Gesellschaft für Anlagen-
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Analysis of options for the environmentally sound management of surplus mercury in Asia and the Pacific

Final Report

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Executive Summary

Mercury in Asia and the Pacific

Mercury is recognized as a toxic substance that poses a serious threat to human health and the environment. Nevertheless, large quantities are still used for the manufacture of products and in industrial processes. For the Asia Pacific region, more specifically East-, Southeast and South Asia, the total demand in 2005 was around 2,100-2,700 t according to a study by Concorde from 2009.[1] In the near future fluctuations in these figures are expected. Demand for mercury for the production of vinyl chloride monomer and manufacturing of fluorescent lamps is likely to increase, while demand for other products such as batteries and measuring devices will probably decline. In the long-term, it is expected that the demand for mercury will decline faster than supply from sources such as mining, decommissioning of chlor-alkali plants, non-ferrous metal production, natural gas production and recycling of mercury-containing waste.

More specifically, it was calculated that, starting in 2029, supply would become higher than demand, leading to an excess supply of mercury of about 5,500 t between 2029 and 2050. This represents a calculation for the regional level (Asia-Pacific). A surplus may occur sooner if countries decide to implement measures to reduce mercury demand, especially for artisanal small-scale mining. In that case, an excess mercury supply of up to 7,500 t may occur between 2027 and 2050. On a national level, an excess supply is possible as soon as a country decides to stop the export of excess mercury. The study by Concorde identified non-ferrous metal production (zinc, gold) as the most important source of future excess supply. In these industrial sectors, mercury may be produced in elemental form or as a compound (like mercury (I) chloride, calomel) during the cleaning of process gases. In addition, the management of mercury-containing waste is a growing concern in the region. Many countries in the region lack separate collection systems for hazardous waste in general and for mercury waste in particular. Combined with inadequate capacities of countries to store, treat and dispose of mercury waste in an environmentally sound manner, this situation leads to the disposal of such wastes under doubtful, unsafe conditions in landfills and open dumps that could be a source of later emissions.

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[1] Concorde (2009) Assessment of excess mercury in Asia, 2010-2050,

Elemental mercury: Removal from the market – storage – disposal

The reduction of supply is regarded as a priority in the overall goal of reducing the mercury-related risk to human health and the environment. Elemental mercury, as well as mercury compounds that are produced by recycling, as a by-product of metal production or by other sources, may enter the market as commodities. If the supply exceeds the demand for socially accepted uses, the surplus of elemental mercury and mercury compounds should be removed from the market in order to prevent unwanted export, use and release to the environment. The report describes and analyses general concepts that could be utilized to support such removal by storage, stabilization and disposal.

The US warehouse concept for storing elemental mercury above ground and the EU approach of underground disposal of hazardous wastes are both promising approaches to the management of the regional mercury surplus. Although there is little doubt about the technical applicability of these concepts in the Asia Pacific Region, the full feasibility of their implementation still has to be shown on a site-specific basis. Preliminary calculations found that the storage of 5,500 t of elemental mercury in one centralized warehouse would probably cost in the order of USD 20 million for a 20-year period, and include additional costs for further storage or disposal. Above ground storage of elemental mercury is a sustainable solution if political, economical and institutional stability can be guaranteed for the full operation time of the corresponding facility.

Underground storage of elemental mercury is still under discussion. The implications of this approach, especially regarding additional safety requirements, are yet unknown, so that a detailed cost analysis is impossible at this point. In Europe, however, storage of stabilized mercury has already been practised in underground disposal facilities.

Stabilization

Taking into account recent research and development, stabilization of elemental mercury must now be acknowledged as available, proven technology. At least one full-scale industrial process is currently available that is able to convert up to 1,000 t elemental mercury per year into solid mercury sulphide at prices starting at USD 2,700 per ton. Several companies are working on similar technologies, whereby alternative processes may become commercially available soon.

Temporary storage and final disposal of stabilized mercury

Stabilized mercury could be handled, transported and stored in a much safer way and may allow for significantly reduced costs for storage and disposal. Specific concepts for the temporary storage of stabilized mercury such as mercury sulphide have not yet been developed, but it may be assumed that storage of stabilized mercury could be based on well-established procedures for the storage of hazardous chemicals or hazardous wastes. It could take place at special storage facilities or at existing hazardous waste landfill sites, if these are constructed and operated in an environmentally sound manner.

According to waste legislation in many countries, mercury sulphide could be disposed of in specially engineered landfills. However, there are doubts about the long-term stability of mercury sulphide at near surface (oxidizing) conditions. Another aspect is the rather easy accessibility and, in the longer term, the potential land use of former landfills. Therefore, the concept of disposal in landfills needs further investigation. The situation may be different for waste with lower mercury content. A given threshold could be decided on to determine whether a waste could be disposed of above ground or underground.

Underground storage – host rocks, mines and concepts

Permanent storage in underground mines is generally regarded as a safe disposal concept for hazardous wastes. Underground waste storage facilities do not yet exist in Asia, but several countries in the region have already investigated options for the underground disposal of nuclear waste. Several typical potential host rock formations that could host an underground storage facility are discussed in this report. Rock salt is globally recognized to be a suitable host rock. Although there are extensive salt deposits in the region, the number of underground salt mines is rather small. Therefore, it would take further efforts to evaluate whether some of these could principally be used for underground storage purposes. On the other hand, underground metal ore mines are abundant in the region. They include underground zinc, lead and copper mines as well as iron mines. Zinc sulphide, for instance, represents an important metal ore that often also contains significant concentrations of mercury sulphide. Returning mercury sulphide to a metal ore mine is an approach that should be further investigated.

Accordingly, a concept has been developed that is based on the assumption that parts of an operating metal ore mine could be used for the permanent storage of mercury sulphide. It would be packed in containers and placed into newly excavated drifts that would be sealed afterwards. As the excess mercury supply has been generated in small quantities over many years (7,500 t in 20 years), moving and storing such small amounts has no significant logistical impact on the mine operation. As technical mine equipment is mostly already available, the additional costs for storing mercury sulphide are rather limited and estimated to amount to approximately USD 750 per ton in addition to the stabilization costs (about USD 2300 per ton). Costs could be lower if existing cavities were used. It should be noted that costs for underground disposal are typically very site specific, and thus these cost estimates should be regarded as being for the purposes of information only. Moreover, the suitability and long-term safety of a specific site strongly depends on additional factors like the overall geological situation and the impact of past, present and future mining. Such an analysis can only be done when a specific site has been chosen, which is not part of this project.

A slightly different approach would be to transform an underground mine, e.g., at the end of its commercial lifetime, into a full-scale underground storage facility. Such a facility would not only allow for the disposal of stabilized mercury, but could also be used for the environmentally sound final disposal of hazardous wastes like mercury waste, waste incineration residues or chemical production wastes in total. The successful implementation of such a concept would help countries or the region to deal with many waste-related issues at the same time: surplus mercury, mercury waste and other hazardous waste. For a reliable cost estimate, site-specific data are necessary. Experience from Germany shows that, for disposal in underground (salt) mines into underground storage facilities, one-time disposal fees in the order of USD 350 to 1,200 per ton are charged depending on the site, the type, and volume of waste.

While the implementation of the warehouse concept depends only on the availability of land for industrial use and, furthermore, the costs may possibly vary only a little from site to site, a full feasibility analysis for the two underground disposal concepts can only be conducted on a site-specific basis. If the one or the other concept is chosen for further consideration, a site selection procedure has to be developed and run through before one or several sites could be identified for in-depth financial and environmental analysis.

Since all concepts for mercury storage and disposal are entirely new for Asia and the Pacific, adequate legislation still has to be developed and implemented by the countries.

Mercury Removal Strategy: Effective Collection - Early Stabilization - Safe Disposal

In order to address the problems related to excess mercury supply, a three-step strategy is proposed to effectively remove mercury from the market and reduce its risk potential by permanent isolation from the biosphere. It consists of the following stages:

Effective Collection - Early Stabilization - Safe Disposal.

Effective collection helps to remove elemental mercury and mercury compounds that are no longer needed for accepted uses from the market. Stabilization of mercury is now a commercially available technology and could render elemental mercury into a non-, or at least much less, soluble chemical form. Temporary storage of elemental mercury will still be necessary in order to collect surplus mercury and prepare it for shipping, but the duration of storing elemental mercury should be kept as short as possible. Finally, it is necessary to develop safe disposal options for stabilized mercury. The concept aims at an early and irreversible isolation of mercury from the biosphere. It is considered the safest long-term concept for dealing with a hazardous and non-degradable substance like mercury.

A successful implementation of this strategy may be characterized by the following milestones:

1. Legal framework that addresses the obligation and requirements for collection (based on a national demand estimate), temporary storage, treatment, disposal (on national level).

2. Improved collection systems and transport quality for elemental mercury and mercury waste (on national level).

3. Availability of temporary storage facilities at end-users or waste collection centres. The duration of storage of elemental mercury should be as short as possible (on national or local level).

4. Availability of a stabilization plant (possibly combined with a mercury waste treatment plant in order to extract mercury from mercury waste) (on regional to national level). The stabilization plant may be owned by private companies (e.g., industry) or by government.

5. Availability of facilities for the disposal of stabilized mercury, mercury waste and possibly other hazardous wastes. Stabilization plant and disposal facility should be in close distance (e.g. in the same country) to reduce unnecessary transportation (on regional to national level).

Some of these milestones may require a certain degree of regional cooperation, especially the operation of a national disposal facility that will also accept stabilized elemental mercury from other countries. According to the Concorde study, significant amounts of surplus mercury may be expected from 2029 onwards. By then, the construction of a stabilization plant should be feasible in the region. It is expected that the one-time costs for stabilizing, temporarily storing and disposing mercury are lower than the costs of storage of elemental mercury for a long time. As above ground storage in warehouses is no final disposal operation,[2] there will be a need to manage elemental mercury further, e.g., storing it for another period or disposing it later. Both options will cause additional costs until the mercury is finally disposed of.

Implementation Strategy

However, the full implementation of such a concept may need some time, so that interim measures are likely to be necessary. These include temporary storage facilities for the management of elemental mercury, mercury compounds and stabilized mercury. For a transitional period, in cases where storage, treatment and disposal facilities are not available in the region, export of elemental mercury and mercury compounds for storage and disposal outside the region may be an option. The implementation could possibly consist of three phases:

- **First phase:** Begin activities to improve situation in the fields mentioned above and gather necessary information. Improve separate collection schemes and make available temporary storage facilities for elemental mercury, mercury compounds and mercury containing waste. Temporary storage facilities could be existing hazardous waste treatment facilities available at national level. Explore possibilities for treatment (chemical conversion / purification / stabilization) of elemental mercury, mercury compounds and mercury waste in the region and foster investments in this sector. If treatment facilities are unavailable in the region, temporarily store surplus elemental mercury and mercury compounds. If such

[2] The term disposal only applies to mercury that is considered waste. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal defines 'disposal' as any operation specified in Annex IV to this Convention. There are two types of disposal: Annex IV A covers operations which do not lead to the possibility of resource recovery, recycling, reclamation, direct re-use or alternative uses. The second group of operations, in Annex IV B, lists operations that may lead to resource recovery, recycling, reclamation, direct re-use or alternative uses. In summary, disposal is understood as an activity that leads to either destruction, placement in a landfill, discharge into the environment, recycling or re-use. The Basel Convention knows no long-term or even indefinite storage of waste, but only (temporary) storage pending disposal (Annex IV A) or recycling / recovery.

storage is not yet feasible, export for disposal in countries outside the region may be an option.

- **Second phase:** If treatment facilities exist, extract and stabilize mercury. As long as disposal facilities are not available, keep stabilized mercury and stabilized mercury waste in temporary storage.
- **Third phase:** Collect, extract, stabilize, and dispose of mercury in suitable disposal facilities in the region

If the polluter pays principle is applied to surplus mercury, the (mostly industrial) producers of by-product mercury and mercury compounds, such as zinc smelters or gold mines, would have to bear the costs of managing surplus mercury.

The proposed strategy is based on available technological concepts and experience, and could open a feasible way towards the environmentally sound management of surplus mercury and mercury waste in the region.

1 Introduction

1.1 Background, goal and scope

The Governing Council (GC) of the United Nations Environmental Program (UNEP) in its decision 25/5 recalled that mercury is a chemical of global concern owing to its long-range atmospheric transport, its persistence in the environment once anthropogenically introduced, its ability to bioaccumulate in ecosystems, and its significant negative effects on human health and the environment. The Governing Council decided to begin the elaboration of a legally binding instrument on mercury. At the same time, the GC decision 25/5 called on the Executive Director of UNEP, concurrently with the work of the intergovernmental negotiating committee, to continue and enhance, as part of the international action on mercury, existing work in a number of areas, including enhancing capacity for mercury storage.

The international community recognizes the importance of identifying environmental sound storage solutions for mercury. Mercury supply exceeds demand in many parts of the world, because of the movement towards the use of mercury-free alternatives. This surplus must be managed and stored properly, thereby preventing its re-entry into the global market and – with it – the environment.

UNEP responded to this challenge by initiating the Mercury Storage Project, which was funded by the Government of Norway and which analysed the excess mercury supply and the options for environmentally sound storage in two UN regions, Asia and the Pacific, as well as Latin America and the Caribbean (LAC). As part of this project, the Asian Institute of Technology / Regional Resource Centre for Asia and the Pacific – with assistance of other institutions – prepared the report 'Development of Options Analysis and Pre-Feasibility Study for the Long Term Storage of Mercury in Asia and the Pacific' [2]. It informed governments in the Asia-Pacific Region about the environmental, economic and legal issues related to the long-term safe storage of excess mercury. Three long-term management options were discussed: above ground storage in warehouses, underground storage in salt mines, and export. The central findings of the study were:

- Underground (permanent) storage was considered not implementable in the region due to a lack of salt deposits and high costs;
- Indefinite storage of elemental mercury in desert areas and the export to other countries was regarded as the preferred options;

- A legal framework is required to regulate storage obligation, site selection, licensing, operation and liability;
- Bi- and multilateral agreements are needed to arrange relationships between countries that export and countries that store mercury.

Discussions among governments and other stakeholder showed that the report could be improved by further investigating aspects not yet or insufficiently addressed, such as, for example, storage and disposal after prior stabilization or underground disposal in geological formations consisting of different host rocks (rock salt, clay formations, crystalline complexes and many more).

Funded by the Department of State of the Government of the United States, the present report constitutes a revision of the AIT study and provides updated and enhanced information on relevant issues. These include stabilization of elemental mercury, presence of geological formations potentially suitable for mercury storage and disposal facilities, geo-environmental hazards that could affect above ground or underground storage or disposal facilities and country-specific and regional agreements, and rules concerning the import or export of commodity grade mercury and mercury compounds. This study builds on the original text of the AIT study, but comprises a complete revision in most sections. The description of storage and disposal options for elemental mercury is partly based (with adaptions) on the corresponding chapters prepared by the Laboratorio Tecnológico del Uruguay (LATU) for the sister options study in the LAC region. Guilberto Borangan (AIT / UNEP RRC.AP) contributed an overview of environmental hazards in the Asia-Pacific region and national / regional agreements on mercury import / export.

Goal of the present study

This report aims to inform governments in the Asia-Pacific region of the current concepts for environmentally sound management of excess mercury, including its storage, stabilization and eventual disposal. A number of technical concepts are presented that could, in principle, be implemented in the region. Information about these concepts includes issues that require consideration (technological, environmental, public health and safety, financial, socio-political, human resources, legal and regulatory). Clear recommendations should be given on the most feasible options for countries in the Asia region to consider.

