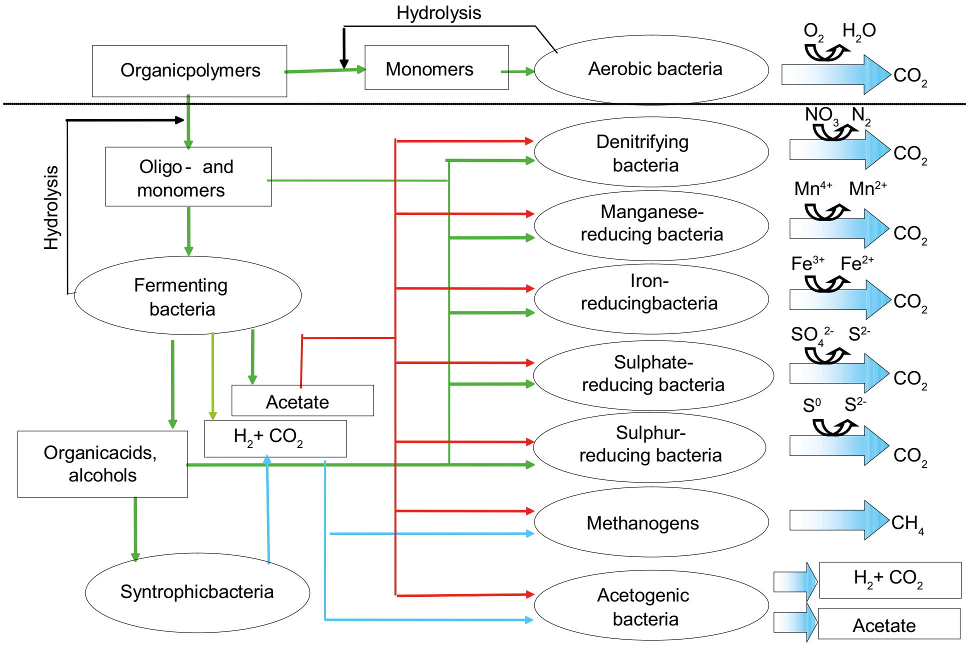

Figure 1-2. *Microbial degradation and the involved microbial groups.*

Two fermenting bacteria common in the environment and often found in soil are *Bacillus* and *Clostridium*. Both are spore formers, but the *Clostridium* genus consists of obligate anaerobes, whereas the *Bacillus* genus contains obligate aerobes, facultative anaerobes, and fermenting species /Madigan et al. 2003/. An example of the fermentation pathway of *B. licheniformis* is as follows (Eq. 1-2):

3 glucose → 2 glycerol + 2.3–butanediol + 4 CO_2 Eq. 1-2

From glucose, the fermenting organism produces glycerol, 2.3-butanediol, and carbon dioxide.

Some *Clostridium* species ferment sugars and occasionally starch and pectin to form butyric acid, acetic acid, CO_2, and H_2 as the principal end-products. As the acids in these fermentations accumulate, so-called butyric acid bacteria begin to produce more neutral compounds, including acetone and butanol, from the acids. There are several other fermentation pathways in other species of fermenting organisms, but the details of those pathways is beyond the scope of this report /Madigan et al. 2003/.

1.3.2 Anaerobic respiration

In natural environments, anaerobic respiratory organisms follow a certain progression (see Figure 1-2). The first anaerobic respiration metabolisms that are activated when oxygen is depleted are those connected with the nitrate-, iron-, and manganese-reducing bacteria. These organisms degrade short-chain organic acids such as lactic acid and acetic acid but rarely larger organic molecules such as six-carbon sugars. The next metabolic type is represented by the sulphate-reducing bacteria, which use the sulphur in sulphate as an electron acceptor and produce hydrogen sulphide. The carbon and energy sources for sulphate reducers are short-chain organic acids.

In a system containing large amounts of organic material, such as compost, various fermentation processes should theoretically produce considerable hydrogen that could be used by methanogens and/or acetogens. In a deep groundwater system, on the other hand, the amounts of hydrogen produced from the degradation of organic material from the surface or, as in the case discussed here, residual organic material in the repository is probably quite small. Therefore, the last part of the degradation chain depicted in Figure 2-2 would be insignificant. This process, based on hydrogen from the degradation of organic materials, must be distinguished from the methanogenesis and acetate production that frequently occur in deep groundwater, using hydrogen coming from thermo-catalytic processes in very deep environments inside the Earth /Pedersen 2001/.

1.4 The chemical composition of microorganisms

Though it can vary somewhat, the chemical composition of most bacterial cells is fairly similar. An average bacterial cell has a total weight of 9.5×10^{-13} g and a dry weight of 2.8×10^{-13} g /Niedhardt et al. 1990/. Table 1-1 lists the weights of the different macromolecules in an average *Escherichia coli* cell.

Various types of microorganisms will grow on the tunnel surfaces of a repository during the construction and operational phases. Microorganisms growing on surfaces produce a film consisting of cells and a gel matrix, called a biofilm. The matrix comprises extracellular material, often polysaccharides /Christensen and Characklis 1990/. Most of the biological growth in a repository environment will occur in various types of biofilms, wherever there is liquid water.

1.4.1 The amount of organic material in biofilms – the microbial cells

The number of microorganisms present in a biofilm depends on the environment, i.e. the nutrients available, water flow, oxygen concentration, surface structure, and temperature. Differences in these variables will be reflected in both the number of bacteria per unit of surface area and the biofilm thickness. To estimate the amount of organic material contained in cells in a biofilm, various reported cell densities are evaluated here. The first such biofilm density, reported by /Pedersen and Ekendahl 1990/, was measured on glass slides placed in water flowing from a depth of 680 m in borehole KLX01 in Laxemar, in Småland, south east Sweden. This biofilm contained approximately 10^9 microorganisms per m^2 and can be regarded as a low-density biofilm compared to the other evaluated biofilm density, reported by /Pedersen et al. 1986/, that was established using a pure culture of *Pseudomonas* sp. The biofilm contained 10^{12} microorganisms per m^2 and is here referred to as a high-density biofilm. In both studies, the glass slides were incubated for a short time, i.e. for days or weeks, and only one layer of microorganisms developed. In older biofilms, several layers of microorganisms can develop. Table 1-2 presents calculations of the number of microorganisms per m^2, the corresponding biofilm thickness, and the amount of organic material contained in microorganisms in hypothetical biofilms. These calculations indicate that the cell contribution to the amount of organic material in a biofilm can range from 10 $\mu g\ m^{-2}$ to 3.0 $g\ m^{-2}$. The contribution of microorganisms in biofilms growing on tunnel surfaces is more likely to be in the range of 0.1–1,000 $mg\ m^{-2}$ of organic material, because the low organic material content of the inflowing groundwater. On special spots with residual organic material a biofilm could growth to higher density.

1.4.2 The amount and composition of organic material in biofilms consisting of cells and exudates

Organotrophic biofilms

Organotrophic microorganisms, the group that degrades organic carbon by a respiratory metabolism, often produce an amorphous, extracellular matrix lacking microscopically recognisable structures. This matrix usually almost exclusively comprises extracellular polysaccharides (EPSs). This gel-like material is formed when organic macromolecules are partly hydrated and partly cross-linked /Christensen and Characklis 1990/. The monomer building blocks of bacterial EPSs can be the following monosaccharides, uronic acids, and amino sugars: rhamnose, fucose, arabinose, xylose, mannose, glucose, glucuronic acid, galacturonic acid, mannuronic acid, N-acetylglucosamine, and 2-keto-3-deoxy-octulosonic acid (KDO). Some bacteria produce EPSs consisting of homopolysaccharides. For example, several *Acetobacter* species produce extracellular cellulose that is chemically similar to cellulose in higher plants, i.e. β-1,4-linked unbranched glucans.

Thickness and density vary among biofilms. Heterotrophic, EPS-producing biofilms from different environments were reported to have thicknesses ranging from 10 to 1,300 µm /Christensen and Characklis 1990/. The density of these biofilms was 5–105 $kg\ m^{-3}$. Calculations of the amount of organic material per m^2 in biofilms are presented in Table 1-3. Three different densities were arbitrarily chosen, i.e. 10, 25, and 75 $kg\ m^{-3}$. These calculations indicate that the amount of organic material in a biofilm can vary between 0.1 and 75 $g\ m^{-2}$ depending on biofilm thickness and density. Based on the calculations of organic material in the biofilm microorganisms, between 0.1 and 1% of the organic material in a biofilm consist of microorganisms; the remainder consists of EPSs.

Table 1-1. Overall macromolecule composition of an average *E. coli* cell /Niedhardt et al. 1990/.

Cell constituent	Weight per cell (10^{-15} g)
Protein	155
RNA	59
DNA	9
Lipid	26
Lipopolysaccharide	10
Murein	7
Glycogen	7
Total macromolecules	273
Soluble pool	8
Total dry weight	284
Total weight	950

Table 1-2. Amount of organic material contained in the microorganisms of a biofilm, together with cell density and number of cell layers.

Cell density per layer (m^{-2})	Number of cell layers	Organic material ($g\ m^{-2}$)
Low density:		
3.5×10^9	1	1×10^{-5}
3.5×10^9	10	1×10^{-4}
3.5×10^9	100	1×10^{-6}
High density:		
1×10^{12}	1	0.03
1×10^{12}	10	0.3
1×10^{12}	100	3

Table 1-3. Amount of organic material in a biofilm depending on biofilm thickness and density.

Biofilm thickness (mm)	Estimated biofilm density ($kg\ m^{-3}$)	Amount of organic material ($g\ m^{-2}$)
0.01	10	0.1
0.1	10	1
1	10	10
0.01	25	0.25
0.1	25	2.5
1	25	25
0.01	75	0.75
0.1	75	7.5
1	75	75

Biofilms of iron- and manganese-oxidising bacteria

The most striking biofilm growth on tunnel walls and in ditches is that produced by the iron- and manganese-oxidising bacteria. Several species in this group of bacteria produce extracellular material that has a distinct and recognisable shape.

Among the iron oxidisers, the species *Gallionella ferruginea* and *Leptothrix ochracea* are predominant. Both were discovered by microscopy and described in the literature /Ehrenberg 1836, Kützing 1843/ in the first half of the nineteenth century.

Gallionella ferruginea

In the Äspö Hard Rock Laboratory (HRL) tunnel, the main biofilm-forming bacterium is the iron oxidiser *Gallionella ferruginea*. This bacterium produces large quantities of organic material, in the form of a helical stalk, and oxidises iron on the tunnel walls and floor at all positions in the tunnel where reduced ferrous-iron-containing groundwater intrudes and flows. /Anderson and Pedersen 2003/ measured the biofilm formation of *Gallionella* and its influence on iron oxide precipitation and the partitioning of lanthanides and actinides. Most of this study was done using a bacteriogenic iron oxide reactor, in situ, continuous flow (BRIC) apparatus. The sampled material was produced inside growth tubes in the BRIC and simulated a biofilm growing in the tunnel very well. In this study, the *Gallionella* organisms produced stalks up to approximately 50 µm long from each cell. The cell density ranged from 10^5 to 10^6 per mL in the growth tubes. The BRIC system contained bacteria other than *G. ferruginea*, but the cell counting method used did not distinguish between different species.

The results of in situ BRIC experiments in the Äspö HRL showed a good correspondence with those from in vitro laboratory experiments in which *G. ferruginea* was grown in pure cultures. In the growth tubes, the highest measured number of *Gallionella* cells was 2.5×10^6 per mL, the average stalk length was 34 µm per cell, and the maximum stalk length was 60 µm /Hallbeck and Pedersen 1990/.

/Hallbeck and Pedersen 1995/ reported that a *Gallionella* biofilm grown in groundwater used for heat-exchange purposes had a total organic carbon (TOC) content of 0.147 µmol cm^{-2} and a Fe content of 0.330 µmol cm^{-2}. This study also demonstrated that the carbon/nitrogen ratio (C/N) of cells was 4.3 and of cells and stalk material was 6.8. The C/N ratio of *E. coli* cells is reported to be 3.4 /Niedhardt et al. 1990/. If the C/N ratio of cells in an iron-oxidising biofilm is assumed to be 4, based on the above data, the ratio between carbon in cells and in biofilms will be 1.7, i.e. there will be 1.7 times more carbon in *Gallionella* biofilms than in the same cells not forming a biofilm. Iron-oxidising biofilms will consequently have a carbon content of 85% content compared to biofilms without stalks, for example, a carbon conten of 50% for the *E. coli* cells presented in Table 1-1. Calculations of the organic material content of biofilms cannot, therefore, be based on cell numbers only.

Using the TOC numbers for biofilm formation presented in /Hallbeck and Pedersen 1995/, 0.147 µmol carbon cm^{-2} corresponds to 17.6 mg carbon per m^2, which in turn corresponds to 20.8 mg of organic material per m^2 if we assume that 85% of the OM is carbon.

The biofilm on the glass slides described above was estimated to be 30 µm thick and represented a thin biofilm of iron oxidisers. If extrapolated, this would represent 690 g per m^3 of organic material. Biofilms up to 10–15 cm thick can be formed on tunnel walls, which corresponds to approximately 70–100 g organic carbon per m^2 of overgrown tunnel wall assuming equal densities of the biofilms – a significant amount of organic material that should be accounted for. In reality, the water content decreases as the biofilm thickness increases, suggesting that the carbon content can be higher.

Composition of the stalks and sheaths of iron and manganese oxidisers

The chemical composition of *Gallionella* stalks is still unknown. Published titration studies of *Gallionella* cells and stalks /Martinez et al. 2003/ demonstrated that functional groups with acidic, basic, and neutral pK_a values were present. Some of these groups are important for the sorption of iron oxides and consequently radionuclides to surfaces. /Emerson and Ghiorse 1993a, b/ analysed the composition of the sheaths of the sheath-forming and manganese-oxidising bacterium *Leptothrix discophora*, finding that dry sheaths consisted of 38% C, 6.9% N, 6% H, and 2.1% S. The sheath mass was distributed into the following groups of compounds: 34–35% carbohydrates (polysaccharides), 23–25% proteins, 8% lipids, and 4% inorganic ash. The recovery of the analyses was approximately 70% of the total mass. The polysaccharides consisted of a 1:1 mixture of uronic acids e.g. glucuronic acid, galacturonic acid, and mannuronic acid and at least one unidentified uronic acid) and one amino sugar, galactosamine. Nine per cent of the dry weight was 2–3 deoxyoctanoic acid. The surface of the sheaths probably contains several hydroxyl groups possessing binding properties for cations.

Biofilms of sulphur-oxidising bacteria

At some places in the Äspö HRL, sulphur-oxidising bacteria can be found, including both unicellular and filamentous organisms. The filamentous group is represented by species of *Thiothrix*, a sheath-forming bacterium that stores elemental sulphur inside its cells. This bacterium oxidises hydrogen sulphide with oxygen. It is thought to use organic carbon as a source of carbon and reduced electrons. Many other sulphur-oxidising bacteria are autotrophic and use carbon dioxide as a carbon source /Madigan et al. 2003/.

The composition of the sheaths of *Thiothrix* and other filamentous sulphur oxidisers is not well explored. One reference suggests that the extracellular material is composed of cellulose because of its neutral sugar composition, the results of methylation analysis, and the identification of free oligosaccharides /Ogawa and Maki 2003/.

The literature on biofilms of sulphur-oxidising bacteria is also sparse. A sulphur-oxidising biofilm probably contains about the same amount of organic material as does a biofilm of iron oxidisers. This suggestion is based on the observation that sulphur-oxidising bacteria commonly occur intermixed with iron oxidisers in the Äspö HRL.

1.4.3 Fungi

Fungi belong to the Eukaryotes, which are organisms possessing a true nucleus and other cellular organelles. The cell wall of fungi consists mostly of chitin, although cellulose is present in some /Madigan et al. 2003/. Chitin is a polymer of the glucose derivative N-acetylglucosamine (Figure 1-3). It is laid down in micro-fibrillar bundles, just as is cellulose. Fungal cell walls are generally composed of 80–90% polysaccharides, with protein, lipids, polyphosphates, and inorganic ions making up the wall-cementing matrix. In some fungi, other glucans such as mannans, galactosans, and chitosans replace chitin in the fungal cell wall. Fungi often spread via spores, which are very resistant to heat and desiccation.

Moulds

Moulds are filamentous, non-differentiated, multi-cellular fungi that are widely distributed in nature. Moulds grow with hyphae that produce asexual spores called conidia, which give moulds their dusty appearance. Filamentous fungi are responsible for the decomposition of wood, paper, and cloth, for example. Both cellulose and lignin are decomposed by fungi, and lignin is decomposed almost exclusively by wood-rotting fungi. Lignin-decomposing fungi are called “white rot” and cellulose-decomposing fungi are called “brown rot”, since they leave the lignin unchanged. White rot fungi also decompose cellulose /Madigan et al. 2003/.

Yeasts

Yeasts are unicellular fungi. The best-studied yeast is *Saccharomyces cerevisiae*, also called baker’s yeast or brewer’s yeast. /Ekendahl et al. 2003/ reported the existence of yeasts in deep granitic groundwater. It is therefore plausible that yeasts might grow in biofilms on rock surfaces in a repository. The yeasts isolated from Äspö HRL groundwater were closely affiliated with *Rhodotorula minuta* and *Cryptococcus* sp. Many yeast species can live both with and without oxygen, and in anoxic systems use a fermentative metabolism; for example, *S. cerevisiae* produce ethanol anaerobically /Madigan et al. 2003/.

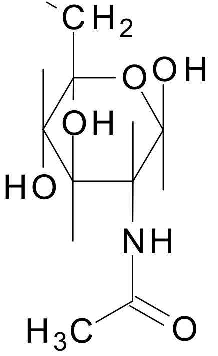

Figure 1-3. *N-acetylglucosamine molecule.*

1.4.4 Photosynthetic organisms

During the repository construction and waste deposition phases, there will be electric light sources along the tunnels in the repository. In most places where the light intensity is high enough and water is present, light-harvesting photosynthetic organisms such as cyanobacteria, green algae and small plants like mosses will grow. This is seen in most tunnels and mines and in the Äspö HRL tunnel and ONKALO in Finland, cyanobacteria are common where the illumination is strong. Mats of mosses are growing on the tunnel floor at some locations, for example, between 1,320 and 1,335 m along the Äspö tunnel.

Cyanobacteria

The cyanobacteria belong to the domain *Bacteria* and are thus organisms without cell nuclei. Many species live as unicellular entities, but filamentous and colony-forming types of cyanobacteria are also common. Some cyanobacteria have cell walls containing peptidoglycan, like those of Gram-negative bacteria. Others have cell walls consisting of cellulose /Nobles et al. 2001/. Many cyanobacteria produce extracellular material resembling envelopes or sheaths that bind groups of cells or filaments together in jelly-like masses.

Since cyanobacteria are photosynthetic, they contain photosynthetic pigments such as chlorophyll a and phycobilins. These pigments are found in large amounts in membrane structures inside the cells /Madigan et al. 2003/.

Many cyanobacteria have nitrogen-fixing ability. In some species, this unique process takes place in specialised cells called heterocysts, the cell walls of which contain large amounts of glycolipids. In nitrogen-fixing cyanobacteria, up to 10% of the cell mass can consist of a nitrogen copolymer of aspartic acid and arginine called cyanophycin.

