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Hazardous Waste Disposal – A Global Challenge

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Basel Convention, Hazardous Waste, Environmental Sound Management

Abstract
Hazardous wastes cannot be meaningfully addressed in isolation from the entire economic, social, health and other waste issues. Therefore, a need to strengthen measures applying to the entire waste cycle, moving mindset from “waste” to “resources” exists. Furthermore, also promoting modern waste management system is needed in all countries. In this context, strategic partnerships among parties, industry, NGOs and local governments, and strengthen cooperation and synergy with other MEAs in chemicals and wastes area is important.
The Basel Convention at a Glance

• The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal is an international treaty which is administered by the United Nations Environment Programme.

• It was adopted in Basel in March 1989, and entered into force in May 1992.

• As of today, there are 175 Parties.
The Basel Convention at a Glance

The goal of the Convention is to protect human health and the environment from the adverse effects which may result from improper management of hazardous and other wastes.

This includes handling, transporting, storing, treating, processing and the disposal of these wastes.

• The Convention is based on two pillars;

• a control regime for the transboundary movements of hazardous wastes, and

• the promotion of the environmentally sound management (ESM) of hazardous wastes. The principle of ESM centres around
  – the treatment and disposal of hazardous wastes as close as possible to their source of generation,
  – the reduction of transboundary movements of hazardous wastes and other wastes to a minimum consistent with their environmentally sound management and
  – the minimization of the generation of hazardous wastes.
Workshop Underground Disposal of Hazardous Waste

Why the Basel Convention was created…

• The cross-border transport of hazardous wastes seized the public’s attention in the 1980s.

• Tighter environmental regulations in industrialized countries.

• “Toxic traders” searching for cheaper solutions started shipping hazardous wastes to Africa, Eastern Europe and other regions.

• High profile chemical accidents (e.g. Seveso and subsequent mismanagement of wastes).

• To eliminate these practices, the Basel Convention was negotiated under the auspices of the United Nations Environment Programme in the late 1980s. It was adopted in 1989 and entered into force in 1992.

What is waste under the Convention?

• Wastes listed in Annexes I and II of the Convention, as further clarified in Annexes VIII and IX. Parties may also inform the Convention Secretariat of additional wastes, considered or defined as hazardous wastes under their national legislation and of any requirements concerning transboundary movement procedures applicable to such wastes.

• “Disposal” (as defined by the Convention) includes operations resulting in final disposal and operations which may lead to resource recovery, recycling, reclamation, direct re-use or alternative uses.
Challenges why ESM of hazardous waste cannot be ensured:

1. Economic Issues (= drivers for transboundary movement):
   - Lack of national facilities to treat hazardous wastes
   - Inadequate hazardous waste collection system in the importing country
   - Demand-gap, different state of development and different type of industries
   - Price-gap, costs for disposal and prices for recycling differ because of:
     - different environmental standards,
     - different technical facility standards, etc.

2. Legal Issues (= implementation issue):
   - Lack of legal clarity, namely with regard to:
     - definition/classification of hazardous / non-hazardous waste and differentiation between waste / non-waste,
     - definition/classification of reuse / direct reuse, including repair, refurbishment, upgrading but not major reassembly, etc.
   - Gaps in legislation, e.g. existing legislation seems often not to cover adequately:
     - materials that are not declared as hazardous waste when exported and which are determined to be hazardous waste in the receiving countries, etc.
   - Different competent authorities to issue permission, lack of coherence between different ministries / agencies.
   - Different approaches taken within a country, e.g. when in a federal system different regions / states within one country take different approaches.
Challenges why ESM of hazardous waste cannot be ensured:

3. Enforcement Issues (= implementation issue):
   • Lack of capacity for border control
   • Difficulty of risk profiling of containers inspection or no environmental aspects (e.g. trends, main waste stream) included in national risk profiling;
   • Custom tariff codes differ from Basel waste lists and codes, making enforcement by custom officers difficult.
   • Customs officials are more focused on control of imports than exports.
   • Difficulty of formalising the informal sector to promote ESM.
   • The legal uncertainties lead generally to problems of enforcement.
   • No uniform level of enforcement at the regional and federal level.

4. Awareness Raising Issues and Knowledge (= implementation issue):
   • Lack of awareness and knowledge of all those involved /should be involved on the hazardous waste issues and especially the requirements of the Basel Convention
   • Promotion of the Basel Convention and engaging the public and politicians.
Challenges why ESM of hazardous waste cannot be ensured:

5. Others (= implementation issue):
   • Increase in production of hazardous waste is due to changing consumption patterns → increasing TBM
   • "Illicit" transboundary movements, such as charity, donations, humanitarian aid
   • Administrative difficulties in applying the Basel Convention (i.e. delays in processing notifications; obtaining responses from importing authorities; difficulty in obtaining movement documents and certification) may have impact and promote illegal movements.
   • Lack of effective use of economic instruments, fees, taxes, prioritising waste policy etc.
   • Lack of data due to difficulties in obtaining inventory information on the generation and disposal of hazardous waste and on export and import statistics
   • Need for ESM facility-related technical standards to be developed under the Basel Convention.

Possible solutions

1. Providing further legal clarity in particular on:
   – The coverage of the Basel Convention, and in particular the distinction between wastes and used goods;
   – National definition: distinction between hazardous and not hazardous;
   – The harmonisation of reporting codes;
   – Terms such as re-use, repair and refurbish.
Possible solutions

2. Ensuring that vulnerable countries do not receive wastes that they do not want:
   – Highlighting the right of countries to prohibit the import of hazardous wastes (Art 4);
   – Improving and facilitating the mechanism through which such prohibitions are notified;
   – Encouraging countries which prohibit the import of hazardous waste to provide the SBC with full list of the hazardous wastes covered by the prohibition.

Possible solutions

3. Improvement of existing tools, promotion of better application of existing measures and instruments within the Convention, and possible extensions or enhancements of the Convention:
   • Promote the utilisation of the technical guidelines, manuals and tools developed under the Basel Convention;
   • Implementation of the Ban by those Parties that have ratified the Ban Amendment;
   • Extending the provisions of the Convention to cover second-hand goods and charitable donations e.g. by making producers responsible for taking back such goods if they become waste;
   • Streamlining reporting mechanisms and improving feedback of results to those providing the information;
   • Strengthening the implementation of the notification procedure for national definitions of hazardous waste (Art 3);
   • Promotion of 3Rs and sustainable materials management policies
Possible solutions

4. Support for the Basel Convention Regional Centres:
   • The Regional Centres play a key role in promoting the effective implementation and application of the Convention and their role should be strengthened and adequate financing of any additional tasks should be ensured.

Possible solutions

5. Dealing with illegal traffic
   • Establishing networks and maintaining cooperation between actors at all levels is important to address illegal traffic:
   • At national level, between environmental inspectorates, customs and police is important because each has specific competences and roles within the administrative system;
   • At regional level via BCRCs, IMPEL TFS, Asian Network etc.;
   • At international level via INECE, World Customs Organisation, Interpol, etc.
Possible solutions

5. Dealing with illegal traffic (cont)
- The networks could also play a role to:
  - Facilitate dissemination of knowledge about illegal practices and good practice in enforcement and control;
  - Improve knowledge about understanding of the notification procedure for businesses;
  - Explore ways of improving enforcement (also by seeking experiences from other conventions, e.g. CITES);
  - Explore ways of developing tools for enforcers, for example reducing time scales and assisting with linguistic obstacles.

Possible solutions

6. Building Capacity:
- Specifying and quantifying clearly the needs for capacity building for different Parties. The Regional Centres might take the lead in this;
- Securing resources through political engagement with other processes;
- Securing funds e.g. through fees for certification, financial instruments;
- Technology transfer;
Possible solutions

7. Standards of Environmentally Sound Management (ESM)
   - ESM relates to facilities, waste streams, waste management systems, and to national legislation.
   - Elements of ESM should include consideration of emissions, efficiency, and management; other considerations might include contribution to chemicals management, climate change, lifecycle analysis and environmental impact assessment.
   - ESM standards should be consistent with other international agreements.
   - Will provide level playing field.

Conclusions

- Hazardous wastes cannot be meaningfully addressed in isolation from the entire economic, social, health and other waste issues;
- Need to strengthen measures applying to the entire waste cycle, moving mindset from “waste” to “resources”;
- Need to promoting modern waste management system in all countries;
- Strategic Partnerships among Parties, industry, NGOs and local governments, and strengthen cooperation and synergy with other MEAs in chemicals and wastes area.
Underground Disposal – a Key Element of the German Waste Management Concept

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Keywords

Hazardous Waste, Waste Treatment, Underground Disposal, European Waste Catalogue

Abstract

Hazardous waste represents around 3 % of the total waste arising in the EU 27 and in Germany. Despite this small percentage the volume of hazardous waste generated is still significant and its treatment requires special care due to the potential risk to human health and the environment. In general waste producers are obliged to ensure that waste is either avoided, or properly and harmlessly recycled, whereby every effort should be made to achieve high-quality recycling. The obligation to recycle must be met wherever technically feasible and financially reasonable. If disposal is the more environmentally-compatible solution the precedence of waste recycling does not apply. Underground disposal is mainly foreseen for hazardous waste that may not be easily decontaminated due to economical or ecological reasons.
1 Hazardous waste - generation and treatment

Hazardous waste is generally understood as waste that poses an actual or potential danger to human health and or the environment. The classification and definitions for hazardous waste though vary worldwide. Data on the generation of hazardous waste compiled by the United Nation Statistic Division illustrate that most of hazardous waste is generated in industrialised countries. It also demonstrates that little or no data is available for Latin American, African, Middle East and Central Asian Countries. Because of inadequate waste management the generation of hazardous waste in low and middle income economies often poses a serious threat to human health and the environment. In future, due to economic growth a significant increase of hazardous waste is forecasted for these countries; hence the need for environmental sound waste management options will be even more pressing.

Figure 1  World-wide generation of hazardous waste /UNI 09/

Within the EU the definition of hazardous waste is laid down in the Waste Framework Directive (2008/98/EC). According to the directive ‘hazardous waste’ means waste which displays one or more of the hazardous properties listed in Annex III. The associated European Waste Catalogue (EWC 2000/532/EC) establishes a non-exhaustive list of waste types setting the basis for harmonized implementation of waste legislation across all Member States. The list categorizes wastes based on a
combination of its origin and the process or activity by which it is generated. The list is divided into 20 chapters. Each chapter is represented by a two-digit code between 01 and 20 and comprises one or more subchapters. Individual waste types are detailed in the subchapters and are assigned a six-digit code that comprises two digits for the chapter, two for the subchapter and two specific to the waste type. Hazardous wastes are signified by entries where the EWC code is marked by an asterisk (*). The definition of hazardous waste in the Basel Convention is based more or less on the same principles as the EU definition, but refers to the national legislation and the OECD refers to the Basel Convention definition. Within the European Union 27 the quantity of hazardous waste expressed as a percentage of total waste represents 3% of all waste.

Figure 2  Ratio of hazardous and non-hazardous waste generation in the EU 27 in 2006 /KLO 09/

1.1  Hazardous waste - generation and treatment in Germany

Hazardous waste generation in Germany

In 2008 the volume of primary waste in Germany amounted to 382,812 million tonnes, 21,963 million tonnes of which was hazardous waste. Altogether 6 above-ground landfill sites for hazardous wastes are provided for the disposal of hazardous waste. In addition, there are four underground landfill sites for waste that cannot be disposed of either in above-ground landfill sites for hazardous wastes or in hazardous waste incineration plants. For waste requiring thermal disposal, there are 28 publicly-owned and company-owned hazardous waste incineration plants as well as 11 special plants
(primarily in the chemical industry) for the disposal of specific hazardous wastes (fluids, waste water etc.).

**Figure 3**  Hazardous waste generation in Germany 2008 (in 1,000 t) /STA 10/

### 1.1.1 Basic principles of hazardous waste treatment in Germany

The implementation of statutory and administrative provisions in the waste sector, i.e. the enforcement of these provisions, is the sole responsibility of the Länder. For example, the Länder are exclusively responsible for supervising waste management, licensing waste disposal facilities, organising the management of hazardous wastes, and preparing waste management plans. The Closed Substance Cycle and Waste Management Act primarily obligates the producers and proprietors of waste to take responsibility for the avoidance, recycling or disposal of waste. A modern closed substance cycle can only be effective if those responsible for the generation of waste also accept responsibility for, and bear the costs of, its recovery and disposal. Consequently, waste producers from trade and industry are required to accept responsibility for the recovery and in some cases also the disposal, of their waste. However, hazardous wastes are a key exception to this rule. For such wastes, the law stipulates that the competent Länder authorities may specify so-called obligations to offer waste, and even obligations to make waste available to parties responsible for waste disposal.
The ‘obligation to offer waste’ requires the waste producer to notify the institution designated by the Land that he has waste of a certain type, quantity and composition, and that he is either looking for or already has a disposal facility for this waste. The institution then assigns the waste to its selected facility. The waste producer is responsible for disposal. As a general rule, the institution’s decision is subject to payment of a fee. Under the “obligation to make waste available”, the waste producer must make his waste available to the institution specified by the Land. This institution is obliged to carry out disposal, and receives a waste management fee in exchange for its services. If waste is destined for recovery, the obligation to offer and make waste available to parties responsible for waste disposal may only be specified in exceptional cases by the Länder, if proper recovery cannot be guaranteed in some other way.