Scope of the present study

This study analyses concepts for the sound environmental management of surplus mercury independent of its status (waste or commodity). It also highlights technologies for the stabilization of elemental mercury and the potential consequences of choosing a storage or disposal concept.

1.2 Objectives and principles of mercury storage and disposal

Recent studies have shown that in many regions of the world regional mercury supply may soon exceed regional demand for socially accepted applications. The excess supply mainly originates from sources such as non-ferrous metal production and the recycling and decommissioning of chlor-alkali cells, and may occur as elemental mercury or mercury compounds. Elemental mercury and mercury compounds may enter the market as commodities – goods that are traded for the purpose of later use. Elemental mercury and mercury compounds that are no longer needed should be removed from the market by placing them in storage or by disposing of them otherwise. Storage and disposal are two ways to prevent unwanted uses and release into the environment, and should be carried out in an environmental sound manner. This entails taking all practicable steps to ensure that elemental mercury and mercury wastes are managed in a way that will protect human health and the environment against the adverse effects that may result from mercury and mercury wastes.

In addition, the objective of storage and disposal is to deal with elemental mercury and mercury waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations. The following IAEA principles, although originally developed for nuclear waste management but having been adapted to mercury, may shed light on what the guiding principles of surplus mercury management could be [43]:

1. **Protection of human health**: Elemental mercury and mercury waste shall be managed in such a way as to secure an acceptable level of protection for human health.

2. **Protection of the environment**: Elemental mercury and mercury waste shall be managed in such a way as to provide an acceptable level of protection of the environment.

3. **Protection beyond national borders**: Elemental mercury and mercury waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.

4. **Protection of future generations**: Elemental mercury and mercury waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.

5. **Burdens on future generations**: Elemental mercury and mercury waste shall be managed in such a way that they will not impose undue burdens on future generations.

6. **National legal framework**: Elemental mercury and mercury waste shall be managed within an appropriate national legal framework, including clear allocation of responsibilities and provision for independent regulatory functions.

7. **Control of mercury waste generation**: Generation of mercury waste shall be kept to the minimum practicable.

8. **Mercury waste generation and management interdependencies**: Interdependencies among all steps in mercury waste generation and management shall be appropriately taken into account.

9. **Safety of facilities**: The safety of facilities for elemental mercury and mercury waste management shall be appropriately assured during their lifetime.

2 Description of current situation in selected countries

2.1 Inventory of surplus elemental mercury in the Asia Pacific region

As part of the UNEP mercury storage project, Concorde, a Belgian consultancy company, presented a study about current and future supply and demand of mercury in the Asia region in 2009 [22]. The study covered East, Southeast and South Asia. Not covered were the Middle East, Australia, New Zealand and Oceania. An important part was the analysis of the quantities of mercury that are likely to be produced over the next 40 years by different industrial sectors. These include by-product mercury from various mining and smelting activities, from the cleaning of natural gas, from the closure / conversion of mercury cell chlor-alkali plants and from other significant sources such as end-of-life products. The author of the study, Peter Maxson, compared regional sources of mercury with regional uses, such as lamps, measuring devices, dental amalgam, and production of vinyl chloride monomer, etc., over the same period. As a result, it was possible to estimate the probable generation of excess mercury in the region, and the amount of that which could be temporarily or permanently stored in appropriate facilities.

In the Concorde study, some basic assumptions were necessary with respect to supply, trade, demand, and their future developments. These include:

- Assume there are continuing transfers of mercury between the countries in the region;
- Assume there are no imports of metallic mercury into the region and no exports of metallic mercury or by-product mercury outside the region (mercury added products are not affected);
- Assume that the main regional ‘sources’ of mercury, other than imported mercury-added products, are decommissioned chlor-alkali facilities, by-product mercury recovered from mining and non-ferrous metal smelting operations, natural gas cleaning, and some recycling of mercury-added products;
- Assume that if regional policies dictate that mercury should be removed from the market, the mercury will go to terminal storage;
- The Chinese domestic market is assumed to receive no imports. Exports to other countries in the region are only considered if China generates excess mercury (without prima-

ry mining). Moreover, it is assumed that domestic production from primary mining declines alongside domestic demand.

Current regional supply and demand were estimated based on earlier global estimates ('Trade Report' UNEP 2006 [73]) and further information according to its specific availability for the region.

In the reference year 2005, the most important uses of mercury in the region were vinyl monomer production (700-800 t), small-scale gold mining (400-630 t), measuring and control devices (340-390 t) and batteries (230-370 t). The total demand is around 2,100-2,700 t. Estimates on future demand were based on the objectives for future reductions in mercury consumption as agreed by the 'Mercury in products' partnership area under the UNEP Global Mercury Partnership.

Regional sources of mercury taken into account include primary mining of mercury ores, decommissioning of chlor-alkali plants, by-product mercury from non-ferrous metal production and cleaning of natural gas, stockpiles and recycling. The study describes important mercury-containing waste streams in the described industrial sectors and the status thereof, as well as the technically achievable practice of recovery / recycling operations. Non-ferrous metal production (zinc, gold) is thought to be the most significant source of future excess supply in Asia and the Pacific (up to 518 t from 2030). In these industrial sectors mercury may be produced in elemental form or as a compound. Modern zinc smelters that are equipped with the Boliden-Norzinc process to recover mercury from flue gases produce mercury (I) chloride (Hg_2Cl_2, calomel) that may be converted into commodity mercury if there is a market demand and a sufficiently high mercury price [22].

It was pointed out that the recycling of mercury-containing waste (e.g. from chlor-alkali production and mercury added products) is not common practice in Asian countries and contributes only little to the overall supply. Exceptions are depleted mercury-containing catalysts from vinyl monomer production that, to some degree, already undergo recycling.

Estimates on future supply were based on realistic, achievable recovery / recycling rates for the chlor-alkali, metal production and waste management. Based on Chinese data, primary mining is expected to decline after 2015, going down to about 300 t/a.

Three scenarios have been considered when calculating excess mercury supply in 2010 - 2050. In all cases, the domestic supply and demand in China was analysed first.

1. The first scenario assumes that Chinese primary mining will work at maximum capacity, even though exceeding domestic demand. Taking into account declining demand, con-

stant high production from mercury mining means that a slight surplus mercury supply is expected in 2013, but a substantial excess of mercury will occur only in 2025.

2. It is more realistic to assume that mercury mining will decrease in accordance to decreasing demand, in which case, between 2029 and 2050, about 5,500 t excess mercury will have to be stored.

3. A third scenario analyses the effect of restricted supply (-50%) of mercury to small-scale gold mining. Such a policy will result in 7,500 t excess mercury between 2027 and 2050, or possibly even earlier (2017).

The authors pointed out that the analysis only gives an idea of when it might be necessary to collect and store excess mercury. Estimates for future demand and supply are subject to significant uncertainties and have to be regarded as order-of-magnitude estimates rather than precise predictions. Information on mercury waste product may be found in the Annex.

2.2 Challenges of surplus mercury management in the region

The analysis of future demand and supply demonstrates that, on a regional basis, a significant surplus is not to be expected before 2027. However, the situation may be quite different on a sub-regional or national basis if, for example, there are stronger reductions in demand than anticipated or if there are increased efforts to extract mercury from mercury waste. If countries decide that the export of national mercury surplus should no longer be allowed, this would result in an immediate need to store and eventually dispose of elemental mercury in an environmentally sound manner.

Another important problem is the storage, treatment and disposal of mercury waste. More than 800 t of mercury are used each year in the manufacturing of products, and it can be assumed that most of these products will become waste eventually. Some countries have started a separate collection of mercury waste, especially waste products (Cambodia, Indonesia),[3] but are now facing the problem of not having adequate treatment or disposal facilities for mercury waste.

[3] Information given by country delegates at the second meeting of the UNEP Mercury Partnership Advisory Group. Sep. 2010, Geneva.

2.3 National / regional agreement regarding import / export of commodity mercury / mercury containing waste regional agreements

Currently, there are no regional agreements, rules and legislation on import and export of mercury, mercury compounds and mercury-containing waste in place in the Asia-Pacific region. At the national level,[4] most countries do not even have rules and / or regulations on import and export of mercury specifically.

Indonesia, for example, has the following regulations:

- Regulations on the importation of used products for reconditioning, remanufacturing or reuse (Decree of Ministerial Trade Number: 63/M-DAG/PER/12/2009) and
- Regulation on the prohibition of Hazardous Waste Import (Decree of Ministerial Trade and Industry Number 520 Year 2003). The hazardous waste regulation includes the products and the content of heavy metals such as lead, mercury, cadmium, and chromium.
- Government Regulation Number 18 Year 1999 and
- Government Regulation Number 85 Year 1999, regarding Hazardous Waste Management, e.g., handling, transportation, storage and disposal.

Corresponding Philippine regulation pertains to the importation, manufacture, distribution and use of mercury and mercury compounds and the storage, transport, and disposal of the wastes:

DENR Administrative Order No. 38, Series of 1997.

This Chemical Control Order for Mercury and Mercury Compounds (CCO) is being issued on the basis of authorities given to the Department of Environment and Natural Resources under Republic Act 6969 of 1990 and DENR Administrative Order (DAO) No. 29, Series of 1992. This CCO applies to the importation, manufacture, processing, use and distribution of mercury and mercury compounds. It also addresses the treatment, storage and disposal of mercury-bearing or mercury-contaminated wastes in the Philippines. For instance, general

[4] A selection among Asian countries was made and Thailand, India, Indonesia, Philippines and China were chosen for a detailed investigation.

requirements and procedures have been established for importers and industrial users of mercury and mercury compounds, as well as treatment and disposal of mercury-bearing or mercury-contaminated wastes.

China has a comprehensive and developed system for restricting the trade (import and export) of toxic chemicals. No toxic chemical can be imported to China without the prior consent of the Ministry of Environment, the nodal agency for environment protection in China.

In India, there is no restriction on the import of metallic mercury. The import of mercury waste is prohibited.

Thailand has legislation on exportation or importation of hazardous wastes in general (including mercury). This national legislation (Hazardous Substance Act B.E. 2535) also stipulates penalties regarding compliance with the law.

3 Overview of surplus mercury management concepts

3.1 Two levels of mercury removal

The following diagram gives a short overview of surplus management options. As mentioned above, excess mercury supply may occur in the form of elemental mercury and of mercury compounds such as calomel. Both forms could enter the market as a commodity. Reducing this source of supply may take place in two steps (Figure 1):

- **Removal from the market**: All operations that make elemental mercury and mercury compounds legally unavailable to the market by storing them in warehouses or other storage facilities for a short (months up to a few years) or possibly a very long time (decades). However, mercury and mercury compounds remain in the biosphere and can easily be retrieved – at least technically.
- **Removal and isolation from the biosphere**: All operations that actually lead to a final disposal of elemental mercury and mercury compounds in landfills, deep wells or underground mines, so that mercury is permanently isolated from the biosphere. According to the Basel Convention, material that is disposed of, or intended or required to be disposed of, is considered waste. Retrieval is generally not intended, often technically not feasible or feasible only for a very limited time or only at great expense.

3.2 Technical concepts for elemental mercury, stabilized mercury and mercury compounds

For elemental mercury, stabilized mercury and mercury compounds, the following specific management concepts could be identified:

Concepts for elemental mercury:

- Elemental mercury could be stored in above ground storage facilities (warehouses) for a limited (months or years) or very long time (40 years or more).
- Principally, permanent storage (disposal) of elemental mercury may take place in underground mines (underground storage facilities), but scientific investigations are underway to clarify whether this is an advisable option.

- If such above ground storage in warehouses or underground storage (disposal) facilities is not (yet) available, temporary storage may take place, for example at hazardous waste management plants or specially engineered landfills.
- Elemental mercury may be chemically stabilized into solid materials like mercury sulphide.
- If none of the above-mentioned concepts is available in the region, export to another region may be the only feasible approach.

Concepts for stabilized mercury:

- Stabilized mercury may be temporarily stored at places like waste collections centres, mercury waste treatment centres or at hazardous waste landfills.
- Disposal at specially engineered landfills, although there are doubts whether this is an advisable concept.
- Permanent storage (disposal) of stabilized mercury in underground mines is already being practised.
- Deep well injection of stabilized mercury (in the form of a slurry) has been proposed, but in some countries deep well injection of hazardous waste is not allowed.

Concepts for mercury compounds in general (such as by-product calomel):

- Calomel may be converted into elemental mercury and then (or directly) into stabilized mercury.
- Temporary storage of mercury compounds may take place as long as final disposal options are not available. Potential sites could be waste collections centres, mercury waste treatment centres or hazardous waste landfills.
- Another option for calomel or other mercury compounds would be direct permanent storage in underground mines without prior treatment, if the geological conditions at the underground storage facility are such that disposed mercury compounds are permanently isolated from the biosphere.

The characteristics of all general concepts (above ground storage in warehouses, temporary storage, disposal in specially engineered landfills, permanent storage in underground mines) are discussed in the following chapters.

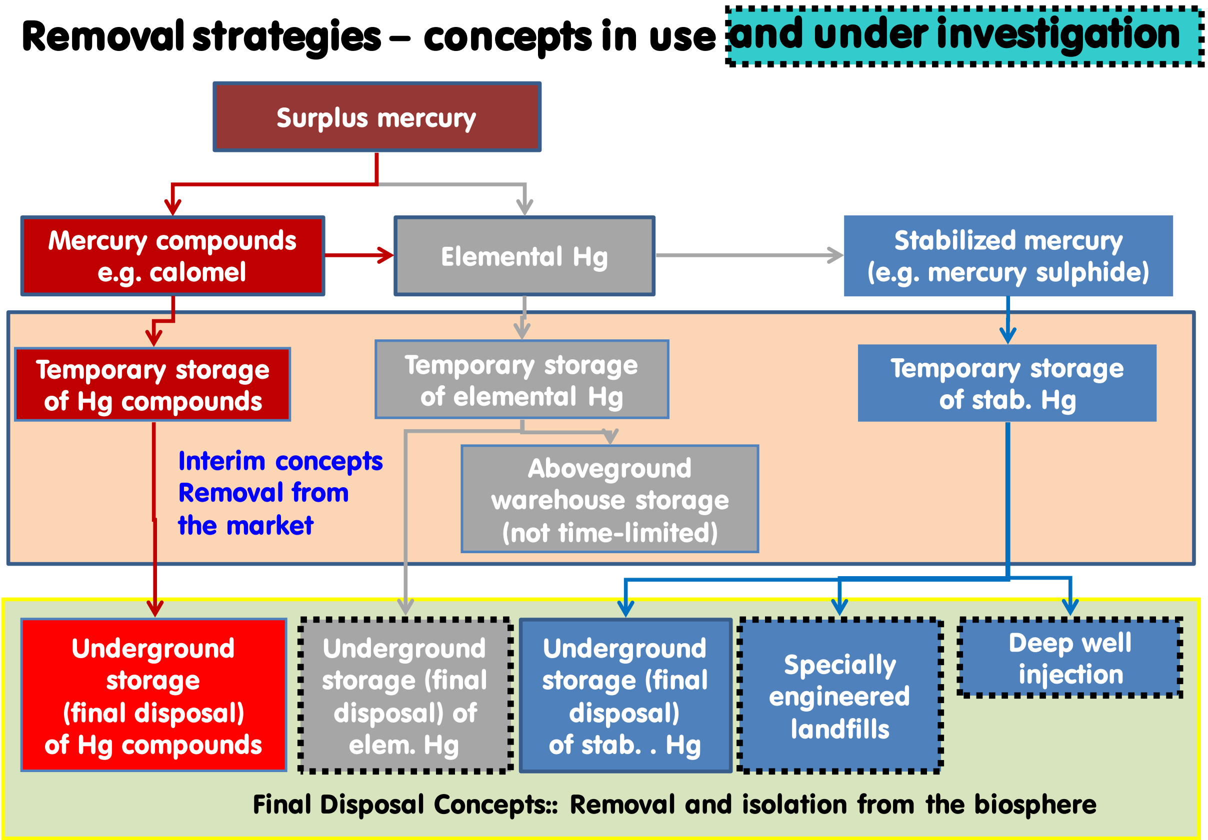

Figure 1 Overview of management concepts for surplus mercury and two levels of a mercury removal strategy

4 Stabilization of elemental mercury

4.1 Introduction and overview

The goal of stabilization / solidification is to chemically convert elemental mercury and mercury-containing waste into thermodynamically more stable and solid compounds with considerably less volatility and less solubility. Such compounds may pose a smaller risk to human health and the environment. In the past decades, companies and institutions have developed several approaches to the stabilization of elemental mercury and mercury-containing waste. Stabilization approaches belong to four categories:

1. Stabilization as mercury sulphide or mercury selenide
2. Stabilization as mercury sulphide in a sulphur-polymer matrix
3. Stabilization as amalgam
4. Stabilization in an insoluble matrix (cement, phosphate ceramic, magnesia binder)

All processes described in the literature are based on one or a combination of two of these approaches. In each case, elemental mercury and / or oxidized forms of mercury are brought into reaction with certain chemical agents, which convert mercury into a less soluble and less volatile chemical compounds.