The chemical composition of the biomass of two cyanobacteria, *Phormidium* sp. and *Spirulina maxima*, indicates that the proportions of the main cell components differ considerably (Table 1-4).

Extracellular polymeric substances of cyanobacteria

The extracellular polymeric substances produced by cyanobacteria vary between species. The sugar components of the extracellular polymeric substance of a pure culture of *Phormidium* 94a were galactose, mannose, galacturonic acid, arabinose, and ribose /Vicente-Garcia et al. 2004/. Another study of four filamentous cyanobacteria and one coccoid, single-celled green algae demonstrated that the extracellular polymeric substance contained 7.5–50.3% protein and 16.2–40.5% carbohydrates /Hu et al. 2003/; these carbohydrates included monosaccharides such as mannose, glucose, galactose, arabinose, and rhamnose.

Unicellular green algae

Green algae should not be confused with cyanobacteria, since they belong to a completely different domain of organisms. Green algae are eukaryotic organisms and thus have a cell nucleus and other cell organelles. In green algae, photosynthesis takes place in organelles called chloroplasts. The cell walls of green algae consist of cellulose and their main carbon reserve materials are starch and sucrose /Perry et al. 2002, Madigan et al. 2003/. The cells themselves contain all the components included in bacterial cells (see Table 3-1).

Unicellular green algae are often found in environments inhabited by cyanobacteria, and are therefore likely found in green biofilms supported by artificial light sources in a repository.

Table 1-4. The percentage chemical composition of *Phormidium* sp. and *Spirulina maxima* biomasses grown on synthetic media (% dry weight) /Cañizares-Villanueva et al. 1995/.

Component	*Phormidium* sp	*Spirulina maxima*
Protein	53.4	45.5
Lipids	9.4	2.5
Carbohydrates	27.5	42.5
Ash	9.7	9.5

Mosses

Mosses are plants without clear differentiation between stems and leaves. They have a cell nucleus and other cell organelles, such as chloroplasts and mitochondria. Their cell walls are composed of cellulose and their carbon reserve material is starch.

Mosses thrive in environments with relatively low light intensity and high humidity. They are not a common part of the biota in tunnels and caves, but have been observed in the Äspö HRL tunnel as mentioned above.

1.5 Biodegradation of organic material produced by microorganisms, fungi, and photosynthetic organisms

The organic material produced by microorganisms will be degraded by other microorganisms during both the construction and deposition periods. During the construction period, most of the degradation will be aerobic, when oxygen is present. The first part of the deposition period in the closed repository will still be aerobic, but within a relatively brief time the oxygen will be consumed by the degradation of organic material and anaerobic processes will become ascendant.

Since the organic material discussed above is produced by living organisms, most of it is in turn degradable by microorganisms, given enough time, if water is available. This conclusion is based on the prominent role of microorganisms in perpetuating life and can be summed up in two principles referred to as Van Niel's postulate /Perry et al. 2002, p. 238/.

- There are microorganisms present in the biosphere that can utilise every constituent part or product of living cells as sources of carbon and/or energy.
- Microbes with this capacity are present in every environmental niche on Earth.

Even if the degradation processes of one organism do not run all the way to carbon dioxide, the organic waste products of this organism will be further degraded by other microorganisms. Fermentation products are good examples of such waste products. Acids, alcohols, and ketones produced during fermentation can act as complexing agents, but will probably be consumed by other microorganisms present in groundwater in the repository long before any radionuclides can possibly escape a canister.

1.6 Organic material in the ventilation air

The air coming from the ground surface via the ventilation system to the repository tunnels will contain organic material, comprising seeds, pollen grains, spores, and dust.

1.6.1 Seeds

Seeds from plants carry all the nutrients necessary for the development of the new plant until a functional root and the first leaves have grown. The chemical composition of seeds therefore differs from that of the vegetative cells of plants.

Seeds from cane berries, *Rubus* spp. such as red raspberry, blackberry, and cloudberry, contain 6–7% protein and 11–18% oil /Bushman et al. 2004/. It is difficult to find the chemical composition of coniferous seeds therefore some other examples are given. The composition varies mostly with the amount of lipids. Most data are found on lipid rich seeds. The seeds of *Xylopia aethiopica*, a rainforest tree, contain 63.65 g of carbohydrates, 12.45 g of protein, and 9.58 g of lipids per 100 g of seed (wet weight) /Barminas et al. 1999/. Another example is dry weight composition of date seeds which contain 5.5% protein, 10–13% of oil and 81–83% carbohydrates /Besbes et al. 2004/. The carbohydrate in seeds is starch, which hydrolyses to sugar in a germinating seed. The composition of the seeds is of minor importance for the safety assessment..

1.6.2 Pollen

Pollen grains contain the male gametophyte produced by angiosperms and gymnosperms. They are the vegetative and generative cells formed after meiosis (i.e. reduction division) of the microspore structure. They are usually between 10 and 100 µm in diameter and are encapsulated in a complex, sculptured cell wall.

Pollen grains contain cellulose and polymers consisting of carotenoids and carotenoid esters. They also contain lipids as an energy source, phytates as a phosphorous source, as well as enzymes, and RNA and DNA /Rowley et al. 1981, Brooks and Shaw 1968/.

1.6.3 Spores

Spores can be both the asexual reproduction bodies of filamentous fungi and the reproduction structures of cryptogams. These spores resemble seeds and pollen grains in their structure and composition.

1.6.4 Organic dust

This kind of dust comes from living organisms and consists of a wide array of different biomolecules.

1.7 Biodegradation of organic material from the ventilation

The seeds, pollen grains, and spores borne by the ventilation air into the repository are products of living organisms and are generally biodegradable. The seeds and spores can germinate in the repository, as in the case of the moss in the Äspö HRL tunnel. Plant material, if not removed, will be degraded by microorganisms when the tunnels are closed and backfilled. One special property of seeds and spores is that the outer part is very resistant. If they do not germinate or are not biodegraded, nothing else will affect them and they will probably remain intact, buried in the repository. Organic dust can also be degraded by microorganisms.

The amounts of seeds, pollen grains, spores, and dust vary over the course of the year with peaks in spring, summer, and early autumn.

1.8 Organic material in construction material

1.8.1 Concrete

Concrete is a cement paste containing various filling materials, all of which are inorganic. To enhance various properties of concrete, several additives can be added to the paste. The degradation of these additives will, given time, generate low-molecular-weight organic materials and eventually carbon dioxide. These additives can be divided into accelerating, retarding, water reducing, superplasticising, and air-entraining agents /Lindvall 2001/.

Accelerators are inorganic salts, the most commonly being $CaCl_2$. There are also alternative accelerators such as 2,2-imino-diethanol, which is biodegradable, at least in aerobic environments.

Retarders are any reactive chemicals that extend the pumping time and/or thickening time of cement slurry; among the more common are powdered, organic retarders, such as lignosulphonates (solid) or organosulphonates (liquid). These compounds are adsorbed to or precipitated on the surface of the cement particles. Cellulose derivatives such as carboxymethyl hydroxyethyl cellulose (CMHEC) have also been used as cement retarders for many years.

Antifoamers or *defoamers* are added to concrete to reduce foaming during mixing operations. These are usually organophosphates.

Water-reducing additives reduce the water content of the cement paste by up to 15%, and the most commonly used ones are lignosulphonates and sulphonated naphthalene or formaldehyde (Figure 1-4). These additives disperse the cement particles because of their dipolar charging properties, and comprise 0–0.1% of concrete by weight.

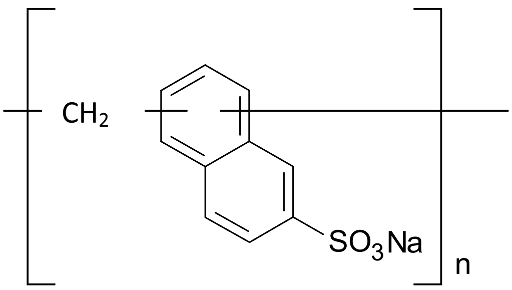

Figure 1-4. Chemical structure of naphthalene sulphonate.

Superplasticisers are the same as the water-reducing additives but have stronger effects. They are used to lower the mix water requirement of concrete and are added in amounts up to 0.4% by wet weight. Superplasticisers can be broadly classified into four groups:

1. sulphonated melamine-formaldehyde condensates (SMFs),
2. sulphonated naphthalene-formaldehyde condensates (SNFs),
3. modified lignosulphonates (MLSs),
4. others, including sulphonic acid esters and carbohydrate esters.

Most available data, however, pertain to SMF- and SNF-based admixtures, which are supplied as either solids or aqueous solutions. One of the most common superplasticisers is sodium-sulphonated naphthalene formaldehyde condensate (Na-SNFC). Other known superplasticisers are polymers of sulphonated melamine formaldehyde, sodium lignosulphate, and gluconic acid /Gascoyne 2002/.

Air-entraining agents (AEA) are used to enhance the resistance to freeze-thaw action by increasing the air content of the concrete. The most commonly used such compounds are acryl sulphonates, alkyl sulphonates, and phenol ethoxylates, which are added in amounts up to 0.01% by wet weight.

1.8.2 Asphalt

Asphalt is composed of a bituminous binding agent and a stone material. The binding agent can be in the form of bitumen, soft bitumen, or bitumen emulsion. Bitumen, which has thermoplastic properties, is a distillation product of crude oil. Road oil and bitumen lacquer are other products used in asphalt, along with bitumen emulsion which is bitumen and water mixed together with an emulsifier /Swedish National Encyclopedia 1990a, b/.

The composition of bitumen is greatly dependent on the source of the crude oil and the distillation procedure, but the main fraction comprises various heavy hydrocarbons. Bitumen is what is often left after refining has yielded gasoline, diesel, and other fuels. This fraction includes very heavy organic molecules that often contain oxygen, sulphur, and nitrogen atoms in their structures /Tissot and Welte 1984/. The chemical composition and physical properties of bitumen are still not fully understood.

1.8.3 Bentonite clay

Bentonite is an inorganic clay currently mined in many places around the world. Its chemical name is hydrated sodium calcium aluminium silicate, and its composition (in wt%) is 9.98% Al, 20.78% Si, 4.10% H, and 65.12% O. The exact composition depends on the origin of the clay.

Chemical analysis data on the organic material in bentonite are very sparse. /Sjöblom 1998/ assumed that bentonite would become contaminated by organic material in the environment in which it was deposited and by the operations involved in mining and transporting it. This organic material was suggested to be humus and the calculated amounts were <0.1 g/kg bentonite from the environment and <0.1 g/kg bentonite from mining operations. There would also be some contamination with lubricants, amounting to 0.5 g/kg bentonite, during the compaction of bentonite into blocks.

Humus is a collective name for organic material in soil and water composed of large organic molecules that are not easily degraded. It has three different fractions, one insoluble fraction, humin, and two soluble fractions, the humic and fulvic acids. Humic acids, which are melanin-like polymeric aromatic phenols and carboxylic acids, can be isolated by lowering the pH. At pH 2, the humic acids start to coagulate and the formed precipitate can be separated by filtration, while the fulvic acids are left in the filtrate. Fulvic acids are small aromatic and aliphatic compounds soluble at all pH values. They have molecular weights between 1,000 and 10,000 and have many carboxyl and hydroxyl groups that make them chemically active /Stevenson 1994/.

It has been suggested that three different types of bentonite clays be investigated for potential use in the repository: Friedland Na^+, Milos Ca^{2+}, and Wyoming Na^+ bentonites /SKB 2004a/. Analyses of the organic carbon content of the Milos and Wyoming bentonites are presented in Table 1-5, where the weight percentage values are recalculated as the mass of organic material. The gross formula used for organic material is CH_2O.

1.8.4 Wood

The main components of wood are cellulose and lignin /Fries 1973/. Cellulose is a linear polymer of D-glucose with beta 1,4-linkages (Figure 1-5), whereas lignin is a polymer with aromatic structures (Figure 1-6).

Wood contains secondary compounds produced by the tree; for example, a characteristic compound produced by the pine tree is pinene, a terpenoid. Tannin is another compound produced by trees and an example of its structure is shown in Figure 1-7 /Hagerman and Butler 1994/.

1.8.5 Steel

Although steel is not organic, the anaerobic corrosion of steel could contribute indirectly to the pool of organic material in a repository. The hydrogen produced in the oxidation–reduction process then acts as an energy source for various microbial processes.

The details of the process of anaerobic corrosion of steel are still under discussion, but most of the reactions involved are well known /Cord-Ruwisch 2000/. The main principle of the corrosion process is that protons from the dissociation of water act as electron acceptors in the oxidation of the iron atoms, resulting in hydrogen formation, see Eq. 1-3.

$$Fe^0 + 2H^+ \rightarrow Fe^{2+} + H_2 \qquad \text{Eq. 1-3}$$

The hydrogen can be used by sulphate-reducing bacteria, which reduce sulphate to hydrogen sulphide by oxidising hydrogen, either by autotrophy, with carbon dioxide fixation, or by heterotrophy, using organic carbon as a carbon source. The produced hydrogen sulphide reacts with the ferrous iron to form iron sulphide, and by that releases more protons. A schematic of the chemical route is shown in Figure 1-8. The energy-transforming reaction in sulphate-reducing bacteria can be written as:

$$4H_2 + SO_4^{2-} + 2H^+ \rightarrow H_2S + 4H_2O \qquad \text{Eq. 1-4}$$

The incorporation of carbon into the cells of sulphate reducers can occur by the addition of carbon dioxide and hydrogen to acetate. The reaction is described in Eq. 1-5.

$$CH_3COO^- \text{- } CoA + CO_2 + H_2 \rightarrow CH_3COCOO^- + CoA + H_2O \qquad \text{Eq. 1-5}$$

The acetate can be produced by the oxidation of hydrogen and the reduction of carbon dioxide made by acetogens, as described in Eq. 1-6.

$$2CO_2 + 4H_2 \rightarrow CH_3COO^- + 2\,H_2O + H^+ \qquad \text{Eq. 1-6}$$

Table 1-5. Amount of organic material in different bentonite clays.

Bentonite material	Organic carbon (wt%)	Organic material (wt%)	Organic material (kg/ton of bentonite)
Milos Ca^{2+}	0.24	0.64	6.4
Wyoming Na^+	0.20	0.5	5.0

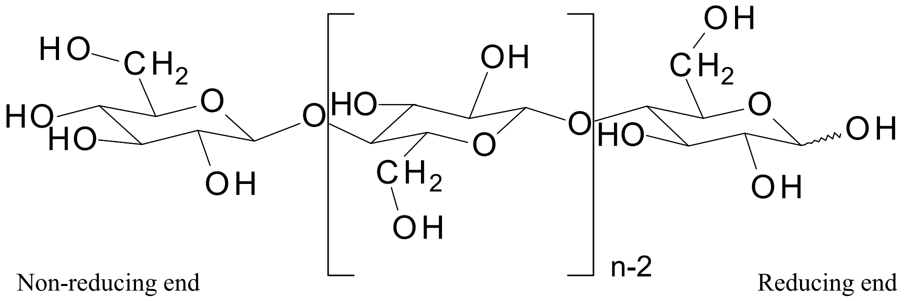

Figure 1-5. The cellulose subunits.

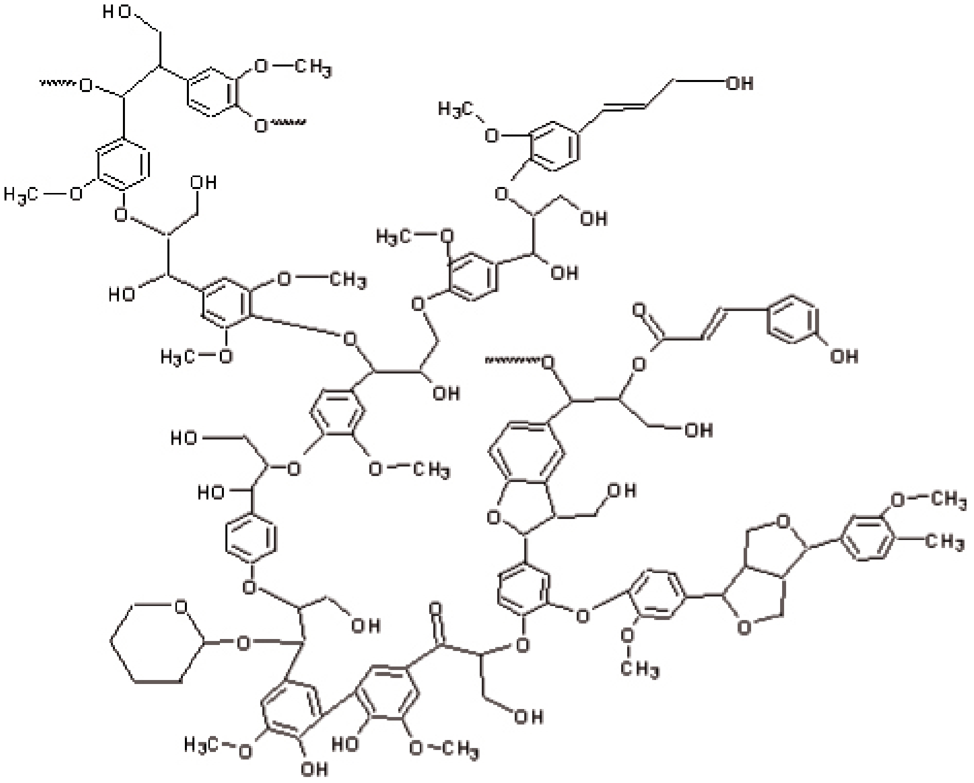

Figure 1-6. Part of the lignin molecule.

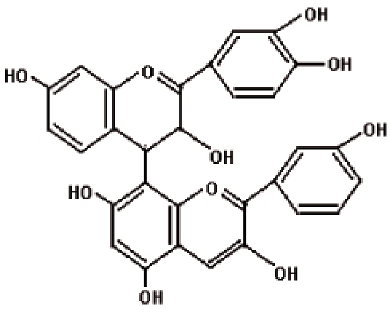

Figure 1-7. Example of a tannin.

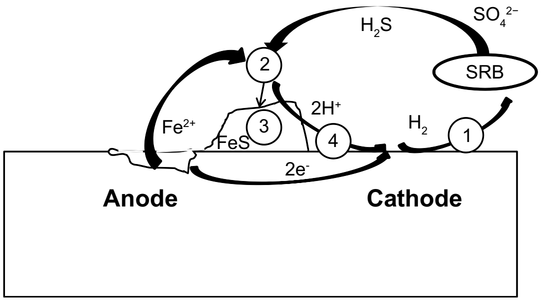

Figure 1-8. *Role of hydrogen-consuming SRB in the anaerobic corrosion of steel. In principle, four different ways to stimulate the corrosion process can be visualised: 1) consumption of cathodic hydrogen (cathodic depolarisation), 2) anodic depolarisation by Fe^{2+} removal, 3) stimulation by formation of an iron sulphide layer, which may be cathodic, and 4) supply of protons to the cathode.*

Acetate production has been reported to occur in Fennoscandian Shield groundwater from the Äspö HRL /Hallbeck and Pedersen 2008/.