Of the 16 Länder, a few - including Bremen, Hamburg, Mecklenburg-Upper Pomerania, North-Rhine Westphalia and Saxony - have appointed private disposal firms to dispose of hazardous wastes. Most of these companies are members of one of the major waste management organisations (e.g. Bundesverband der Deutschen Entsorgungswirtschaft [BDE], Bundesverband Sekundärrohstoffe und Entsorgung e.V. [bvse]). Other Länder have charged Landesgesellschaften (Land companies) with disposal. These state companies have formed a working party of special waste management organisations. A number of private companies are also involved in these Landesgesellschaften. In some of the aforementioned Länder, the responsibilities of the Landesgesellschaften are confined to assigning the hazardous waste to a third party or their own facilities. In the remaining Länder, the Landesgesellschaften are obliged to accept the special waste made available to them and to dispose of it by themselves. Only one Land merely stipulates a disclosure obligation to the Landesgesellschaft, which monitors the disposal procedures but does not actually assign the waste itself.

1.1.2 Hazardous waste treatment in Germany

The respective treatment of hazardous waste depends on the type of waste and the objective of the waste treatment process. In case hazardous waste is not treated by incineration also conditioning of hazardous waste can take place. This is done primarily for contaminated construction and demolition waste as well as for contaminated soils. The main purpose of this treatment is the separation of hazardous substances in order to fulfil the landfill criteria for the waste fraction in question. When recycling hazardous waste the focus is on the recovery of secondary raw materials that meet the quality
requirements of the market. Physical treatment methods like filtration or sedimentation are used for separating materials whereas chemical treatment methods are applied in order to transform waste materials. In particular liquid hazardous waste is pre-treated in chemical-physical treatment facilities. The pollutants are extracted via phase separation or destroyed. Waste with a high content of organic and inorganic substances, are kept in separate chemical physical treatment facilities strands. In the organic treatment line e.g. waste from oil extractors, gasoline and grease traps, are treated. The solids are separated and fed into the thermal recovery or treatment system. The process is followed by an oil-water separation. Waste originating from metal surface treatment or non-ferrous hydrometallurgy is treated in the inorganic chemical physical treatment facilities strand. At large it concerns used acids, alkalis, concentrates with toxic components and industrial sludge.

![Graph of hazardous waste treatment in Germany 2008 (in 1,000 t) /STA 10/](image)

**Figure 4:** Hazardous waste treatment in Germany 2008 (in 1,000 t) /STA 10/

Due to the potential threat for human health and environment the landfill of hazardous waste requires special care. The landfill ordinance provides for the division into different classes of landfills. Site qualification, sealing requirements and specification for geological barrier systems as well as waste parameter are allocated to the landfill classes reflecting the potential risk of the specific waste. The landfill class III is reserved for above-ground landfill of hazardous waste whereas landfill class IV provides for the underground storage in salt rock formation.

In 2008 67 % of the hazardous wastes in Germany were recovered. 5,175,000 tons were landfilled above ground and 106,700 tons disposed off in underground landfill sites.
1.1.3 Underground disposal of hazardous waste

The option of a permanent underground storage is mainly foreseen for hazardous waste that may not be easily decontaminated due to economical or ecological reasons. Examples are heavy metals containing filter dusts, specific contaminated soil, slags, sludges, linings or construction waste containing PCB (polychlorinated biphenyls).

In the European Union the conditions for the permanent storage of hazardous waste in underground landfills are outlined in the ‘Council Decision 2003/33/EC of 19 December 2002 establishing criteria and procedures for the acceptance of waste’ at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC”. This includes criteria on underground landfills, on wastes and on waste management. In Germany the decision is implemented in the Ordinance Simplifying Landfill Law. Among others the landfill ordinance sets special standards as regards the location and geological barrier: ‘When the location for a class IV landfill site in salt rock (underground landfill site) is chosen, it shall be taken into consideration that the wastes will be permanently removed from the biosphere and may be deposited in such a way that no aftercare measures are required. As the crucial geological barrier, the salt rock at the location must

- be impervious to liquids and gases,
- be of sufficient spatial extent,
- possess a sufficient unworked thickness of salt in the selected deposition area, which shall be so great that the barrier function will not be permanently impaired, and
- gradually close around the wastes and, at the end of the deformation process, enclose them with a frictional closure as a result of its convergence behaviour. In addition to this,
- the underground cavities used with the landfill site must be stable for at least the duration of the deposition and closure phase, and
- locations in which there is a 99-percent probability that the regional intensity of earthquakes will exceed 8 on the Medvedev-Sponheuer-Karnik scale (MSK scale) shall be avoided.
The landfill ordinance excludes the following wastes from being deposited in a class IV landfill site:

- liquid waste
- infectious wastes body parts and organs
- unidentified or new chemical wastes from research, development and educational activities, the impacts of which on humans and the environment are not known,
- whole or shredded used tyres,
- wastes that bring about considerable odour nuisances for those employed at the landfill site and the neighbourhood,
- biodegradable wastes and wastes with a gross calorific value (Ho) of more than 6,000 kJ/kg,
- wastes that, under deposition conditions, due to reactions among the wastes or between the wastes and the rock, bring about
  a) increases in volume,
  b) the formation of self-igniting, toxic or explosive substances or gases, or
  c) other hazardous reactions,
  in so far as this would call into question the operational safety and integrity of the barriers,
- wastes that, under disposal conditions,
  a) are explosive, highly flammable or easily flammable,
  b) release a pungent odour or
  c) do not exhibit sufficient stability under the geomechanical conditions.
Bibliography


Criteria for Site Selection and Long-Term Safety Assessment

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Underground Disposal, Safety Concept, Site Selection, Safety Assessment, Multi-Barrier System

Abstract
Hazardous waste management and disposal poses a serious challenge especially to developing countries due to growing amounts of these wastes that are generated by increasing industrial production and consumption of imported goods. Underground waste disposal, an essential element of the German and European waste management system since decades, could be a possible approach to address these problems. To allow a common and uniform understanding, firstly a definition of essential terms is given, followed by an explanation of underground disposal’s safety-concept and safety-philosophy. With it, numerous regulations and requirements - already being in effect - point out that underground disposal doesn’t reflect the proverb ‘out of sight, out of mind’, but constitutes the only option to isolate hazardous substances from the biosphere permanently. Indispensable prerequisite is a thorough conception and operation as well as a long-term safety assessment.
2 'Long-term Storage’ vs. ‘Disposal’

The non-uniform use of both terms long-term 'storage' as well as 'disposal' in practice, so far has caused misunderstandings and misinterpretations (e.g. of regulations, guidelines) and also has led to the development of concepts which haven't been in consistency with the original idea behind it. Even regulation (EC) No 1102/2008 /EUR 08/ just applies the term 'storage' for both, the above-ground temporary storage (sensu stricto) as well as for the long-term safe storage (sensu lato) in geological formations which is, based on subsequent definitions rather to be quoted as disposal. A clear definition and discrimination of terms used are indispensable in order to avoid such nonconformance in the future. We therefore submit the recommendation to differentiate between the terms 'storage' and 'disposal' according to the following definitions.

**Storage**, in any case, is a temporally limited keeping / care of wastes. The protection of wastes against release of its hazardous constituents (e.g. heavy metals) into the environment (but also against theft, terrorism etc.) is mainly guaranteed by technical measures. A typical storage-concept for such wastes e.g. can be realized by a warehouse, which warrants physical protection of the waste and allows a continuous monitoring of its state as well as of the storage conditions. Since technical measures inherently show a limited durability, storage - under no circumstances - is able to constitute a lasting and final solution to keep waste and its hazardous constituents (e.g. heavy metals) out of and to avoid any release into the biosphere. In such technical context the item 'long-term' is often used to describe a time period of few up to several decades and will never exceed a time period of several hundred up to a maximum of few thousand years. It must be clear that even such time-frame of thousands of years - which is, in fact, not experienced in daily life of men - is a temporally limited one and necessitates, due to the persistence of the contaminants stored, further measures after that time. In addition / as an alternative to an above-ground warehouse also underground mine openings might be used for storage-purposes. On no account such a procedure is to be equated with the underground disposal (see below) of hazardous wastes. Underground storage also might require specific conditions significantly different or even oppositional to those needed in case of underground disposal. For example, the creeping behavior of rock salt as a favored host rock in Germany and Europe is a property which is claimed to enclose wastes totally as soon as possible in case of underground disposal - in contrast, the same rock property might feature a major disadvantage for an underground storage facility which must guarantee safe
access to the wastes over a certain time period. On the other hand, a cavity in hard-rock might show a high mechanical stability which allows storage as well as monitoring for long time periods. With regard to requirements on disposal, however, the stable cavities don’t encapsulate the waste like rock salt, a disadvantage which needs to become offset by further measures resp. additional barriers.

Compared with this, Disposal constitutes a definite, irreversible measure to exclude the hazardous substance (e.g. heavy metals) from the biosphere for ever without any further needs for treatment or surveillance after termination of the disposal operation and proper sealing of the facility. According to regulation (EC) No 1102/2008, this concept can best become realized in salt mines or in deep underground, hard rock formations (providing an equivalent level of safety) on the condition that all requirements and criteria developed for the concept in question, the waste itself and the site on national or European level are fulfilled. An occasionally postulated retrievability of wastes from a facility is being opposed to the underground disposal concept in general, as described above, but might be applicable for a rather limited time period, whose maximum is the operational phase of the facility before performing all final backfilling and sealing measures (as far as requested).

3 Underground Disposal - Safety-Concept and Safety-Philosophy

The underground disposal of hazardous wastes (e.g. heavy metals, resp. HM-containing wastes) in salt mines or in deep underground hard rock formations (providing an equivalent level of safety) represents a concept to durably keeping away hazardous wastes (and the contaminants contained therein) from the biosphere by a) including them completely and permanently in a suitable host rock (e.g. salt rock, figure 1) and / or b) protecting them from becoming leached and released by a combined system of several natural and artificial barriers (e.g. hard rock, clay stone) in deep geological formations, both in a way that no aftercare measures are needed.
In an ideal case already the host rock chosen evinces properties which enable a fast and total inclusion / encapsulation of the waste and its hazardous constituents without any further barriers needed. Due to their unique properties, in particular their creeping, resp. plastic behavior, especially rock salt formations might offer such a host rock which allows the complete and permanent inclusion of contaminants (figure 2). In order to warrant the complete inclusion, the disposal mine itself as well as any area around it which might become influenced by the disposal operations (e.g. geomechanically or geochemically), must be surrounded by host rock in sufficient thickness, with sufficient homogeneity, with suitable properties and in suitable depth (see figure 1).

Figure 1  Concept of complete inclusion (schematically)

In an ideal case already the host rock chosen evinces properties which enable a fast and total inclusion / encapsulation of the waste and its hazardous constituents without any further barriers needed. Due to their unique properties, in particular their creeping, resp. plastic behavior, especially rock salt formations might offer such a host rock which allows the complete and permanent inclusion of contaminants (figure 2). In order to warrant the complete inclusion, the disposal mine itself as well as any area around it which might become influenced by the disposal operations (e.g. geomechanically or geochemically), must be surrounded by host rock in sufficient thickness, with sufficient homogeneity, with suitable properties and in suitable depth (see figure 1).

Figure 2  Image of the principle of complete inclusion: a former drift in a salt mine (with originally several square-meters cross-sectional area), filled with some mining residues, is - due to creeping behavior of rock salt - now compacted and the residues (black color) completely included in rock salt.
As a basic principle it must be proved by means of a long-term safety assessment that the construction, the operation as well as the post-operational phase of an underground disposal facility will not lead to any derogation of the biosphere. Thereto all technical barriers (e.g. waste-form, backfilling, sealing-measures), the behavior of the host rock and surrounding, resp. overburden rock formations as well as courses of possible events in the overall system need to be analyzed and assessed by appropriate models.

If the salt rock formation taken into consideration shows any deficiencies (e.g. homogeneity, thickness) or if other types of host rock must be chosen due to the overall geological situation available (e.g. hard rock, clay formations), missing or insufficient barrier properties of the host rock might become offset by means of a so-called multi-barrier system.

In general such a multi-barrier system might be composed of one or several additional barrier components (see table 1 and figure 3) which are able to contribute to the super-ordinated aim to permanently keeping away the wastes from the biosphere.