For each of these approaches a number of technological implementations exist. The degree of industrial scaling varies widely: some processes have been tested only in laboratories, while one process which is described below has reached full-scale industrial application (> 1000 t/a).

Most processes described in the literature succeeded in producing a chemically and physically more stable product. Standard leaching procedures showed that, under defined conditions, mercury concentrations in leachates were below regulatory standards (EU, USA, Japan). The same result was often found when the vaporization of mercury from the products was tested. But, according to reviews conducted in the past ten years, two methods were unable to reduce the leachability and volatility of mercury sufficiently. Unfortunately, for some procedures such investigations were insufficiently documented or not conducted so far. Moreover, it seems to be questionable whether it is sufficient to apply standard leaching tests in order to assess the long-term behaviour of stabilized mercury-containing waste forms. The leachability and volatility of mercury in solids strongly depends on the physical and chemical conditions at the place of storage. These might not be the same as presumed in standard leaching procedures. Further experimental work, assisted by geochemical modelling, which is tailor-made to the conditions of existing and potential future disposal sites, could be one way to identify further suitable technological approaches.

This chapter concentrates on stabilization technologies for elemental mercury. Technologies that deal mainly with mercury containing waste are briefly discussed in Annex B - Technologies for the stabilization of mercury waste (except elemental mercury). More information on stabilization technologies can be found in GRS (2009) [36] and BiPro (2010) [11].

4.2 Outline of four principle approaches to the stabilization of elemental mercury

Stabilization in the form of sulphides and selenides

The most important approach to the stabilization of mercury is its conversion to mercury sulphide. Processes that implement this approach often start with elemental mercury that reacts with elemental sulphur or with other sulphur-containing substances such as thiosulphate or pyrite (FeS_2) to mercury sulphide:

$$Hg_{(l)} + S \rightarrow HgS$$

The conversion into mercury sulphide can be achieved by mechanically mixing solid sulphur with liquid mercury, by dissolving mercury in liquid sulphur or in a gas phase reaction between gaseous mercury and gaseous sulphur.

At room temperature, solid mercury sulphide exists in two kinetically stable modifications (Figure 2):

α-HgS cinnabar (red) and

β-HgS metacinnabar (black)

The latter is thermodynamically less stable but it is the primary reaction product at lower temperatures. Another insoluble compound is mercury selenide, which results from a reaction between elemental mercury and selenium:

$$Hg_{(l)} + Se \rightarrow HgSe$$

HgSe is also known under its mineral name Tiemannite. Mercury selenide cannot be synthesized by mixing the elements at room temperature. Therefore, either a gas phase reaction is required or a reaction in aqueous media after oxidation of $Hg_{(0)}$ to $Hg_{(II)}$.

If mercury is present in its oxidized form Hg^{2+}, a sulphide-containing agent is needed for the reaction to mercury sulphide:

$Hg^{2+} + HS^{-} \rightarrow HgS + H^{+}$

Agents can be hydrogen sulphide (H_2S), alkali sulphides (like Na_2S) or certain thiols (organic compounds with an -S-H group). In some processes, elemental mercury is first oxidized by strong oxidizing acids like nitric acid (HNO_3) to aqueous Hg^{2+} and then precipitated as mercury sulphide.

Figure 2 Black mercury sulphide (metacinnabar) and red mercury sulphide (cinnabar)

A somehow similar approach was followed in the development of a new, quite exotic looking, sulphur-containing material: thiol functionalized zeolites. Zeolites are a group of porous silicate minerals. To functionalize them, chains of silanes[5] are chemically attached to the surface of the zeolite particles. Thiol-groups, which have an exceptionally high affinity towards any kind of mercury, are placed at the end of each chain. Important realizations of this stabilization type are the DELA/SAKAB and the Bethlehem processes (see below).

Stabilization as mercury sulphide in a sulphur-polymer matrix

[5] Silanes are molecules on the basis of silicon (Si) and hydrogen (H).

Processes under this headline consist of two steps. In the first step, mercury is mechanically mixed with elemental mercury at ambient or elevated temperatures. The interim product is an impure black mercury sulphide. In the next step, mercury sulphide is mixed with liquid sulphur. The product solidifies after cooling. The product is a dark monolith of so-called sulphur cement (Figure 3). Sometimes organic polymers are added to increase the mechanical strength and the durability of the product.

Important realizations of this approach are the processes of MAYASA and ADA Technologies (see below). Several similar processes have been developed by other companies and institutions [11][36].

Figure 3 Example for mercury sulphide in a sulphur polymer matrix (source: MAYASA)

Amalgams

Mercury is the only metal that is liquid at ambient temperature, and is also the only one that readily forms alloys by simply being brought into contact with other metals like lead, copper, zinc, silver, gold, nickel or cobalt (iron is an exception, which allows for the storing of mercury in iron flasks). Mercury alloys are called amalgams. They are solid, but sometimes quite soft or paste-like materials (Figure 4). In some processes, amalgamation is used as a stabilization technique. Then, mercury or the mercury-containing waste is mixed with a metal powder (mostly zinc or copper) to form the solid amalgam, e.g.:

$x\ Hg_{(l)} + y\ Cu \rightarrow Cu_yHg_x$

Several methods have been described that solidify elemental mercury as an amalgam with either copper or zinc. Although the product is solid, for at least some amalgams there is doubt whether their solubility and vaporization characteristics show any advantage in comparison with liquid elemental mercury.

Figure 4 An amalgam

Stabilization in an insoluble matrix

Under this headline, several processes are subsumed that do not convert mercury into a distinct compound or alloy, but rather create a media in which mercury forms less soluble compounds. A quite common method that is successfully applied for many types of hazardous wastes is the stabilization / solidification with Portland cement-based materials. They consist of chemical substances and minerals like Portlandite (calcium hydroxide, $Ca(OH)_2$), calcium silicates and aluminates. After mixing with water, these minerals form a slurry that hardens due to the formation of a three-dimensional network of interlinked calcium silicate hydrates (CSH). At the same time, depending on the cement and the additives (fly ash, blast furnace slag) an alkaline or at least near-neutral medium is maintained in the remaining pore water. Most heavy metals form insoluble hydroxides under such conditions. Some metals are even incorporated into the CSH-matrix.

The same principle is utilized in Sorel cements (also called ‘magnesia cement’. If magnesium oxide reacts with a magnesium chloride solution (or other soluble magnesium compounds) magnesium hydroxide chlorides are formed, e.g.:

$$3MgO_{(s)} + MgCl_{2(aq)} + 11H_2O \rightarrow Mg_4Cl_2(OH)_6(H_2O)_8$$

The resulting pore water has a near-neutral pH and ensures a low solubility for many heavy metals.

Another way to stabilize mercury and other heavy metals is the formation of phosphates. If magnesium oxide is mixed with an aqueous solution of hydrogen phosphates (or phosphoric acid), a solid magnesium phosphate is formed:

$MgO + KH_2PO_4 + 5H_2O \rightarrow KMgPO_4 \cdot 6H_2O$

Heavy metal ions such as lead (Pb^{2+}) or mercury (Hg^{2+}) form insoluble phosphates that are embedded in an impermeable matrix of magnesium phosphates. It should be noted that the reagents discussed do not chemically bind elemental mercury.

4.3 Technologies for the stabilization of elemental mercury that are available or under development

4.3.1 Overview

Numerous methods and technologies for the stabilization of elemental mercury are described in the literature. GRS (2009) [36] and BiPro (2010) [11] list about 25 approaches that are in different stages of implementation. Many of them never left the laboratory stage, some of them have been demonstrated in small batches and few are in a status that allows full-scale application now or in the near future. The following chapter gives an overview of some technological approaches that achieved a promising level of implementation. This does not mean that methods not mentioned here should be disregarded. Technologies for the stabilization of mercury waste other than elemental mercury may be found in the Annex. For more information on other methods, please refer to reports cited above**.**

4.3.2 DELA/ SAKAB

Description

DELA GmbH in Essen, Germany, is a company specializing in the treatment of mercury waste and the recovery of liquid mercury. Together with the Swedish company SAKAB, a technological process has been developed in which elemental sulphur and elemental mercury are vaporized and mixed in a heated vacuum mixer. Both elements react in the gas phase to form solid mercury sulphide.

Process

The process utilizes a vacuum mixer, a device that is also employed at DELA to treat different types of mercury-containing waste. First, the vacuum mixer is flooded with nitrogen in order to replace any oxygen in the system that might oxidize mercury or sulphur. A vacuum (<0.9 bar) is applied and, at a temperature of 250 - 350 °C, sulphur and mercury are added. Unlike processes at lower temperatures, a nearly stoichiometric ratio between mercury and sulphur can be used. Mercury and sulphur react immediately in the gas phase to form mercury sulphide. After mixing has been continued for a certain time, the surplus gaseous mercury sulphide can be condensed by cooling down the gas phase. The full-scale plant is shown in Figure 5.

Figure 5 DELA stabilization plant (Source: DELA GmbH)

Product

The product is a heavy powder of pure red cinnabar (HgS) that is 16% heavier than elemental mercury and has a density between 2.5 and 3.0 g/cm^3 (Figure 2, right). The volume of the mercury sulphide powder is about six times the volume of elemental mercury. The weight has increased by about 16%. Optionally, the product could be manufactured in the form of pellets. The product shows no detectable release of mercury vapour. The concentration of mercury after leaching with water is below 0.002 mg/kg dry substance.

Implementation and costs

In June 2010 the patented process (EP 2072 467 A2) was successfully implemented in a full-scale plant with a maximum annual capacity of 1000 t. In each batch, up to 800 kg of mercury could be treated. The plant is licensed by German authorities and has already been used to stabilize 10 t of elemental mercury from Swedish sources. According to company information, the costs for stabilizing one tonne of mercury amount to EUR 2,000 (about USD 2,700), which already includes the costsfor disposal in an underground storage facility. The plant is ready to accept and process additional quantities of mercury.

Additional information

The plant design principally allows for shipment in a container, so that it is possible to have a mobile plant that could be transported to the mercury instead of needing to transport mercury to the plant. Whether this could be a model for Asia or other regions should be investigated further.

4.3.3 Bethlehem Apparatus

Description

Bethlehem Apparatus Co., Inc. (Hellertown, PA, USA) is an American recycling enterprise. The company has developed a process that converts liquid mercury into high purity mercury sulphides and encapsulates them in a polymer matrix.

Process

The process is similar to the DELA technology, but instead of a vacuum mixer, a heated reaction vessel without mixing devices is applied [7].

Product

The material is claimed to be identical in its physical and chemical properties to naturally occurring cinnabar. The final product is cinnabar with a density of 5-6 g/cm^3. According to company information, the produced mercury sulphide did not show any trace of elemental mercury and headspace analyses also confirmed the absence of mercury in the gas phase [9]. It meets Canadian regulatory standards for land disposal [8].

Implementation and costs

In each batch, 45 kg of mercury are stabilized. It is planned to attach 10 or 20 units to a single mercury feed. With such a set-up, the operating system will be capable of processing 500 to 1000 kg of mercury per day [11]. When brought to full-scale, the process is expected to have an annual conversion capacity of 1.000 t [9]. The stabilization costs are reported to amount to approximately USD 5-6 per pound (USD 11,000 -13,000 per ton, EUR 8,000-10,000 per ton) [11].

4.3.4 MAYASA – sulphur polymer cement

Description

MAYASA is a Spanish state-owned company that operated the famous mercury in Almadén until it was shut-down in 2003. The company is still engaged in recycling and trading mercury. Within the EU project MERSADE, MAYASA has developed a stabilization process that fixates mercury as mercury sulphide in a sulphur polymer cement.

Process

The process consists of two steps: In the first step, elemental mercury is stabilized with sulphur to meta-cinnabar with a planetary ball mill. In a second step, this meta-cinnabar is incorporated at 140°C in a polymeric sulphur-concrete matrix, composed of gravel, sand, filler, elemental sulphur and modified sulphur [51].

Product

The final product is prepared in the form of a very hard monolithic block of 16x16x4 cm (Figure 3). The shape of the blocks can be changed. The US EPA Toxicity Characteristic Leaching Procedure (TCLP) was used to control the leaching behaviour of mercury and the average value was ~0.102 mg/l [limit 0.2 mg/l]. The volume of the product is approximately 13 times higher than elemental mercury and the weight has increased by a factor of three.

Implementation and costs

The facility is still only on a small scale, producing 6 kg of a final product per batch and a throughput of 4 kg. The costs for the stabilization of metallic mercury at a full-scale application are estimated to be between EUR 35,000 and 4,000 per ton metallic mercury (USD 4,600 to 5,200 per ton).[6]

Similar processes

Brookhaven National Laboratory has developed a process that stabilizes and encapsulates mercury in a sulphur polymer cement in one process step. More information may be found in [31][36].

4.3.5 ADA stabilization process

Description

The stabilization process of ADA Technologies was developed for treating radioactive mixed mercury waste [1][47]. The purpose of the method is to stabilize both elemental mercury as well as mercury compounds. Therefore, several agents that react with both types of mercury in the waste are added in the process.

Process

Powdered sulphur (10-500 micrometers) is added to an (open) pug mill with a set of counter-rotating blades [47]. After starting the mixing blades, mercury is poured in. Mixing is continued for 5-10 minutes, when a bulking material (typically sand) is added to the mixture and mixing is continued for an additional 10-30 minutes. Then, a polysulphide (calcium, sodium or any other alkali or earth alkali compounds) is added, and acts as an activator for the reaction between mercury compounds and the sulphur reagent. Further agitation typically takes place for 60 to 120 minutes. Since the reaction between mercury and sulphur is exothermal, the end of the reaction is indicated by the end of heat generation. No operations require heating.