In line with the above theory, rock supports and other steel bolts left in the repository may corrode and produce hydrogen, which is a possible energy source for some microorganisms, such as sulphate reducers and acetogens. This will result in the production of hydrogen sulphide and biomass.

1.9 Degradation of organic material in construction materials

1.9.1 Concrete, grout and shotcrete

After hardening, superplasticisers are strongly bound and immobilised within the hydrated phases of the Portland cement /Onofrei et al. 1992/, although relatively little is known of their precipitation in insoluble form /Atkins and Glasser 1992/. It is possible that superplasticisers could decompose in a repository if subjected to radiation /Gascoyne 2002/.

The additives in cement based construction materials are strongly bound to the cement particles. As long as the structures remain intact, these compounds will remain in place. Removing the structures will give rise to concrete dust, however, and this will increase the risk of additive release to the groundwater. Naphthalene sulphonates have been demonstrated to be degraded in aerobic environments /Brilon et al. 1981, Ruckstuhl et al. 2002/.

One problem with the use of organic additives in concrete, grout and shotcrete is that non-polymerised monomer and oligomer additives can dissolve in groundwater and be flushed away from the fracture or borehole where they were supposed to remain. This will increase the amount of material that needs to be used in construction and rock support.

Microbial growth on leakage from grouting has been observed in the Posiva Onkalo tunnel in Olkiluoto /Pedersen et al. 2008/. The leakage of superplasticisers has also be reported during tunnel construction in Switzerland /Ruckstuhl et al. 2002/.

1.9.2 Asphalt

Most components of asphalt are large organic molecules with low water solubility. The most soluble organic molecules are those of the “BTEX” group – benzene, toluene, ethyl-benzene, and xylene – all of which are biodegradable at slow but significant rates. None of these compounds is found in large quantities in asphalt.

1.9.3 Bentonite

The organic material in bentonite is assumed to mainly comprise humic substances. These compounds will probably be bound to clay particles and trapped in the bentonite. A possible problem is the oxidation of organic material in the bentonite by sulphate-reducing bacteria to form carbon dioxide and hydrogen sulphide /Masurat et al. 2010a, b/. If a lubricant will be used during the production of the bentonite blocks this can be available for degradation.

Humic and fulvic acids contain many carboxylic and hydroxyl groups, which make them possible complexing agents. In conclusion, the lack of data on organic material in bentonite calls for more thorough investigation of the amounts and composition of this organic material.

1.9.4 Wood

The cellulose part of wood is readily degraded by both bacteria and fungi. These organisms produce extracellular cellulolytic enzymes, which break the bonds in cellulose to form glucose units /Perry et al. 2002/. Furthermore, cellulose easily degrades under alkaline conditions, commonly occurring in nuclear repositories built of cement. The main degrading reactions of cellulose as well as the main degradation products are described in section 1.15.5.

Lignin, on the other hand, is only degraded by the white rot fungi (basidiomycetes). The degradation involves the action of oxygen, peroxides, and the enzyme ligninase. Though fungi do not use lignin in their metabolism, other microorganisms can use the phenolic degradation products as substrate /Perry et al. 2002/.

Secondary compounds produced by trees, for example, pine tree tannins, are slowly biodegradable. Their chemical structure with many hydroxyl groups makes them potential complexing agents. For example, sawdust was traditionally used to reduce clogging by iron precipitates in drainage systems because of the ability of tannins to bind iron.

Most wood constructions will probably be removed before repository closure. A source of wood material that might be more problematic to eliminate is sawdust from construction work that has ended up in drainage water or become mixed with gravel.

1.10 Diesel and emissions from diesel engines

Diesel is a distillation product of crude oil defined by the temperature interval used in distilling it, i.e. 150–350°C. Given this temperature range, diesel is a very complex mixture of compounds with different properties. The largest part of diesel is alkanes, but diesel also contains polyaromatic hydrocarbons (PAHs), alkyl-benzenes, branched or unsaturated aliphatic hydrocarbons, and sulphur. The exact composition of diesel varies from type to type; the diesel in Sweden with the best environmental specifications is called MK-1 diesel (see Table 1-6; /Swedish National Road Administration 2002/).

The products of complete combustion are carbon dioxide and water. Combustion in diesel engines, however, is generally incomplete. Unless efficient filters and catalysts are installed, there will be particles in emissions from diesel engines. These particles are 0.1–0.3 μm in size; they mostly comprise soot (carbon) from the engine, but also contain water, sulphuric acid, and condensed hydrocarbons.

Diesel that is partly or completely made from organic material, such as waste products from the sugar and/or forest industries, is also available. These diesel products may emit less of the condensed hydrocarbons and sulphuric acids that are found in diesel produced from mineral oil.

Table 1-6. Composition of MK-1 diesel.

Compound	MK-1 diesel
Polyaromatic hydrocarbons (PAHs)	Maximum 200 ppm, often below 80 ppm
Aromatic hydrocarbons	Maximum 5 wt%
Benzene	Not detectible
Olefins	Not detectible
Sulphur	Maximum 10 ppm, often 1–5 ppm
Oxygenates	Not added
Cyclo-aliphates, naphtenes	Not regulated up to 50 wt%

1.10.1 Other particles from vehicles

Tyre wear can also produce particulate matter consisting mostly of rubber, some of which contains PAHs. The chemical name of natural rubber is isoprene. The rubber in tyres is cross-linked with sulphide bridges to enhance the elastomeric properties /Swedish National Encyclopedia 1992b/

Particles from brake linings can be deposited on the rock walls and floor. These particles are mostly metal, mainly copper, and do not contain organic material /Johansson et al. 2004/.

1.11 Degradation of diesel and related emissions

If a diesel spill occurs in a repository during construction, most of the diesel will be pumped out with the infiltrating groundwater. Some of the diesel may adhere to the surfaces of rock material, but it will probably be biodegraded in the presence of oxygen and water. Hydrocarbons have very low solubility in water, and there will be a two-phase system if diesel and water come into contact. Since it is an equilibrium system, there will be a slow partitioning of hydrocarbons into water for a long time. The components of diesel are different kinds of hydrocarbons, most of which are degraded by bacteria in both aerobic and anaerobic environments. In anaerobic environments, diesel hydrocarbons are degraded by sulphate- and/or iron-reducing bacteria /Meckenstock et al. 2000, Annweiler et al. 2002, Eriksson et al. 2005/.

Condensed polyaromatic hydrocarbons, PAHs, are large molecules that are more slowly degraded, especially in anaerobic systems, than are aromatic or aliphatic hydrocarbons, although the anaerobic degradation of PAHs has been reported /Annweiler et al. 2002/.

The organic material from diesel will probably have a negligible influence on the safety assessment, except as a source of oxygen-consuming carbon compounds in microbial degradation. Diesel remaining after the oxygen is consumed will be degraded by anaerobic microorganisms. Aerobic degradation of natural rubber (NR) in tyres has been reported /Tsuchii and Tokiwa 2006/. When NR is mixed with synthetic isoprene rubber only the NR is degraded. Rubber particles will in the repository will probably generally not be degraded by microorganisms. The oxygen will be consumed by more readily degraded OM and the flow of water will decrease considerably when the buffer and backfill is fully saturated.

1.12 Detergents and lubricants

During repository construction, detergents and lubricants will be used at many places.

1.12.1 Detergents

Surfactants are the most widely used ingredients in detergents and degreasing agents. The two most common surfactant groups are linear alkylbenzene sulphonates (LASs) and alkylphenol ethoxylates (APEs) (see Figure 1-9 (a) and (b), respectively). LASs are the quantitatively most important surfactants for household and industry. Surfactants based on plants are also available.

1.12.2 Hydraulic oils and lubricants

As discussed in section 2.3, the main sources of hydrocarbons in the repository are diesel oil and hydraulic and lubricating oils. Oil spills usually contain a complex mixture of aliphatic hydrocarbons, PAHs, and cyclic hydrocarbons.

Lubricants are widely used in all kinds of vehicles and machines. There are both natural, i.e. mineral and plant based, and synthetic lubricants, the main components of which are fats and oils. Various additives can be added to lubricants.

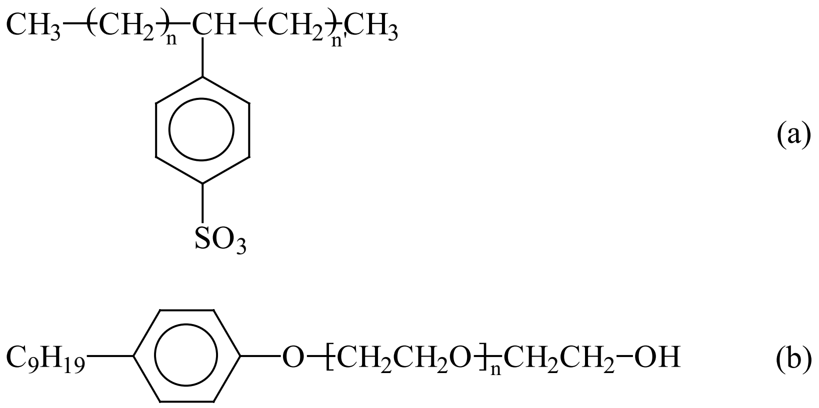

Figure 1-9. *Molecular formula of generic (a) LASs and (b) APEs.*

Dispersants keep sludge, carbon, and other deposit precursors suspended in oil; detergents keep the engine parts clean of deposits; and rust/corrosion inhibitors prevent or control oil oxidation, varnish and sludge formation, corrosion, and viscosity increase. Extreme-pressure (EP), anti-wear, and friction modifiers form protective films on engine parts and reduce wear and tear. Metal deactivators form surface films so that metal surfaces do not catalyze oil oxidation. Pour-point depressants lower the freezing point of oils, assuring free flow at lower temperatures, while antifoamers reduce foam in the crankcase and during blending /Leugner 2005/.

Lubricating oils have a broad profile in the C18–C40 range, with resolved alkanes being almost entirely absent. Common types of lubricating oils include crankcase oil, transmission fluid, hydraulic fluid, and cutting oil. In some hydraulic fluids, the PAH concentrations can be much lower than in most other refined products. However, as stated by /Wong and Wang 2001/, degrading lubricant oils can also be an important source of PAHs.

1.13 Degradation of detergents and lubricants

1.13.1 Detergents

The natural degradation of LASs appears to be very efficient under oxic conditions, reaching levels of 95–99% and with half-times of between a few to hundreds of days. The breakdown of LAS surfactants involves the degradation of the straight alkyl chain, the sulphonate group, and finally the aromatic group /Scott and Jones 2000/. Half-life time reported in the same review was from 1 to 117 days depending on surfactant, environment and temperature.

On the other hand, APEs are less biodegradable than LASs. Estimated biodegradation ratios are between 0–20% /Swisher 1987, Scott and Jones 2000/. In addition, restrictions on the use of APEs have arisen since the discovery that their breakdown products are more toxic to aquatic organisms than are the APEs themselves.

The biodegradation of APEs leads to the shortening of the ethoxylate chains to form alkylphenol carboxylates, leading ultimately to the formation of nonyl- and octylphenols. Nonylphenol (NP) is approximately 10 times more toxic to water living organisms than its ethoxylate precursor and also more persistent to degradation.

Many of the tensides and emulsifiers used formerly had long and heavily branched non-polar chains. Those products are poorly biodegradable and some, for example, alkylphenol ethoxylates, have degradation products that are very stable /Swedish National Encyclopedia 1995/.

Several emulsifiers and tensides made from plant sources or produced by microorganisms are now available on the market. These products are biodegradable and do not produce long-lived metabolites.

1.13.2 Lubricants

Lubricants can also be mineral or plant based. Plant-based fats and oils are more easily degraded, wheras mineral oils degrade slowly.

Degradation is fastest in oxygenated environments, and tensides, emulsifiers, and lubricants will form part of the pool of organic material that contributes to oxygen consumption in the repository after closure.

Of all the organic compounds found in oils or refined petroleum products, the monoaromatic hydrocarbons are the most water soluble /Eganhouse et al. 1996/. Consequently, benzene and its alkylated derivatives are the hydrocarbons most frequently found in groundwater. Once groundwater moves away from the oil source, microbial degradation is the dominant process controlling the fate of these compounds /Eganhouse et al. 1996, Massias et al. 2003/.

It should be noted that no single strain of bacteria has the metabolic capacity to degrade all the components of crude oil. In nature, the biodegradation of crude oil typically involves a succession of species in the consortia of microbes present /Venosa and Zhu 2003/. Petroleum degradation involves progressive or sequential reactions in which certain organisms carry out the initial attack on a petroleum constituent; this produces intermediate compounds subsequently used by a different group of organisms in a sequential process that results in further degradation.

The characterisation of bacterial communities that grow efficiently in the presence of hydrocarbons has been the subject of decades of academic and industrial research /Zobell 1946, Atlas 1977, Foght et al. 1990, Pelletier et al. 2004/. Results have been applied in developing commercial fertilizers, which all involve the addition of nutrients to oily residues and the induction of optimal conditions for hydrocarbon degrading bacteria (HDB). HDB have been found to be active in most marine environments including the Arctic Ocean. Generally, saturated n-alkanes are the most readily degradable components of a petroleum mixture /Zobell 1946, Atlas 1981/. The biodegradation of n-alkanes with molecular weights up to C44 has been demonstrated.

As previously stated, aerobic conditions are generally considered necessary for the extensive degradation of oil hydrocarbons in the environment, since the major degradative pathways of both saturates and aromatics involve oxygenases /Atlas 1981, Cerniglia 1992/. Many studies have demonstrated that oxygen depletion leads to sharply reduced biodegradation activity in marine sediments and in soils /Atlas 1981, Hambrick et al. 1980/.

Although some studies have demonstrated that anaerobic oil degradation occurs only at negligible rates /Atlas 1981/, recent studies have found that anaerobic hydrocarbon metabolism may be an important process under certain conditions /Head and Swannell 1999/. The biodegradation of some aromatic hydrocarbons, such as BTEX compounds, has been clearly demonstrated to occur under a variety of anaerobic conditions. Studies have also demonstrated that in some marine sediments, PAHs and alkanes can be degraded under sulphate-reducing conditions at rates similar to those under aerobic conditions /Caldwell et al. 1998, Coates et al. 1997/. The importance of the anaerobic biodegradation of oil in the environment still merits further study.

One way to minimise oil spill problems over a longer time scale is to use biodegradable hydraulic oil and lubrication greases. Most of these oils are based on biological oils and alcohols from mineral oils. The use of biodegradable hydraulic oils and lubrication greases is an option for the SKB repository /SKB 2004b/, since, in nature, true biological oils based on rapeseed oil degrade within a few weeks, synthetic oils within a few months, and mineral oils within several years under aerobic conditions.

1.14 Organic materials from human activities

1.14.1 Tobacco products

Smoking will be prohibited in the repository during both the construction and deposition phases. Smoking residues will therefore not be present in the repository. However, snuff is widely used in Sweden and will certainly be used by personnel during the construction and deposition periods, especially if smoking is prohibited. Instructions should be given how to handle such tobacco when it is used. Still, a significant amount of the snuff used will certainly be dropped, leaving behind residues.

Snuff is made of dried and ground tobacco leaves to which water and sodium chloride are added. Propylene glycol is added to maintain the humidity level in the snuff, and sodium carbonate is used as a pH regulator. Most snuff residues consist of ground tobacco leaves mixed with user saliva. One portion of snuff weighs approximately 1 g. Nicotine, the predominant alkaloid component of the tobacco plant, is a tertiary amine composed of a pyridine and a pyrrolidine ring. Nicotine exists in two different three-dimensional forms or stereoisomers. Tobacco contains only (S)-nicotine (also called L-nicotine), which is the most pharmacologically active form /Pool et al. 1985/. The nicotine content of snuff is 8–10 mg per portion; when it has been used, only 10–20% of the nicotine is left, that is, between 0.8 and 2 mg. Although the major alkaloid in tobacco is nicotine, there are others as well, including nornicotine, anabasine, myosmine, nicotyrine, and anatabine. These comprise 8–12% of the total alkaloid content of tobacco products /Piade and Hoffmann 1980/. In some varieties of tobacco, nornicotine concentrations exceed those of nicotine /Schmeltz and Hoffmann 1977/.

Tobacco mostly consists of plant cell wall material, which consists of pectic acid and small amounts of galactan and arabane. The cell wall also consists of the polymerisation products of hexoses (i.e. glucose, galactose, and mannose), of uronic acids (i.e. glucuronic acid and galacturonic acid), and of some pentoses. Some parts of the leaf are made of cellulose /Fries 1973/.

1.14.2 Dust from human skin and hair

The dust that comes from the human skin consists mainly of dead cells from the outermost cell layer of the skin and is composed of keratin, a threadlike protein compound /Swedish National Encyclopedia 1992c/. Hair is a special development of the keratin layer of the skin, differing from skin in the higher sulphur content of its keratin /Swedish National Encyclopedia 1992a/. Consequently, dust from humans mostly consists of protein compounds.

1.14.3 Fibres from clothes

The fabrics used in working clothes are made of synthetic fibres and/or cotton. Polyester is the most-used synthetic fibre. Refined and bleached cotton fibre comprises up to 99% cellulose (see cellulose in section 1.15.5).

1.14.4 Urine

Construction personnel must be informed of the importance of keeping the tunnel clean of waste of different kinds. Portable toilets will be available at convenient intervals in the tunnel during construction, but some urination will probably take place in out-of-the-way locations. The main organic components of urine are urea, creatinine, ammonia, uric acid, amino acids, and other inorganic components such as sodium, chloride, sulphate, and carbonate /Lehninger 1982/.

1.14.5 Plastics and paper

Plastics are synthetic materials made from fractions of natural gas or crude oil changed chemically into solid form. These fractions are the building blocks of plastics and they form chemically linked subunits called monomers; long chains of monomers in turn form polymers that compose plastics. There are two basic types of plastic, *thermosetting* and *thermoplastics*. *Thermosetting* plastics are moulded into a permanent shape and thereafter cannot be softened. These plastics are used primarily for multiple-use items, such as dishes and furniture. *Thermoplastics* become soft when exposed to heat and pressure and harden when cooled. Thermoplastics are the most common type of plastic and are used to make a variety of products.

Paper is made of cellulose. Cellulose is a relatively common material in low- and intermediate-level radioactive repositories, due to its presence in daily use objects such as tissues, clothes, and paper. However, its presence poses an important risk to repository assessment, due to the complex binding capacity of polyhydroxy ligands, which is described in section 1.8.4.

1.15 Degradation of organic material from human activities

1.15.1 Tobacco products

The tobacco residues from snuff mainly comprise plant leaf material and will be easily degraded by microorganisms, thus contributing to oxygen consumption in a closed repository.