<table>
<thead>
<tr>
<th>Barrier component</th>
<th>Example for mode of action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste content</td>
<td>Reducing the total amount of contaminants to be disposed off</td>
</tr>
<tr>
<td>Waste form</td>
<td>Treatment of waste in order to get a less soluble contaminant</td>
</tr>
<tr>
<td>Waste canister</td>
<td>Bridging of a limited time period until natural barriers become efficient</td>
</tr>
<tr>
<td>Backfill measures</td>
<td>Backfill of void mine spaces to improve geomechanical stability and / or to provide special geochemical conditions</td>
</tr>
<tr>
<td>Sealing measures</td>
<td>Shaft sealing must provide same properties where the natural barrier(s) is disturbed by mine-access</td>
</tr>
<tr>
<td>Host rock</td>
<td>Complete inclusion of contaminants (in ideal case)</td>
</tr>
<tr>
<td>Overburden</td>
<td>Additional natural (geological) barrier, e.g. overlaying clay layer with sufficient thickness and suitable properties (inter alia sorption)</td>
</tr>
</tbody>
</table>

Their need as well as their mode of action within the disposal system is to be proved by means of a long-term safety assessment (see above). As an example, the geological formation(s) overlaying a disposal mine (‘overburden’) might be efficacious in different ways by a) protecting the underlying host rock from any impairments of its properties.
and / or b) provision of additional retention capacities for contaminants which might become released from the disposal mine under certain circumstances.

Since the geological situation at a site definitely should represent the most effective barrier, it is significant to know about the geological evolution of the structure chosen. Understanding of the past allows for prognoses in future development, i.e. if natural events like uplift, erosion, volcanism and many more could have a negative effect on the barrier’s properties. Understanding the nature could also be achieved by so-called “Natural Analogues”.

![Figure 3](image)

Figure 3  Main components of a multi-barrier system (schematically)

In general, the realization of an underground disposal concept as described, including all criteria, requirements, and final layout etc. must be worked out waste specific and site specific, taking into consideration all relevant regulations and experiences. In order to convey a very rough idea about depth and thickness of different host rock types, typical numbers which are based on current experiences and plans are compiled in the following table 2.

Practice, so far (the first underground disposal mine in Germany is operating since 1972), has shown that the use of already existing mines for disposal purposes holds several advantages (e.g. broad knowledge of geological situation, existing infrastructure which might allow to operate the disposal mine very cost-efficient). In such case very specific attention must be paid to the fact, that the former mining of raw material normally hasn't been designed considering a subsequent use of the mine as disposal facility. Therefore barriers, needed or at least wanted for disposal purposes
might be affected, reduced or even destroyed. If necessary, the disposal area must be clearly separated from still existing and/or former mining activities by qualified technical measures.

**Table 2** Typical numbers of host rock thickness and potential disposal depth for different geosystems

<table>
<thead>
<tr>
<th>Geosystem</th>
<th>Thickness of host rock body</th>
<th>Potential disposal depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host rock</td>
<td>Variation</td>
<td></td>
</tr>
<tr>
<td>Rock salt</td>
<td>Salt dome</td>
<td>up to &gt; 1,000 m</td>
</tr>
<tr>
<td>Rock salt</td>
<td>Layered salt</td>
<td>app. 100 m</td>
</tr>
<tr>
<td>Clay / Claystone</td>
<td></td>
<td>up to 400 m</td>
</tr>
<tr>
<td>Rocks under clay cover</td>
<td></td>
<td>app. 100 m</td>
</tr>
</tbody>
</table>

An occasionally postulated retrievability of wastes from a facility is being opposed to the underground disposal concept in general, and the concept of complete inclusion in particular, but might be applicable for a rather limited time period, whose maximum is given by the operational phase of the facility before performing all final backfilling and sealing measures.

Beside all above explanations, considering the overall concept of underground disposal as well as its long-term safety aspects, it is obvious that such facility, handling and operating with hazardous materials, must be physically protected during its operational phase against any form of inadmissible access to that material (e.g. theft, terrorism).

All explanations given in that chapter are especially valid for hazardous wastes which, by all means, must be kept away from the biosphere. In case of a treated waste, whose hazardous content is, for instance, chemically bound and which therefore poses no (or at least just minor) risk to the environment, underground disposal in an appropriate geochemical milieu might be possible, too. As an example one could mention the disposal of a sulfidic waste form into a sulfidic mineral deposit which will warrant long-lasting stable geochemical conditions, the deposit itself serving as a proof for retention of hazardous substances.
4 Regulations and Requirements in Germany

Today, in Germany the most essential regulations as well as requirements concerning the underground disposal of hazardous wastes are compiled in the so-called “regulation on simplification of disposal law” /BMU 09/). With it, the annex 2 is of prime importance, which is entitled as “requirements concerning site, geological barrier, long-term safety-assessment and closedown measures of class IV disposals in salt rock”. Since such national regulations are intended to lay down the state of science and technology, mainly salt rock is covered - due to the only technical experience of underground disposal in this host rock. But, other potential host rock types are not excluded inherently, they must warrant comparable safety.

4.1 Site and Geological Barrier

During site selection of an underground disposal, it has to be considered that a) the waste will be kept away from the biosphere permanently, and b) no aftercare will be necessary. In the German concept, salt rock constitutes the most decisive geological barrier. Therefore the following properties must be guaranteed:

- Tightness against fluids and gases,
- Sufficient spatial extent,
- Sufficient maiden thickness in the disposal horizon (no impact on barrier function in the long run),
- Gradual enclosure of the wastes due to salt convergence (force-fit at the end of deformation processes),
- Stable cavities during disposal and close-down operations,
- Regional earthquake intensity below MSK 8.

4.2 Site-related Safety Assessment

The suitability of the host rock must be proved by a site-related safety assessment, whose basis is formed by an analysis of potential threats during construction and operation of the disposal facility as well as in the post-operational phase. Such proof resp. site-related safety assessment comprises:
- Geotechnical proof of stability,
- Safety assessment for operational and close-down phase,
- Long-term safety assessment.

### 4.3 Long-term safety assessment

The long-term safety assessment must be performed for the overall system consisting of a) the waste itself, b) the technical underground constructions, and c) the rock mass (comprising the host rock as well as the overburden). With it, possible event-series, according to plan, but also unplanned (hypothetical) have to be considered, bearing in mind the site specific conditions. It is based mainly on the results of

- The geotechnical proof of stability, and the
- Safety assessment for operational and close-down phase.

![Overall system consisting of waste, technical underground constructions and rock mass (schematically) with representation of a scenario for hypothetical release of hazardous substances from underground disposal (UTD)](image)

**Figure 4** Overall system consisting of waste, technical underground constructions and rock mass (schematically) with representation of a scenario for hypothetical release of hazardous substances from underground disposal (UTD)

The geotechnical proof of stability is supposed to be most important for the long-term assessment of the efficiency and integrity of the salt barrier.
4.4 Basic information needed

For a long-term safety assessment detailed basic information is needed regarding the geological, geotechnical, hydrogeological and geochemical site parameters as well as the concentration and mobility behavior of any hazardous waste content. This detailed basic information also allows the development of an overall safety concept.

Geological conditions

- Thickness and extent of the geological barrier, stratigraphy of the mining claim, geological cross sections of the mine layout,
- Mineral content and structure of the host rock,
- Grade of exploration of the deposit (host rock), exploratory drillings from aboveground and underground,
- Grade of tectonic stress, geothermal gradient, regional seismic activity (past and present), subrosion, depressions, halokinesis.

Mine openings

- Technical details (depth, volume, drifts shafts and so on),
- Safety relevant details (stability of drifts, shafts and rooms, roof falls, fluid inflows, gas release, oil / gas in place, safety pillars, drillings, areas to be dammed up etc.).

Hydrogeological conditions

- Stratigraphy, petrography, tectonics, thickness, bedding conditions of the overburden,
- Ground-water storeys and flow, hydraulic conductivities, flow velocities,
- Ground-water chemistry, mineralization,
- Ground-water use,
- Surface waters.


**Waste disposal**

- Waste-types, amounts, constitution,
- Disposal concept and technique,
- Waste behavior (geomechanical, chemical in case of fluid contact).

**Geotechnical Stability Verification**

To guarantee the permanent keep away of the hazardous waste from the biosphere, the stability of cavities has to be verified by the following measures:

- No deformations during or after construction of the underground cavities which may vitiate the operativeness of the disposal mine,
- The load behavior of the rock mass must not negatively impact the long-term safety,
- Disposed waste should be effective for the stability of the cavities.

In this context, a rock mechanical expertise should cover the following aspects:

- Classification and appraisal of geological, tectonic, and hydrogeological awareness,
- Analysis of mining situation,
- Analysis of rock behavior,
- Derivation of potential rock mechanical endangering,
- Development of a safety plan,
- Definition of potential impact factors (geological, tectonic),
- Lab experiments for investigation of rock mechanical properties,
- In situ measurements to assess the stress situation in the mine,
- Computed rock-mechanical modeling,
- Rating of rock-mechanical conditions,
- Derivation of required measures.
4.5 Proof of Long-term Safety

To be able to guarantee the long-term safety of the overall system "waste - technical underground constructions - rock mass" the following single systems need to be assessed:

- Natural barriers (behavior of host rock and overburden),
- Technical interferences by e.g. shafts, drifts, rooms, drillings, rock loosening,
- Technical barriers, e.g. waste constitution and conditioning, disposal method, drift dams, shaft seals,
- Natural events, like diapirism, subrosion,
- Engineering caused events and processes which might endanger the enclosure of waste in the host rock and effectuate a mobilisation of its hazardous content (e.g. untightening of drillings, water or gas inflow, failure of seals, rock loosening, and invasion during the post-operational phase).

4.6 Closedown

Completion of an underground disposal facility must assure that the waste disposed is withdrawn from biosphere reliably. With it, the shafts must be backfilled fully, considering the geological profile and in a technical manner that any circuit between disposal area and biosphere is inhibited.

5 Conclusion

Underground disposal constitutes the only option to isolate hazardous waste from the biosphere permanently. While in Germany especially rock salt is esteemed as an applicative host rock - due to the rock’s properties and the overall geological situation in the country - also other rock types like clay or crystalline come into question. On the whole, a multi-barrier system must ensure the protection of groundwater and biosphere. Indispensable prerequisite is a thorough conception and operation as well as a long-term safety assessment.
Bibliography


/BRA 08/ Brasser, T. et al. (2008): Endlagerung wärmeentwickelnder radioaktiver Abfälle in Deutschland (Final disposal of heat-generating radioactive wastes in Germany). - GRS-247, Köln. Download: http://www.grs.de/module/layout_upload/index.html [covers also general aspects of underground disposal concepts, e.g. safety-philosophy, long-term safety, technical aspects].


**Practical Implementation of Underground Waste Disposal**

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**Keywords**

Underground, Waste Disposal, Plant, Rock Salt, Germany

**Abstract**

Good disposal concepts in terms of sustainability must have long-term practicality, as well as being lastingly safe and economically viable.

The safest form of disposal is to collect the harmful substances separately in the most concentrated form possible and to remove them for good from the biosphere.
1 Introduction

K+S is world leader in fertilisers and salt products with an expected revenue in 2010 of 4.5 - 5 billion €. Our group of companies employs more than 15,000 worldwide. Our main mining activities are in Germany, North and South America.

![K+S Group, facts and figures](image)

*Figure 1*  K+S Group, facts and figures

The core business in our mining activities is potash and salt. Both are used for example in the chemical industry. However, potash is mainly used in the fertilisers business and salt is used in such as the de-icing segment.

![K+S Group, business units](image)

*Figure 2*  K+S Group, business units

One of complimentary business units within the K+S Group is K+S Entsorgung, with a turnover of nearly 70 million € in 2009. K+S Entsorgung is responsible within our Group for all business related to waste. Furthermore, Entsorgung coordinates for the various sites all activities, both in Germany and abroad. This includes the activity of our two underground waste disposal facilities, of which Herfa-Neurode is the first underground waste disposal worldwide (since 1972).
Workshop Underground Disposal of Hazardous Waste

- A K+S Group business segment since 1991
- Disposal activities are centrally steered from Kassel
- Reutilisation, disposal and recycling at company-owned facilities
- Largest number of sites and technologies on the market
- Internationally active, with representatives in 8 countries
- Pioneer of underground waste disposal with first facility worldwide: Herfa-Neurode (1972)
- Revenue 2009: 67.2 m. €

Figure 3  K+S Entsorgung, profile

2  Technical Description

Four underground waste disposal plants, for a permanent and sustainable exclusion of the contaminants from the biosphere, maintenance free, are at work.

Underground disposal:
- Safest solution for the disposal of hazardous waste
- The permanent and sustainable exclusion of the contaminants from the biosphere
- Maintenance free

Underground disposal plants (UTD):
- Herfa-Neurode
- Zielitz
- Heilbronn
- Sondershausen

Figure 4  K+S Entsorgung, solutions

An orientation map, of the facilities, much in the middle of Europe, is given in the following figure.
Figure 5  Underground waste disposal facilities in Germany

Basically the origin of all is the same what we can see presently at the Dead Sea. The salt and potash deposited through evaporation – caused by solar heat – of the semi-enclosed sea. The salt deposit is rather flat; the salts, which were deposited during the Zechstein-age approximately 240 million years ago, has a thickness of about 300 metres and consists mainly of rock salt.