Product

In the case of elemental mercury, the product achieves a granular state. In order to prevent the formation of dust, up to 30 wt.% water may be added. The final product contained about

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[6] M. Ramos (MAYASA). Personal communication, 14 January, 2011.

600 ppm free elemental mercury, and leachable mercury was below 0.1 mg/l (TCLP test, limit 0.2 mg/l). Omission of sand and calcium polysulphide resulted in large amounts of unreacted metallic mercury. The weight of the material increases by about 100% and the volume increases by a factor of about 22.

Implementation and costs

A batch size of 50 kg has already been used, which would result in a daily throughput of 250 kg. A possible scale of up to 375 kg/batch is considered by the vendor. In this case, the yearly throughput is expected to be 1,000 t/a, if five mixers are used in parallel. Altogether, 10 metric tons of radioactive mercury have already been stabilized by the company. Process costs to treat 1,500 kg of mercury were estimated to be in the order of USD 300 per kg (cost estimate for 1999) [78]. In another study (2005) costs for stabilizing 1,000 t mercury (5000 t in total) annually were estimated to be in the order of USD 4,900 to 8,200 per ton, including disposal in a new monofill [65]. It was impossible to separate the treatment costs from the calculation.

Figure 6 ADA Technology Mercury Treatment Skid (Source: ADA Technologies, Inc.)

Additional information

A similar process by Brookhaven National Laboratory was estimated to cost about USD 15,000 per ton [36].

4.4 Potential advantages of elemental mercury stabilization for safe storage and disposal

The physical and chemical properties of elemental mercury pose some challenges for storage. Unlike all other metals, it is liquid and could be spilled if a mercury containing flask, container or other packaging is damaged by an accident or by corrosion. Upon spillage, mercury tends to form many, often tiny droplets because of its high surface tension. Standard cleaning procedures that remove this finely dispersed mercury from the surfaces, cracks and corners of a contaminated area are often not sufficient. Moreover, if done improperly, cleaning may cause secondary contamination of other areas, tools and equipment.

Vapour pressure

One central problem of liquid mercury is its vapour pressure. At 20 °C it amounts to 13.2 mg/m^3, at 30 °C to 29.5 mg/m^3 and at 40 °C to 62.5 mg/m^3 [46]. In Germany, the maximum allowable concentration in the workplace is 0.1 mg/m^3 [17], while in the USA a value of 0.05 mg/m^3 has been defined [57]. It is obvious that these limit concentrations may be easily exceeded if liquid mercury is not contained entirely.

In contrast to liquid mercury, stabilized mercury, at least from some producers, did not show any mercury vapour pressure, which is a sign for complete conversion into mercury sulphide. If elemental mercury were still present, the mercury vapour pressure could be as high as above pure elemental mercury.

Another feature of solid mercury compounds is their presumably lower physical mobility in case of a leakage. While mercury droplets easily spread over large areas, solid mercury compounds are likely to stay close together, so that the area of contamination would be significantly smaller and the clean-up easier.

Mercury alloys, the amalgams, are easily formed when mercury is brought into contact with suitable metals like zinc, copper or nickel. Amalgams are solids and therefore fulfil the criteria of safer handling. On the other hand, it has been shown by experiment that copper or zinc amalgams do not have a lower mercury vapour pressure [49], and they are therefore not considered suitable alternatives for storing elemental mercury.

Aqueous solubility

If contact between water and mercury cannot be excluded in a storage facility, the leaching behaviour of the stored waste must be taken into account.

At 25 °C, the solubility[7] of pure elemental mercury in pure water is approximately 0.06 mg/l [20]. This is less than the regulatory limit of 0.2 mg/l stated in the US Resource Conservation and Recovery Act (RCRA). Unfortunately, neither elemental mercury waste nor other mercury-containing wastes consist only of pure mercury. All wastes contain mercury compounds to some extent. Potential impurities could be mercury oxide (HgO) or mercury chloride ($HgCl_2$). Their aqueous solubility is higher by several orders of magnitude and may further increase if ions like chloride or hydroxide are present in the solution.

A conversion of elemental mercury and mercury compounds to mercury sulphide (HgS) results in products of very low solubility. The minimum solubility of mercury sulphide is estimated at 10^{-10} mol/l or $2{\cdot}10^{-5}$ mg/l, while that of mercury selenide amounts to $10^{-7.8}$ mol/l, resp. $3.2{\cdot}10^{-3}$ mg/l [29].

Thus, leaching of stabilized products should give lower concentrations of mercury than observed for elemental mercury. In practice, however, often much higher concentrations have been found. Reasons for this behaviour could be incomplete conversion (leaving some elemental mercury or mercury compounds unreacted) and the formation of by-products like mercury oxide that have a much higher solubility.

Stability, storage and disposal

Under dry conditions, mercury sulphide is stable and does not decompose. Submerged in water, sediments or soil, mercury sulphide may be very slowly converted by dissolved oxygen into sulphate and ionic mercury [5]. Mercury sulphide lacks the hazardous properties that

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[7] Most thermodynamic data have been determined at 25 °C. Temperature in landfills might be higher or lower. The resulting temperature effects cannot be foreseen in every detail at the time, but within a margin of 15 - 35 °C it is not expected that they exceed one order of magnitude.

make elemental mercury dangerous (vapour pressure, liquid state). If kept dry and in a closed container (to avoid dust), mercury sulphide may be stored for a long time and with little danger to human health and the environment. Precautions should be taken to avoid fire since at high temperatures mercury sulphide may decompose and emit toxic fumes of hydrogen sulphides, sulphur oxides and mercury oxides. The stabilized product that is to be stored should show very low gaseous mercury releases. In a report for the European Commission BIPRO (2010), it is proposed that the stabilized product should have a mercury vapour pressure of below 0.003 mg/m³ and mercury concentrations in aqueous leachates should be below 2 mg/kg dry mass (L/S=10 l/kg). No justification was given for these values.

In Europe, mercury sulphide may already be disposed of in underground storage facilities. In contrast to elemental (liquid) mercury, no further requirements for acceptance, transport and disposal are necessary. In Europe and Canada, above ground disposal in open landfills is also allowed, because all acceptance criteria (leaching concentrations) are fulfilled. Before a wider application of this option will be started, further studies should be carried out as landfills may become a source of mercury emissions in the future.

4.5 Conclusions

Based on a literature survey, additional information from other studies [11] [45] and direct contacts with companies, a number of technologies were identified that have been proven successful in stabilizing / solidifying elemental mercury and mercury-containing waste. Most of them, but not all, aim to convert mercury and mercury compounds into mercury sulphide or similar sulphide-containing compounds. At least one of them (DELA/SAKAB) is now operating at full industrial scale with an annual capacity of up to 1000 t/a. Other technologies (ADA, Bethlehem Apparatus, MAYASA) have successfully been operated in smaller batches, but could possibly be up-scaled to higher capacities, once there is a market demand..

Stabilization costs start at EUR 2,000 per ton (USD 2,700 per ton). They are based on the assumption that elemental mercury is delivered to the plant, but include costs for underground disposal. Within the borders of this study, it was impossible to calculate costs for a potential implementation of stabilization technologies in Asia and the Pacific.

Temporary storage of stabilized mercury is expected to pose fewer challenges to developing countries than storage of elemental mercury, because safety requirements could more easily be met. Options for temporary storage and final disposal are discussed in the following chapters.

Table 1 Overview of existing pre-treatment technologies for elemental mercury (Sources: [25] [45])

	Existing pre-treatment technologies						
Process	Company	Costs (USD/t)	Elemental mercury per batch	Daily throughput for one existing line	Complete stabilization	Hg content in product	Comments
Sulphur stabilization	DELA	2,700)*	800 kg	3,000 kg/day	✓	86 wt. %	Large scale application available and licensed, 10 tons already stabilized and disposed
	Bethlehem apparatus	11,000 – 13,000 (USD 1,008,000 investment for 300t/y)	50 kg	275 kg/day	✓	84 wt. %	No up-scaling is planned, but the generation of many small lines is proposed to meet quantity needs, when needed
Sulphur polymer cement	ADA Technologies	2,700,000 (investment)	50 kg	250 kg/day	✓	50 wt. %	10 tons already stabilized
	Brookhaven National Laboratories	2,880	20 kg	40 kg/day	X	33 wt. %	Incomplete reaction, presence of elemental mercury in the product
	MAYASA	4,600 – 5,200)**	2 kg	100 kg/day	✓	30 wt %	Time needed to develop large scale application 2 t/day): 3-5 years
	* EUR 2000, includes costs for disposal, approximately EUR 300						

5 Storage of elemental mercury and stabilized mercury

5.1 Overview

If surplus elemental mercury shall not enter the market, it has to be stored or disposed of in an environmentally sound manner. In the USA, storage of elemental mercury for a very long time (up to 40 years or possibly even longer) or in above ground warehouses for a long-time period is considered one option to implement this goal. Elemental (commodity) mercury has been stored in the USA for more than 50 years in the form of governmental stockpiles in warehouses. Stocks have been managed by the US Department of Defense (DOD, about 4,300 t) and the US Department of Energy (DOE, about 1,200 t). In the past, these stocks had strategic significance, but in the meanwhile they have been declared in excess of national needs. Until the 1990s, part of these stocks were sold to the market, but due to environmental concerns sales stopped and are now prohibited by the Mercury Export Ban Act of 2008 (MEBA).

5.2 Storage of elemental mercury in warehouses:

5.2.1 Description of the concept

Until 2010, the DOD, through its Defense National Stockpile Center (DNSC) stored elemental mercury in warehouses in three locations. It decided to consolidate these stocks at one site, Hawthorne, and in September 2010 began the transportation of mercury to this facility [28]. The DOE is planning the operation of a facility that is able to store mercury from governmental sources (other than DOD) as well as private sources. According to the Mercury Export Ban Act, this facility shall go into operation before 2014. The DOD and the DOE concepts are very similar: Elemental mercury in air- and liquid-tight containers (in the case of DOD, original flasks of different formats were over-packed in steel drums) are placed in specially equipped and monitored warehouses in remote locations.

Figure 7 Warehouses in Hawthorne (Nevada, USA) selected for above ground storage of elemental mercury (source: DNSC)

Both facilities are based on similar safety concepts. They include technical and organizational measures that will provide a continuously high level of environmental and occupational safety. They include:

- **Low permeable floors, walls, ceilings**: Special mercury resistant sealing for the floor (Figure 8) and, in particular, the packaging system of the waste and installation of a slope towards a collection sump; containment dikes.
- **Lighting**: Sufficient lighting to allow inspections.
- **Fire protection**: Buildings constructed of materials resistant to fire such as concrete and steel. Heat and smoke fire detection system – monitored continuously. Automatic, dry-pipe (water supply) fire suppression system, portable fire extinguishers.
- **Ventilation**: Static ventilation.
- **Containers:** Air- and liquid-tight non-corrosive containers, licensed for transport.
- **Security**: Preventing of unauthorized access. Positive contact intrusion detection on all doors, windows and vents, monitored continuously. Located in a protected area (within security fence / boundaries). Security patrols.
- **Monitoring:** Monitoring systems (air, containment, blood and urine of workers); regular emission control of the facility surroundings; permanent mercury vapour monitoring with a sensitivity ensuring at least that the recommended indicative limit value of 0.025 mg mercury/m³ is not exceeded; equipped with a visual and acoustic

alert system in case the limit values are exceeded; calibration of the monitoring system checked at least annually; if 0.025 are exceeded, employees should implement respiratory protection.

- **Prevention of vapour emissions** produced during packaging, handling, internal transportation, and temperature control; vapour emission detection near to the ground floor as mercury vapour is heavier than air;
- **Only mercury**: No storage together with other waste;
- **Inspection:** Visual inspections (walkthroughs) performed on a routine basis: Inspection of general storage facility, receiving, handling and storage areas.
- **Emergency response procedures / Continuity planning:** Identification and impact assessment of events that may have an impact on environmental safety of the facility. These include spillage of mercury and natural (e.g., earthquake, flooding) or human-made disasters (e.g., fire, terrorist attack) that have an impact on the integrity of the facility. Elements of an emergency response plan include a description of response measures, equipment and responsibilities. Repeated training of personnel with regard to emergency response is essential to allow for an effective implementation of these measures in case of an event.
- **Risks and accident prevention system**, regular independent auditing.
- **Skilled workforce** specialized in the handling of hazardous materials and technical ordnance material.
- **Transportation:** Transportation in accordance with national and international requirements for shipment of hazardous materials. All truck drivers will be trained and certified in the handling of hazardous materials, shipments will be tracked via Global Positioning Satellite. In case of a transportation incident, drivers are instructed to call specific emergency telephone numbers via cell phones or Citizens' Band radio (CB). No announcement of specific shipping dates or routes for security reasons.
- **Placing of containers:** Rows of pallets allow 3-foot aisle space between rows and along warehouse walls (Figure 9). Reversibility of storage to allow relocation in case of accident or movement to a different storage facility.

More information on management practices may be found in

- Mercury Stewardship (2003) Best Management Practices [52]

- DNSC (2008). Defense National Stockpile operations manual. Appendix 4-A Storage instructions for individual commodities. Mercury [27]
- US DOE (2009) U.S. Department of Energy interim guidance on packaging, transportation, receipt, management, and long-term storage of elemental mercury [79].

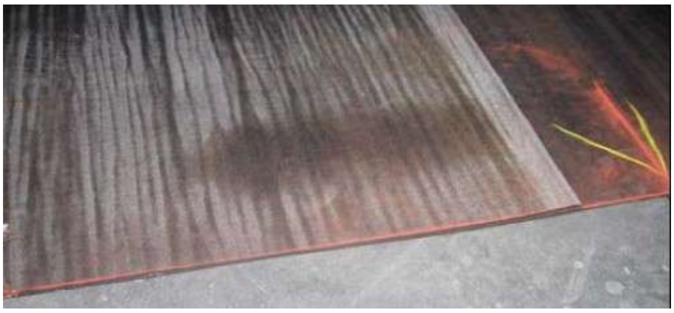


Figure 8 Enhancement of a concrete floor by application of impermeable flooring (source: DNSC)

Figure 9 Placement of drums on pallets in a warehouse in Hawthorne (source: DNSC)

Concepts for temporary storage (months to a few years) may be based on similar principles, but could possibly take place at already existing facilities, e.g., at or near the place of production or at hazardous treatment facilities.

5.2.2 Site selection and exclusion criteria

The overall safety and performance of an above ground storage facility may be only as good as the site characteristics allow. Therefore, a thorough site selection process that analyses the fulfilment of general site criteria and considers the potential impact on the environment and the society is a prerequisite before a location can be chosen. It may consider:

- Site exclusion criteria and infrastructure
- Social parameters
- Socio-economic stability

Site exclusion criteria and infrastructure

A facility for the long-term management of elemental mercury should be situated such that environmental hazards have no impact on its overall performance. The following criteria may act as orientation [81]:

- **Floodplains** : Avoid floodplains, build facilities above 100 year flood-level.
- **Unstable terrain**: Avoid unstable terrain: the movement of rock and soil on steep slopes by gravity (e.g., landslides), and rock and soil sinking, swelling, or heaving.
- **Wetlands**: Avoid wetlands like swamps, marshes, bayous, bogs, and Arctic tundra.
- **Unfavourable weather**: Avoid areas with stagnant air.
- **Groundwater conditions**: Not be located over high-value groundwater or areas where the underground conditions are complex and not understood.
- **Earthquake zones**: No facility within 200 feet of a Holocene fault (that is, faults that have been active within the last 10,000 years).
- **Incompatible land use**: Avoid locating near sensitive populations or in densely populated areas.
- **Karst Soils**: Avoid locating in ‘active’ karst areas.