The destruction of nicotine by microorganisms was investigated by /Batham 1927/, who observed an increase in the nitrate content of soil to which nicotine had been added. He assumed that this increase was due to the conversion of the alkaloid to nitrate by soil bacteria. The quantitative destruction of nicotine in a synthetic medium by individual species of bacteria was studied by /Bucherer and Enders 1942/ (cited in /Hylin 1958/), who isolated three organisms in pure culture. /Wada and Yamasaki 1953/ reported the destruction of nicotine by a microbe as well, while /Tabuchi 1954/ further characterised and classified this microorganism. In addition, /Hylin 1958/ described several organisms isolated in pure culture from tobacco seeds and from soil. Nicotine-decomposing bacteria described by several investigators /Sguros 1954, Conn and Dimmick 1947, Weber 1935, Wenusch 1942, 1943, Bucherer 1942, 1943, Hylin 1958, Frankenburg and Vaitekunas 1955, Wada and Yamasaki 1953, 1954/ have been reported to be both aerobic and anaerobic depending on the microbial species.

The ability to use nicotine as a carbon and nitrogen source seems to be possessed by relatively few microorganisms, since the toxicity of this substrate inhibits the adaptation of many bacteria to using it as a metabolite.

Some degradation products have been identified as products of microbial nicotine degradation, including 6-hydroxynicotine and 6-hydroxy-3-succionoylpyridine /Hylin 1958, Frankenburg and Vaitekunas 1955/. In addition, nicotine oxidation may produce 3-carboxylic pyridine acid or nicotinic acid.

1.15.2 Dust from skin and hair

The proteins in skin and hair will be degraded by microorganisms in the repository, including both aerobic and anaerobic bacteria.

1.15.3 Fibres from clothes

Cellulose fibres will be degraded by microorganisms, including both bacteria and fungi. Polyesters, on the other hand, are relatively resistant to biodegradation. The possible amounts of fibres from clothes are expected to be minor and will most likely be washed out with drainage water from cleaning of the tunnels before closure.

1.15.4 Urine

Urine contamination in the repository positively affects the biodegradation of most organic material, as it constitutes an additional nitrogen source. Nitrogen is generally a limiting nutrient when energy and carbon are available in excess.

The great amount of biodegradable substrate in urine triggers rapid microbial growth, which strongly alters its chemical composition. One dominant reaction is the decomposition or hydrolysis of urea, a microbially catalyzed reaction that produces ammonia and raises the pH above 9.

Urea is the major component of urine. The release of urea to an environment is known to affect the N cycle. Urea hydrolyses rapidly, producing ammonia and releasing OH^-, Urea hydrolysis is catalysed by the large heteropolymeric enzyme urease using a bimetallic nickel centre. Urease occurs in a wide range of organisms, and the organisms able to degrade urea using this enzyme include bacteria, algae, fungi, and higher plants. The primary function of this enzyme is to let the organism use urea as a nitrogen source. Urease, like any enzyme, is a catalyst that increases the chemical reaction rate without being affected itself.

During urea hydrolysis, an unstable intermediate product forms that rapidly degrades to ammonia and carbon dioxide. This intermediate product is $H_2NCOONH_4$ (ammonium carbamate) although, due to its instability, the transformation of urea in soil can essentially be described by the following overall reaction:

$$H_2N\text{-}CO\text{-}NH_2 + 3\ H_2O \rightarrow 2\ NH_4^+ + OH^- + HCO_3^- \qquad \text{Eq. 1-7}$$

During hydrolysis, soil pH can increase to pH > 7 because the reaction requires H^+ from the soil system.

1.15.5 Plastics and paper

In recent years, several of biodegradable thermoplastics have been developed. A plastic is known as biodegradable when living organisms (e.g. fungi, bacteria, and algae) can attack the chemical structure of the polymer to convert it into nutrients. The susceptibility of a plastic to biodegradation depends on its chemical structure, and polyethylene or polyester are just slightly biodegradable, whereas polyurethanes are very biodegradable. A biocompatible polymer is one that does not damage any living organism, either by chemical effects or because of its own biodegradability.

For example, poly tetramethylene succinate, an aliphatic polyester with a high-melting-point, was found to be degradable by some soil bacteria in an aerobic environment /Pranamuda et al. 1995/. In addition, polyurethane, polyester polyurethanes, and polyether polyurethanes were reported to be degraded by microorganisms, especially fungi, in an aerobic environment /Nakajima-Kambe et al. 1999/. The repository environment will become oxygen-depleted relatively quickly after closure, and there are limited supplies of the important nutrients nitrogen and phosphorous, so plastic degradation will probably be very slow. Unless removed in advance, plastics will therefore remain in the repository for a considerable time.

Paper left in the repository will be degraded by microorganisms according to the degradation of cellulose (see section 1.9.4). Cellulose easily degrades under alkaline conditions without the presence of microorganisms. This is a common process assumed to occur in nuclear repositories containing concrete as part of the engineering barriers. There will be some concrete left in repository but the main backfill material will be bentonite and rock so the alkaline degradation of cellulose is not likely to happen to any greater extent. The process will however be described here.

There are three main degrading reactions: i) the peeling-off reaction, ii) the base-catalysed cleavage of glycosidic bonds (alkaline hydrolysis), and iii) the formation of nonreactive end groups through the chemical transformation of reducing end groups to metasaccharinate, which in fact are interrelated /Van Loon and Glaus 1998, Glaus and Van Loon 2004/. Isosaccharinic acid (ISA) is the main product of anaerobic cellulose degradation formed at room temperature /Van Loon and Glaus 1998/. ISA is a general term for 3-deoxy-2-C-(hydroxymethyl)-D-aldonic acids with both α and β diastereoisomers. Its structural formula is shown in Figure 1-10.

Furthermore, ISA has been conclusively identified as a key component of the degradation products of cellulose, being one of the organic materials most responsible for influencing the speciation and mobility of radionuclides in a radioactive waste repository.

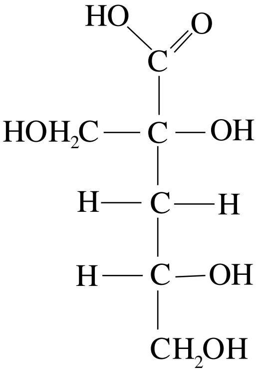

Figure 1-10. *α-Isosaccharinic acid.*

In general, carbon mass balances indicate that the large majority of reaction products found in solution can be explained by the formation of ISA and other low-molecular-weight carboxylic acids. On the other hand, as described elsewhere /Motellier and Charles 1998, Glaus et al. 1999/, some other degradation products of cellulose can be identified at alkaline pH. These degradation products include glycolic acid, lactic acid, acetic acid, formic acid, and metasaccharinate, although together they represent only 10% of the total dissolved organic compounds. All of them are acids with important complexation capacity. Table 1-7 presents the degradation kinetics of cellulose for a final analysis time of 239 days.

1.16 Organic material from blasting and/or rock-drilling

Depending on the method used for construction, i.e. either blasting or rock drilling, the activity will leave a certain amount of debris.

1.16.1 Blasting

Paper and plastic material from cables and detonators are typical blasting residues (see section 1.14.5). In mining considerable amounts of unused explosives might be left. During the construction and before closure of the repository, cleaning procedures will minimise the risk for this and is not included in the calculations of the amounts of foreign materials that will be left in the repository /Lindgren et al. 2009 a, b/.

A Canadian study demonstrated that blasting left nitrate on rock surfaces and in the groundwater /Stroes-Gascoyne and Gascoyne 1998/. Although nitrate is not an organic material, it can affect organic material since it is a crucial nutrient for microorganisms. A supply of extra nitrate will increase the possibility of degradation of the organic material left in a repository. Nitrate is also an electron acceptor for nitrate-reducing microorganisms and will be consumed quickly when the repository starts to become anaerobic (see section 1.3.2).

1.16.2 Rock drilling

Rock drilling machines may leave spills of various hydrocarbons, as discussed above (see section 1.10).

Table 1-7. Degradation kinetics of cellulose. Product concentrations are relative to the total DOC content in %. Data from /Glaus et al. 1999/.

Analytes	7 days	40 days	62 days	119 days	181 days	239 days
Formic	0.60	1.22	1.09	1.19	1.30	1.30
Acetic	1.80	2.66	2.12	2.39	1.93	2.07
Glycolic	0.37	0.71	0.66	0.70	0.83	0.85
Pyruvic	0.20	0.23	0.17	0.11	0.13	0.10
Glyceric	0.46	1.68	1.27	0.90	1.05	0.94
Lactic	1.22	1.79	1.51	1.60	1.63	1.59
Threonic	1.59	1.77	1.32	0.94	0.99	1.16
Isosaccharinic	56.6	85.0	76.1	74.0	78.1	77.1
DOC (mM)	123	317	471	685	784	910

2 Inventory and mass estimates of organic material in the repository area

2.1 Organic material in buffer and backfill in the repository system

As described previously, organic materials will remain in both buffer and backfill. This section compiles estimates of the amount of organic material left in different parts of the repository system at closure. The categorisation follows that used in the report SKB TR-06-21 and is as follows:

- deposition holes,
- deposition tunnels,
- transport tunnels,
- central area,
- shafts and ramps.

In the final summary, the repository area is divided into the *deposition area*, comprising deposition holes and tunnels, and *other areas*, comprising the remaining tunnels, central area, shafts, and ramps. The estimates of the amount of organic material are based on the dimensions of the different parts as described in Layout D2 for Forsmark with 6,000 canisters and Layout D2 for Laxemar, also with 6,000 canisters. Table 2-1 presents the dimensions of Forsmark and Table 2-2 the dimensions of Laxemar.

Table 2-1. Dimensions used for estimating the amount of organic material remaining in the Forsmark repository according to Layout D2 from /Lindgren et al. 2009a/.

Area	Theoretical area (m^2)	Total length (m)	Theoretical volume (m^3)	Rock volume* (m^3)
Deposition holes			1.15×10^5	1.15×10^5
Deposition tunnels	19 (23)*	52,200	1.0×10^{6} a)	1.2×10^{6} a)
Main and transport tunnels	60 (69)*	10,700	5.57×10^{5} b)	6.40×10^{5} b)
Central area		2,900	1.19×10^{5} c)	1.36×10^{5} c)
Shafts and ramps		Shafts: 800 Ramps: 4,700	2.16×10^{5} d)	2.45×10^{5} d)
Total		71,300	2.007×10^6	2.336×10^6

* the extra blasting volume is included

a) including chamfering of the deposition holes

b) including chamfering of deposition tunnels and roofs

c) including rock-loading station

d) including exhaust air shaft in the deposition area.

Table 2-2. Dimensions used for estimating the amount of organic material remaining in the Laxemar repository according to Layout D2 from /Lindgren et al. 2009b/.

Area	Theoretical area (m^2)	Total length (m)	Theoretical volume (m^3)	Rock volume* (m^3)
Deposition holes			1.15×10^5	1.15×10^5
Deposition tunnels	19 (23)*	80,400	1.54×10^{6} a)	1.8×10^{6} a)
Main and transport tunnels	60 (69)* 39 (45)*	14,800	7.7×10^{5} b)	8.9×10^{5} b)
Central area		2,900	1.19×10^{5} c)	1.36×10^{5} c)
Shafts and ramps		Shafts: 800 Ramps: 5,200	2.36×10^{5} d)	2.66×10^{5} d)
Total		104,100	2.780×10^6	3.207×10^6

* the extra blasting volume is included

a) including chamfering of the deposition holes

b) including chamfering of deposition tunnels and roof

c) including rock-loading station

d) including exhaust air shaft in the deposition area.

2.1.1 The deposition holes

Material in the deposition holes

The volume around the canisters in the deposition holes will be filled with bentonite blocks and pellets. Figure 2-1 shows the reference geometry of the copper canister with the surrounding deposited buffer.

The volume of all deposition holes taken together is calculated to be 1.15 × 10^5 m^3 (see Table 2-1). The volume of one copper canister is 4.35 m^3, so the volume of 6,000 canisters is 2.61 × 10^4 m^3; the volume to be filled with bentonite is then 8.89 × 10^4 m^3. If the mean dry density of the bentonite is conservatively set to 1,780 kg/m^3 (see Table 2-3), there will be a total of 1.58 × 10^8 kg of bentonite in the deposition holes, which corresponds to approximately 26 tons of bentonite clay per deposition hole.

Organic material in the deposition holes

The average amount of organic carbon contained in the bentonite used for the repository is reported to be 0.25 wt%, with an upper limit of 0.40 wt% and a lower limit of 0.1 wt% /Karnland et al. 2006/. Using these values, the total amount of organic carbon in the bentonite used in deposition holes will be 3.9 × 10^5 kg (3.9 × 10^2 tons), representing 9.8 × 10^2 tons of organic material. The organic material in bentonite clay is assumed to be mostly humic and fulvic acids.

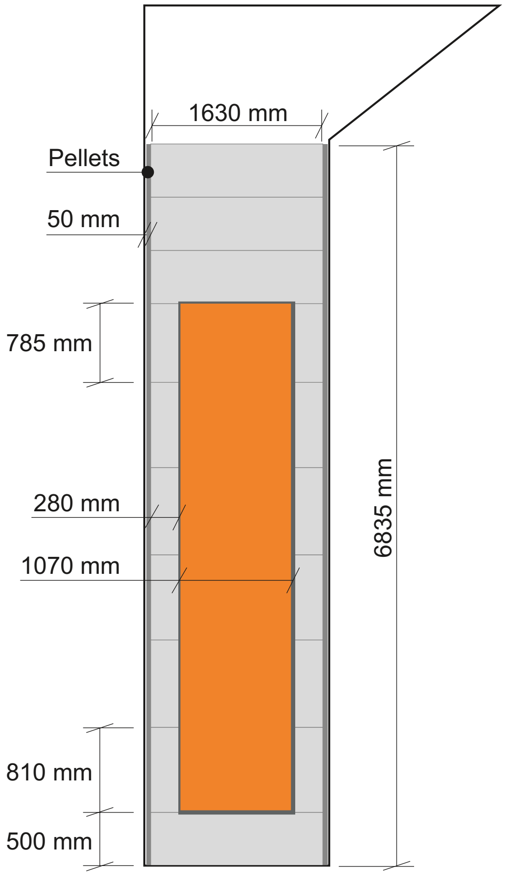

Figure 2-1. *Reference geometry of the deposited buffer /SKB 2010a/.*

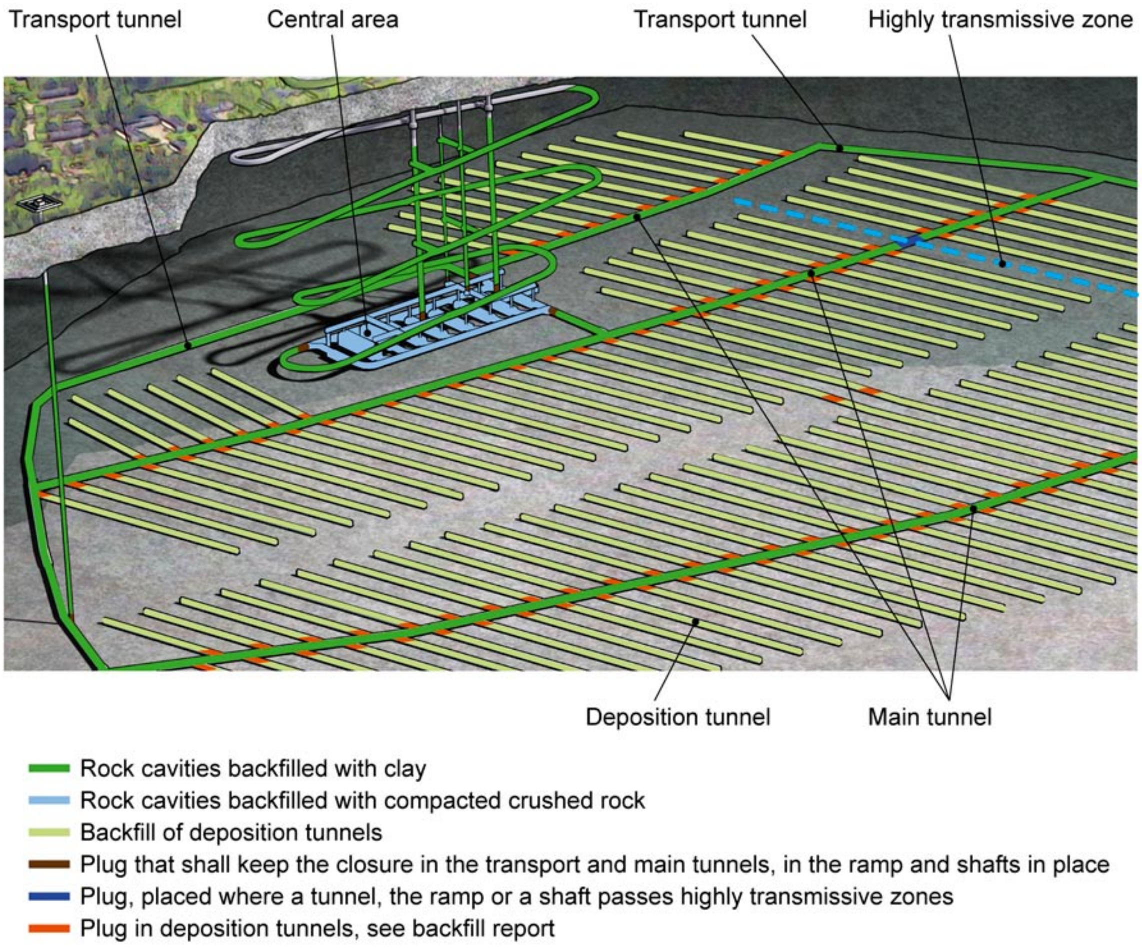

Figure 2-2. *Outline of the reference design for the closure of the main and transport tunnels and the central area. From /SKB 2010b/.*

Table 2-3. Dry densities of the different types of bentonite structures used in a deposition hole in a repository. Data from Buffer Production Report.

Bentonite type	Dry density (kg m^{-3})
Solid blocks	1,705
Ring-shaped blocks	1,770
Pellets	1,820

2.1.2 The deposition tunnels

The reference backfill material in the deposition tunnels will be low-grade bentonite with a 50–60% content of montmorillonite /SKB 2010a/.

There will be one slit at the top of each deposition hole (see Figure 2-1). Bentonite pellets will be poured into the deposition holes through these slits; the total amount of pellets is calculated to be four tons per deposition hole, representing a total of 2.4×10^4 tons for all 6,000 holes.

Material in the deposition tunnels – Forsmark

The total volume of the deposition tunnels in Forsmark, including the extra blasting rock volume, is estimated to be 1.2×10^6 m^3.

Since the dry densities of both bentonite blocks and pellets are the same, i.e. 1,700 kg/m^3, the total mass of bentonite in the deposition tunnels will be 2.0×10^9 kg or 2.0×10^6 tons.

Table 2-4. Dry densities of the different types of bentonite structures used in the deposition tunnels in a repository. Data from /SKB 2010a/.

Bentonite type	Dry density (kg m^{-3})	Amount of the total volume
Solid blocks	1,700	60%
Pellets	1,700	
Bottom bed pellets	1,700	

Organic material in bentonite in the deposition tunnels – Forsmark

The average organic carbon content of the low-grade bentonite is 0.25 wt%. The total amount of organic carbon in the backfill of the deposition tunnels is therefore 5 × 10^6 kg or 5 × 10^3 tons, calculated to represent 1.2 × 10^4 tons of organic material. No exact description is available of the character of the organic material present in the bentonite clay but it is suggested to be humic and fulvic acids.