Figure 6  Formation of salt and potash deposits, 250 m.y. ago

As cross section one has to image there is a potash salt deposit imbedded in these mighty salt masses. The thickness of such potash deposited is i.e. in Herfa-Neurode approximately 2.5 – 3 metres. In Herfa-Neurode, for instance, the rock salt mass is covered by layers of clay and dolomite, which is again buried under approximately 300 - 600 metres of new red sandstone. These clay layers, together approximately 100 metres thick, serve to safely seal off the rock salt mass against the water-bearing new red sandstone.
These clay layers are pliable and waterproof. During previous movements within the earth's crust (for example during the folding of the Thüringen Forest) they maintained their sealing qualities. They guarantee reliable and enduring protection for the rock salt deposit below. These extremely beneficial geological conditions were the reason for the decision to operate an underground waste disposal plant in Herfa-Neurode.

The extraction of potash salts is done in accordance with the „room and pillar“-system. This system entails the construction of right-angular tunnels, leaving rectangular or square “pillars” supporting the overlying rock mass. These are dimensioned in such a way as to safeguard permanent stability of the cavities. Before the cavities may be used to deposit waste, they are again secured mechanically, clearing out any loose rocks from shaft walls, and with rock anchors. This assures their stability beyond the operational phase.
Prerequisites

Taking the example of our underground waste disposal Herfa-Neurode, it is part of an agglomeration of potash mines. This site called Werra can be compared for its size with the city of Munich and its surroundings (four times Manhattan). In this huge area, at the site within the mine where an underground disposal facility is operated, the geological situation is of crucial importance. The dimension of the rock salt beds needs to be large enough and needs to be particularly thick in the area selected for disposal. Basically, the thickness of the existing salt deposit needs to be thick enough to safeguard a long-term barrier. No mining activity must be done in the area, the cavities must be stable and - needless to say - the area must be dry and free of water.

![Prerequisites for underground waste disposal](image)

**Figure 9** UTD Herfa-Neurode, prerequisites

All underground waste disposal facilities operate according to the valid waste legislation. All plans and procedures for the underground waste disposal plant have undergone official approval.

![Underground disposal, specific safety assessment](image)

**Figure 10** Underground disposal, specific safety assessment
The basis for issuing the necessary license is the production of a long-term safety analysis, within the scope of a site-specific safety evaluation for the respective salt mine (technical planning, geological data, waste data and environmental impact assessment), which must prove that the setting-up, the operation and the post-operational maintenance of the underground waste disposal plant does not lead to any interference with the biosphere.

The aforementioned underground waste disposal plants have all been accepted by the long-term safety assessment.

Wastes intended for storage in the underground waste disposal plant need to adhere to the acceptance criteria for underground waste disposal plants, in agreement with present legislation. This is where characteristics or composition of wastes to be accepted or refused is defined. Especially with view on safety, wastes which are explosive may not be accepted for storage. Wastes may also not react detrimentally with the rock salt environment.

![Not acceptable for underground disposal are wastes that are:]
- explosive
- self inflammable
- spontaneous combustible
- infectious
- radioactive
- releasing hazardous gases
- liquid
- increasing their volume

**Figure 11**  UTD Herfa-Neurode, disposal conditions

### 4  **Practical Description**

Transport of the wastes to the underground waste disposal plant of Herfa-Neurode may be effected by trucks or by rail; the vehicles are initially intercepted at the entrance area of the underground waste disposal plant. The entrance area encompasses the necessary storage space for the delivery vessels, a scale, and an office including an in-house laboratory. The entire compound is leakage-proof and at places fitted with separate collection systems. Before the vehicles reach the entrance area, they have
already passed a radioactivity control. The entrance area also includes facilities for
taking samples from waste deliveries, as well as for the conduct of acceptance and
identity controls.

![Image of waste delivery]

**Figure 12** UTD Herfa-Neurode, waste delivery

The tasks covered by the entrance inspection and the acceptance control include the
control of the waste documents and the accompanying documents, including shipping
papers (issued according to the relevant ADR-Regulation).

The identity control includes sight-control, taking a retain sample and identification
analysis. Before the waste containers are opened, an exhaust system is used to test
for explosive gas/air mixtures. This is also done in reference to dangerous gas
concentrations. Only after these inspections have been done, non-objectionable
containers may be opened and further controls of the contents may take place. This is
also when the retain samples are taken; these are permanently stored in a separate
underground storage space.

The in-house laboratory conducts tests for determining i.e. the pH-value or conduct
identity analyses, using x-ray fluorescence analysis, as well as a variety of testing
methods. Type, scope and frequency of these tests are individually determined for
each type of waste. The results of the identification analyses are recorded and must
correspond to the initial declaration of the waste with which it was transported and
delivered to the underground waste disposal facility, according to all previous issued
documentation (such as for instance a notification file for what concerns waste coming
from abroad). The staff working at the acceptance area records all relevant data
pertaining to a delivery of waste in the plant journal. After a positive evaluation result,
each batch of waste receives an individual routing slip in which clearance and the location for underground storage is recorded.

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**Figure 13** UTD Herfa-Neurode, acceptance control

After conduct of the acceptance controls and determination of the conformity, the waste is cleared for storage. It is then unloaded from the delivery vehicle by forklifts, and is transported to its final destination. At the shaft entrance, the waste enters the underground transport system to the storage area.

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**Figure 14** UTD Herfa-Neurode, shaft transport

Underground, the waste is transported by trucks, all the way to the destined place of storage.
Figure 15  UTD Herfa-Neurode, underground transport

The waste is stacked accordingly at final place of storage.

Figure 16  UTD Herfa-Neurode, storage chambers

The artificial/technical barriers, such as packaging the wastes in containers, closing off of the storage chambers against each other and building of dams between the waste disposal area and other mining fields, serve primarily the safety of the operating phase of the underground waste disposal plant.
All information pertaining to the storage time and location is recorded in detail.

The documentation consists of a mine map, containing all information on the types of wastes stored, as well as on the walls and barriers created. This makes it possible to locate any particular waste at any time.

A main reason for the distribution and the separation of the wastes into the single material groups is the requirement that stored wastes may not react with each other. Even though all wastes are delivered and stored in sealed containers -immediate contact is thereby excluded-, maximal security requires the distribution into separate storage areas, which are sealed off against each other. This is done in consideration of worst-case scenarios, such as fire.
Hazardous wastes, which need to be isolated from the biosphere, may be deposited on a long-term basis in an underground waste disposal plant.

- First underground waste disposal plant worldwide
- Complex safety installations
- Complex documentation to allow precise backtracking
- Retain samples of every single waste delivery
- Retrievability of wastes for recovery of resources
- High capacities and flexibility
- Infrastructure of a major company

Capacities in Germany are sufficient for many decades to come. The wastes deposited are encapsulated in the rock salt mass. A multiple barrier system assures that hazardous deposited wastes are sustainably kept from leaking into the biosphere. Wastes, which are stored underground in this way, are not subject to sometimes significant dissolution and transport processes, such as often the case in above-ground storage.
### Natural barriers
- Salt ( gastight ) 350 m
- Clay ( watertight ) 100 m
- Bunter stone 500 m

### Artificial barriers
- Packaging
- Brick walls & Field dams
- Waste repository zone dams ( accesses barred by massive dams )
- Long-term-safe shaft backfilling ( watertight )

→ No other post closure maintenance, wastes are irrevocably removed from the biosphere

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**Figure 21** UTD Herfa-Neurode, multi-barrier-system
Waste Characterization and Conditioning

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Keywords
Backfilling Ordinance, Backfilling Technologies, Requirements for Backfilling, Testing Suitability of Industrial Wastes as Backfilling Materials

Abstract

The Backfilling Ordinance regulates the legal criteria concerning waste and the requirements of environmental protection as to the recycling of wastes as backfilling material. Salt mines with an admitted long-term safety proof meet the safety requirements of underground depots in Germany. Backfilling has been approved by the European Court as a form of recycling on condition that by means of a necessary measure natural resources are being substituted by industrial wastes and resources are protected. The original qualities of wastes are used directly or for producing backfilling materials following special mix designs. For the backfilling procedure numerous technical possibilities can be applied. An essential pre-condition for admission of waste for backfilling is the preparation of an expert opinion checking the suitability as backfilling material.
1 Introduction

Certain types of hazardous wastes must be disposed in underground disposals that are classified as class IV according Landfill Ordinance of 27th April 2009 (DepV), /DEP 09/ and exclude the wastes permanently from the biosphere. The different types of waste are packaged in permitted containers, drums or big bags and transported into separated disposal chambers. In Germany these special chambers are exclusively erected in evaporate and safely isolated from the other parts of the mine. The disposal of the containers with the waste is carried out very carefully like in a storehouse. Position and time of the disposal are documented by a special waste register to ensure the retrievability of the wastes. For safety reasons only waste types with similar chemical and physical properties are disposed in the same chamber.

In contrast backfilling means the back stowing of mines for safety reasons, mine cavities that have emerged from the exploitation of natural resources by mining. The material properties of the mineral industrial wastes and the resulting backfilling materials are used to minimise convergence, avoid the danger of latent sink holes or seismic events and for technical measures in the mine. Backfilling so meets the target priority of waste recycling over waste disposal of the Closed Substance Cycle and Waste Management Act (KrW-/AbfG), /KRW 94/. Backfilling has been approved by the European Court as a form of recycling on condition that by means of a necessary measure natural resources (e.g. sand, gravel, soil) are being substituted by industrial wastes and resources are protected (assigned backfilling).

It is possible to use mineral industrial wastes with adequate geomechanical properties and low content of toxic substances without further treatment as backfilling material. Furthermore wastes are applied for the production of adequate backfilling mixtures according established and admitted mix designs by using their specific material properties (e.g. binding agent, filling material, mixing liquid). The backfilling materials must be completely enclosed in the host rock after the end of mine operation and sealing the shafts. Thus its long-term elimination from the biosphere is guaranteed.

This paper gives attention to the legal regulation of backfilling in Germany, characterizes the applied backfilling technologies and gives an overview about the procedure and the testing methods for the proof of suitability of inorganic industrial wastes as backfilling material.
2 Ordinance on Underground Waste Stowage
(Backfilling Ordinance)

The Backfilling Ordinance (VersatzV), /ORD 02/ regulates the recycling of wastes in companies that are controlled by the mining authorities. It implements the claims of KrW-/AbfG for high-quality recycling by priority of metal reclaiming (§ 3) and for harmless utilization (§ 4) by definition of material requirements for the waste.

According to § 1 the VersatzV is valid for:

- Waste producers and owners of wastes,
- Managers of mines that are controlled by the mining authorities and
- Operators of facilities producing backfilling materials.

Wastes reaching the metal content value listed in the following table 1 may neither be utilized to produce stowage materials nor for direct use as stowage materials if it is technically possible and economically viable to reclaim these materials from the waste, and insofar as this is feasible while observing the permissibility requirements of such recycling.

Table 1  Limit value concentrations (g/kg) for metals in wastes according VersatzV

<table>
<thead>
<tr>
<th>Metal</th>
<th>≥ 500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>≥ 150</td>
</tr>
<tr>
<td>Zink, lead</td>
<td>≥ 100</td>
</tr>
<tr>
<td>Nickel</td>
<td>≥ 25</td>
</tr>
<tr>
<td>Tin</td>
<td>≥ 15</td>
</tr>
<tr>
<td>Copper</td>
<td>≥ 10</td>
</tr>
</tbody>
</table>

In the Backfilling Ordinance limiting values of harmful substances within waste (appendix 2, table 1) and of the leaching behaviour (appendix 2, table 2) have been determined with respect to environmental protection.

According to § 4 para. 3 these limiting values are not valid for salt mines which have completely enclosed the harmful substances of waste within the mine thus permanently closing them from the biosphere by means of a long-term safety proof. Contact of
wastes with aquiferous layers on the surface resulting in mobilizing the harmful substances in wastes can definitely be excluded. This way salt mines meet the safety requirements of underground depots in Germany. Only the correlation values for the parameters TOC (organic carbon) and glowing loss of the organic substances mentioned according appendix 2, table 1a have to be applied to guarantee the inorganic character of the wastes.

The limiting values for the content of harmful substances (applied to dry matter) and for the eluate mean a serious restriction for backfilling in different geological formations, like ore and coal. Because the harmful substances of the backfilling materials can get in contact with groundwater of deeper horizons or surface waters in these host rocks, the limitation was strongly necessary for the protection of the biosphere. The exceeding of the limiting values is permitted only in the following cases:

- the respective contents do not exceed the contents of the absorbing rock (geogenous basic content) or
- for carbon and secondary rock:
  - for wastes only from coal firing (coal- or lignite-fired power stations)
  - no higher noxious impurities than provided for under a) in the case of co-incineration of other materials

According to VersatzV rock salt or potash mines were selected for backfilling because they offer a total enclosure and permanent isolation of the waste materials from the biosphere after the end of operation and sealing the facility.