Moreover, appropriate distance from national parks, conservation areas and fragile environmental systems should be maintained. It may be advisable to consider more than one area before going into detailed planning. If remote areas are under investigation, the proximity to major transportation routes, power and water supply are prerequisites. There may be the need to check for the facilities’ capability and flexibility for later expansion. The choice of sites where warehouses or equivalent buildings already exist could be an option during a site selection process. Candidate locations where sufficient information to adequately characterize the site is not available may be excluded from the process.

Socio-economic factors

When identifying suitable sites for elemental mercury storage facilities, the involvement of stakeholders may lead to the consideration of more factors that are of importance to the local population. Such factors may include [82]:

- Historic land uses (official and unofficial);
- Existing environmental conditions;
- Conflicting land uses (e.g., use of a stream for fishing, use of a vacant lot for community vegetable gardening);
- Vision of sustainable uses of land, water and air resources;
- Acceptable alternatives or modifications to proposed plans;
- Religious, cultural or other special values of the land.

In addition, the potential impact on local or regional socioeconomics and issues such as environmental justice may be considered.

Socio-economic stability

In addition to these technical requirements, it should be noted that above ground storage of elemental mercury is a sustainable solution only if political, economical and institutional stability can be guaranteed for the full operation time of the corresponding facility. If in times of political or economical crisis governmental surveillance and security measures weaken, unauthorized access to the stored mercury may lead to plunder or destruction of the warehouse – leading to direct environmental release of mercury or to a re-introduction to the market. Many countries in the world have faced such critical periods in the past 20 to 60 years.

5.3 Above ground storage of elemental mercury in the USA

The following subchapters present three warehouses concepts developed for the long-term storage of elemental mercury. Currently, only one of these three, the Hawthorne facility in the USA, is in use.

5.3.1 Storage of elemental mercury by the Defense National Stockpile Center (DNSC) in Hawthorne, Nevada, USA

In the USA, the Defense National Stockpile Center program was originally established to minimize the national dependence on foreign sources of essential materials in times of national emergency. Since 1988, the Defense Logistics Agency (DLA) has been responsible for the program and established the DNSC to manage the program and operate storage depots nationwide. Mercury (4,436 tons) is one of 65 commodities stockpiled and managed by the DLA, and has been in part for over 50 years.

The US Congress has declared that most of the DNSC materials, including mercury, are in excess of national defence needs and has authorized their disposal, generally by sale, until 1994. After the environmental and health risks related to mercury became more and more obvious, the Department of Defense (DOD) halted the sale of elemental mercury.

In 2003/2004 a Mercury Management Environmental Impact Statement (MM EIS) was carried out to find the most appropriate way of dealing with the stored mercury in the future for a period of 40 years. As a result of the MM EIS, the DNSC decided to consolidate mercury holdings from several facilities at one site, the Hawthorne Army Depot in Nevada.

The selected warehouse (Hawthorne Army Depot) was not one of the existing mercury storage sites. The decision to use this depot was based on a combination of environmental, economic and technical factors, policy considerations and public and stakeholder comments. First, shipments to the Hawthorne facility started in September 2010, and are expected to continue through mid 2011 [77]. To fulfil the required safety standards for long-term storage of metallic mercury the selected already existing depot had to be upgraded.

Storage area

The storage facility at Hawthorne Army Depot has a new layout and drums are stored on pallets in lines. Figure 10 provides a diagram of the layout of the mercury storage building. Figure 9 shows the placement of drums within the building while Figure 11 details the acceptance of first shipments to Hawthorne.

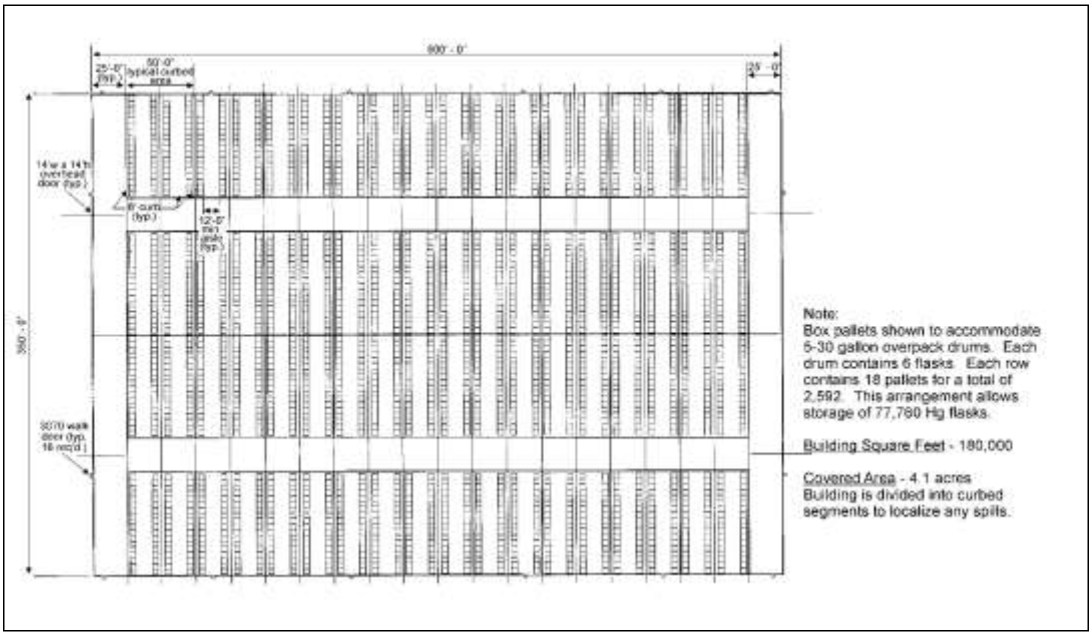


Figure 10 Diagram of the layout in the mercury storage building at Hawthorne, USA (source: DNSC [26]) **.**

Figure 11 Storage of elemental mercury in Hawthorne (source: Rebecca Montgomery, Joint Munitions Command)

Costs

DNSC estimated that storage of mercury at Hawthorne would require investment costs in the range of approximately USD 11.2 million. The costs for storing 4,436 tons of mercury for 40 years amount to USD 68 million [48].

Table 2 Expected costs for the DNSC warehouse in Hawthorne

Cost type	Costs USD
Investment costs	11,209,000
Operational costs -Rent 40 years (storage, maintenance, restoration)	57,018,413
Total	68,227,413
Cost per metric ton	15,380

5.3.2 Storage of elemental mercury by the US Department of Energy (DOE)

The ‘Mercury Export Ban Act of 2008’ (MEBA) bans the export of elemental mercury from the United States from January 1, 2013. It prohibits the sale, distribution, or transfer of mercury by Federal agencies to other government agencies and private entities as of October 14, 2008. MEBA does not specify how long mercury may require storage. The bill also requires DOE to identify a safe, long-term storage site for up to 17,000 tons of mercury, which includes stockpiles held by the Federal Government as well as commercial producers.

DOE must designate one or more facilities for long-term management and storage of mercury generated in the United States and keep it/them ready for operation by January 1, 2013. Any facility must comply with applicable requirements of the Solid Waste Disposal Act, as amended by the Resource Conservation and Recovery Act (RCRA).

Until January 1, 2017, USEPA must report to Congress on the global supply and trade of elemental mercury, including whether additional primary mercury mining has occurred because of the Act. DOE estimates that between 7,500 and 10,000 metric tons of surplus mercury will need to be managed and stored in a facility designed to last for at least 40 years, including 1,200 metric tons of mercury from DOE stocks at its Y–12 National Security Complex in Oak Ridge, Tennessee.

In November 2009, the DOE published the ‘Interim Guidance on Packaging, Transport, Receipt, Management, and Long-Term Storage of Elemental Mercury’ [79]. This Interim guidance is a framework for the standards and procedures associated with a DOE-designated elemental mercury storage facility with focus on the RCRA permitting of such a facility and planning for that storage facility's needs.

On July 2, 2009, DOE issued a Notice of Intent in the Federal Register soliciting public input on developing an Environmental Impact Statement (EIS). DOE considered all comments received during the scoping period (July 2 through August 24, 2009) in preparing a first draft of an EIS, published in January 2010 [80]. The first draft EIS evaluates the potential impact of the establishment of a facility for the long-term management and storage of mercury. After public comments, it is expected that the final version of the EIS will be released by winter 2011.

Considered alternatives

As required by the National Environmental Policy Act (NEPA), the DOE EIS 2010 evaluates a 'No Action Alternative' to serve as a basis for comparison with the site alternatives. Ten potential mercury storage sites were considered: Five owned by DOE, one by DNSC (Hawthorne Army Depot in Nevada) and four by the private sector. Applying the DOE screening criteria, the institution confirmed that seven of the ten storage sites appeared to be reasonable alternatives.

Design of the facility

The mercury storage facilities would have areas for administration, receiving and shipping, storage and handling. The storage area would constitute approximately 90% of the floor space. The storage area would generally be a large open space similar to a warehouse, where storage, inspection and monitoring could effectively be performed. The mercury storage facilities would accept two types of mercury containers: 3-litre (34.6-kilogram [76-pound]) flasks and 1-metric-ton (1.1-ton) containers. Other containers could be approved and accepted on a case-by-case basis. The racks should have a 3° slope towards the aisle to cause leaked mercury to flow towards the edge of the spill tray in order to identify spills quickly. The spill tray on the pallet should have retaining walls with sufficient height to contain at least 10% of the mercury contents on the pallet at the indicated angle.

Figure 12 illustrates how the exterior of a new mercury storage facility may look like: Figure 13 provides a potential conceptual layout of the interior and how the mercury containers might be stored.

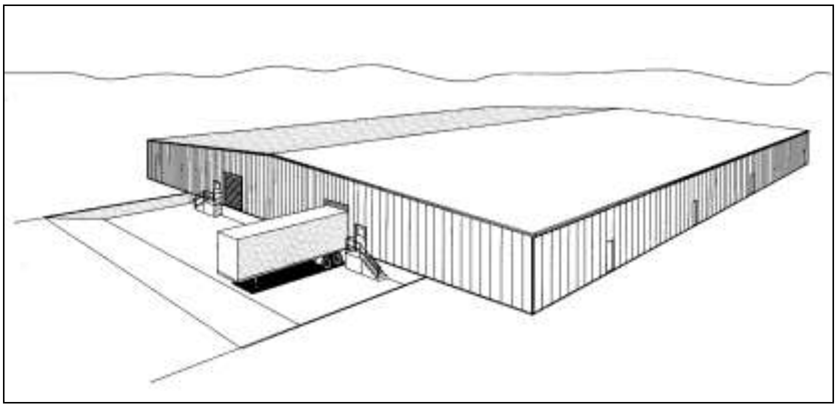


Figure 12 Building exterior of the planned DOE storage facility [80]

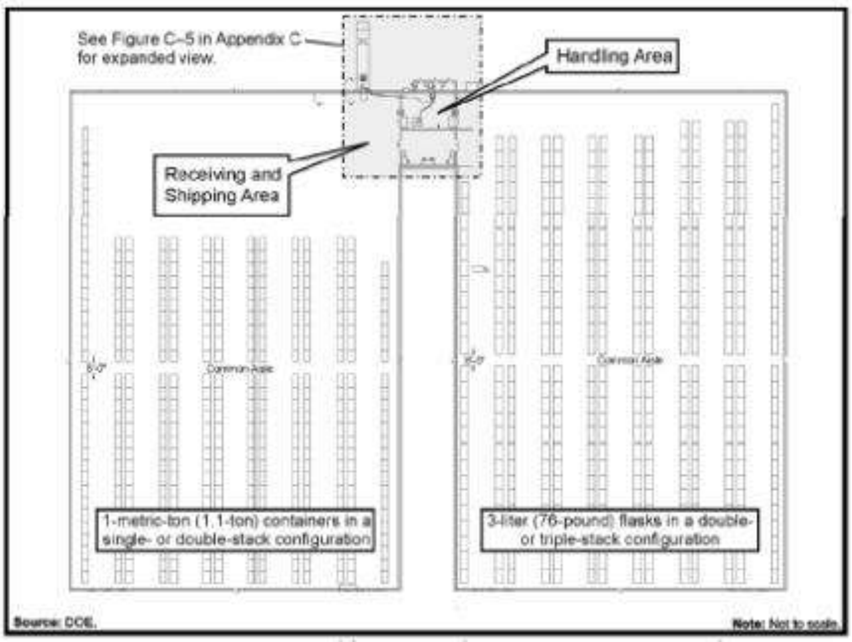


Figure 13 Potential conceptual layout of DOE storage facility [80]

Costs

The US EPA study (US EPA 2007b) examined the costs of storing elemental mercury under two storage scenarios: a storage facility that uses rented warehouses and a storage facility that includes construction of warehouses specifically for mercury storage. Estimates of total storage costs assume that, over a 40-year period, either 7,500 or 10,000 metric tons of surplus mercury will require storage.

Table 3 Estimates of private sector storage costs (USD) for 40 years [86]

Storage Capacity	Total Cost Estimates	Rent Scenario [million USD]	Construction Scenario [million USD]
7,500 tons	Total Project Costs (undiscounted)	59.5 - 144.2	50.0 - 137.7
	Net Present Value of Total Project Costs	18.5 - 39.9	17.8 - 41.0
	Annualized Costs	1.4 - 3.0	1.3 - 3.1
	Annualized Costs per t	185 - 400	179 - 410
10,000 tons	Total Project Costs (undiscounted)	69.8 - 183.9	57.3 - 174.9
	Net Present Value of Total Project Costs	21.3 - 50.9	20.0 - 51.9
	Annualized Costs	1.6 - 3.8	1.5 - 3.9
	Annualized Costs per t	159 - 381	150 - 390

5.4 Temporary storage of elemental mercury and stabilized mercury

5.4.1 Temporary storage concept developed by Minas de Almadén (MAYASA) - SPAIN - EU

Minas de Almadén (MAYASA) is a Spanish company specializing in treating and dealing with mercury, received mainly from decommissioned chlor-alkali plants. MAYASA operated the world's largest mercury mine in Almadén until it was closed in 2003. The company uses an auxiliary above ground building as a warehouse for the storage of mercury. The installation is located above the former mercury mine.

In the course of an EU funded project ('Mercury Safety Deposit' MERSADE) carried out by MAYASA together with national partners, the design and construction of a safe storage installation prototype for mercury metal was investigated. The project was based on the experience in handling and storage of the current installations at the Las Cuevas mercury warehouse in Almadén (Ciudad Real – Spain) [50]. The project developed technical support for a long term storage plan (for the next 50 years), which will define the packaging to be used during the transport from plants to the site where it will be deposited, the procedure for handling the metal and the construction of a prototype facility for depositing surplus mercury deriving from EU countries.

The project is expected to develop a model for a bulk mercury deposit that meets strict safety requirements and prevents mercury emissions after closure.