Material in the deposition tunnels – Laxemar

The total volume of the deposition tunnels in Laxemar, including the extra blasting rock volume, is estimated to be 1.8 × 10^6 m^3.

Since the dry densities of both bentonite blocks and pellets are the same, i.e. 1,700 kg/m^3 the total mass of bentonite will be 3.1 × 10^9 kg or 3.1 × 10^6 tons.

Organic material in bentonite in the deposition tunnels – Laxemar

The average organic carbon content of the low-grade bentonite is 0.25 wt%. The total amount of organic carbon in the backfill of the deposition tunnels is therefore 7.5 × 10^6 kg or 7.5 × 10^3 tons, calculated to represent 1.9 × 10^4 tons of organic material. No exact description is available of the character of the organic material present in the bentonite clay but it is suggested to be humic and fulvic acids.

2.1.3 Plugs in deposition tunnels

The plugs in the deposition tunnels consist of several parts that will contribute in different ways to maintaining plug functions during the different phases of the respository lifetime. The parts of the reference plug are illustrated in Figure 2-3.

Materials in the deposition tunnel plugs

The reference plug consists of a concrete plug, a watertight seal made of bentonite blocks and pellets, a filter made of sand or gravel, concrete beams made of reinforced concrete, and drainage pipes and grouting pipes made of steel and possibly isolated with geotextile. Table 2-5 summarises the amounts of these materials in one plug. Transformable components are such that are considered to be dissolved or transformed in a long-time perspective (Backfill report). Glenium 51 is a polycarboxylic ether hyperplasticer used in concrete to increase the plasticity of the material.

According to the repository designs, there will be 200 deposition tunnels in Forsmark and 300 in Laxemar. Table 2-6 presents the calculated amounts of organic material and steel in the plugs in both sites.

Organic material in the deposition tunnel plugs – Forsmark

The active and organic component of Glenium 51 is polycarboxylate ether, which comprises 35% of the product. The total amount of Glenium 51 used in Forsmark is 140 tons, so the amount of the active component is 49 tons.

Organic material in the deposition tunnel plugs – Laxemar

The total amount of Glenium 51 in Laxemar is 210 tons, which gives 74 tons of the active component.

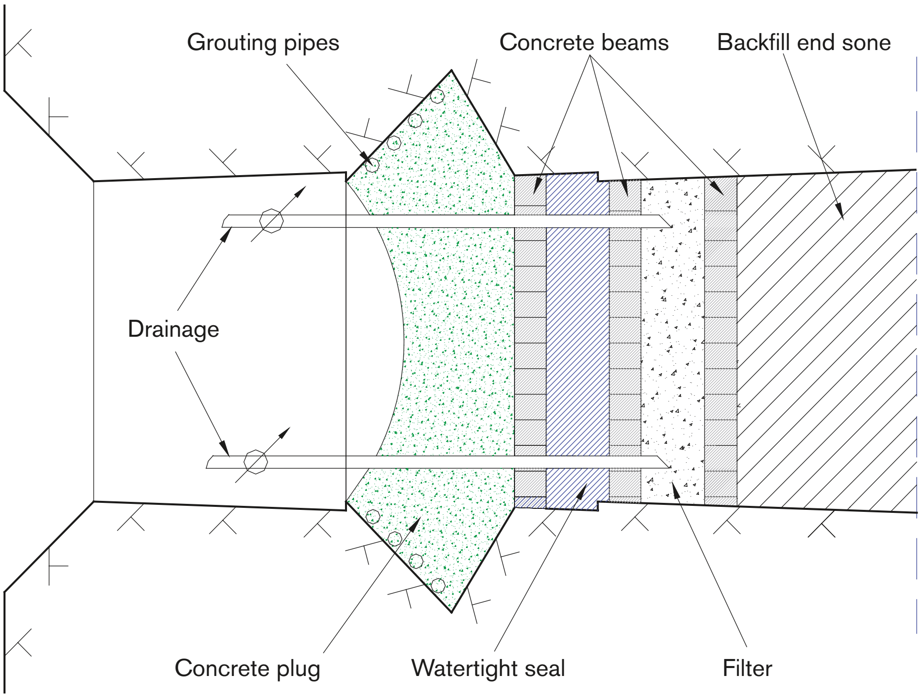

Figure 2-3. *Schematic cross-section of the reference design of the plug. Figure from the Backfill Production Report /SKB 2010a/.*

Table 2-5. Components and substances in the plug and the amounts regarded as stable and unstable. The amounts have been estimated for one plug.

Part of the plug	Substance	Stable [tons]	Transformable [tons]
Concrete plug	Portland cement	12	
	Silica fume, densified		8
	Water		17
	Limestone filler, L25	37	
	Sand, 0–8 mm	104	
	Gravel, 8–16 mm	56	
	Superplasticiser: Glenium 51 (BASF)		0.6
Concrete beams	Portland cement	2.7	
	Silica fume, densified		1.8
	Water		3.7
	Limestone filler, L25	8.3	
	Sand, 0–8 mm	23.3	
	Gravel, 8–16 mm	12.6	
	Superplasticiser: Glenium 51 (BASF)		0.1
	Reinforcement steel		6.8
Filter	Gravel, 8–16 mm	25.3	
Total:		281.2	38

Table 2-6. The amount of organic material and steel in plugs in Forsmark and Laxemar.

Part of the plug	Substance	Forsmark, 200 plugs (tons)	Laxemar, 300 plugs (tons)
Concrete plug	Superplasticiser: Glenium 51 (BASF)	120	180
Concrete beams	Superplasticiser: Glenium 51 (BASF)	20	30

2.1.4 The main and transport tunnels

According to the Closure Production Report /SKB 2010b/, the final design of the backfill for the main and transport tunnels has not yet been definitely determined, but the same reference design as for the deposition tunnels, using low-grade bentonite, is proposed.

Material in the main and transport tunnels – Forsmark

The total volume, including extra blasting rock, of the main and transport tunnels in Forsmark is 6.45×10^5 m^3 and the dry density of the blocks and pellets of bentonite used totals 1,700 kg/m^{-3}. The total amount of bentonite in the main and transport tunnels will thus be 1.1×10^9 kg or 1.1×10^6 tons.

Organic material in bentonite in the main and transport tunnels – Forsmark

The average organic carbon content of the low-grade bentonite is 0.25 wt%. The calculated total amount of organic carbon in the backfill of the main and transport tunnels is 2.8×10^6 kg or 2.8×10^3 tons, calculated to represent 7.0×10^3 tons of organic material. No description is available of the character of the organic material present in the bentonite clay.

Material in the main and transport tunnels – Laxemar

The total volume, including extra blasting rock, of the main and transport tunnels in Laxemar is 8.9×10^5 m^3 and the dry density of the blocks and pellets of bentonite used is 1,700 kg/m^{-3}. The total amount of bentonite in the main and transport tunnels will thus be 1.5×10^9 kg or 1.5×10^6 tons.

Organic material in bentonite in the main and transport tunnels – Laxemar

The average organic carbon content of the low-grade bentonite is 0.25 wt%. The calculated total amount of organic carbon in the backfill of the main and transport tunnels is 3.8×10^6 kg or 3.8×10^3 tons, calculated to represent 9.5×10^3 tons of organic material. No description is available of the character of the organic material present in the bentonite clay.

2.1.5 The central area

The central area will be filled with crushed rock without the addition of any material containing organic substances.

2.1.6 Ramps and shafts

The ramps and shafts will be filled with a bentonite mixture to a depth of 200 m. The composition is supposed to be the same as in the deposition tunnels and the bentonite density is 1,700 kg/m^3.

Material in the ramps and shafts – Forsmark

The total volume, including extra blasting rock, of the ramps and shafts in Forsmark is 2.45×10^5 m^3 and the volume that is to be filled with bentonite is 1.4×10^5 m^3. Assuming bentonite of the same dry density as that used in the deposition, main, and transport tunnels, 1,700 kg/m^{-3}, the total amount of bentonite used in the ramps and shafts will be 2.4×10^8 kg or 2.4×10^5 tons.

Organic material in bentonite in the ramps and shafts – Forsmark

The average organic carbon content of the low-grade bentonite is 0.25 wt%. The calculated total amount of organic carbon in the backfill of the main and transport tunnels is 6.0×10^5 kg or 6.0×10^2 tons, calculated to represent 1.5×10^3 tons of organic material. No description is available of the character of the organic material present in the bentonite clay.

Material in the ramps and shafts – Laxemar

The total volume, including extra blasting rock, of the ramps and shafts in Laxemar is 2.66×10^5 m^3 and the volume that is to be filled with bentonite is 1.6×10^5 m^3. Assuming bentonite of the same dry density as that used in the deposition, main, and transport tunnels, 1,700 kg/m^{-3}, the total amount of bentonite used in the ramps and shafts will be 2.7×10^8 kg or 2.7×10^5 tons.

Organic material in bentonite in the ramps and shafts – Laxemar

The average organic carbon content of the low-grade bentonite is 0.25 wt%. The calculated total amount of organic carbon in the backfill of the main and transport tunnels is 6.8×10^5 kg or 6.8×10^2 tons, calculated to represent 1.7×10^3 tons of organic material. No description is available of the character of the organic material present in the bentonite clay.

2.1.7 Top sealing

The top sealing is assumed to extend to a depth of 200 m and will be backfilled with blast rock and moraine as described in the Closure Production Report /SKB 2010b/. From 200 to 50 m beneath the ground surface, the volume will be filled with crushed rock with a maximum particle size of 200 mm, with a size distribution of the Fuller type. The uppermost 50 m of the ramps and shafts will be backfilled with very coarse crushed rock that must be effectively compacted to minimise self-compaction. Above this level, masonries of well-fitted rock blocks forming a "jigsaw puzzle" will be constructed. Silica concrete will be poured into the joints for mechanical sealing (description from the Closure Production Report /SKB 2010b/).

2.1.8 Total amounts of organic material in buffer and backfill

Table 2-7 and Table 2-8 summarise the amounts of organic material in the buffer and backfill in Forsmark and Laxemar, respectively; also included is the amount of organic material in concrete used in the deposition tunnels.

Table 2-7. Amount of bentonite and organic material in the Forsmark repository according to Layout D2.

Area	Theoretical volume (m^3)	Bentonite dry density (kg m^{-3})	Amount of bentonite (kg/tons)	Organic material (kg/tons)
Deposition holes	8.7×10^4 (with bentonite)	Mean: 1,780	$1.6 \times 10^8/1.6 \times 10^5$	$9.8 \times 10^5/9.8 \times 10^2$
Deposition tunnels	1.2×10^6	1,700	$2.0 \times 10^9/2.0 \times 10^6$	$1.2 \times 10^7/1.2 \times 14^3$
Main and transport tunnels	6.4×10^5	1,700	$1.1 \times 10^9/1.1 \times 10^6$	$7.0 \times 10^6/7.0 \times 10^3$
Central area	1.19×10^5	–	–	–
Shafts and ramps (with bentonite)	1.4×10^5	1,700	$2.4 \times 10^8/2.4 \times 10^5$	$1.5 \times 10^6/1.5 \times 10^3$
Deposition plugs				$4.9 \times 10^4/4.9 \times 10^1$
Total	2.2×10^6	–	$3.5 \times 10^9/3.5 \times 10^6$	$2.2 \times 10^7/2.2 \times 10^4$

Table 2-8. Amount of bentonite and organic material in the Laxemar repository according to Layout D2.

Area	Theoretical volume (m^3)	Bentonite dry density (kg m^{-3})	Amount of bentonite (kg/tons)	Organic material (kg/tons)
Deposition holes	8.7×10^4 (with bentonite)	Mean: 1,780	$1.6 \times 10^8/1.6 \times 10^5$	$9.8 \times 10^5/9.8 \times 10^2$
Deposition tunnels	1.8×10^6	1,700	$3.0 \times 10^9/3.0 \times 10^6$	$1.9 \times 10^7/1.9 \times 10^4$
Main and transport tunnels	8.9×10^5	1,700	$1.5 \times 10^9/1.5 \times 10^6$	$9.5 \times 10^6/9.5 \times 10^3$
Central area	1.19×10^5	–	–	–
Shafts and ramps (with bentonite)	1.6×10^5	1,700	$2.7 \times 10^8/2.7 \times 10^5$	$1.7 \times 10^6/1.7 \times 10^3$
Deposition plugs				$7.4 \times 10^4/7.4 \times 10^1$
Total	3.0×10^6	–	$4.9 \times 10^9/4.9 \times 10^6$	$3.1 \times 10^7/3.1 \times 10^4$

2.2 Organic material in underground constructions

2.2.1 Rock support

When opening and constructing the repository, different types of supporting material will be used to reinforce the construction and maintain worker safety.

To prevent minor spalling, the roof will be supported with shotcrete in all underground cavities except the deposition area, tunnels, and holes. Rock bolts and wire mesh will be used to provide additional support; the rock bolts will be secured with grout.

Shotcrete

The composition of the shotcrete used for rock support in Forsmark and Laxemar and the total amounts of the shotcrete ingredients are summarised in Table 2-9 and Table 2-11, respectively, in terms of both the volume and mass of the various ingredients. Table 2-10 and Table 2-12 list the shotcrete additives together with the active substances and the amounts of organic material. Shotcrete is assumed to remain on the rock surfaces of the underground cavities. The organic materials will contribute to the total amount of organic material remaining in the repository.

Concrete in bolt holes

Rock bolts will be fastened with grout. Table 2-13 and Table 2-14 summarise the composition of the grout used in Forsmark and Laxemar, together with the total amounts of the grout additives. If the bolts are left in the repository, the grout with additives will remain as well. The only organic component of the grout is the superplasticiser Glenium 51 from BASF. Up to 35% of this superplasticiser consists of polycarbonate ether.

In Forsmark, 2.5 tons of Glenium 51 will be used; with an organic component of 35%, 0.9 tons of organic material will remain in the rock bolt holes.

From Table 2-14 it can be seen that in Laxemar, 4.4 tons of the superplasticiser Glenium 51 will be used in the grout for setting the rock bolts. With an organic fraction of 35% in this additive, this will add 1.5 tons to the organic pool.

Table 2-9. The assessed quantities of rock support structural elements in shotcrete in Forsmark required for the reference design at completion of the final repository facility.

Subsidiary material	Kg m^{-3} (from SKB)	Ramps/access area		Central area, including ventilation		Deposition area, including SA01 and SA02*	
		ton	m^3	ton	m^3	ton	m^3
Water	158	240	240	236	236	768	768
Ordinary Portland cement,	210	319	152	313	149	1,020	486
Silica fume	140	213	101	209	99	680	324
Coarse aggregate, 5–11 mm	552	840	494	823	484	2,682	1,577
Natural sand, 0–5 mm	1,025	1,559	917	1,528	899	4,979	2,929
Quartz filler (0–0.25 mm) or limestone filler (0–0.25 mm)	250	380	190	373	186	1,215	607
Superplasticiser: Glenium 51 (BASF)	3	4.6	4.6	4.5	4.5	15	15
Air-entraining agent: AER S (SIKA)	2.5	3.8	3.8	3.7	3.7	12	12
Accelerator: Sigunit (SIKA) or AF2000 Mapequick (Rescon)	7%	0.1	0.1	0.1	0.1	0.3	0.3

* SA01 and SA02 are exhaust shafts.

Table 2-10. The amount of organic material in shotcrete additives used in Forsmark.

Organic additive	Total amount in deposition area (tons)	Total amount other areas (tons)	Active component	Part of total amount (%)	Total organic additive in deposition area (tons)	Total organic additive in other areas (tons)
Superplasticiser: Glenium 51 (BASF)	15	9	Polycarboxylate ether	35	5.2	3.2
Accelarator: Sigunit (SIKA)	0.3	0.2	Na_2CO_3 $CaCO_3$ $Ca(OH)_2$ $AlNaO_2$	25–35 25–35 20–25 10–20	–	–
Alternative accelerator: AF2000 Mapequick (Rescon)	0.3	0.2	2,2-imino-diethanol	5–10	0.015–0.03	0.01–0.02
			$Al_2(SO_4)_3$ and other aluminium salts	30–60	–	–
Air-entraining agent: AER S (SIKA)	12	7.5	Sulphonic-acid-C14–16-alkane-hydroxy and C14–16-alkene-sodium salts	1–5	0.12 –0.6	0.08–0.38
			Disodium lauryl ethoxy sulpho-succinate	1–5	0.12–0.6	0.08–0.38
			Fatty alcohol (C8–C10) alkyl glucoside	1–5	0.12–0.6	0.08–0.38
			Fatty acid alcohol C10–C14	3–5	0.36–0.6	0.22–0.38

Table 2-11. The assessed quantities of rock support structural elements in shotcrete in Laxemar required for the reference design at completion of the final repository facility.

Subsidiary material	Kg m^{-3} (from SKB)	Ramps/access area		Central area, including ventilation		Deposition area, including SA01 and SA02*	
		ton	m^3	ton	m^3	ton	m^3
Water	158	327	327	372	372	1,197	1,197
Ordinary Portland cement	210	435	207	494	235	1,590	757
Silica fume	140	290	138	329	157	1,060	505
Coarse aggregate, 5–11 mm	552	1,143	672	1,299	764	4,180	2,459
Natural sand, 0–5 mm	1,025	2,122	1,248	2,412	1,419	7,762	4,566
Quartz filler (0–0.25 mm) or limestone filler (0–0.25 mm)	250	518	259	588	294	1,893	947
Superplasticiser: Glenium 51 (BASF)	3	6.2	6.2	7.1	7.1	23	23
Air-entraining agent: AER S (SIKA)	2.5	5.2	5.2	5.9	5.9	19	19
Accelerator: Sigunit (SIKA) or AF2000 Mapequick (Rescon) (wet weight%)	7%	0.1	0.1	0.2	0.2	0.5	0.5

*SA01 and SA02 are exhaust shafts.

Table 2-12. The amount of organic material in shotcrete additives used in Laxemar.

Organic additive	Total amount in deposition area (tons)	Total amount other areas (tons)	Active component	Part of total amount (%)	Total organic additive in deposition area (tons)	Total organic additive in other areas (tons)
Superplasticiser: Glenium 51 (BASF)	23	13	Polycarboxylate ether	35	8.0	4.6
Accelarator: Sigunit (Sika)	0.5	0.3	Na_2CO_3 $CaCO_3$ $Ca(OH)_2$ $AlNaO_2$	25–35 25–35 20–25 10–20	–	–
Alternative accelerator: AF2000 Mapequick (Rescon)	0.5	0.3	2,2-imino-diethanol $Al_2(SO_4)_3$ and other aluminium salts	5–10 30–60	0.03–0.05 –	0.02–0.03 –
Air-entraining agent: AER S (SIKA)	19	11	Sulphonic-acid-C14–16-alkane-hydroxy-and C14–16-alkene-sodium salts	1–5	0.19–0.95	0.11–0.55
			Disodium lauryl ethoxy sulpho-succinate	1–5	0.19–0.95	0.11–0.55
			Fatty alcohol (C8–C10) alkyl glucoside	1–5	0.19–0.95	0.11–0.55
			Fatty acid alcohol C10–C14	3–5	0.6–0.95	0.33–0.55

Table 2-13. The assessed quantities of rock support structural elements in bolt holes required for the reference design at completion of the final repository facility of Forsmark.