### 3 Backfilling Technologies

Different backfilling methods are used in Germany, the following figure 1 gives a schematic overview of the actually practiced technologies. Pneumatic stowing has become less important during the last 10 years and is therefore not illustrated in the flow chart.
Mainly wastes that can be backfilled without further treatment (because of low content of hazardous substances and adequate geomechanical properties) are recycled in drop backfilling (e.g. contaminated soil, construction waste, furnace lining and slags). They are transported in containers down the shaft. Special vehicles take over the underground transport. The backfill materials are dumped into the backfilling chambers. If necessary, the bulk goods are sprinkled with water or saline solutions on the surface to make them dustproof.
3.2 Backfilling by Bag Bags

Backfilling can be done also with industrial wastes already packaged by the producer or packaged by the operator of the backfilling mine on-site. This technology is especially used for foundry sands, boiler slags, industrial salts and waste blasting material with low content of hazardous substances and sufficient compression behaviour. Furthermore backfilling by big bags is suited for products of mixing plants or cemented mixed products. The big bags are transported into the underground via the shaft, and there lorries and big vehicles transport them into the backfilling rooms. Forklift-trucks install the big bags into the backfilling chambers in layers. Alternating storage with covering salt is applied to reduce the pores.

![Backfilling of a mining site with big bags](image)

3.3 Hydromechanical Backfilling

Finely grained and grained wastes such as dusts, ashes, products of chemical flue gas treatment from waste incineration, foundry sands, boiler slags and sludge are usually processed into a flowable (flushing backfilling) or pumpable (backfilling by viscous slurry) backfilling material mix with adding a concentrated salt solution. The applied transporting solution must be chemical inactive against the host rock.

In the process of **flushing backfilling** the backfilling suspension is produced on the surface according to various mix designs with a procedure of referring to material groups. The mixture with a considerable excess of mixing liquid remains in a reaction drum to reduce exothermal effects and a possibly existing gas formation potential. After a residence time of 2 to 4 h on average the backfilling suspension is transported into
the backfilling rooms by means of a piping system thus using the geodesic difference in height. The salt solution applied in this procedure serves as a transporting medium for solid particles and reactant for the setting behaviour. The excess transporting solution drains the backfilling material by means of a dam construction respectively a barrier system, and under surveillance it is collected in a brine-collecting basin at a deeper point of the mine. Subsequently it is transported back into the process on the surface (circulation of the transporting solution). Figure 4 shows the flow chart of a flushing backfilling plant.

![Flow chart of a flushing backfilling plant](image)

**Figure 4**  Flow chart of a flushing backfilling plant

By means of flushing backfilling a nearly complete backfilling (> 90 Vol-%) of the mining sites can be achieved.

**Backfilling by viscous slurry** shows the following important differences in comparison with the technology of flushing backfilling:

- No or only low excess of mixing liquid required
- No brine drainage system necessary, small amounts of excess transporting solution are removed by weathering or admitted by excavation disturbed zone
- High saturation of the pore liquid ⇒ can be used also for sensitive host rocks
- Higher viscosity requires the installation of high performance pumps (e.g. plunger pumps)
- Mixing process can be carried out on surface or in the underground

The application of backfilling by viscous slurry for stabilization of brine filled caverns combined with the use of the discharged brine as mixing liquid is a comparatively new technology.

Hydromechanical backfilling is, in comparison with drop backfilling and backfilling by big bags, a cost-saving technology and achieves a high stowing degree with good contact to the host rock. The geomechanical properties of the backfilling material can be adjusted to some degree by selection of the adequate backfilling technology, the use of appropriate waste materials and the additional application of binders (e.g. cement, MgO).

### 4 General Requirements for Backfilling

The recycling of wastes as backfilling material or as component of backfilling mixtures in salt mines with accepted long-term safety proof depends on strict criteria which mainly concern aspects of safety and the requirements of work protection as well as health protection. The essential requirements for the backfilling materials are summarized in the Technical Rules to be applied to industrial wastes for backfilling by the Federal States Committee for Mining /TRA 06/.

Wastes or mixtures that (if applied under underground conditions) are

- spontaneously flammable,
- extremely flammable, highly inflammable or flammable,
- explosive (or tend to be explosive),
- oxidizing or
- infectious

are excluded from underground backfilling. Nuclear wastes are equally excluded.
5 Work and Health Protection

The Ordinance on Hazardous Substances (GefStoffV), /GEF 04/ is valid for the handling of wastes on surface. The requirements of work and health protection in the mine are determined in the Health Protection Ordinance for Mining (GesBergV), /GES 91/. According to § 4 para. 1 GesBergV it is forbidden to let people deal with materials and mixtures that are to be classified and marked as

- carcinogenic,
- mutagenic,
- toxic for reproduction or
- very toxic and toxic.

With respect to backfilling these criteria are only valid for the completed backfilling material. Wastes that show one or more of these characteristics can be processed as a component of the backfilling mixture if it meets the requirements of GesBergV. Recycling of highly odorous backfilling materials is not permitted either.

6 Verification of the Suitability for Backfilling in Laboratory Scale

Before the operator of a salt mine can apply for admission for the application of a special industrial waste as backfilling material, it has to be examined as to its characteristics relevant to backfilling by an expert opinion regarding its suitability. This expert opinion also verifies the suitability of the examined waste as component of a mix design.

The following basic investigations are carried out in an expert opinion:

Phase 1: Examination of the waste properties

- Preparation of a chemical declaration analysis according to fixed standards taking into consideration the origin of the harmful substances
- Determination of essential physical parameters (humidity, densities, grain size distribution)
- Investigation of hazardous waste properties (e.g. flammability)
- Investigation of the gas forming behaviour (gas forming potential in highly acid and alkaline solutions, gas emission in contact with water and saline brines)
- Examination of the waste as to its characteristics as a binder in contact with brines
- Evaluating the waste according to legal instructions concerning waste management (VersatzV), industrial hygiene and chemicals (GefStoffV, GesBergV)

**Phase 2: Evaluation of the waste as a component of a mix design**

- Preparation of exemplary mix designs with the waste in laboratory scale, testing of the processing properties
- Examination of qualifying for backfilling under aspects of building physics (density, strength)
- Determination of the properties regarding mining safety (tolerance of backfilling materials among one another, hydrogen formation, behaviour against host rock)
- Evaluation of aspects of work protection of the backfilling mixtures

![Figure 5](image1) **Figure 5** Determination of the flow extent of a viscous slurry mixture

![Figure 6](image2) **Figure 6** Test sample of a hardened backfilling product

Expert opinions about the suitability for backfilling certify that the wastes examined show the same characteristics as building material as the natural resources they substitute and they also confirm that there are no dangers arising from the harmful substances in the waste, when backfilling materials are produced and processed.
7 Summary

By applying mineral industrial wastes as backfilling measures in salt mines ordered by the Mines Inspectorates a kind of waste disposal has been created that provides a highly environmentally-friendly form of recycling industrial wastes by encapsulating them in a depth of a few hundred meters. As to environmental standards these backfilling mines meet the requirements of underground deposits in Germany. Such a high amount of environmental protection cannot be guaranteed by disposing of the wastes in other rock formations or by the deposition of wastes with or without pre-treatment (e.g. immobilization) on landfills on the surface.

The Backfilling Ordinance regulates the legal criteria concerning waste and the requirements of environmental protection as to the recycling of wastes as backfilling material.

Backfilling has been approved by the European Court as a form of recycling on condition that by means of a necessary measure natural resources are being substituted by industrial wastes and resources are protected (assigned backfilling).

The original qualities of wastes are used directly or for producing backfilling materials following special mix designs. For the backfilling procedure numerous technical possibilities can be applied.

An essential pre-condition for approving wastes for recycling or producing backfilling material is the analysis of their characteristics as to their relevance for recycling. That is usually carried out by means of an expert opinion checking the suitability for backfilling. If waste shows dangerous properties that do not allow its application for backfilling it is excluded from recycling. All approved wastes are regularly checked as to their quality.

Waste producers will be guaranteed maximum safety by German salt mines with assigned backfilling over a period of several years.
Bibliography

/DEP 09/  Landfill Ordinance, 27th April 2009

/KRW 94/  Closed Substance Cycle and Waste Management Act, 27th September 1994

/ORD 02/  Ordinance on Underground Waste Stowage (Backfilling Ordinance), 24th July 2002


/GEF 04/  Ordinance on Hazardous Substances, 23th December 2004

/GES 91/  Health Protection Ordinance for Mining, 31th July 1991
Long Term Chemical Behavior of Waste Components

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Waste, Leaching, Reaction, Modeling, Data base

Abstract
Wastes are safely stored in an underground facility until chemical reactions take place that lead to a release of their hazardous contents. The paper discusses some important reactions types that may occur if wastes get into contact with water. In some cases even moisture like the water content of the waste or of the mine air might be enough to start chemical or microbial reactions. Some principle approaches of leaching tests are briefly introduced before finally the opportunities and challenges of geochemical modeling are reviewed. The development of the German Thermodynamic Reference Database THEREDA strongly improves the theoretical basis for modeling but an in-depth understanding of real processes of waste-water interaction is still needed to allow for reliable predictions.
1 Potential chemical reactions of waste in an underground storage facility

1.1 No water – no reaction – with few exceptions

Underground storage facilities are chosen for the disposal of hazardous waste because they provide an opportunity to permanently isolate waste and their hazardous components from the biosphere. In order to ensure such isolating properties sites are chosen that possess favorable hydrogeological properties: surrounded by geological barriers that prevent or at least minimize water influx from the surrounding environment into the facility and thus, prevent to the largest extent possible the chemical reaction of water with waste containers and waste components. Hazardous components of wastes with very few exceptions can only be mobilized and transported by water. Transport via the gas path is possible only for very few substances, including radioactive gases like tritium or radon and volatile substances like organics and elemental mercury. However, technical and geological barriers that are water tight, most often are gas tight as well.

Therefore, the absence of water effectively prevents transport of hazardous substances to the biosphere. There are few host rock formations which are really dry. Among these rock salt and potash deposits are the most prominent1. Other examples may be elevated rock structures in very arid areas where the groundwater level is very deep and the minimal precipitation vaporizes before it drains away. For a waste facility in a dry host formation under normal conditions (that means: after effective sealing of the facility) no chemical reactions between water and waste are expected - with few but important exceptions that are discussed later.

1.2 Potential sources of water

In a dry underground storage facility no or relatively few chemical reactions are expected to happen. If the geological situation does not allow for permanently dry conditions as it is the case in most hard rock formations, intrusion of water into the facility and contact with the waste cannot be avoided. Another aspect that has to be considered is the presence of water in the host formation. Limited amounts of salt solutions are sometimes encountered in salt formations as well. They can be of different origin. In most cases brine seepages are harmless as they have very limited volumes and are not connected with the overburden.

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1 Limited amounts of salt solutions are sometimes encountered in salt formations as well. They can be of different origin. In most cases brine seepages are harmless as they have very limited volumes and are not connected with the overburden.
taken into account is the failure of important geological and technical barriers. The sealing of drafts and shafts is an essential element in the safety concept of every underground storage site. Should these seals fail or not (yet) be in place water threatens to flood the mine (possibly at a very low speed) up to a point where remediation is no longer technically possible. Another unplanned event is the opening of new fissures in the host rock after the closure of the mine due to huge differential stresses. For all these cases it is necessary to investigate the potential chemical process that may occur when water gets into contact with the disposed wastes.

1.3 Chemical reactions without water intrusion

Often neglected but potentially critical are chemical reactions that can take place either on the basis of small amounts of water present in the air or the waste or without any water present at all. Important types are

a) Microbiologically driven decomposition of organic waste components

b) Corrosion of metallic waste components and containers through action of moisture or oxygen and other gas generating processes

c) Reactions of liquid waste with containers, host rock and technical barriers

All of these reaction types are enhanced if additional water from the host rock is available.

1.4 Biodegradation of organic waste components

Bacteria are ubiquitous and may also be found in wastes. If the microbial microfauna find favorable conditions like temperature, nutrients (energy sources) and moisture they may adapt to the situation and make use of any decomposable organic material. The consequences are the production of gases (carbon dioxide, methane and higher hydrocarbons), water and heat. Such a process occurred in the underground disposal facility Stocamine in Wittelsheim in 2002. A mixed waste from a pesticide warehouse fire, rich in organics, obviously fermented, got heated and finally caught fire and lead to the ignition of adjacent waste containers. The fire caused widespread contamination in the facility and could be extinguished only two and a half months later. By then a
decision was taken to finally close the facility and the adjacent potash mine as well /CAF 10/, /LUD 09/.

1.5 Generation of hydrogen and other gases through corrosion of metallic waste components or hydrolysis of metal sulfides, nitrides and carbides

Corrosion is a natural process that occurs with almost all metals. Its speed depends on the metal involved, its physical properties (specific surface) and the geochemical conditions (oxygen, pH, solution composition). Normally, like with iron or steel, the process is rather slow and has no relevance for the operational or long-term safety. The situation is different for wastes that contain batteries or metal in powders or otherwise dispersed forms. Wastes that may contain dispersed metallic components include gas cleaning residues from waste incineration plants (presumably aluminum and iron) that could be produced under anoxic conditions in the gas stream) and wastes from metal production (gas cleaning residues) and working (like sandblast residues or abrasive slurries).