Operation

Elemental mercury is stored in flasks (34.5 kg net), containers (1 ton) or bulk tanks. The flasks and containers fulfil the requirements of transport regulations and are used for shipping elemental mercury as well. The filling and re-filling of tanks with mercury takes place via pipes and valves. Air displaced during filling activities is extracted and cleaned via special filters with activated carbon. The purity of the stored mercury is 99.9%. In case the delivered mercury does not meet this criterion, a cleaning of the mercury takes place before storage.

The bulk tanks are placed in a collecting basin made of concrete, which is capable of receiving all mercury included in the bulk tanks in case of an accident. All the areas where mercury is handled, stored or packaged are specially treated with waterproof protective epoxy-based paint on walls and flooring. In addition, the floors have a slight slope directed to a central collecting basin.

Gas displacement systems and activated carbon filters are installed. Mercury emissions from operational processes (e.g., filling of tanks) are monitored by mercury emission monitoring systems. The measurement results are regularly evaluated. Accompanying studies related to possible impacts of mercury emissions have been carried out bythe Mersade project. According to these studies, direct impacts of the emissions on environmental surroundings are expected up to a maximum distance (along the direction of the prevailing wind) of 300 m from the central point of the installation.

The project also includes investigations on existing storage containers in order to identify the most appropriate material for long-term storage.

5.4.2 Temporary storage of stabilized mercury

If stabilization of elemental mercury is regarded as one element of a market removal strategy, there could be a need to store the stabilization product temporarily until a final disposal solution becomes available.

Specific concepts for the temporary storage of stabilized mercury such as mercury sulphide have not yet been developed, but mercury sulphide could be managed in the same way as hazardous substances or hazardous waste, for which storage concepts and requirements already exist in many countries.

According to German legislation, waste may be stored for more than one year at sites that fulfil the same requirements as landfills of the same class (e.g., for hazardous waste) [33].

Further information on designing and operating specially engineered landfills may also be found in the Basel technical guidelines [62].

Another option would include the storage of stabilized mercury at waste collection centres (see example in Figure 14) or existing hazardous waste landfill sites, if these are constructed and operated in an environmentally sound manner and fulfil the national environmental, operational and occupational safety requirements. More guidance on the temporary storage of mercury containing waste may be found in the draft Basel Technical Guidelines for the Environmentally Sound Management of mercury waste [63] and in the UNDP (2010) guidelines mercury waste from healthcare facilities [72].

Important requirements for the storage of stabilized mercury may include:

- Mercury sulphide should be stored in watertight containers such as drums or plastic bags in order to prevent any kind of leaching if transported or stored under open sky. The area that is chosen for storing should have a stable, smooth surface so that the containers can be moved at any time without damage to the containers.
- Mercury sulphide may still have a value in near future so that there is a risk of theft. Security measures might be necessary to control access to stabilized mercury. An inventory of stored materials should be done from time to time. Therefore, another temporary storage option could be the usage of warehouses on military compounds or at industrial sites, if these provide a sufficient level of environmental safety and security.
- Mercury sulphide decomposes when it is subject to fire. Flammable materials should be removed from the storage location and adequate measures should be taken to ensure that fires can be extinguished within short time. In addition, the general criteria set out above for above ground storage facilities may be applied as well.

The safest approach is to keep the amount of stored stabilized mercury as low as possible by disposing mercury in stabilized form as soon as possible.

Figure 14: Temporary storage of hazardous waste in a waste collection centre in Göppingen, Germany (source: ETG Entsorgung + Transport GmbH)

6 Concepts for the final disposal of mercury waste

6.1 Overview

Mercury waste, including stabilized mercury, could principally be disposed of in several different ways. These include:

1. Above ground disposal of stabilized mercury in specially engineered landfills.
2. Permanent storage of stabilized mercury and mercury compounds in underground mines (underground storage).
3. Deep injection of slurries containing mercury sulphide.
4. Export for disposal in countries outside the region.

6.2 Above ground disposal in specially engineered landfills

Specially engineered landfills should be located at sites with favourable containment properties, these being natural, augmented by or provided directly by liners. The overall engineering of specially engineered landfills should ensure the isolation of wastes from the environment as far as possible. This is an environmentally sound system for solid waste disposal, in which solid wastes are capped and isolated from each other and the environment. Specially engineered landfills are often regarded as a disposal option for waste with low mercury content, if the waste fulfils the national acceptance criteria (often only after stabilization).

In principle and for a certain limited period, a landfill site can be engineered to be environmentally safe if proper precautions and efficient management are guaranteed. Preparation, management and control of the landfill must be of the highest standard to minimize the risks to human health and the environment. Such preparation, management and control procedures should similarly apply to the process of site selection, design and construction, operation and monitoring, closure and post closure care [62].

According to Japanese requirements, landfill sites should be completely shut off from the outside natural world. The entire landfill is enclosed in watertight and reinforced concrete and covered with equipment preventing rainwater inflow such as a roof and a rainwater drainage system [53] (Figure 15).

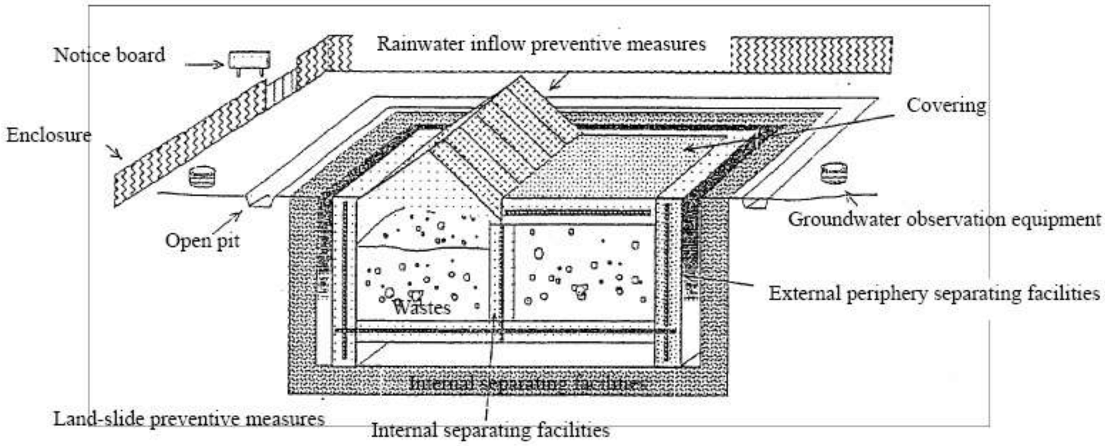


Figure 15 Possible layout of a specially engineered landfill (source: Ministry of the Environment, Japan)

Stabilized mercury, like other hazardous wastes, may in principle be disposed of in an above ground landfill (e.g., a specially engineered landfill for hazardous waste). Many countries have developed criteria for the acceptance of hazardous wastes at landfills. With respect to mercury, these criteria typically include a threshold leaching value – a concentration of mercury in the resulting solutions from a leaching experiment – that should not be exceeded [23]. The same applies for stabilized mercury. Several companies that have developed stabilization technologies stated that their product met the waste acceptance criteria for landfills in several countries (see chapter 4.3). It should be noted that some countries prohibit the disposal of waste with a mercury content above a certain limit (among which are Sweden, Austria, Belgium [10]). In these countries, above ground disposal of stabilized mercury would be impossible.

However, some precautions might be necessary in the case of mercury sulphide. Under oxidizing conditions, mercury sulphide is thermodynamically unstable. It could be oxidized to sulphate and ionic mercury [5] [40], which in turn could be converted to elemental mercury [21]. It has been shown that mercury sulphide could also be directly converted into methyl mercury by bacteria [6]. Thus, a massive deposit of mercury sulphide in a near-surface landfill might become a source of mercury release and contamination in the long-term.

For this reason, additional safety measures need to be considered for above ground disposal of mercury sulphide. A set of requirements has recently been proposed by BIPRO [11]:

1. Storage in separated cells, no storage together with other waste (especially biodegradable waste or waste with a high pH value, e.g., above pH 10).
2. The cell shall be sufficiently self-contained.
3. Appropriate measures shall be taken to limit the possible uses of the land after closure of the landfill in order to avoid human contact with the waste.
4. After closure, a plan shall be kept of the location of the landfill / cell indicating that stabilized mercury waste has been deposited.
5. No works shall be carried out on the landfill / cell that could lead to a release of the stabilized mercury (e.g. drilling of holes).
6. A final top cover should be added to the landfill / cell.

6.3 Further investigations are necessary to assess the long-term behaviour of metallic mercury under landfill conditions with a special focus on potential methylation effects.Permanent storage in underground mines (underground storage)

6.3.1 General aspects

Underground storage means to place waste in an ordered manner in deep geological cavities (e.g., in an underground mine). It is currently practised in Europe for a wide variety of waste types. Underground disposal in general represents a concept of permanently isolating hazardous wastes (and the contaminants contained therein) from the biosphere by:

- Including them completely and permanently in a suitable host rock (e.g., in salt rock or clay formations, Figure 16) and / or
- Protecting them from becoming leached and released by a combined system of several natural and artificial barriers (e.g., in hard rock, clay stone).

After being sealed, no aftercare measures are needed to ensure the long-term safety of an underground disposal facility.

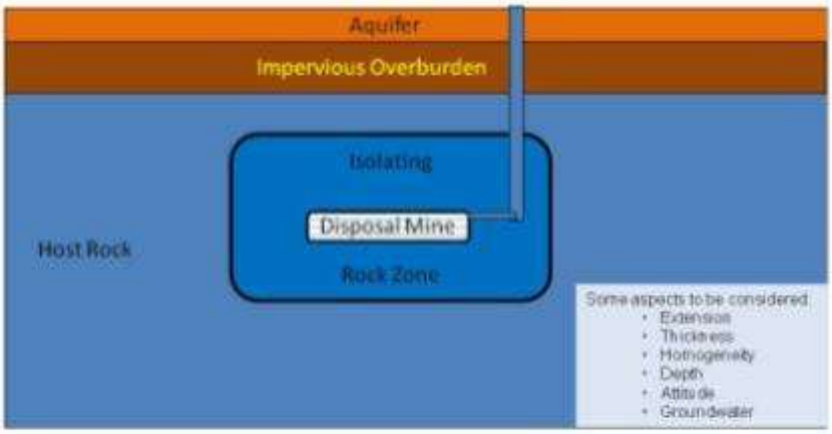


Figure 16 Concept of complete inclusion (schematically) (source: GRS)

In an ideal case, the host rock exhibits properties that 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, respectively plastic behaviour, rock salt formations might offer such a behaviour, which leads to a complete and permanent inclusion of contaminants (Figure 17).

Figure 17 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 now compacted and the residues (black colour) completely included in the rock salt due to creeping behaviour of the rock salt (source: GRS).

To a lesser extent, this also applies to clay formations. In order to warrant complete inclusion, the disposal mine itself as well as any area around it that might become influenced by the disposal operations (e.g. geomechanically or geochemically) must be surrounded by host rock in sufficient thickness, with sufficient homogeneity, suitable properties and in suitable depth.

Hard rock formations could also be used for constructing an underground disposal facility. They are characterized by quite different properties, e.g.:

- High rock permeability in jointed areas
- Heterogeneous distribution of hydraulic conductivity

Technical barriers – in addition to the natural, geological ones – become strongly significant (see details in chapter multi-barrier concept 6.3.4).

Figure 18 Sketch view of an underground disposal facility in crystalline rock – this option is characterized by potential (groundwater-) pathways to the biosphere (source: Bundesamt für Strahlenschutz, BfS)

As a basic principle, a long-term safety assessment needs to show that the construction, the operation and the post-operational phase of an underground disposal facility will not lead to any significant negative impact on the biosphere. Within such an assessment, all technical barriers (e.g., waste-form, backfilling, sealing-measures), the behaviour of the host rock and the overburden of rock formations as well as courses of possible events in the overall system need to be analysed by appropriate models (Figure 19).

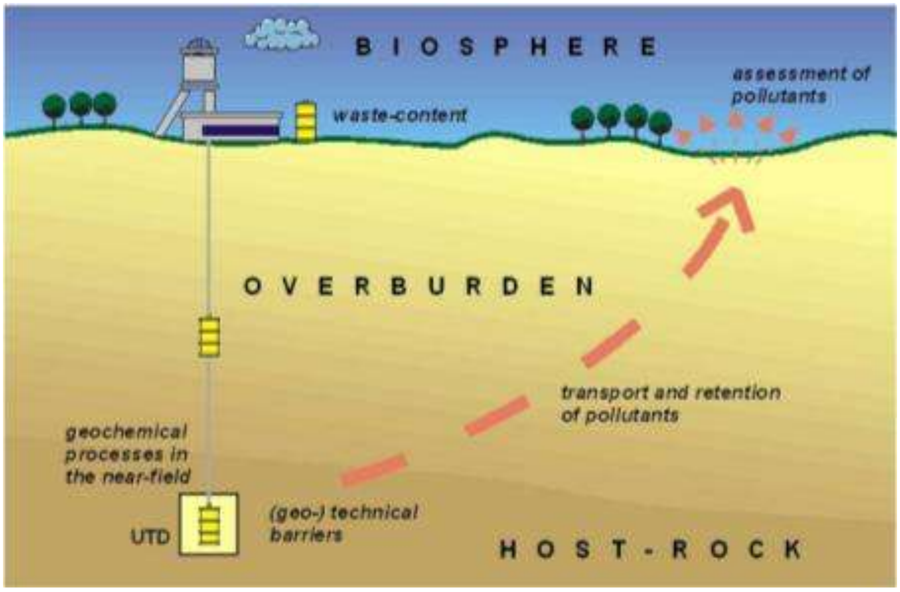


Figure 19 Sketch of the overall system of an underground disposal facility (source: GRS)

6.3.2 Operational procedure

The mode of operation in an underground storage facility follows well-established procedures, which can be summarized by the following steps ([4], see also Figure 20):

1. Generator / Owner of the waste must obtain the facility's approval before transporting the waste to the facility by sending a description and analysis of the composition of the waste to the regulation authorities.

2. After a first check at the disposal site, the documents have to be sent to the relevant authorities for approval and acceptance of the waste.

3. Wastes may be transported to the underground waste disposal facility by means of trucks or rail. The vehicles are initially intercepted at the entrance area of the underground waste disposal plant. Before the vehicles reach the entrance area, they have already passed a radioactivity control.

4. At reception, the waste documents, the delivered amounts and the packaging are checked and random samples of the waste are analysed (degassing, visual inspection, chemical composition). The waste is only unloaded if it is identified as indicated in the waste documents and fulfils specific waste acceptance criteria. Otherwise, the disposal of the waste is rejected.

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

6. The waste is then stacked accordingly at its final place of storage, i.e., the respective chamber, drift or other part of the mine area.

7. At an operating German underground waste disposal site, salt dams or stonewalls are built in order to separate the storage cells and to facilitate the ventilation of the disposal site.

8. As soon as a field is filled, it is closed off with dams (in practice, up to 15-metres-wide). The underground disposal sites are organized in a manner similar to warehouses. A sample of each waste is stored in a sample room underground. Storage place and storage time is documented. In exceptional cases, and only for a limited time, waste can be recovered from the mine if required.