Subsidiary material	Kg/m^{-3} (from SKB)	Ramps/access area		Central area, including ventilation		Deposition area, including SA01 and SA02	
		ton	m^3	ton	m^3	ton	m^3
Cement	340	15	7.2	29	13.9	172	82
Silica	226.7	10	4.8	19	9.2	115	54.7
Water	266.6	12	12	23	23	135	135
Glenium 51	4	0.2	0.2	0.3	0.3	2	2
Quartz filler	1,324	118	59	113	56.7	671	335

Table 2-14. The assessed quantities of rock support structural elements in bolt holes required for the reference design at completion of the final repository facility of Laxemar.

Subsidiary material	Kg/m^{-3} (from SKB)	Ramps/access area		Central area, including ventilation		Deposition area, including SA01 and SA02	
		ton	m^3	ton	m^3	ton	m^3
Cement	340	40	19	31	15	301	143
Silica	226.7	26	13	21	10	200	95
Water	266.6	31	31	25	25	236	236
Glenium 51	4	0.5	0.5	0.4	0.4	3.5	3.5
Quartz filler	1,324	154	77	122	61	1,171	585

Total amount of iron in rock support structural elements left in the repository

As described in section 1.8.5, iron can indirectly contribute to the production of organic material and to sulphate reduction by promoting hydrogen production during anaerobic corrosion. In Forsmark, the total amount of steel in rock bolts used for rock support is calculated to weigh 402 tons and in wire mesh to weigh 5.6 tons, giving a total of 407.6 tons of steel (see Table 2-15). If iron is taken to comprise 97% of this amount of steel, the total amount of iron will be 395 tons. Rock bolts and wire mesh are supposed to remain after repository closure in rock walls and in roofs of the underground cavities.

In Laxemar 1,070 tons of steel will be used for rock support structural elements and left in the repository at closure (see Table 2-16). If iron is taken to comprise 97% of this amount of steel, the total amount of iron will be 1,038 tons.

Hydrogen production from the anaerobic corrosion of steel.

According to the theory described in section 1.8.5, hydrogen will be produced in the oxidation-reduction reaction with protons according to Eq. 2-1.

$$Fe^0 + 2H^+ \rightarrow Fe^{2+} + H_2 \qquad \text{Eq. 2-1}$$

The produced hydrogen can then be used as an energy and electron donor by anaerobic microorganisms.

The theoretical maximum quantity of hydrogen that can be produced is equimolar to the amount of iron. The values for Forsmark and Laxemar are compiled in Table 2-17, including for partial hydrogen production if only 50, 10, 1 and 0.1% of the iron oxidises produce hydrogen.

Table 2-15. The assessed quantities of rock support structural elements required for the reference design in Forsmark at completion of the final repository facility.

Subsidiary material	Ramps/access area ton	Central area, including ventilation ton	Deposition area, including SA01 and SA02 ton
Rock bolts (l = 3 m, d = 25 mm, ρ = 4 kg/m^{-3})	28	54	320
Wire mesh (1.7 kg/m^2)	–	–	5.6

Table 2-16. The assessed quantities of rock support structural elements required for the reference design in Laxemar at completion of the final repository facility.

Subsidiary material	Ramps/access area ton	Central area, including ventilation ton	Deposition area, including SA01 and SA02 ton
Rock bolts (l = 3 m, d = 25 mm, ρ = 4 kg/m^{-3})	73	58	558
Wire mesh (1.7 kg/m^2)	–	–	381

Table 2-17. Calculated theoretical amount of hydrogen that can be produced by anaerobic corrosion of iron in rock support structural elements in the repositories. See text for explanation.

	Iron		Hydrogen 100%	Hydrogen 50%	Hydrogen 10%	Hydrogen 1%	Hydrogen 0.1%
Site	Mass (tons)	Amount of substance (mol)	Amount of substance (mol)	Amount of substance (mol)	Amount of substance (mol)	Amount of substance (mol)	Amount of substance (mol)
Forsmark	395	7.1×10^6	7.1×10^6	3.6×10^6	7.1×10^5	7.1×10^4	7.5×10^3
Laxemar	1,038	1.9×10^7	1.9×10^7	9.5×10^6	1.9×10^6	1.9×10^5	1.9×10^4

Table 2-18 presents the same calculations for the theoretical production of acetate by acetogenic bacteria. Values for partial production are also presented, if only 50, 10, 1 and 0.1% of the total iron amount is anaerobically corroded and the resulting hydrogen is used to produce acetate.

Table 2-18 presents a range of production values for organic material in the form of acetate. The highest value is the amount that can be produced if all the iron is corroded, whereas the lowest value is the amount that will be produced if 0.1% of the iron is anaerobically corroded and the resulting hydrogen is used for acetate production. Table 2-19 summarises the theoretical amounts of acetate produced in the deposition area and elsewhere in the repository.

2.2.2 Grouting

The specifications for the buffer, backfill, and closure state that water inflow because of groundwater drawdown must be minimised due to the risk of piping erosion and environmental impact. The reference design contains an assessment of the amount of grouting that must be used to meet the inflow requirements. Pre-grouting, a normal measure in tunnels, shafts, and deposition tunnels, is done concurrently with rock excavation. Transmissive fractures with small apertures may require post-grouting with silica sol. If the requirements for piping erosion are not fulfilled in a tunnel section, post-grouting with cement or silica sol is done after rock excavation is completed in the section of concern.

The estimated quantities of grouting material that will remain in the rock after excavation are taken from the Grouting Report by /Ellison and Magnusson 2009/. Details concerning water flow, drilling, number of boreholes, etc. are found in this report. Table 2-20 and Table 2-21 summarise the composition of grout proposed for different parts of the repositories at Forsmark and Laxemar, respectively.

The only grout additive that contains organic matter is the superplasticiser, which in this case contains naphthalene sulphonate. For Forsmark, calculated using data from Table 2-20, the total amount of plasticiser will be between 30 and 120 tons. Between 30 and 50% of the superplasticiser is the active component, i.e. polymerised naphthalene sulphonate. With a 30% content, the total amount of polymerised naphthalene sulphonate can vary from 9 to 36 tons and with a 50% content, from 15 to 60 tons. Consequently, the total quantity of naphthalene sulphonate could vary from 9 to 60 tons, depending on the need for grouting in the underground cavities.

Table 2-18. Calculated theoretical amount of acetate that can be microbially produced from hydrogen produced by anaerobic corrosion of iron in rock support structural elements in the repositories. See text for explanation.

	Iron		Acetate 100%	Acetate 50%	Acetate 10%	Acetate 1%	Acetate 0.1%
Site	Mass (tons)	Amount of substance (mol)	Amount of substance (mol)/mass (tons)	Amount of substance (mol)/mass (tons)	Amount of substance (mol)/mass (tons)	Amount of substance (mol)/mass (tons)	Amount of substance (mol)/mass (tons)
Forsmark	395	7.1×10^6	1.8×10^6/ 1.0×10^2	9×10^5/ 0.55×10^2	1.8×10^5/ 1.1×10^1	1.8×10^4/ 1.1	1.8×10^3/ 0.11
Laxemar	1,038	1.9×10^7	4.75×10^6/ 2.8×10^2	2.4×10^2/ 1.43×10^2	4.75×10^5/ 2.85×10^1	4.75×10^4/ 2.85	4.75×10^3/ 0.285

Table 2-19. Theoretical amounts of acetate produced from 100% corrosion of iron in rock support structural elements.

	Forsmark			Laxemar		
	Deposition holes (tons)	Deposition tunnels (tons)	Other areas (tons)	Deposition holes (tons)	Deposition tunnels (tons)	Other areas (tons)
Percentage of iron corroded						
100%	–	84	21	–	245	34

Table 2-20. Estimated quantities of grout materials and extent of drilling remaining in the rock mass after excavation of the various underground cavities in Forsmark.

Element	Material	Ramps/shafts (tons)1)		Central area (tons)		Deposition area	
		Min	Max	Min	Max	Min	Max
Cement grouting	Water	350	1,360	3	10	110	440
	Portland cement2)	330	1,310	3	8	100	400
	Silica fume3)	460	1,790	4	11	140	550
	Superplasticiser 4)	23	90	0.2	0.5	7	30
Chemical grouting	Silica	105	410	3	9	160	640
	NaCl solution	21	85	0.6	2	30	130
Volume of grout (m^3)		910	3,580	10	30	405	1,620
Drilling	Number of holes	7,980		300		17,160	
	Drilling length (km)	205		6		343	

1) Including exhaust shafts SA01 and SA02.

2) Sulphate-resistant ordinary Portland cement with d_{95} on 16-μm type.

3) Dispersed silica fume, microsilica with d_{90} = 1-μm type. The density is to be 1,350–1,410 kg m^3 and 50% ± 2% of the solution is to consist of solid particles.

4) Superplasticiser, naphthalene sulphonate based, density approximately 120 kg/m^3

Table 2-21. Estimated quantities of grout materials and extent of drilling remaining in the rock mass after excavation of the various underground cavities in Laxemar.

Element	Material	Ramps/shafts (tons)1)		Central area (tons)		Deposition area	
		Min	Max	Min	Max	Min	Max
Cement grouting	Water	120	470	40	120	620	2,500
	Portland cement2)	90	360	30	85	540	2,200
	Silica fume3)	120	490	40	120	740	3,000
	Superplasticiser 4)	6	25	2	6	40	150
Chemical grouting	Silica	110	420	40	110	4,000	16,000
	NaCl solution	20	80	8	20	790	3,200
Volume of grout (m^3)		350	1,400	120	350	5,000	20,500
Drilling	Number of holes	8,900		5,100		180,000	
	Drilling length (km)	220		100		3,700	

1) Sulphate-resistant ordinary Portland cement with d_{95} on 16-μm.

2) Dispersed silica fume, microsilica with d_{90} = 1-μm. The density is to be 1,350–1,410 kg/m^3 and 50% ± 2% of the solution is to consist of solid particles.

3) Superplasticiser, naphthalene sulphonate based, density approximately 120 kg/m^3.

Similar estimates of the amount of organic material in grout in Laxemar can be made using data from Table 2-21. The total amount of plasticiser will be between 48 and 181 tons. Between 30 and 50% of the superplasticiser is the active component, i.e. polymerised naphthalene sulphonate. With a 30% content, the total amount of polymerised naphthalene sulphonate can vary from 14 to 54 tons and with a 50% content, from 24 to 90 tons. Thus, in Laxemar, the total quantity of naphthalene sulphonate in grout could vary from 14 to 90 tons depending on the need for grouting in the underground cavities.

2.3 Foreign and stray organic material left in the repository

Apart from construction material, other organic material will remain in the repository at the time of closure. Estimates of the remaining amounts of various stray materials are found in /Lindgren et al. 2009a, b/, respectively. The routines and methods to be used to remove the installations and constructions and to clean the deposition tunnels and other rock cavities have not yet been determined, making it difficult to estimate the remaining amounts of materials. There will be restrictions on how much foreign material can be left, especially in the deposition tunnels. In most cases, a level of 1% of the used material is used in estimating the amount of material remaining at time of closure. Here, only the estimated amounts of stray material that can contribute to the pool of organic material are compiled and the possibility of biodegradation is discussed.

2.3.1 Organic materials in stray material left in the repository

Tables 2-23 and 2-24 compile all the estimated amounts of foreign material that could be left in the repository. A short summary of the materials is presented below. A more detailed description of the material and the calculations underlying the estimated quantities are found in the background reports /Lindgren et al. 2009a, b/.

Table 2-22 present the amount of organic material that will be left in the repository. In the case of iron, the *total* amount is presented, and not recalculated as related organic material. The repositories are divided into the *deposition area*, i.e. the deposition holes and tunnels, and *other areas*, i.e. the main and transport tunnels, central area, ramps, and shafts.

Plastics

Some plastic residues will come from detonators, mostly from the polypropylene coating of the electric cables. The estimates are made assuming that 1% of the used material will be left in the repository at closure.

Anchoring bolts

Anchoring bolts are used for ventilation channels, tubes, and cables. These are made of steel, which is 97% iron. In the deposition area, the bolts will be of an expander type that can be removed at closure. In the other areas, the bolts will be attached to the rock wall with grout. It is calculated that 0.5 kg of each 2-kg bolt will remain at closure.

The organic material in concrete is the added superplasticiser, which is suggested to be Glenium 51 (BASF). Its main component is modified polycarboxylate ether and it is added at a rate of 4 kg/m^3 or 0.4% by volume of the concrete; 35% of Glenium 51 consists of the active organic compound.

Table 2-22. The amount of organic material in foreign material left in the repositories in Forsmark and Laxemar at closure.

Total amount (kg)	Forsmark		Laxemar	
	Deposition area	Other areas	Deposition area	Other areas
Polypropylene	100	130	100	82
Polycarboxylate ether	0	81	0	97
Iron	4.8×10^4	6.8×10^4	7.6×10^4	9.0×10^4
Modified lignin sulphonate	0	7	0	10
Polycarboxylate ether	4	5	4	7
Bitumen	0	30	0	36
Rubber	2	14	2	14
Hydraulic and lubrication oil	200	80	360	110
Urea	6	2	6	2
Wood	10	4	10	4
Organic materials in human waste	60	19	60	19
Organic materials from ventilation	10	8	10	8

Table 2-23. Total quantity of foreign material left in the Forsmark repository.

Material		Amount of foreign material left in the Forsmark repository after closure (kg)					
		Deposition holes	**Deposition tunnels**	**Main and transport tunnels**	**Central area**	**Ramps and shafts**	**Total quantity**
Detonators with cables	Zinc	*	3×10^{1}	1×10^{1}	3	5	4.8×10^{1}
	Plastics	*	1×10^{2}	8×10^{1}	2×10^{1}	3×10^{1}	2.3×10^{2}
Explosives	NO_x	*	7	4	1	2	1.4×10^{1}
	Nitrate salts	*	2×10^{3}	1×10^{3}	2×10^{2}	4×10^{2}	3.6×10^{3}
Anchoring bolts	Steel	*	5×10^{4}	4×10^{4}	1×10^{4}	2×10^{4}	1.2×10^{5}
	Concrete	0	0	3×10^{4}	8×10^{3}	2×10^{4}	5.8×10^{4}
Roads	Concrete	0	0	2×10^{3}	6×10^{2}	1×10^{3}	3.6×10^{3}
	Asphalt**	0	0	0	0	5×10^{2}	5×10^{2}
Concrete constructions	Concrete	*	3×10^{3}	2×10^{3}	6×10^{2}	1×10^{3}	6.6×10^{3}
Tyres		*	1.5	8.5	1.7	3.4	5.1×10^{1}
Exhaust	NO_x	*	7	3×10^{2}	9	2×10^{1}	3.36×10^{2}
	Particles		0	0	0	0	0
Hydraulic and lubricating oil		*	2×10^{2}	5×10^{1}	1×10^{1}	2×10^{1}	2.8×10^{2}
Diesel		*	*	*	*	*	*
Battery acid		*	*	*	*	*	*
Metal chips and hard metal		*	5	1	0.3	1	7.3
Wooden chips	Wood	*	10	2	1	1	1.4×10^{1}
Corrosion products	Rust	*	4×10^{3}	184	50	95	4.3×10^{3}
Urine	Urea	*	6	1	0	1	8
Other human waste	Organic materials	*	6×10^{1}	1×10^{1}	3	6	7.9×10^{1}
Ventilation air	Organic materials	*	10	5	1	2	1.8×10^{1}

* Limited amounts, difficult to quantify.

** Asphalt will only be present in the ramps.

Table 2-24. Total quantity of foreign material left in the Laxemar repository.

Material		Amount of foreign material left in the Laxemar repository after closure (kg)					
		Deposition holes	Deposition tunnels	Main and transport tunnels	Central area	Ramps and shafts	Total quantity
Detonators with cables	Zinc	*	8	4	1	1	1.4×10^{1}
	Plastics	*	1×10^{2}	60	8	1.7×10^{1}	1.8×10^{2}
Explosives	NO_x	*	10	6	1	2	1.9×10^{1}
	Nitrate salts	*	3×10^{3}	2×10^{2}	2×10^{2}	5×10^{2}	3.9×10^{3}
Anchoring bolts	Steel	*	8×10^{4}	6×10^{4}	1×1^{4}	2×10^{4}	1.7×10^{5}
	Concrete	0	0	4×10^{4}	8×10^{3}	2×10^{4}	6.8×10^{4}
Roads	Concrete	0	0	3×10^{3}	6×10^{2}	1×10^{3}	4.6×10^{3}
	Asphalt**	0	0	0	0	6×10^{2}	6×10^{2}
Concrete constructions	Concrete	*	2×10^{3}	3×10^{3}	6×10^{2}	1×10^{3}	6.6×10^{3}
Tyres		*	2	8	2	3	1.5×10^{1}
Exhaust	NO_x	*	10	60	11	24	1.05×10^{2}
	Particles	*	0.1	1	0.1	0.3	1.5
Hydraulic and lubricating oil		*	4×10^{2}	70	10	30	5.1×10^{2}
Diesel		*	*	*	*	*	*
Battery acid		*	*	*	*	*	*
Metal chips and hard metal		*	8	2	0.3	0.6	1.1×10^{1}
Wooden chips	Wood	*	10	2	0.4	0.8	1.3×10^{1}
Corrosion products	Rust	*	6×10^{3}	2×10^{2}	50	1×10^{2}	6.4×10^{3}
Urine	Urea	*	6	1	0.2	0.5	8
Other human waste	Organic materials	*	61	11	2	5	$7.\ 9 \times 10^{1}$
Ventilation air	Organic materials	*	11	5	0.8	2	1.9×10^{1}

* Limited amounts, difficult to quantify.

** Asphalt will only be present in the ramps.

Roads

It is suggested that the roads in the deposition tunnels be made of macadam; these roads will be removed before closure. Neither concrete nor asphalt will be used in this area.

The ramps, transport tunnels, main tunnel, and central area will have roads paved with concrete, which should be removed. As the concrete will be placed on a bed of macadam, it should be possible to remove almost all the concrete at closure. Some small pieces and dust will be left and it is assumed that 0.01% of the road concrete will remain. The roads on the ramps will be asphalt paved. These roads will also be removed, and it is estimated that 0.01% of this asphalt will remain at closure. The organic fraction of asphalt is 6% bitumen, the rest being macadam.

Concrete constructions

Minor amounts of concrete will remain from constructions built to facilitate drilling and deposition of the canisters. It is estimated that 0.01% of this concrete will remain at closure. The organic fraction of the concrete is the superplasticiser, which is suggested to be Glenium 51 (as in the concrete used with the anchoring bolts). Its main component is modified polycarboxylate ether and it is added at a rate of 4 kg/m^3 or 0.4% by volume of concrete; 35% of Glenium 51 consists of the active organic compound.

Wear of tyres

A very limited amount of rubber from tyres will remain in the repository, since most of the particles and dust will be pumped out with the drainage water. It is assumed that 1% of the calculated total amount of particles and dust from tyres will remain in the deposition tunnels and other tunnels and areas.

Emissions from diesel engines

The exhaust from diesel engines consists mostly of carbon dioxide and water, but also contains some particles, soot, and nitrogen oxides. It is calculated that approximately 1% of these total diesel-related emissions of particles and nitrogen oxides will remain in the repository.