Under certain circumstances such wastes may react with traces of moisture in the waste itself or the surrounding air to produce hydrogen gas. In a GRS research project three wastes were identified that produced more than 1 m³ and up to 4.7 m³ hydrogen gas per ton waste after 28 days contact with an atmosphere of 51 % relative humidity /HAG 06/. In one case (an abrasive slurry) the gas generation continued for more than two years and resulted in 14.6 m³/t hydrogen gas (Figure 1). It should be noted that the generation of hydrogen gas was not higher when this waste was in direct contact with water, but showed no gas generation when put in a dry atmosphere. Mixing of waste with water produced up to 28 m³/t Wastes with a high gas generation potentials (> 1 m³/t) included fly ashes, waste incinerations residues, metal production wastes, batteries, but also debris and slurries.
Such gas quantities may lead in the short term to explosive gas mixtures (if air exchange is low) and in the long-term to a pressure build-up (if gas permeability of host rock and barriers is low) which could affect the integrity of technical and geological barriers.

Beside hydrogen gas, methane and gaseous ammonia were observed in some experiments. It is assumed that certain wastes (especially those from thermal processes like metal production but also waste incineration) not only contain metallic aluminum but also traces of aluminum carbide and aluminum nitride that readily release methane and ammonia when brought into contact with water.

Even more critical are wastes that have the potential of self-ignition. Among these are wastes that contain aluminum in dispersed form, especially in form of tiny particles. An example for such a dangerous material is the pyrolysis residue from a metallurgical plant that was used as a backfill material in a German salt mine. In 2002 several big bags filled with these residues – a mixture presumably consisting of coal and aluminum ignited underground and above-ground. The fire burnt for weeks /MDZ 02/.

Figure 1  Gas release of abrasive slurry after contact with humid air or water
1.6 Reactions of waste with host rock

Some potential host rocks are susceptible to the attack of chemicals agents. If liquid wastes or wastes with free water content are excluded, no reaction is expected to happen. But if water is present the waste might react with the host rock:

- Rock salt and potash: Water from the waste may dissolve the salt minerals present in the mine. Therefore the disposal of liquid (water containing) waste is not allowed.

- Limestone, dolomite: Wastes that have a high acidity may react with carbonate minerals to form carbon dioxide, which could lead to a pressure built-up. Such wastes should be avoided or neutralized before.

- Sulfide ores: Reactions with acidic waste may lead to the generation of toxic hydrogen sulfide gas. A pressure built up could be the consequence. Wastes that contain oxidizing components (like chromate (VI) may oxidize sulfides to sulfur or sulfites and generate sulfur dioxide. Acidic and oxidizing wastes should be avoided in sulfide ores.

No critical reactions are expected for silicate based rock like granites, gneisses or iron ore deposits. Argillaceous formations may contain carbonates and sulfides, but only in minor concentrations so that no limitations regarding acidity, water content or oxidation potential will apply.

2 Chemical reactions in case of water intrusion

2.1 Reaction types

In the previous chapters chemical reactions have been discussed which can occur even in the absence of intruding water. Such reactions can be avoided if wastes with unwanted or incompatible properties are not accepted for disposal or if they are pretreated. In such cases the mobilization of non-gaseous substances can only begin if there is a water inflow into the waste disposal area. Intruding water can leach substances from the waste body by dissolution of solid phases, desorption and ion exchange. On the other hand part of these mobilized substances can almost immediately be retained by precipitation of insoluble solid secondary phases, co-precipitation or sorption.
In most cases only a part of the waste’s hazardous content is available for mobilization and transport. Other parts are tightly bound in almost inert matrices or in very insoluble compounds which will not be dissolved at all or very slowly. Figure 2 shows the relationship between total, available and already leached amounts. The relationship between total and available content can be investigated in laboratory by leaching experiments and theoretically by geochemical modeling. Both approaches will be discussed in the following chapters.

![Figure 2](image-url)

**Figure 2**  Total, available and mobile amounts of hazardous substances in waste

/CEN 08/

### 2.2 Leaching tests

The purpose of leaching tests is to determine the quantity of a particular hazardous substance that can be mobilized by water. According to the German Landfill Ordinance the leaching procedure 12457-4 shall be applied to test the mobility of a number of hazardous substances: Waste with a particle size below 10 mm is mixed with de-ionized water at a liquid to solid ratio of 10 l/kg and shaken for 24 h. Waste that shows leaching concentrations above certain limits are excluded for underground disposal. It should be noted that these limits do not apply for salt mines. Here, the long-term safety assessment must show that the risk of water intrusion is negligible and consequently the risk of leaching does not exist.
The leaching test EN 12457-42 has been recognized as a simple, cheap, fast, and reproducible procedure and was recommended for the testing of industrial waste that should be disposed in above-ground landfills /LFU 1994/. However, the test gives less valuable information on the long-term behavior of waste in underground disposal facilities. On the one hand, the reaction time (24 h) is very short so that slow leaching processes are not fully covered. The mobile ratio of hazardous substances may be significantly higher. On the other hand the use of de-ionized water does not correspond with the geochemical situation in underground mines, where often a high salt content or other mobilizing factors like complex forming agents are found that may lead to a much higher mobility (Table 1).

**Table 1** Relative mobility of selected heavy metals in leaching tests with salt solutions in comparison to test with water (flue gas residue)

<table>
<thead>
<tr>
<th>Element</th>
<th>Leaching test with water</th>
<th>Leaching test with solution saturated with NaCl and gypsum</th>
<th>Leaching test with ‘Q’–solution (rich in MgCl₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb</td>
<td>100</td>
<td>847,1</td>
<td>617,9</td>
</tr>
<tr>
<td>Ni</td>
<td>100</td>
<td>0,25</td>
<td>1,25</td>
</tr>
<tr>
<td>Cu</td>
<td>100</td>
<td>0,21</td>
<td>2,20</td>
</tr>
<tr>
<td>Cd</td>
<td>100</td>
<td>3,64</td>
<td>1,03</td>
</tr>
<tr>
<td>Zn</td>
<td>100</td>
<td>0,48</td>
<td>2,80</td>
</tr>
</tbody>
</table>

The standardized leaching procedure 12457-4 is most probably a good screening test to roughly evaluate the leaching behavior of wastes in pure water but it does not give the central answers needed for a long-term safety assessment of an underground storage facility: the maximum leachable amount and the maximum concentration of a hazardous substance. To generate such information other leaching tests are needed. Examples are:

- Availability test / Maximum leachability: The waste (often with reduced particle size) is repeatedly leached by fresh solution. Examples are the Canadian Soxhlet Test (MCC-5s) or the Dutch ‘maximum availability leaching test’ (EA NEN 7371:2004, /UEA 05/)

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2 Former DIN 38414 Teil 4 (DEV S4)
Maximum concentration: waste and solution are mixed; the resulting leachate is then mixed with fresh waste. The concentrations of substances rise until they reach a solubility limit. Also called 'leachate concentration build-up tests'. Examples are the (Wisconsin’s Standard Leach Test, Procedure C /Ham 79/, or the GRS cascade test /HER 96/).

3 Modeling of waste-water interaction

3.1 The need for thermodynamic data

Leaching tests give only limited information about the behavior of wastes in contact with solutions. Depending on the nature of the chosen procedure the results of leaching tests only give a rough idea about the mobile content of a waste. Due to their short reaction times long-term processes generally cannot be investigated. Such information could be made available by geochemical modeling. From a purely thermodynamic point of view only limited information is needed to make a prediction for the interaction of waste and water:

- The masses of elements in waste and water
- A thermodynamic model, including data on the thermodynamic stability (free enthalpy) of all solid, liquid and gaseous phases that could principally form. Because we are dealing with aqueous solutions, a physical-chemical model is needed that describes the speciation (oxidations state, chemical complexes) of every element in solution.

While the masses of elements may be rather easily determined by instrumental analysis, each entry in the thermodynamic model needs a close investigation. It may be assumed that for every element in the database several dozens of complexes and even more solid phases are involved and have to be considered. Chemists around the world have investigated these parameters since more than 100 years and huge amounts of data are available. The product of these international efforts is an impressive number of important databases that are used by most modelers worldwide. These include the thermodynamic databases of the Nuclear Energy Agency (NEA) /NEA 10/, the Paul-Scherrer-Institute (PSI) /HUM 02/, National Institute of Standards and technology (NIST) /NIS 10/, Japan Nuclear Cycle Development Institute (JNC)
These databases work well for the purposes they have been developed for—but they are not fully applicable in Germany. First, in many cases sufficient data for non-radioactive elements are missing and second, additional data for solutions with a high salt content are completely lacking.

### 3.2 THEREDA - the German Thermodynamic Reference Database project

Based on this analysis three German Ministries decided in 2006 to team up and fund THEREDA, the German Thermodynamic Reference Database project /THE 10/. The goal of the project is to develop a high quality internally consistent thermodynamic database that builds as far as possible on already existing data sets like the NEA database but adds data that are of importance for the specific situation in Germany. THEREDA will include data for all elements that are relevant for the underground disposal of hazardous (e.g. Zn, Pb, Cd, Se, Co, Ni, Cu, Cr, As) and nuclear waste (3) at temperatures between 25 and 90°C and builds on earlier projects that developed thermodynamic data for these elements. The project is carried out by a consortium of German and Swiss institutions and lead by GRS.

The first project phase concentrated on data for 25°C and the description of the salt system (Na-K-Mg-Ca-Cl-SO₄) at temperatures up to 180°C. In the second project phase identified gaps will be closed and data for temperatures other than 25°C collected and evaluated.

<table>
<thead>
<tr>
<th>Host Rock components</th>
<th>Container, waste matrix components</th>
<th>Radionuclides/toxic metals:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt rock/potash rock</td>
<td>Concrete and its corrosion products: Ca-Mg-Al-SiO₄·Cl-SO₄·OH</td>
<td></td>
</tr>
<tr>
<td>Clay, Granite: Al, Fe, Si</td>
<td>Iron, other steel components and their corrosion products: Fe, Cr, Ni …</td>
<td></td>
</tr>
<tr>
<td>(seawater system)</td>
<td></td>
<td>Actinides Th, U, Np, Pu, Am, Cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fission products: Cs, Sr, Ra, Eu (Nd), I, Tc</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other toxic metals: As, Co, Ni, Cr, Zn, Hg, Cu, Pb, Cd …</td>
</tr>
</tbody>
</table>

**Figure 3** Chemical elements in the German Thermodynamic Reference Database THEREDA
3.3 Challenges of geochemical modeling

Quantitative prediction of waste-water interactions are a challenging task for modelers. Typical industrial wastes like fly ashes or residues form metal processing contain a large number of elements in significant concentrations. The number of potential solid phases and aqueous species increases exponentially with each element added. Even more challenging are assumptions on the chemical model:

- Which solid phases will really be present at the end of the reaction? Which phases are thermodynamically more stable but will not be formed because the formation rate is too small? For example under reducing conditions iron would probably be bound in magnetite $\text{Fe}_3\text{O}_4$, the formation rate is very low at ambient temperature. Instead, ferrihydrite ‘$\text{Fe(OH)}_3$’, goethite $\alpha-\text{FeOOH}$ or ‘green rust’, Fe(II),Fe(III) hydroxy salts may be the more important phases to be found during a reaction.

- What is the fate of elements with minor or trace concentrations? Theoretically all elements may form their own solid phases, but in practice many of them will be bound in ‘host phases’ of more abundant elements. The fact is well established through experiments with water-water mixtures where often only a limited number of phases could be found /REI 95/. It is also very well documented for the leaching of nuclear waste, where minor components may be found as impurities in structurally flexible, sometimes amorphous secondary phases of major components.

If these questions can be answered to a certain degree and sufficient thermodynamic data are available to describe all relevant equilibria then geochemical modeling has a good chance to predict element concentrations correctly. If not geochemical modeling is speculative.

In the following example experiment and geochemical modeling gave corresponding results /HER 99/. A waste a flue gas cleaning residue from the production of industrial glass was mixed with the so called ‘Q’ solution, a solution that typically forms when potash minerals get into contact with water. The leachate was mixed with fresh waste and the procedure repeated several times. Figure 4 shows the development of the lead concentration as it was found in the experiment and in the geochemical calculations. The first calculation was done on the basis of available literature. It was impossible to predict any lead solubility in the system. After new experiments on lead containing systems two new datasets were developed, one that explicitly included lead chloride.
complexes and another where the complex formation was only considered as a strong interaction with chloride /HAG 99/. The calculations with the new data sets correspond reasonably well with the experiments: the predicted and found lead containing solid phase (lead sulfate) were the same. The concentrations differed by a factor of two to three. Such a difference may be considered high. But taking into account that only a part of the elemental spectrum was considered in the calculations the results are quite good. Moreover, it should be noted that for underground disposal studies, calculations with an uncertainty below one order of magnitude are mostly sufficient.

**Figure 4** Leaching of a flue gas residue the waste with ‘Q’ solution (GRS cascade procedure). Experimental data (points) and geochemical modeling (lines) /HAG 99/

### 4 Conclusions

Chemical reactions of waste in underground storage facilities typically take place only in case of water intrusion. Biodegradation and metal corrosion are important exceptions from this rule. Both could lead to a pressure build-up and in extreme cases to self-
ignition of wastes. The occurrence of these processes should be prevented by carefully excluding wastes with a high organic or metallic content from underground storage.