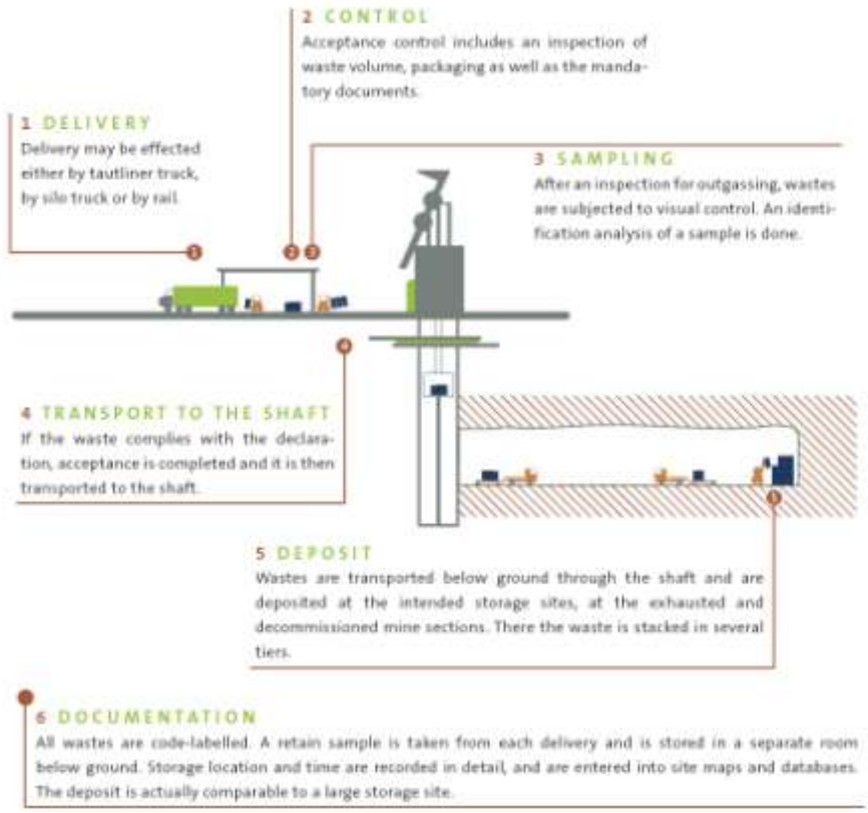


Figure 20 Disposal procedures (source: K+S Entsorgung)

Besides all technical requirements, as a matter of course the disposal has to meet all legal requirements of the country where the waste is to be disposed of. Regulations regarding the treatment of waste, occupational safety and mining operations need especial consideration.

6.3.3 Accepted waste types

All operating underground hazardous waste disposal facilities accept a broad range of waste types that have been approved for acceptance at the facility by the licensing authority. The waste must fulfil the acceptance criteria set out by national legislation. Within the European Union, the following wastes are strictly excluded from underground disposal [23]: Wastes

- that are liquid
- that may react with the host rock
- that are biodegradable
- that can generate a gas-air mixture, which is toxic or explosive
- that are auto-flammable or liable to spontaneous combustion
- from hospitals or clinics

Solid stabilized mercury (mercury sulphide) as well as mercury-containing wastes are waste types that are accepted at several underground waste disposal facilities in Europe. They may be stored in drums or big bags. The situation is completely different for waste consisting of elemental mercury. Because elemental mercury is a liquid, it is excluded from underground disposal. Currently, requirements that shall define under which circumstances permanent storage of elemental mercury may take place are being discussed in the EU [11].

6.3.4 Multi-barrier concept

Current thinking prescribes that an underground waste disposal facility should rely on not only one but several barriers. The host rock may be the most important barrier in most cases, but its performance is complemented and safeguarded by other isolating elements as well – the so-called multi-barrier system.

In general, such a multi-barrier system might be composed of one or several additional barrier components (see Table 4 and Figure 21), which are able to contribute to the overarching goal to permanently isolate the pollutants in the facility from the biosphere.

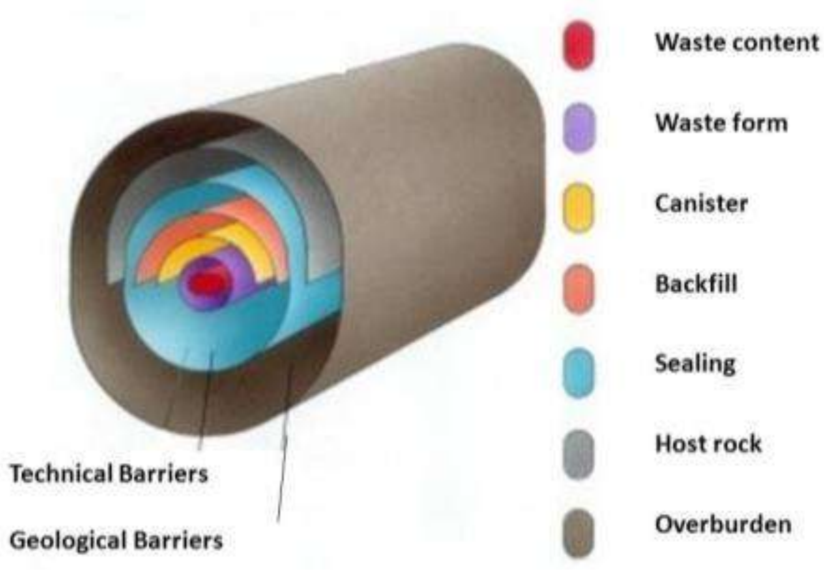


Figure 21 Main components of a multi-barrier system (schematically) (source: GRS)

Their need, as well as their mode of action within the disposal system, has to be proven 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 be released from the disposal mine under certain circumstances.

Since the geological system at a site should represent the most effective barrier, it is important to know about the geological evolution of the chosen structure. Understanding of the past allows for a prognosis of future developments, i.e., whether natural events such as uplift, erosion, volcanism and many more could have a negative effect on the barrier’s properties. Greater understanding of long-term natural processes could also be achieved by investigating so-called ‘natural analogues’.

Table 4 Barrier components and examples for their mode of action

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

In addition, organizational barriers can also be realised by installing effective monitoring systems and the technical organization of the emplacement, which consists of preparing the rooms, positioning the waste packages and inserting the backfill.

6.3.5 Site selection criteria

The selection of a suitable site is a key step in implementing an underground disposal strategy. So far, only few underground hazardous waste disposal facilities have gone into operation, and a site selection process has not been documented for any of them. Information on site selection criteria and site selection processes is available from a closely related waste management field, that of underground disposal of radioactive waste. Below, some important site selection criteria are listed, as based on an international status of discussion with regard to radioactive wastes. With respect to hazardous waste, these criteria should be regarded as an orientation only. National authorities may define criteria and requirements in accordance to their specific situation, and these may differ from those presented here.

A German expert panel for underground repositories for radioactive waste (AkEnd [18]) has developed some general site selection criteria:

- Seismic activity: In the repository area, the seismic activities to be expected must not exceed Earthquake Zone 1 according to the German norm DIN 4149.

- Volcanic activity: In the repository area, there must be neither any quaternary nor any expected future volcanism.
- The thickness of the isolating rock zone must be at least 100 m and must consist of rock types to which a field hydraulic conductivity of less than 10^{-10} m per second can be assigned. The depth of the top of the required isolating rock zone must be at least 300 m.
- The repository mine must lie no deeper than 1,500 m.
- The isolating rock zone must have an areal extension that permits the realisation of a disposal facility (minimum 10 km^2 in clay stone).
- There must be no findings or data that can give rise to doubts about whether the geoscientific minimum requirements regarding field hydraulic conductivity, thickness and extent of the isolating rock zone can be fulfilled over a period of time in the order of magnitude of one million years.

The figures used to quantify the criteria based on specific concepts and conditions, which are not necessarily applicable for a specific region or form of waste, are discussed in this report. Nevertheless, they give an impression of existing experience and status of discussions.

In addition, the International Atomic Energy Agency (IAEA) has developed a guideline on site selection for the geological disposal of radioactive waste [42]. The principles therein may be adapted to the disposal of hazardous waste (Table 5). . Similar information may be found in Pusch (2006 [60]).

Table 5 Siting factors that may be considered in a siting process (IAEA guidelines for the siting of geological disposal facilities [42], adapted to hazardous waste)

Factor	Guideline
Geological setting	The geological setting of a repository should be amenable to overall characterization and have geometrical, physical and chemical characteristics that combine to inhibit the movement of pollutants from the repository to the environment during the periods of concern.
Future natural changes	The host rock should not be liable to be affected by future geodynamic phenomena (climatic changes, neotectonics, seismicity, volcanism, diapirism) to such an extent that these could unacceptably impair the isolation capability of the overall disposal system.
Hydrogeology	The hydrogeological characteristics and setting of the geological environment should tend to restrict groundwater flow within the repository and should support safe waste isolation for the required times.
Geochemistry	The physicochemical and geochemical characteristics of the geological and hydrogeological environment should tend to limit the release of radionuclides from the disposal facility to the accessible environment.
Events resulting from human activities	The siting of a disposal facility should be made with consideration of actual and potential human activities at or near the site. The likelihood that such activities could affect the isolation capability of the disposal system and cause unacceptable consequences should be minimized.
Construction and engineering conditions	The surface and underground characteristics of the site should permit application of an optimized plan of surface facilities and underground workings and the construction of all excavations in compliance with appropriate mining rules.
Transportation of waste	The site should be located such that radiation exposures of the public and the environmental impacts of transporting the waste to the site are within acceptable limits.
Protection of the environment	The site should be located such that the quality of the environment will be adequately protected and the potentially adverse impacts can be mitigated to an acceptable degree, taking into account technical, economic, social and environmental factors.
Land use	In the selection of suitable sites, land use and ownership of land should be considered in connection with possible future development and regional planning in the area of interest.
Social impacts	The site should be located so that the overall societal impact of implementing a repository system at the site is acceptable. Beneficial effects of the siting of a repository in a region or area should be enhanced whenever feasible and any negative societal impacts should be minimized.

6.3.6 Potential host rocks

The realization of an underground disposal concept may be achieved in a wide variety of host rock types. The final concept, however, must take into account the types of wastes to be disposed and the site-specific properties and parameters. These include the overall geological situation, rock and site properties as well as all relevant regulations and experiences. Worldwide, discussion about suitable host rocks is mainly focused on the following rock types:

- Salt rock (see above),
- Clay formations and
- Hard rock (e.g. granite), including metal ore deposits.

No rock type provides a perfect overall performance, but has advantages as well as disadvantages (Table 6).

Table 6 Properties of some host rock types; colours indicate their suitability for underground disposal purposes (note: not all properties shown may be relevant in each disposal concept, this being strongly depending on the waste itself) [green = suitable; red = unsuitable; yellow = ambivalent) (Source: BGR [18])

Properties	Rock Salt	Clay / Claystone	Crystalline (e.g. Granite)
Thermal Conductivity	high	low	medium
Hydraulic Conductivity	nearly impermeable	very low - low	very low (without joints) - permeable (jointed)
Mechanical Strength	medium	low - medium	high
Deformation Behavior	viscous (creep)	plastic - brittle	brittle
Stability of Cavities	self-stability	timbering necessary	high (without joints) - low (intensively jointed)
In-situ-Stress	lithostatic isotropic	anisotropic	anisotropic
Solubility	high	very low	very low
Sorption Capability	very low	very high	medium - high

No exact value – valid for any conceivable situation with regard to geology and waste – can be given as an irrefutable rule. However, experience so far shows that some ranges of values might give a hint for probably suitable conditions. In order to convey an idea about depth and thickness of different host rock types, typical numbers, based on current experiences and plans, are compiled in Table 7.

Table 7 Typical thickness of host rock body and potential disposal depth for different geosystems

Geosystem		Thickness of host rock body	Potential disposal depth
Host rock	Variant		
Rock salt	Salt dome	up to > 1,000 m	800 m
Rock salt	Layered salt	app. 100 m	650 – 1,100 m
Clay / Claystone		up to 400 m	400 – 500 m
Rocks under clay cover		app. 100 m	500 – 1,000 m

The last line in Table 7 already indicates that the concept of underground disposal is not dependent on a suitable host rock, which fulfils all requirements. In fact, the overall geological situation is crucial for the whole system. An example is given in Figure 22.

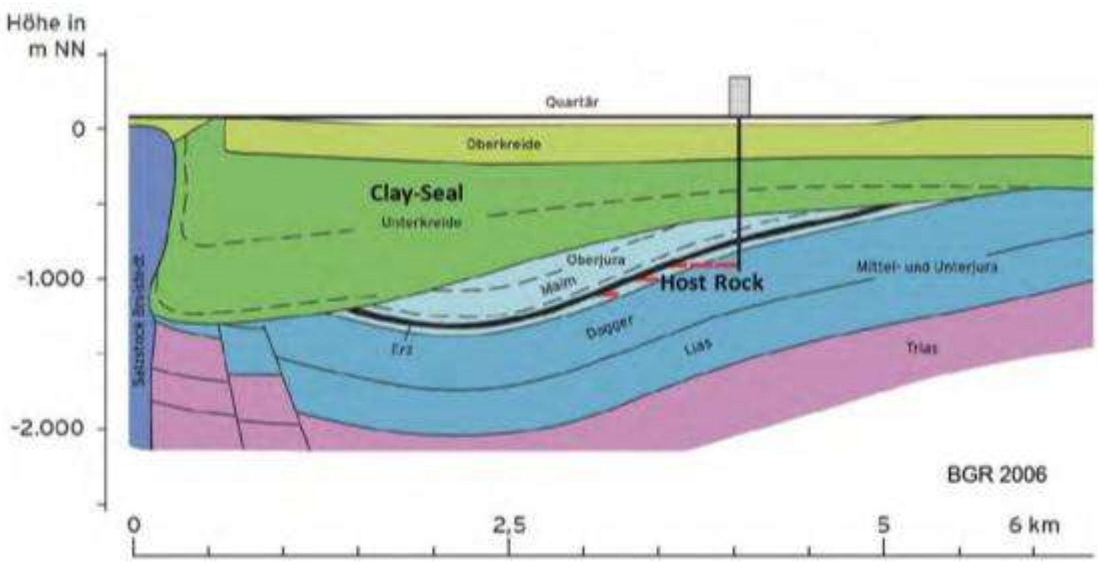


Figure 22 Example for an underground repository covered by clay layers (Konrad mine, Germany – schematic geological cross-section, source: Bundesamt für Strahlenschutz, BfS)

The ‘host rock’ of the Konrad underground disposal site, as pictured in Figure 22, is formed by a so-called iron-oolite. This rock type shows a rather high porosity as well as permeability: it would not represent a suitable geological system by itself. However, the oolite today appears in a geological trough-structure, which is spaciously (over several 10 kilometres) superposed by clay sediments of some 100 m thickness that prevent any possible exchange of hazardous substances with the biosphere. However, man-made interference with the natural, geological barriers needs to be compensated by technical measures (e.g., shaft sealing) for at least a limited time to enable the healing of the natural barrier.

6.3.7 Specific aspects of disused or still operating mines

Practice so far (the first underground disposal mine in Germany has been operating since 1972) has shown that the use of already existing mines for disposal purposes holds several advantages. Typically, there is a broad knowledge of the geological situation and the existing infrastructure, which often allows the disposal mine to be operated at low-cost. In such cases, very specific attention must be paid to the fact that the former mining of raw materials has normally not been designed for the purpose of subsequent use as a disposal facility. Here, part of the natural geological barrier might be affected, reduced or even destroyed. If the mine is still operating, the disposal area must be clearly separated by qualified technical measures from areas with active or expected mining.