Detergents and degreasing agents

The detergents and degreasing agents will mostly be used in the central area, and there will be systems to take care of the waste. There will be no spills of these materials during normal operations and only limited amounts will remain at closure.

Hydraulic and lubrication oil

Many vehicles and machines used in construction and waste deposition incorporate hydraulic equipment. Breakage of hydraulic tubes is relatively common during use and repairs. To minimise spillage of hydraulic oil, it is possible to:

- equip machines with containers for collecting spilt oil,
- absorb larger spills from drilling machines using absorbant material,
- use biodegradable oils based on rapeseed oil.

It is calculated that 1% of the spilt oil will remain by the time of closure.

Diesel

Spills of diesel can occur from leaking fuel tanks, tubes, and pumps in vehicles and when refuelling vehicles. Refuelling will be done in the central area at a tank station equipped with an oil separator and flooding protection. Diesel spills in other areas will probably be pumped out with the drainage water. Overall, only a minor amount of diesel will remain in the repository.

Metal chips and hard metal

The most important components of hard metal are bismuth carbide and cobalt. Residues of hard steel will come mainly from drilling machines and excavators. Most of it will be drained out with the drainage water and it is assumed that 1% will remain. This amount will not contribute any organic material of significance to the repository.

Wooden chips

Wooden chips from construction work will remain on the floor and in the rock debris ("syltan"). Most of them will be drained out with drainage water, and it is calculated that 1% of the wood will remain.

Organic material from human activities

Urea

Due to restrictions on urination in the repository area, only a minor amount of urea will remain. Most of any urine will be drained out; since the nitrogen of urea is a major nutrient for microorganisms, it will probably be readily consumed during the operational phase of the repository.

Other human waste

This is assumed to consist mostly of snuff mixed with saliva. There should of course be restrictions concerning spitting snuff in the tunnels. Calculations in /Lindgren et al. 2009a, b/ assume that all the snuff used will be spat out in the tunnel and that most of this will be pumped out with the drainage water. The amount of organic material in the "other human waste" is calculated assuming that 1% of the material will remain at repository closure.

Ventilation

Regarding organic material, it is assumed that 1% of the particles in the ventilation air will remain in the repository. Only part of this consists of organic material, such as spores.

2.4 Organic material in microbial biofilms

In Table 2-25 and Table 2-27, the surface areas of the different parts of the Forsmark and Laxemar repositories are presented, respectively. If it is assumed that microbial biofilms will grow on approximately 5% of the wall and ceiling area, Table 2-26 and Table 2-28 present the calculated amounts of organic material in such biofilms in the Forsmark and Laxemar repositories, respectively. This is an estimation based on experiences from work in tunnel environments by the author. This factor is difficult to define with confidence because it differs between the groundwater environments and is also due to the cleaning of walls and ceiling before closure of the repository. The true factor has to be determined during the construction phase

Table 2-25. Dimensions of the repository based on layout D2, Forsmark.

	Deposition tunnels	Main and transport tunnels	Central area	Access ramp
Width (m)	10	8.5 (mean value)	6.5 (mean value)	5.5
Height (m)	4.8	6.3 (mean value)	5.5 (mean value)	6
Length (m)	52,200	10,700	2,900	4,700
Total area (without roadways) (m^2)	1,023,000	257,800	50,750	82,300
5% of the total area (m^2)	51,100	11,300	2,500	4,100

Table 2-26. Organic material in a 1-mm-thick biofilm of varied density in Forsmark.

	Density 10 (kg/m^{-3}) Organic material: 10 g m^{-2}	Density 25 (kg/m^{-3}) Organic material: 25 g m^{-2}	Density 75 (kg/m^{-3}) Organic material: 75 g m^{-2}
Deposition tunnels (kg)	511	1,278	3,833
Main and transport tunnels (kg)	113	282	848
Central area (kg)	25	62	188
Access ramp (kg)	41	102	308
Total amount (kg)	690	1,724	5,180

Table 2-27. Dimensions of the repository based on layout D2, Laxemar.

	Deposition tunnels	Main and transport tunnels	Central area	Access ramp
Width (m)	10	8.5 (mean value)	6.5 (mean value)	5.5
Height (m)	4.8	6.3 (mean value)	5.5 (mean value)	6
Length (m)	80,400	14,800	2,900	4,700
Total area (without roadways) (m^2)	1,576,000	312,280	50,750	82,300
5% of the total area (m^2)	78,800	15,600	2,500	4,100

Table 2-28. Organic material in a 1-mm-thick biofilm of varied density in Laxemar.

	Density 10 (kg/m^{-3}) Organic material: 10 g m^{-2}	Density 25 (kg/m^{-3}) Organic material: 25 g m^{-2}	Density 75 (kg/m^{-3}) Organic material: 75 g m^{-2}
Deposition tunnels (kg)	788	1,970	5,910
Main and transport tunnels (kg)	156	390	1,170
Central area (kg)	25	62	188
Access ramp (kg)	41	102	308
Total amount (kg)	1,010	2,524	7,576

2.5 Estimates of the amounts of organic material left in the repository system

2.5.1 Estimates of the total amounts of organic material in buffer, backfill, rock-support structural elements, and grouting

Table 2-29 presents the total amounts of organic material contained in buffer, backfill, rock-support structural elements, and material used in tunnel construction and grouting in both sites. For steel, a maximum corrosion scenario is assumed and the produced hydrogen gas is recalculated to acetate synthesised by microorganisms as described in section 1.8.5. The table is divided according to the three different areas of the repository:

1. the deposition holes,
2. the deposition tunnels,
3. other areas.

"Other areas" include transport and main tunnels, the central area, ramps, and shafts. The bentonite is the major source of organic material in all areas. (See discussion below on the likelihood of dissolution of this material). The second largest source is the superplasticiser in shotcrete.

Table 2-29. Organic material in buffer, backfill, rock-support structural elements, and grouting.

	Forsmark			Laxemar		
	Deposition holes (tons)	Deposition tunnels (tons)	Other areas (tons)	Deposition holes (tons)	Deposition tunnels (tons)	Other areas (tons)
Buffer and backfill:						
Bentonite	9.8×10^2	1.2×10^4	8.5×10^3	9.8×10^2	1.9×10^4	1.2×10^4
Rock support:						
Shotcrete:						
super-plasticiser	–	5.2	3.2	–	8.0	4.6
alternative accelerator	–	0.02–0.03	0.01–0.02	–	0.03–0.05	0.02–0.03
air-entraining agent	–	<2.4	<1.5		<3.8	<2.2
Rock bolts:						
super-plasticiser	–	0.7	0.2	–	1.2	0.32
acetate from iron corrosion*	–	0.084–84	0.02–21	–	0.24–240	0.03–34.2
Grouting:						
super-plasticiser	–	2.1–9.0** 3.5–15***	7.0–27** 12–45***	–	12–18** 20–75***	2.4–4** 9.3–16***

* See section 1.8.5

** With 30% of the active component

*** With 50% of the active component

2.5.2 Estimates of the total amounts of organic material in foreign material in the repository

Table 2-30 presents the total amounts of organic material originating from so-called foreign material. The organic material from steel is calculated as acetate produced by microorganisms (see section 1.8.5). None of this material is to remain in the deposition holes.

2.5.3 Calculations of water volumes in the repository

To calculate the concentrations of various organic materials in a closed and water-saturated repository, the porosities of the different backfill materials must be estimated. The void ratio, e, is related to the porosity, $\o$, by the following equation:

$$\o = e\,(1 + e)^{-1} \qquad \text{Eq. 2-2}$$

Porosity is described as the fraction of the void space included in the material and is defined by the following ratio:

$$\o = V_v / V_T \qquad \text{Eq. 2-3}$$

where V_v is the volume of void space and V_T is the total or bulk volume of material including the solid and void components.

Table 2-31 and Table 2-32 present the calculated volumes of water in the different areas of the repositories in Forsmark and Laxemar, respectively. The background information comes from /Pusch 2008/.

Since the intention is to fill the central area and upper part of the ramp with crushed rock having a Fuller-type size distribution, which allows for the most effective compaction of the material, the lowest porosity of crushed rock cited by /Pusch 2008/ was used in the water volume calculations for these areas.

It is assumed that 82% of the volume is filled with bentonite blocks and 17% is filled with pellets in the deposition tunnels, and this proportion is also used for the shafts and ramps. Of the total volume of the shafts and ramps, 2.45×10^5 m^3, 1.4×10^5 m^3 will be filled with bentonite. Of this volume, 1.1×10^5 m^3 will be filled with blocks and 2.4×10^4 m^3 with pellets.

Table 2-30. Organic material in stray material to be left in the repository.

	Forsmark			Laxemar		
	Deposition holes (tons)	**Deposition tunnels (tons)**	**Other areas (tons)**	**Deposition holes (tons)**	**Deposition tunnels tons)**	**Other areas (tons)**
Detonators						
Plastics	–	0.10	0.13	–	0.10	0.08
Anchoring bolts						
Steel**	–	0.013–13	0.018–18	–	0.020–20	0.023–23
Concrete	–	–	0.08	–	–	0.1
Roads						
Concrete	–	–	0.01	–	–	0.01
Asphalt	–	–	0.03	–	–	0.04
Concrete constructions						
Concrete	–	0.003	0.005	–	0.002	0.007
Tyres						
Rubber	–	*	*		*	*
Particles	–	*	*		*	*
Hydraulic and lubrication oil	–	0.2	0.08	–	0.36	0.11
Metal chips**	–	*	*	–	*	*
Wooden chips	–	0.01	0.004	–	0.01	0.004
Urine						
Urea	–	0.006	0.002	–	0.006	0.002
Other human waste						
Organic materials	–	0.06	0.02	–	0.06	0.02
Ventilation air						
Organic materials	–	0.001	0.008	–	0.001	0.007

* Negligible amount.

** See section 1.8.5 for calculations.

Table 2-31. The calculated volumes of water to fill the areas in the Forsmark repository, assuming total saturation for the different backfill concepts under study.

	Backfill material	Void ratio	Porosity	Total rock volume (m^3)	Water volume (m^3)
Deposition tunnels	Bentonite:				
	blocks,	0.35	0.259	82%: 9.8×10^5	2.5×10^5
	pellets	1.45	0.592	17%: 2.0×10^5	1.2×10^5
	Total			1.2×10^6	
Main and transport tunnels	Bentonite:				
	blocks,	0.35	0.259	82%: 5.2×10^5	1.3×10^5
	pellets	1.45	0.592	17%: 1.1×10^5	6.5×10^4
	Total			6.4×10^5	
Central area	Crushed rock	0.54	0.350	1.36×10^5	4.8×10^4
Shafts and ramps	Bentonite:				
	blocks	0.35	0.259	1.4×10^5	3.6×10^4
	pellets	1.45	0.592	2.4×10^4	1.4×10^4
	Crushed rock	0.54	0.35	1.05×10^5	3.7×10^4
	Total			2.45×10^5	
			Total volume of water		7.0×10^5

Table 2-32. The calculated volumes of water to fill the areas in the Laxemar repository, assuming total saturation for the different backfill concepts under study.

	Backfill material	Void ratio	Porosity	Total rock volume (m^3)	Water volume (m^3)
Deposition tunnels	Bentonite:				
	blocks	0.35	0.259	82%: 1.5×10^6	3.9×10^5
	pellets	1.45	0.592	17%: 3.1×10^5	1.8×10^5
	Total			1.8×10^6	
Main and transport tunnels	Bentonite:				
	blocks,	0.35	0.259	82%: 7.3×10^5	1.9×10^5
	pellets	1.45	0.592	17%: 1.5×10^5	8.9×10^4
	Total			8.9×10^5	
Central area	Crushed rock	0.54	0.350	1.36×10^5	4.8×10^4
Shafts and ramps	Bentonite:				
	blocks,	0.35	0.259	1.3×10^5	3.4×10^4
	pellets	1.45	0.592	2.7×10^4	1.6×10^4
	Crushed rock	0.54	0.35	1.0×10^5	3.5×10^4
	Total			2.66×10^5	
			Total volume of water		9.8×10^5

2.6 Evolution with time: degradation processes

Of the stray material in a repository, the main organic compounds left are carbohydrates and hydrocarbons. The presence of water is crucial for all degradation processes. When the bentonite has gained its eventual swelling pressure, the flow of water will decline dramatically over the areas where the stray materials will be found. The exception is compounds that are water soluble and have been transported with the groundwater flow during the construction and filling-up of the repository. Most of the degradation will occur over the first 100 years. Below follows a description of each group of material.

2.6.1 Organic material in bentonite

Most of the organic material left in the repository will be the organic material in bentonite. There are difficulties finding information about the composition of this material. /Stevenson 1994/ states that humic substances can be retained by clay minerals in two different ways:

1. by attachment to clay mineral surfaces, such as through cation and anion exchange, bridging by polyvalent cations (clay-metal-mineral-humus), H-bonding, or van der Waals force,
2. by penetration into the interlayer spaces of expanding-type clay minerals.

Most of the organic material in bentonite clay is probably very closely attached to the clay, so when the clay has reached its swelling pressure, very little of the organic material will be available for dissolution into the groundwater.

The release of organic materials from bentonite could increase if the bentonite loses its swelling properties due to changes in the chemical environment (e.g. a large decrease in salinity or a major pH change) or in physical conditions (e.g. freezing). In such cases, the organic materials in bentonite could become more soluble in the groundwater and thus more available for microbial degradation.

2.6.2 Concrete additives

There are several reports of the leakage of additives, mostly plasticisers or superplasticisers, from concrete. Most such leakage will occur as the non-polymerised monomers of the plasticisers. Many of the different types of additives are degraded by microorganisms, at least in the initial stages of degradation, but can also be degraded to complete mineralisation. Most relevant studies have been done under aerobic conditions. Since grouting will be ongoing during construction, the environment near the tunnel wall will be aerobic; very soon after repository closure, however, the groundwater will become anaerobic.

Any degradation of concrete additives will occur early on, from the time of construction to 100 years after repository closure, and then mainly of the monomers of these substances.

2.6.3 Degradation of carbohydrates

Urea

As described in section 1.15.4, urea will very rapidly be hydrolysed and degraded into ammonium and carbon dioxide. The degradation process starts immediately and the ammonium will be consumed by microorganisms. By the time of closure, only a small fraction will be left, which will be degraded within a period of weeks to months.

Other human waste

Materials such as hair, skin, fibres from clothes, and some snuff are included here. These materials will be disposed randomly in small amounts and will thus have a large surface area. These materials are biologically degradable and their decomposition will start immediately. By the time of closure, only a small amount will be left, which will be degraded in approximately 1–5 years.

Organic materials from ventilation

These materials are small-sized particles with a large surface area to volume ratio, which enhances degradation. These materials are mostly biological in origin and will be degraded in approximately 1–5 years.

Wooden chips and sawdust

The degradation of wood is dependent on specialised fungi and oxygen. Larger pieces are more difficult to degrade because of their small surface area to volume ratio. There are several examples of wood that has been preserved for very long time. One extreme example is the wood of the Dunarobba “fossil forest” in Italy, which is 1.5 million years old. This wood was buried in sediment and clay, which protected it from degradation, presumably by reducing the flow of water and thereby the transport of electron acceptors and nutrients. Another example is mosses. In mosses in Sweden, intact wood can be found that has been deeply buried for up to several thousand years. This is because no electron acceptors other than carbon dioxide have been present so no degradation has occurred. Carbon dioxide can only be used as an electron acceptor by methanogens and acetogens, and they cannot use long-chained carbohydrates as a substrate.

A situation of almost no water transport is comparable to that of the repository once the bentonite clay is fully saturated. How long wood can remain intact depends on the function of the bentonite; if there is no water flow, wood can persist for hundreds of thousands of years.

One group of compounds present in wood is the degradation-resistant tannins (see section 1.9.4). Their molecular structure includes many hydroxyl groups, making them possible complexing agents.

2.6.4 Degradation of hydrocarbons

Plastics

The degradation of plastic depends greatly on the size of the pieces. Small pieces and dust of plastic will be degraded faster than large pieces due to their large surface area to volume ratio. Other important factors affecting plastic degradation are water flow and thus the transport of nutrients and electron acceptors. Plastic degradation will be fast during the operational phase of the repository, because of available flowing water and oxygen. Plastics left near bentonite in the closed and saturated repository will probably remain intact for several thousand years.

Rubber

Rubber is even less degradable than plastic. Residues of rubber dust from tyres will be minimal, and degradation in groundwater will probably be negligible. Any degradation that does occur will, like all other degradation processes, be dependent on flowing water. Rubber left surrounded by or near bentonite will probably remain intact for several thousand years.

Hydraulic and lubrication oils

These compounds are more soluble in water than are plastics or rubber, although their solubility is low. During the operational phase and the first years after closure when water is flowing and oxygen is present, degradation of hydraulic and lubrication oils will occur, especially if biodegradable types are used. In addition, degradation will occur under anaerobic conditions as long as there is flowing water.

Asphalt

The more soluble compounds in asphalt will degrade as long as water is flowing in the repository. Most of the heavy hydrocarbons will remain in the asphalt and not degrade for several thousand years.

2.6.5 Time scale for the degradation of organic materials in the deposition tunnels in Forsmark and Laxemar

Estimations of the degradation of organic materials have been made by classifying the different types of organic substances according to the following categories: organic materials in buffer, backfill, and construction material; organic materials in construction materials classified as foreign; and carbohydrates and hydrocarbons in stray material. For the purposes of the estimations, the repository has been divided into two areas:

Deposition holes: Since the expected amounts of these chemical substances in stray materials in the deposition holes are negligible or limited and not quantified, they are disregarded here.

Deposition tunnels and other areas: The total potential volume of water assumed to fill the deposition tunnel cavities (see Table 2-31 and Table 2-32) have been calculated by taking into account both the total volume of these systems and the total porosity of the different backfill concepts.

From information given in sections 2.1.8, 2.5.1, and 2.5.2, it is possible to calculate the expected amounts of construction and grouting material and stray materials likely to remain in the deposition tunnels classified according to three categories (i.e. carbohydrate, hydrocarbons, and surface active substances), together with their estimated concentrations (in kg/m^3). They include:

- carbohydrate substances from humus, wooden chips, ventilation air, and human wastes,
- hydrocarbons from, for example, oils, degreasing compounds, plastics, and rubber.

Table 2-33 to 2-47 present the estimated amounts of various materials remaining in the repository after degradation for up to 120,000 years.

In the case of carbohydrates, it is assumed that compounds that can degrade will do so over the first 100 years, if there is enough flowing water. Any remaining compounds will probably still remain after 120,000 years.

Table 2-33. Estimated amounts of organic material from buffer, backfill, and construction material remaining after different periods in deposition tunnels in Forsmark.

Compound	Amounts left (tons)	Left after 100 years (tons)	Left after 1,000 years (tons)	Left after 10,000 years (tons)	Left after 120,000 years (tons)	Left (tons)
Bentonite: humic and fulvic acids*	5.0×10^3	?	?	?	?	?
Concrete additives	<8.3	<7.5	<7.5	<7.5	<7.5	<7.5
Acetate from anaerobic steel corrosion**	0.08–84	0	0	0	0	0

* No assumption because of limited knowledge of the organic materials in bentonite.
** Assuming 0.1–100% corrosion of the iron.