The long-term behavior of waste in contact with water or aqueous solutions could in principle be predicted by geochemical modeling. It requires an in-depth understanding of the processes and solid phases than can be expected to occur. But even more, thermodynamic data of high quality are needed to describe the solubility of inorganic hazardous substances like lead, cadmium or mercury. Otherwise geochemical modeling is closer to speculation than to reality. Information on the thermodynamic properties of inorganic hazardous substances is critically reviewed in the German database project THEREDA. Nevertheless, further efforts are needed to close existing data gaps, especially with regards to the speciation and of heavy metals in natural solutions.

Bibliography


http://www.iss.it/binary/publ/cont/252%20-%20ANN_08_36%20Centioli.1224497272.pdf


Workshop Underground Disposal of Hazardous Waste


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Geotechnical barriers - shaft and drift sealings

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Keywords
Shaft and Drift Sealing, Compacted Bentonite, Asphalt / Bitumina Sealing, Brine Concrete

Abstract
Several research projects have been concerned with shaft and drift sealings of hazardous waste disposals in Germany. Large scale tests have been performed in the mines Salzdetfurth, Sondershausen, Teutschenthal and others. A 200 m high filling column has been build up to test the silo effect in a 1:1 scale. A 25 m high bentonite bore shaft sealing has been performed to test the hydraulic conductivity of Bentonite binary mixtures. A 1:1-drift-sealing (bentonite and asphalt sealing) has been tested in Sonders-hausen mine. Bentonite and Asphalt are the main sealing materials used in Germany. The status of research is far advanced for shaft sealings. The focus is on shaft sealings in rock salt. For drift sealings further research is necessary.

1 Introduction
Underground disposals filled up with hazardous waste in a mine have to be isolated from the biosphere after closure of the disposal. The main barriers to isolate the
hazardous waste from the biosphere are shaft and drift seals. Both are technical precisely geotechnical barriers. In this presentation an overview will be given to the status of research projects concerning shaft and drift sealings for hazardous waste disposals in Germany.

Nearly all underground disposals are located in salt, mainly rock salt in Germany. So the research projects are also focused to shaft and drift seals in rock salt.

For shaft and drift seals in mudstone or clay only theoretical considerations have been worked out till now in Germany. No large scale tests in mudstone have been planned. But German researches are involved in several international projects (e.g. ESDRED) concerning seals in mudstone.

2 Aims of shaft sealings

Figure 1 shows a principal solution for a shaft sealing. The first aim is to avoid a contact of the ground water with hazardous waste. The second aim is to avoid contact of (perhaps contaminated) salt water or perhaps gas from the inner mine with the ground water and the biosphere.

![Scheme of a shaft sealing in rock salt](image)
So we have to distinguish for shaft sealings between pressures from

1) The upper side (mostly fresh water),
2) The disposal side (salt water or gas),
3) Both sides.

3 Existing shaft sealings

Figure 2 and 3 show existing shaft sealings in Germany. They are no research projects but they are important projects to show the possibilities and the status of practice in Germany /SIT 04/.

Figure 2 shows the shaft sealing System of the gas storage Burggraf–Bernsdorf. The gas pressure within the mining layout is 3.7 MPa. The sealing system is an active sealing with a sealing pressure of 4.2 MPa.
Clay sealing elements for shafts are well known in German classic salt mining and in underground gas storage facilities in rock salt. The system consists of two independent sealing systems between convex concrete abutments. In the combination seal the annular space to the rock salt is sealed with oil under high pressure. The hydraulic sealing system consists of a clay suspension under high pressure between two clay-bitumen sealing elements. The system is gas proofed.

Figure 3 shows the shaft sealing system of the Glückauf II shaft. It is located within rock salt. It was built in 1993. It is designed for pressure from both sides up to 6 MPa. The abutments consist of brine-concrete (cement + aggregate + saturated NaCl-solution). The shaft sealing system "Glückauf" is a typical construction in salt mining with upper and lower clay – asphalt - sealing elements against the assumed fluid pressure from both sides – freshwater from the roof and salt solution from the base.
There also exist shaft sealing concepts for nuclear waste disposals in Germany /HUN 07/ for

1) Shaft “Konrad” 1 and 2 (LLW and ILW)

2) Shaft “Asse” 1 and 2 (LLW and ILW), (not finally decided)

3) Shaft “Endlager für radioaktive Abfälle Morsleben” (ERAM) (LLW and ILW)

A repository for HAW is still looked for; perhaps it may be located at Gorleben. A concept for a shaft sealing system for a HAW-Repository does not exist currently.

4 Research projects to shaft sealings

A comprehensive summary of German shaft sealings is collected in a preliminary report /SCH 95/. So the next figures show only research projects after 1996.

One of the biggest research projects is in the last 15 years was the shaft sealing at Salzdettfurth mine /SIT 03/, /GRU 08/. Performer of the Research project Salzdettfurth II are K+S, DBE, IfG Leipzig, GRS Braunschweig and the Institute for Mining and Foundation Engineering at the Technical University Bergakademie Freiberg.

In a shaft with a depth of 770 m a filling column has been erected with a height of more than 200 m (see Figure 4). The material was course grained ballast also used in railway construction. Pressure pads were used to measure the vertical and horizontal ballast pressure. A special geometry was designed for the shaft landings. The main purpose was to prove the silo effect in a very large dimension if there are several shaft landings. The settlement of the ballast column was very small. One of the important results is that the shaft landings must be stabilized with discharge proof dimensioned gravel construction faces.
Figure 4  Research project Salzdetfurth II, filling column with very low settlements

The second part of the Salzdetfurth research project has been the sealing drilling shaft test (see Figure 5). A drilled shaft with 2 m diameter and a length of about 25 m has been sealed mainly with bentonite. The bentonite has been compacted (see Figure 6).

Figure 5  Research project Salzdetfurth II, test of the sealing elements

In the midth of the test there is a pressure chamber. The pressure chamber is filled by fluid from a small drilling from beside. The maximum pressure has been up to 4 MPa.
and then 7 MPa. The infiltrations rate has been measured and is charted in Figure 7. The long term k-value was calculated to $5.8 \times 10^{-11}$ m/s at 4 MPa and $4.4 \times 10^{-11}$ m/s at 7 MPa salt solution pressure.

**Figure 6**  Used Bentonite types for the in situ test in Salzdetfurth

![Bentonite types](image)

**Figure 7**  Sealing performance of bentonite sealing elements in Salzdetfurth

![Sealing performance](image)

At Technical University Bergakademie Freiberg there are several large scale test facilities where sealing materials like bentonite can be tested in cylinders with a diameter of 0.8 m up to 10 MPa pressure with different salt solutions (see Figure 8).
With these facilities different tests with equipotential-layers of sand within bentonite granulate have been carried out. The tests demonstrated the ability of the sand layers to avoid a fingering effect of the infiltrated water within the bentonite sealing /KÖN 08/, /GRU 10/.

**Figure 8**  Cylindrical test facilities for equipotential-sand layers within a bentonite sealing

The shaft sealing systems can be systemized as shown in Figure 9. In Germany it is distinguished between sealings with concrete abutments and sealing without concrete abutments. Mainly Bentonite and bitumen respectively asphalt is used as sealing material.

**Figure 9**  Types of shaft sealing systems
5 Existing drift sealings

At drift sealings the flow through the sealing element (e.g. bentonite) through respectively along the contact area and the flow through the excavation disturbed zone have to be distinguished (see Figure 10). Special efforts have been made to seal the contact zone by grouting. A two-component-bitumen /KAW 05/ and an epoxy resin /KAL 08/ has been developed and tested at several sites with hopeful results.

**Figure 10** Different flow areas at a drift sealing element

In 1998 the drift sealing systems in the mine Immenrode has been erected in rock salt (see Figure 11), which is mentioned here respectively (no research project). The sealing system consists of a short term and a long term sealing element. The long term sealing elements consist of compacted sand-bentonite blocks with 50 % and 70 % percent silica sand.

**Figure 11** Immenrode drift sealing

- Short term sealing element: 1 - 4 / 10 - 13
- Long term sealing element: 5 - 7 / 7 - 9
- Abutment (4, 10) Brine-Concrete with standard aggregate
- Sealing element (2, 12) with ring-seal (3, 11) Bentonite - Blocks FS50 (50 % silica sand)
- Main-Seal with FS50 (7) and FS70 (6, 8) (70 % silica sand)
- Gravel-Sand-Intersection (5, 9)
- (No current fluid pressure load)
Unfortunately the drift sealing has not been under salt solution pressure. So no conclusion to the serviceability and the hydraulic conductivity can be made.

Other realized drift sealing projects exist at the mine Hope /FIS 87/ in rock salt and at the mines Königstein and Warndt-Luisenthal /KUD 06/ in hard rock. Also drift sealing projects are planned and partly realized in the repository ERAM /MÜL 03/.

6 Research projects to drift sealings

One of the largest 1:1-scale tests (see Figure 12) has been performed in 1997 till 2003 in the Sondershausen salt mine after several half technical and laboratory pre-tests. It was financed with the support of the Federal Ministry for Education and Research (BMBF) and co-financed of the Federal State of Thuringia.

**Figure 12** Scheme of the drift sealing (bentonite-bricks) and the abutment (salt-bricks) at Sondershausen mine

The sealing system of the drift sealing experiment consists of the following main elements (from the pressure side to the air side):

- pressure chamber,
- main sealing element with Bentonite Blocks,
- pressure chamber II for the determination of the tightness of the surrounding rock and of the sealing element I as well as for the direct pressure built-up on the static abutment in the final testing stage,
- sealing element II,
- a prismatic-shaped static abutment with pressed rock-salt bricks as an alternative performance to concrete constructions.

![Fabrication of the wall](image)

**Figure 13** Fabrication of the wall; the hydraulic conductivity of the bricks with 50% bentonite–content tested with NaCl-brine is about $2 \times 10^{-11}$ m/s

A further large scale test is performed since 2004 in the potash-mine of Teutschenthal. The main difficulty is the Carnallitite-host rock, which contains also Tachyhydrit and Kieserit. Especially Tachyhydrit wears very fast. Figure 14 shows the cross section of the Test No. 1 in Teutschenthal. A sealing and abutment element has been erected using MgO-conrete /KUD 09/. Several pressure pads and moisture content sensors are built within the MgO-concrete. There is still no fluid pressure at the structure because the rock pressure at the contact area is still too low.
In Teutschenthal mine also a large scale test with shotcrete with a length of 10 m of has been performed, but still not pressure tested.

Also first concepts exist to transcribe the proof of safety from the Eurocodes in civil engineering to the long term sealing elements of shaft and drift sealings for repositories (see e.g. /MÜL 10/).

### Figure 14  MgO-concrete of large scale test 1 in potash-mine Teutschenthal

The following conclusions can be drawn:

- Shaft sealings
  - Research in shaft sealings far advanced in Germany
  - Some detail problems to solve (e.g. EDZ, Hot construction technology Asphalt, etc.)
- Drift sealings
  - Research to drift sealings not so far as to shaft sealings
  - Further large scale tests necessary (e.g. injection testing, hot asphalt technology for vertical panels, etc)
- Main used materials: Bentonite-bricks and Bentonite-mixtures, asphalt, compacted rock salt, concrete with salt solution.

Bibliography


Workshop Underground Disposal of Hazardous Waste


Backfilling and Sealing Materials

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Abstract
The concept of the long term safe disposal of wastes in underground disposal facilities is based on several independent barriers: immobilized waste, engineered barriers, natural rock and further natural formations above. By preventing or minimizing the contact between water and wastes, the multi barrier system provides an isolation of the waste from the biosphere. In between the canisterized waste and the natural rock, one or more engineered barriers are added. These engineered barriers primarily must be compatible (chemically, physically, etc.) with both the natural rock and the immobilized waste. That implies different and specific materials for each geological host rock. This paper deals with the different functions of the backfilling and sealing materials and presents the most important materials used in salt formations, argillaceous and crystalline rocks.


1 Introduction

Technical barriers play a crucial role in the long term safety of underground repositories for radioactive and hazardous chemical wastes. Technical barriers with combinations of different backfilling and sealing materials must be built in order to isolate open mine workings, prevent or retard the mobilisation and transport of toxic components from the repository and to stabilize mechanically the repository. The backfilling and sealing materials must have well defined thermo-hydraulic mechanical and chemical properties and must be long term stable under the prevailing conditions.

Figure 1 shows the different types of backfill and sealing materials and their functions. The locations where these materials will be emplaced in underground disposal facilities are shown in figure 2. Figures 3 - 5 illustrate concepts of shaft and drift seals in underground disposal sites in salt formations and show some of the materials involved.

2 Specific functions of the backfill

Backfill materials in underground disposal facilities for chemical wastes in former ore mines have three main functions:

- Guarantee compliance with the protection goal
- Technical functions connected with the mining activities
- Additional functions connected with particular aspects of the disposal facility

According to German regulations for the underground disposal of hazardous chemical wastes the compliance with the protective goal is linked mainly to the stabilization of the mine workings. The emplacement of backfill enhances the total stability of the surrounding host rock. The concentration of differential stresses and failure of the host rock can be avoided. Cement based backfill materials can be used for the construction of technical seals with well-defined hydraulic and mechanical properties. Backfilling reduces the extend of the excavation damaged zone (EDZ) in the mine workings and subsidence damages on the surface.

The following functions are linked to mining technology aspects:

- Minimizing the loss of extractable ore/increasing the amount of extractable ore
• Avoiding additional waste rock piles above ground
• Avoiding roof falls
• Reducing maintenance costs
• Amelioration of the quality of the mine air by reducing outgassing

Some of these functions are more important for the ore extractions than for the safe disposal of chemical wastes. Nevertheless these functions are important. While enhancing the profitability of the extraction mines the costs for disposal in the same mines can be reduced.

Additional important functions of the backfill are connected directly with the long term safe disposal of wastes are:

• Backfill is an integral part of the multi barrier concept
• Backfill largely reduces the open pore space which can be filled with water or brines. The water path is the main vehicle for the mobilisation and transport of toxic substances.

3 EBS concepts for different wastes

The geological barrier, i.e. the host rock is the main barrier against the release of toxic components from the repository to the biosphere. Engineered barrier systems (EBS) are required to ensure repository stabilization and sealing. The German disposal concept for heat producing radioactive wastes is based on crushed salt as the main EBS material. Low and intermediate level wastes have been disposed of in the former potash mines Asse and Morsleben, in the vicinity of Braunschweig. In the Asse salt mine the old mine workings have been filled with crushed salt. Dams will be built using Mg-resistant cementitious materials. The backfilling and sealing concept for the Morsleben repository is based upon cementitious materials as well. The salt and potash mines Zielitz/Sachsen-Anhalt, Herfa-Neurode/Hessen and Heilbronn/Baden-Württemberg are presently used for the disposal of hazardous chemical wastes. To our knowledge no final concepts for the backfilling and sealing of these mines have been elaborated yet. But extensive laboratory and large scale in-situ experiments with compacted bentonites have been conducted.
Figure 1  Types of backfill and their functions in an underground disposal mine
/BRA 91/

Different materials have been investigated extensively for the different concepts. The most important materials crushed salt, self-sealing backfill, salt concrete, magnesia concrete, bentonite and bitumen, will be discussed below. All these materials may be used in different combinations in the construction of technical barriers in salt formation. In other host rocks concretes, bentonite and bitumen are the main materials involved. This presentation cannot cover all thermo-hydraulic-mechanical and chemical aspects of these materials. We will concentrate on important chemical and hydraulic properties of these materials and show the present status of knowledge and the open questions which still must be investigated. Further information can be found in the cited literature.

Figure 2  Technical barriers in an underground final repository /ROT 04/
Figure 3  Principle elements of a shaft seal in salt mines /ROT 04/

Figure 4  Schematic layout of a drift seal (dam) /ROT 04/

Figure 5  Draft of a drift seal for the low level waste repository Morsleben (ERAM) /BOL 08/
4 Loose, uncemented backfill materials

4.1 Crushed salt

Crushed salt has been selected as the most suitable backfill material in disposal rooms containing heat generating high-level radioactive waste (HLW). Stress and creep-induced room closure (convergence) ultimately leads to consolidation of crushed-salt backfill and to the complete encapsulation of waste containers. The backfill material in drifts will consist of crushed salt as received by drift excavation. It is a coarsely grained material with a maximum grain size of 60 mm. The initial porosity of crushed salt backfill will be about 35%. Due to the creep of the surrounding salt the initial permeability of the crushed salt backfill will be reduced continuously until it finally reaches permeability values of the undisturbed rock salt (<10⁻²¹ m²). From a mineralogical and geochemical point of view crushed salt is an ideal barrier material as it is in perfect equilibrium with the host formation and potentially occurring brines. The thermo mechanical behaviour is well understood and can be predicted with accuracy /ROT 04/. The same is true for the geochemical behaviour and the interactions of water with the host rock. Solutions resulting from these interactions are high saline of the six component system Na-K-Ca-Mg-Cl-SO₄ /HER 00/.

Figure 6 Pneumatic emplacement of crushed salt backfill in the Asse salt mine (Photo: Helmholtz Zentrum München)
4.2 Self-sealing backfill (SVV)

Crushed salt minimizes and stabilizes the open voids and reduces the total permeability. This material however does not act as a barrier against intruding brines. The addition of reactive self-sealing minerals to crushed salt backfill can render it into a reactive salt mixture that upon contact with brine increases its volume and leads to the formation of a very effective seal.

![Figure 7](image-url)  Principle of the self-sealing salt backfill SVV /SAN 00/

GRS has developed such a self-sealing salt backfill material (SVV) based on anhydrous magnesium sulphate for the sealing of drifts and boreholes in salt mines. Fine grained dry magnesium sulphate with salt additives (rock salt and/or sylvite) can be emplaced pneumatically and flooded with brine. The exothermic reaction leads to the formation of a brine tight seal. The reaction consumes the brine completely and forms an impermeable plug with a new mineralogy and higher volume. The volume expansion leads to a considerable crystallization pressure. This leads to the closure of fractures in the excavation damaged zone. The initial high porosity is reduced to about 2 - 3 vol.-% of isolated pores. The new mineralogical assemblage is metastable in the beginning but is transformed successively in a long term stable phase assemblage. The geochemical modelling allows the quantification of the short- and long-term volume changes in the system and confirms that in the long run stable mineral assemblages will be obtained. The porosity/permeability relationship resembles that of highly compacted crushed rock salt backfill. The mechanical properties are comparable with the values of undisturbed rock salt. These results indicate that SVV is a self-sealing and long-term stable i.e. a predictable sealing material.
Figure 8  Scheme of a large scale in-situ experiment for the sealing of a vertical borehole in the potash formation Carnallitite in the Asse salt mine, with an SVV sealing element and a static abutment of sorel concrete /HER 10/

5  Cemented backfill materials

Cements and concretes are part of EBS concepts in any kind of host rocks. They are used for the construction of dams in final repositories for radioactive and hazardous wastes in salt formations and will be used in repositories for radioactive wastes in clay and crystalline rocks as well. Cements can also be used for the conditioning and solidification of liquid and other waste forms. Cemented waste based on cements and fly ashes can represent a significant part of the inventory in an underground disposal mine. Additionally, fly ashes can also be used as backfill materials in the final disposal of radioactive and hazardous wastes. The long history of cementitious materials is founded on the durability and persistency under environmental conditions. These materials have chemical and physical retention potential and are tolerant against many solutions and materials.

In contact with high saline solutions cementitious materials can be corroded. Corrosion changes their structure, their mechanical and hydraulic properties and
thus their sealing potential. Therefore the safety assessment of the repository system implies detailed knowledge of the geochemical behaviour of cements and concretes in their environment. Dissolution and precipitation processes will result in changes of the brine composition and pH. These changes have an impact on the long-term performance of the technical barriers but also on the solubility of radionuclides and toxic heavy metals in the repository.

5.1 Long term behaviour – thermodynamic stability

Only few concrete compositions are long term stable in a salt environment. There is no general composition for concretes that can universally be used in all mineralogical environments. The compositions must be carefully selected in order to guarantee the highest possible longevity. In rock salt and potash salts different concrete recipes must be used.

A concrete developed for EBS constructions in a rock salt environment is called saltcrete. In saltcrete crushed salt is used as an additive instead of sand or gravel which are the usual additives in normal concretes. The additive crushed salt is in chemical equilibrium with the surrounding rock and gives the concrete similar mechanical properties. Saltcrete has a relatively high chemical stability against NaCl rich brines. With increasing Mg content in the brine however the chemical stability of saltcrete decreases. The calcium-silicate hydrates (CSH) phases are destroyed because Ca from the CSH minerals is replaced with Mg from the brine.

In potash seams the presence of potash minerals leads to Mg and K rich brines. Here no saltcrete with Portland cement should be used. In such an environment MgO concretes are the stable materials. These concretes are stable in the presence of Mg rich brines but unstable in contact with Na and Ca rich brines.

5.2 Saltcretes

Saltcretes are mixtures of Portland cement and additives (crushed rock salt and fly ash) and water. The recipe used in the repository Morsleben the so called M2 consists of: 328 kg CEM III-cement, 1072 kg salt, 328 kg fly ash and 267 kg water.
Saltcrete has two specific properties: 1) saltcrete shrinks due to evaporation of water and 2) saltcrete creeps like rock salt under a constant load. The phases which are responsible for the stability are CSH and CAH minerals which are stable in the presence of Na and Ca rich brines but unstable in Mg rich brines.

The reactions of saltcrete with brines are well known and can be modelled. Thus it is possible to determine the stability in different brines.

![Figure 9](image)

**Figure 9**  Comparison of experimental data and geochemical modelling of the concentrations in solution of calcium, silicon and pH-values in equilibrium with C-S-H phases with different C/S-ratios /MEY 03/

### 5.3 MgO concretes

MgO concretes are also known under the name of Sorel concretes. These concretes contain Mg hydrates. These hydrates are formed in the reaction of MgO in the concrete and MgCl$_2$ in the brine. MgO concretes can reach very high hardness and they cure very fast. The main phases which are responsible for the stability of the MGO concrete texture are magnesium-silicate-hydrates (MSH) like:

- 3-1-8 phase (Magnesiumoxichlorid: Koshunowskit) a thermodynamically long term stable mineral in brines with MgCl$_2$ contents above 50 g/l.
- 5-1-8 phase, a metastable mineral
- 9-1-4 phase, a high temperature phase

The thermodynamic properties of the MSH phases are well known for ambient temperatures. They must still be determined for higher temperatures. The highest
degrees of hardness can be reached with the 5-1-8 phase. This phase however is metastable and will be converted in the thermodynamically stable 3-1-8 phase. The mechanical consequences of this transformation must still be investigated.

Depending on the recipe and the temperature MgO concretes may shrink, maintain their volume or expand. The technological handling of this type of concrete is not easy but it can be handled. Presently dams of MgO concrete are built in the Asse salt mine.

6 Other backfill and sealing materials

6.1 Bentonites

Bentonites are important EBS materials for repositories in all kind of host rocks including salt, clay and crystalline rocks. Compacted bentonites will be used for the construction of shaft, drift and borehole seals. Bentonites are considered to be ideal sealing and backfilling materials because of their swelling capacity. The swelling develops when bentonites react with water or aqueous solutions. The swelling capacity is the key parameter of all technical barriers build with compacted bentonites. Due to the swelling the pore space of the seal is reduced and water flow is inhibited. Thus the mobilisation and transport of toxic substances can be reduced considerably.

A drift sealing system combining bentonite-sand bricks and compacted crushed salt bricks was tested in the potash mine in Sondershausen. A shaft seal combining crushed salt and bentonite has recently been tested at the Salzdetfurth mine. Nevertheless reliable conceptual models which can predict the combined hydro-mechanical behaviour of seals with compacted bentonites are not yet available.

Long term behaviour of bentonites in salt solutions

Pore solutions with increasing ionic strength (salt content) change the interlayer charge and the swelling capacity of the clay mineral montmorillonite. Montmorillonite is the main mineral component of the different types of bentonites. Thus the sealing properties of bentonites depend on the composition of its pore solution.

In open systems with free water flow montmorillonite is covered in illite. Thus the swelling (and sealing) capacity decreases. In closed systems montmorillonite will be
transformed in kaolinite or pyrophyllite. Again the swelling (and sealing) capacity decreases. High pH of the pore solutions accelerates the transformation and the loss of swelling capacity.

In conclusion, from a thermodynamic point of view bentonites are not indefinitely stable. They will slowly lose their swelling and sealing capacity. Therefore the question which has to be answered is: for how long do we need which hydraulic property? More research is needed for the assessment of the kinetics of the transformation processes. Regardless of these open questions bentonite are very valuable sealing materials in all kind of host rocks.

6.2 Bitumen/Asphalt

In the German salt and potash industry the use of bituminous materials for the construction of sealing elements in shaft and drift seals has a long and successful tradition. Examples are:

- Several combined clay-bitumen/asphalt elements for shaft seals since 1960
- Gas tight systems for underground gas caverns (Burgraf-Bernsdorf)
- Drift seals (Leopoldshall 1898, Hope 1983)

However some technical aspects still must be investigated. The liquid nature of these materials requires special techniques. Asphalt blocks may be an alternative to hot fluid emplacement. The adhesion to salt surfaces should be investigated as well as the long term behaviour in contact with brines. Biological degradation is another point of interest.

6.2.1 Combined backfill materials, crushed salt – bentonite

Combinations of different backfill materials are also under consideration in order to improve certain properties of the backfill. Bentonite as an additive to crushed salt improves the compatibility and leads faster to much lower permeability of the backfill material crushed salt.
Sand as an additive to bentonite makes this backfill impermeable for fluids but it maintains its permeability for gases which are very desirable features for every backfill and sealing material.

![Figure 10](image1.png)  
**Figure 10** Combination of crushed salt and bentonite /STU 10/

7 Conclusions

A large variety of different backfill and sealing materials with well-known properties are available. The optimal combination of these materials guarantees very effective EBS systems and the long term safety of underground disposal facilities in all kind of host rocks.

Bibliography