Table 2-34. Estimated amounts of organic material from construction material classified as foreign, remaining after different periods in deposition tunnels in Forsmark.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Concrete additives	3	2.7	2.7	2.7	2.7	2.7
Asphalt: bitumen	–	–	–	–	–	–
Acetate from anaerobic steel corrosion	13–1.3 × 10^4	0	0	0	0	0

Table 2-35. Estimated amounts of carbohydrate material remaining after different periods in deposition tunnels in Forsmark.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Urea	6	0	0	0	0	0
Other human waste	60	0	0	0	0	0
Organic materials from ventilation	10	0	0	0	0	0
Wooden chips and sawdust	10	7.5	5.0	5.0	5.0	5.0

Table 2-36. Estimated amounts of degraded hydrocarbon material remaining after different periods in deposition tunnels in Forsmark.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Plastics	100	100	100	50	50	50
Rubber	*	*	*	*	*	*
Hydraulic and lubrication oil	200	100	0	0	0	0

Table 2-37. Estimated amounts of organic material from buffer, backfill, and construction material remaining after different periods in deposition tunnels in Laxemar.

Compound	Amounts left (tons)	Left after 100 years (tons)	Left after 1,000 years (tons)	Left after 10,000 years (tons)	Left after 120,000 years (tons)	Left (tons)
Bentonite*: humic and fulvic acids	1.9 × 10^4	?				
Concrete additives	<13	<12	<12	<12	<12	<12
Acetate from anaerobic steel corrosion**	0.24–2.4 × 10^2	0	0	0	0	0

* No assumption because of limited knowledge of the organic materials in bentonite.
** Assuming 0.1–100% corrosion of the iron.

Table 2-38. Estimated amounts of organic material from construction material classified as foreign remaining after different periods in deposition tunnels in Laxemar.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Concrete additives	2	1.8	1.8	1.8	1.8	1.8
Asphalt: bitumen	–	–	–	–	–	–
Acetate from anaerobic steel corrosion	20–2 × 10^4	0	0	0	0	0

Table 2-39. Estimated amounts of carbohydrate material remaining after different periods in deposition tunnels in Laxemar.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Urea	6	0	0	0	0	0
Other human waste	60	0	0	0	0	0
Organic materials from ventilation	11	0	0	0	0	0
Wooden chips and sawdust	10	7.5	5.0	5.0	5.0	5.0

Table 2-40. Estimated amounts of hydrocarbon material remaining after different periods in deposition tunnels in Laxemar.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Plastics	100	100	100	50	50	50
Rubber	*	*	*	*	*	*
Hydraulic and lubrication oil	360	180	0	0	0	0

Table 2-41. Estimated amounts of organic material from buffer, backfill, and construction material remaining after different periods in other areas in Forsmark.

Compound	Amounts left (tons)	Left after 100 years (tons)	Left after 1,000 years (tons)	Left after 10,000 years (tons)	Left after 120,000 years (tons)	Left (tons)
Bentonite**: humic and fulvic acids	8.5 × 10^3					
Concrete additives	<5	<4.5	<4.5	<4.5	<4.5	<4.5
Acetate from anaerobic steel corrosion*	0.02–21	0	0	0	0	0

* No assumption because of limited knowledge of the organic materials in bentonite.

** Assuming 0.1–100% corrosion of the iron.

Table 2-42. Estimated amounts of organic material from construction material classified as foreign remaining after different periods in other areas in Forsmark.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Concrete additives	90	81	81	81	81	81
Asphalt: bitumen	30	25	20	15	15	15
Acetate from anaerobic steel corrosion	18–1.8 × 10^4	0	0	0	0	0

Table 2-43. Estimated amounts of carbohydrate material remaining after different periods in other areas in Forsmark.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Urea	2	0	0	0	0	0
Other human waste	20	0	0	0	0	0
Organic materials from ventilation	1	0	0	0	0	0
Wooden chips and sawdust	10	3	2	0	0	0

Table 2-44. Estimated amounts of degraded hydrocarbon material remaining after different periods in other areas in Forsmark.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Plastics	130	130	130	65	65	65
Rubber	*	*	*	*	*	*
Hydraulic and lubrication oil	80	40	0	0	0	0

Table 2-45. Estimated amounts of organic material from buffer, backfill, and construction material remaining after different periods in other areas in Laxemar.

Compound	Amounts left (tons)	Left after 100 years (tons)	Left after 1,000 years (tons)	Left after 10,000 years (tons)	Left after 120,000 years (tons)	Left (tons)
Bentonite*: humic and fulvic acids	1.2 × 10^4	?				
Concrete additives	7	6	6	6	6	6
Acetate from anaerobic steel corrosion**	0.03–34	0	0	0	0	0

* No assumption because of limited knowledge of the organic materials in bentonite.

** Assuming 0.1–100% corrosion of the iron.

Table 2-46. Estimated amounts of organic material from construction material classified as foreign remaining after different periods in other areas in Laxemar.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Concrete additives	110	99	99	99	99	99
Asphalt: bitumen	40	35	25	20	20	20
Acetate from anaerobic steel corrosion	23–2.3 × 10^4	0	0	0	0	0

Table 2-47. Estimated amounts of carbohydrate material remaining after different periods in other areas in Laxemar.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Urea	2	0	0	0	0	0
Other human waste	20	0	0	0	0	0
Organic materials from ventilation	1	0	0	0	0	0
Wooden chips and sawdust	10	7.5	5.0	5.0	5.0	5.0

Table 2-48. Estimated amounts of hydrocarbon material remaining after different periods in other areas in Laxemar.

Compound	Amounts left (kg)	Left after 100 years (kg)	Left after 1,000 years (kg)	Left after 10,000 years (kg)	Left after 120,000 years (kg)	Left (kg)
Plastics	80	80	80	40	40	40
Rubber	*	*	*	*	*	*
Hydraulic and lubrication oil	110	55	0	0	0	0

Hydrocarbon degradation will generally be somewhat slower than carbohydrate degradation. In addition, in the case of hydrocarbons, the more easily degraded compounds will be degraded over the first 100–10,000 years; the rest will remain after 120,000 years.

The organic material in both sites is presented in Table 2-49. Here it can be seen that most of the organic material is found in the bentonite, and it is questionable whether this material is available for degradation. If this material is omitted, most of the organic material will be the acetate produced using the energy in hydrogen from the anaerobic corrosion of steel. This is probably a much more important source of organic material that can be degraded by microorganisms.

Table 2-50 presents the theoretical amounts of hydrogen sulphide produced from acetate originating from the hydrogen produced by anaerobic iron corrosion in a repository; values from 100% corrosion and 0.1% corrosion are presented. These values are used in Table 2-51, together with the calculated volumes of water in the different parts of the repository, presented in section 2.5.3.

In Forsmark, the highest calculated hydrogen sulphide concentration is 0.13 mg L^{-1} in the deposition tunnels, while in Laxemar the highest value is 0.22 mg L^{-1}. In the other areas, the highest values are 0.054 mg L^{-1} in Forsmark and 0.063 mg L^{-1} in Laxemar.

Another source of organic material accessible to sulphate-reducing bacteria is the material in biofilms on tunnel walls and ceilings. Using the values from sections 2.4 and 2.5.3, the theoretical concentrations of hydrogen sulphide produced from this material are calculated and presented in Table 2-51. These calculations presuppose no cleaning whatsoever of the rock walls before repository closure.

These theoretic calculation show that in Forsmark the highest calculated hydrogen sulphide concentration in the deposition tunnels from the degradation of microbial biofilms on rock surfaces is 5.8×10^{-3} g/L, the same value as found for the deposition tunnels of Laxemar. It has to be considered that all numbers are uncertain.

The highest calculated hydrogen sulphide concentration found in the other areas of the repository is 2.3×10^{-3} g/L for both Forsmark and Laxemar.

Table 2-49. Total amount of organic material in a repository, with and without the organic materials in bentonite.

	Deposition holes		**Deposition tunnels**		**Other areas**	
	With bentonite organic materials (kg)	**Without bentonite organic materials (kg)**	**With bentonite organic materials (kg)**	**Without bentonite organic materials (kg)**	**With bentonite organic materials (kg)**	**Without bentonite organic materials (kg)**
Forsmark	9.8×10^5	–	5.1×10^6	1.3×10^4	8.5×10^6	1.8×10^4
Laxemar	9.8×10^5	–	1.9×10^7	2.0×10^4	1.2×10^7	2.3×10^4

Table 2-50. Theoretical amounts of hydrogen sulphide produced from hydrogen originating from anaerobic iron corrosion.

	Deposition tunnels		**Other areas**	
	H_2S from 100% iron corrosion (mol)	**H_2S from 0.1% iron corrosion (mol)**	**H_2S from 100% iron corrosion (mol)**	**H_2S from 0.1% iron corrosion (mol)**
Forsmark	1.6×10^6	1.6×10^3	6.5×10^5	0.65×10^3
Laxemar	4.3×10^6	4.3×10^3	9.0×10^5	0.9×10^3

Table 2-51. Theoretical concentrations of hydrogen sulphide produced from hydrogen originating from anaerobic iron corrosion in the different parts of the repositories.

	Deposition tunnels				Other areas			
	Concentration of H_2S: 100% iron corrosion (g L^{-1})	Concentration of H_2S: 100% iron corrosion (M)	Concentration of H_2S: 0.1% iron corrosion (g L^{-1})	Concentration of H_2S: 0.1% iron corrosion (M)	Concentration of H_2S: 100% iron corrosion (g L^{-1})	Concentration of H_2S: 100% iron corrosion (M)	Concentration of H_2S: 0.1% iron corrosion (g L^{-1})	Concentration of H_2S: 0.1% iron corrosion (M)
Forsmark	0.14	4×10^{-3}	1.4×10^{-4}	4×10^{-6}	6.7×10^{-2}	2.0×10^{-3}	6.7×10^{-5}	2.0×10^{-6}
Laxemar	0.27	8×10^{-3}	2.7×10^{-4}	8×10^{-6}	7.5×10^{-2}	2.2×10^{-3}	7.5×10^{-5}	2.2×10^{-6}

Table 2-52. Theoretical hydrogen sulphide concentrations produced by biofilms on rock surfaces in different areas of the repositories.

	Deposition tunnels				Other areas			
	Low density		High density		Low density		High density	
	Concentration (M)	Concentration (g/L)	Concentration (M)	Concentration (g/L)	Concentration (M)	Concentration (g/L)	Concentration (M)	Concentration (g/L)
Forsmark	2.3×10^{-5}	7.8×10^{-4}	1.7×10^{-4}	$5.8 x10^{-3}$	9.0×10^{-6}	3.1×10^{-4}	6.8×10^{-5}	2.3×10^{-3}
Laxemar	2.3×10^{-5}	7.8×10^{-4}	1.7×10^{-4}	5.8×10^{-3}	9.0×10^{-6}	3.0×10^{-4}	6.7×10^{-5}	2.3×10^{-3}

3 Summary and conclusions

The largest pool of organic material in a repository at closure is the organic material in the bentonite in buffer and backfill. It is impossible to make any assumptions as to how much of this material will be available for biodegradation, since the character of the material is unknown. However, it is unlikely that this organic material can dissolve in groundwater unless the bentonite loses its swelling capacity. The second largest pool will be the biofilms formed on the rock surfaces. This assumption presupposes that no cleaning is undertaken before repository closure. The third largest pool is the organic material produced by microorganisms using hydrogen from the anaerobic corrosion of iron in steel as an energy source.

The following provides summary descriptions of the different pools of organic material that will remain in the repository:

1. *Microorganisms*. Their effect would mainly be to reduce the redox potential soon after repository closure. They may contribute to the depletion of the oxygen entrapped during repository construction, an effect that would not jeopardise repository stability.

   If the dominant microorganisms in the anaerobic environment are sulphate-reducing bacteria, oxidation of organic material would lead to the formation of HS^-. The produced sulphide could corrode the copper canisters under anaerobic conditions if it reaches them.

   Another effect of microorganisms would be to increase the complexing capacity of the groundwater due to excreted metabolites. The impact of these compounds is not yet clear, although it will surely not be very important, due to the small amounts of such substances.
2. *Materials in the ventilation air*. Their effect will probably be to help maintain reducing conditions in the area, although this effect will likely be minimal or negligible.
3. *Construction materials*. Among these materials, we emphasise the organic materials present in concrete, asphalt, bentonite, and wood. Hydrocarbons from asphalt may help reduce the redox potential within the repository. The products of cellulose degradation may help enhance the complexing capacity of the groundwater around the repository, so the amount of cellulose left in the repository should be minimised.
4. *Fuels and engine emissions*. No important effects are expected from these organic materials in the repository. Although the presence of aromatic compounds and PAHs in groundwater is not desirable in itself, these compounds are of no consequence for long-term repository performance.
5. *Detergents and lubricants*. The same reasoning as for fuels and engine emissions can be applied to these materials. The amount of detergents should be minimised, although in the amounts in which they are expected to occur, no important impact is foreseen.
6. *Materials from human activities*. Of these materials, fibres from clothes could have a more important effect, due to the presence of cellulose. Accordingly, human-related wastes should me minimised, although no large amounts of these materials are expected to be present after repository closure.

Three processes are considered to have the largest potential impact on repository performance:

i) Increasing the reducing capacity and reducing the redox potential in the short term, and increasing the depletion rate of oxygen trapped during the repository operation stage.

ii) Increasing the complexing capacity of the groundwater due to the presence of organic complexants, which is expected to be a more relevant process in the long term. Many organic molecules with complexing capacity, for example, short-chain organic acids such as acetate, however, will be oxidised due to microbial metabolism. The projected acetate concentration in groundwater is below the detection limit of available analytical methods. The amount of organic material in groundwater is usually only being a few mg L^{-1}, and 25–75% of this material is non-humic material, i.e. short-chain acids (see, e.g. /Nissinen et al. 2001/).

iii) Production of HS^- from the oxidation of short-chain organic acids by sulphate-reducing bacteria using sulphate as an electron acceptor. The produced sulphide can corrode copper canisters if it comes into contact with them.

The decrease in O_2 concentration is a largely positive, so no specific measures need be taken to counteract substances having only this effect contribution to safety. However, when oxygen is depleted, sulphate reduction or some other anaerobic degradation process can occur. The increase in complexing capacity, however, may be relevant if the organic matter degradation products coexist with radionuclides over the long term or if they can exert an influence by worsening the performance of the engineering barriers.

Table 3-1. Organic material in a spent fuel repository: categories, chemical composition, possible effects, and recommended actions.

Categories of organic material	Chemical composition	Effect in the repository after closure	Recommended action
Growth of microorganisms	Biological compounds, EPSs, polymers, and excreted metabolites.	Oxygen consuming, E_h lowering because of action as substrate for groundwater microorganisms. Possible increase in the complexation capacity due to the excreted metabolites.	None Study the amount of excreted metabolites. Is it enough to provide important complexing capacity?
Organic material in ventilation air	Biological compounds in seeds, spores, and pollen.	Oxygen consuming, E_h lowering because of action as substrate for groundwater microorganisms.	Minimise. Not foreseen to be important, due to the small amount of compounds introduced in this way.
Construction materials			
Concrete	Lignosulphonates, lignosulphates, sulphonated naphthalene sulphonated formaldehyde, acryl sulphonate, alkyl sulphonate, and phenol ethoxylates.	Strongly bound to concrete particles. Possible decomposition in radiation field /Gascoyne 2002/ Probably no effect on the repository.	None
Asphalt	Heavy hydrocarbons and compounds containing oxygen, sulphur, and nitrogen atoms	Some leakage to groundwater of low-molecular-weight hydrocarbons, some of which are biodegradable and thus E_h lowering.	Remove
Bentonite clay	Thought to be humic and fulvic acids as well as humin, but not examined.	Function as substrate for microorganisms. E_h lowering but can increase hydrogen sulphide production in the bentonite buffer. Possible effect on Cu canisters.	None
Wood	Cellulose, lignin, and secondary products such as tannins and terpenes.	Cellulose is both easily degraded by many microorganisms and theoretically assumed to degrade under alkaline conditions, commonly projected to occurring in nuclear repositories that include cement construction. Lignin is degraded by white rot fungi. Tannins and terpenes are very slowly decomposed and can act as complex binding agents. In summary, these species enhance the complexing capacity of the media.	Remove
Fuels and engine emission			
Diesel	*n*-alkanes, PAHs, alkyl benzenes, aromatics, branched and unsaturated aliphatic hydrocarbons, and cycloaliphatic naphthenes.	Diesel hydrocarbons are easily degraded in the presence of oxygen, although condensed polyaromatic hydrocarbons (PAHs) are slowly degraded. Degradation also occurs in anaerobic conditions. Oxygen consumption and E_h lowering effects.	Minimise and if possible pump out.
Engine emissions	Carbon soot, water, sulphuric acid, and condensed hydrocarbons.	Condensed hydrocarbons can be degraded in the presence of oxygen but also by some anaerobic microorganisms.	Minimise
Rubber from tyres	Isoprene cross-linked with sulphur bridges.	Not easily degraded. Probably no effect on the repository.	Minimise
Detergents and Lubricants	Alkylbenzene sulphonates, alkylphenol ethoxylates, plant-based tensides, and C18–C40 alkanes.	The “old” tensides are often difficult to degrade but “new” plant-based ones are more readily degraded. Oxygen depletion.	Minimise and if possible remove.

Categories of organic material	Chemical composition	Effect in the repository after closure	Recommended action
Organic material from human activities			
Tobacco products	Plant leaf components containing nicotine, nornicotine, anabasine, myosmine, nicotyrine, and anatabine.	Increase in the nitrate content of groundwater.	Minimise
Cigarettes			Prohibit
Snuff	Including glycerol, sodium chloride, and sodium carbonate.	Biodegradable. The amount can be easily minimised by restriction.	Minimise
Dust from skin and hair	Protein	Biodegradable. No large effect expected.	None. Unavoidable.
Fibres from clothes	Polyesters Cellulose	Polyesters will remain but probably not affect the repository. Cellulose is both biodegradable and easily degrades under alkaline conditions common in nuclear waste repositories that include cement construction. Not expected to be very important.	Remove
Urine	Urea, creatinine, ammonia, uric acid, and amino acids.	Urine is degradable and functions as a nitrogen source for the oxygen-consuming and E_h-lowering degradation in the repository. Its degradation and consequent urea hydrolysis can increase the pH. Should be minimised mainly for hygienic reasons. Expected effect not very important.	Minimise
Paper and plastic waste	Cellulose and plastic polymers (see “Blasting” below).	Cellulose will be biodegraded. Some plastics will be degraded and others not depending on their composition. Can be avoided by restriction.	Remove
Blasting and/or rock-drilling			
Paper	Cellulose	Biodegradable. Large quantities can be removed. Small residues can be left.	Remove
Plastics	Polyethylene terephthalate, polyethylene, polyvinylchloride, polypropylene, and polystyrene.	Most of these plastics are not biodegradable. There are so-called bio-plastics produced by microorganisms and these are more or less biodegradable.	Remove

4 References

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