Wastes that have been placed into an underground mine are – in principle – technically retrievable, but only until the cavity is backfilled or the whole mine is closed and sealed.

Apart from all the above-mentioned explanations, considering the overall concept of underground disposal as well as its long-term safety aspects, it is obvious that any 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).

6.3.8 Permanent storage of waste in salt rock

Salt rock already serves as host rock for underground storage facilities in Germany and the UK. The following subchapter is an overview of the main rock proprieties and the experience of these countries with salt-related storage issues.

Geological salt formations occur as either layered salt or as salt domes, mainly consisting of sodium or potassium salts. In general, salt rock is very dry; it contains no free water and offers very good isolation of the waste.

Overlying and underlying impermeable rock strata (e.g., clay or shale), if needed, may act as additional geological barriers to prevent groundwater entering the storage facility and, where necessary, effectively stop any possible transport of contaminants and protect salt from becoming dissolved.

Salt rock generally has a low sorption capability. The hydraulic conductivity of rock salt is very low. A liner is usually not required in salt formations. Here, rock creep is a continuous process leading to deformation in response to lithostatic pressure. Salt creep will close the void space around waste packages in the emplacement cells, leading to complete encapsulation. The creep rate depends on in-situ stress (increasing with depth) and temperature [11].

The investigation of the structure of layered salt mines is easier than that of salt domes, and well-established investigation methods are available [35]. In particular, the presence of brine in local lenses or irregular structures or fissures may cause difficulties for a safe storage. Therefore, the presence of such structures needs to be excluded via a site-specific exploration [59].

Currently, underground waste disposal facilities in salt mines are in operation in three countries:

- Germany (four facilities for hazardous waste)
- United Kingdom (one facility for hazardous waste)
- USA (one facility for low level and medium level radioactive waste)

Approximately three million tons of hazardous waste have been disposed in Herfa-Neurode (since 1972) and Zielitz (since 1995) alone.

Table 8 Underground waste disposal facilities in salt mines (in operation)

Country	Facility
Germany	-Herfa-Neurode (Hesse) -Zielitz (Saxony-Anhalt) -Heilbronn (Baden-Wuerttemberg) -Sondershausen (Thuringia)
United Kingdom	-Winsford (Cheshire)
USA	-Waste Isolation Pilot Plant (WIPP), Carlsbad (New Mexico)

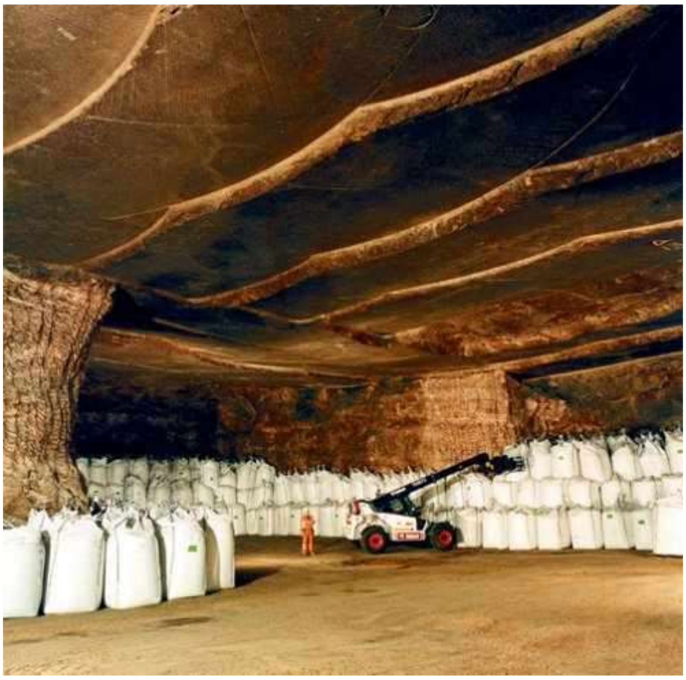


Figure 23 Underground waste storage facility in Winsford, Cheshire, UK (source: Minosus [24]**)**

Environment and safety

Due to its plastic deformation behaviour, salt rock may completely enclose waste, including metallic mercury, in a gas-tight and impermeable geological barrier. Under natural disposal conditions, rock salt is practically impermeable to gases and liquids [18]. For long-term storage of hazardous waste, rock salt is the first and most effective barrier due to its specific isolation criteria. However, a minimum thickness of the salt layer is needed around the waste to ensure a safe encapsulation.

Economical Aspects

The final cost for disposal of one ton of hazardous waste amounts to between USD 340 and USD 1,200 in Europe, irrespective of the hazardousness of the disposed waste (e.g., metallic mercury or pre-treated mercury), if the site-specific waste acceptance criteria are fulfilled [11]. The upper end of the price already includes additional costs that might result from specific storage requirements for a special type of hazardous waste (e.g., separate chamber, isolated area). According to the necessity of additional requirements to be fulfilled, the price will be higher.

Currently, the permanent storage of liquids such as elemental mercury in underground storage facilities is not allowed. The circumstances under which elemental mercury may be stored are currently being discussed in the EU and are under investigation. Without these requirements, it is yet not possible to estimate the costs for storing elemental mercury underground.

6.3.9 Storage in hard rock formations

The permeability of hard rock formations is highly dependent on whether it is fractured or not. In-situ stress and the typical brittle deformation behaviour may lead to fractures in the host rock [12].

In the case of hard rock, safe containment and isolation of the waste from the biosphere is not possible. Due to its brittle deformation behaviour, cracks and faults in the host rock may occur and liquids and gases could escape from a hard rock depository. Moreover, an underground storage facility needs to be constructed in a way that natural attenuation of the surrounding strata mediates the effect of pollutants to the extent that they have no irreversible negative effects on the environment. This means that engineered barriers are needed to attenuate and degrade pollutants, and that the state of the waste (e.g., solid waste with a low solubility and volatility) will determine the acceptability of a release from such a facility [23].

Hard rocks are effectively self-supporting, and minimal engineered support and maintenance is required to prevent failure of the rock walls in the emplacement cells and access drifts. Crystalline rock has excellent stability of the drifts and room even at large depths but it has a relatively high permeability [59].

Hydraulic conductivity [35] and homogeneity of crystalline rock (granite) is strongly site-related and examination of a homogenous rock structure is very complex. Low permeability properties are only guaranteed in unfractured rock bodies. In the case of fractured rocks, engineered barriers, appropriate containers or backfilling are required to avoid contamination of the environment.

For the backfilling of rooms and drifts, dense clay material seems to be the most appropriate material for crystalline rock. Various techniques for preparation and application of the clay-based materials have been tested and found to be very effective as 'near-field' isolation of solid waste. The best isolating medium turned out to be dense clay material applied in the form of pre-compacted blocks of clay powder or as on-site compacted clay layers.

Dense clay (bentonite) is also recommended [18] as an appropriate backfilling material for crystalline rock. Experiences related to the storage of waste in crystalline rock are available but only for stabilized waste.

Experience of underground disposal of mercury containing waste in hard rock formations

Although there are many hard rock mines (both active and inactive) in Europe, experience with the disposal of mercury-containing waste in hard rock formations is very limited. Deep underground hard rock formations are typically used for storage of solid industrial waste, such as fly ash from incineration plants [59]. These waste types might contain small amounts of mercury, but only in a solid matrix.

In 2005, the Swedish government commissioned an inquiry into permanent deep bedrock storage of mercury-containing waste. The inquiry concluded that the technical conditions required to build secure underground depositories in stable geological formations are very good. This report further states that all waste, including metallic mercury, must be appropriately stabilized prior to deposition, as the direct deposition of metallic mercury (for example in steel containers) poses safety issues and raises new problems for which there is currently no adequate knowledge.

In Norway, mercury-residue from zinc-production is cemented into sarcophagi and placed in a bedrock hall at the production site. Other disposal facilities in rock caverns are used mostly for industrial waste. Disposal of mercury waste in Norway (the maximum contents allowed in waste is 10% Hg) will need stabilization (with gypsum, cement, sulphur and sulphides as binders) prior to disposal. A national study recommends a temporary storage until immobilization technologies are developed. Temporary storage could typically take place in salt mines, rock caverns, or preferably in deep bedrock permanent depositories, seeking non-oxidative conditions [44].

In addition, a Swedish study assessed Swedish bedrock as able to meet specific requirements for the storage of stabilized mercury [68]. Hard rock formations are seen as particularly suitable for the storage of stabilized mercury [39][68].

Economic Aspects

There are no estimations of costs relating to the storage of elemental mercury. In 2001, a report published by the Swedish EPA estimated the cost of a deep bedrock repository with a capacity of about 1,000 - 20,000 tons of high-level mercury waste to be about USD 26 to 40 million (USD 25 to 85,000/TM) [56]. The highest figure refers to storage of mixed waste, such as process waste containing 1-10 % mercury. This estimate refers to the construction of a completely new underground mine the only purpose of which would be the storage of mercury. It is not comparable to the concept of using existing mines for underground storage.

Environmental and safety aspects

Total enclosure of the waste is technically not feasible in hard rock depositories. Due to its brittle deformation behaviour, hard rock cannot encapsulate and fully enclose metallic mercury or mercury compounds. Additional artificial or engineered barriers are needed to achieve better enclosure results and to ensure a safe encapsulation of the hazardous waste over a very long time.

Although hard rock has a very low hydraulic conductivity and gas permeability – under the condition of unfractured rock – the investigation on the homogeneity of this type of specimen is very complex. It is difficult to exclude the occurrence of fractures or faults for a relevant variety of host rock [35].

Containers, which may for instance provide an important additional safety factor for the storage of metallic mercury, cannot be considered for long-term storage (see Decision

2003/33/EC, Appendix A, point 1.2.7 [23]). Therefore, considerations for long-term safety are based solely on engineered barriers.

The presence of ground water flow in hard rock formations cannot be excluded, but the exchange rate of deep groundwater in hard rock is expected to be very low [39]. The effect of chemical stabilization of metallic mercury will further reduce the release rates to the environment by a factor of 100 in all alternatives [39].

In Canada and the USA, disposal of pre-treated (stabilized) mercury waste is considered an appropriate approach (Environment Canada, 2001 [30] in [45], and (US-EPA, 2003 [85]). The temporary storage of liquid (bulk) mercury in existing mine cavities has been identified as a possible option [84], whereas the storage of liquid mercury in deep underground hard rock formations has not been recommended [68].

6.3.10 Storage in sedimentary rocks

Argillaceous rock covers a wide range of rock types from plastic clays with transitional types to strongly consolidated and partially fractured clay stones. Argillaceous rock formations in France (Callovo-Oxfordian), Canada (Ordovician argillites) and Switzerland (so-called Opalinus Clay) are highly consolidated sediments.

Argillaceous rock has a very low hydraulic conductivity but poor stability and the vicinity of the drifts may be very conductive. Argillaceous rock formations possess a relatively high mechanical strength, depending on the particular structure (fracturing) and mineralogy of the rock. They may exhibit some plastic behaviour; this progressively reduces fracturing, but may also lead to excavation damage zones around shafts, drafts and other cavities. Appropriate support would be required for operational safety, although it is considered that excavations could be kept open with suitable maintenance over extended periods. In argillaceous rock, short-term support (from a few months to some years) is often provided by means of rock bolts with metallic arches, metallic meshes and / or shotcrete. Concrete linings can subsequently be deployed to provide mechanical stability for a longer period.

Regular maintenance of the excavation lining may be necessary should the access remain open to enable easy access to the waste emplacement cell. The frequency and scale of any maintenance work will depend on the deformation rate of the rock at the proposed depth and on the design and properties of the lining.

Argillaceous rock is generally assumed to have adequate strength for the construction and maintenance of underground drifts, but the stability of the drifts can only be guaranteed by additional reinforcement and supporting measures [35]. These measures are particularly complex and expensive in unconsolidated clay; therefore, storage in consolidated clay is more appropriate. As in the case of crystalline rock, clay material rich in smectites is particularly required as backfilling material due to its high isolating potential [59]. Argillaceous rocks have proven their long-term effectiveness as geological barriers, where they form tight seals, for example above hydrocarbon reservoirs. Mineralogical, geochemical and geotechnical investigations of argillaceous rocks are currently being conducted in international rock laboratories. Little information is available due to a lack of mining experience with these rocks [35].

6.3.11 Storage in a metal ore mine

All explanations given in the previous chapters are especially valid for hazardous wastes, which must by all means be isolated from the biosphere. In case of a treated waste the hazardous content of which is, for instance, chemically bound and which therefore poses no (or at least only a minor) risk to the environment, underground disposal in an appropriate geochemical milieu might also be possible.

As an example, one could envisage the disposal of mercury sulphide in a metal sulphide mineral deposit, which will warrant long-lasting stable geochemical (reducing) conditions (see Figure 24). In such a case, both the waste form and the sulphide deposit serve as two barriers that provide for retention of the hazardous substances in deep underground. An important metal ore is zinc sulphide, which often contains significant concentrations of mercury sulphide. Putting mercury sulphide back into a zinc mine, where it originally comes from, could be regarded as an environmentally neutral disposal operation.

Nevertheless, it must be verified that the man-made access to deep underground does not affect the geochemical milieu as well as the possible function of the overburden in a way that a contamination of the biosphere has to be expected. Sealing of the mine after the end of mining and disposal operations is an essential element in the overall safety concept. It is especially important for metal sulphide mines, where intrusion of oxygen-containing surface waters leads to acid mine drainage and the mobilization of heavy metals from the primary ores.

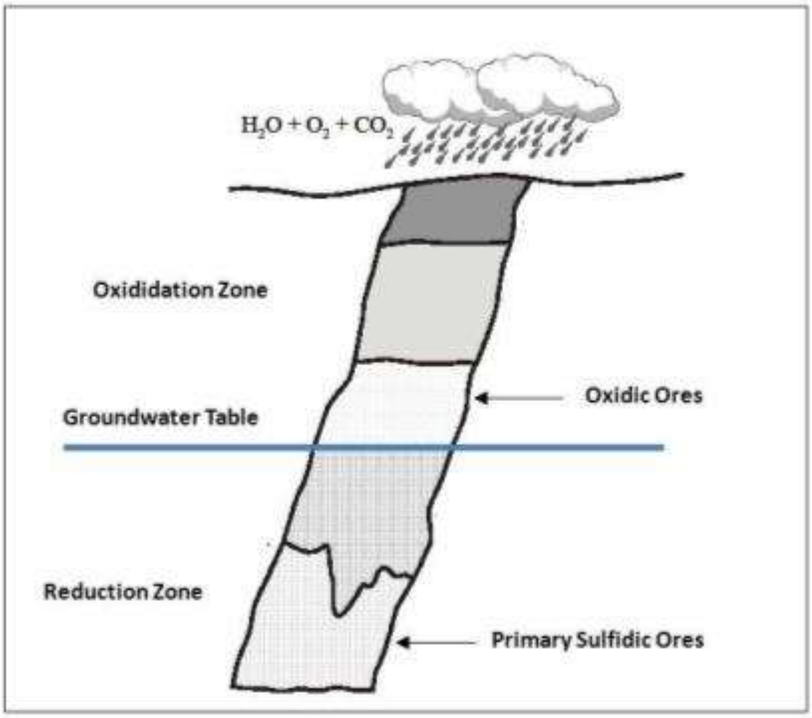


Figure 24 Underground deposits of sulphide ores might be suitable to host rock for disposal of distinct waste types of similar chemical / geochemical behaviour (source: Sievers, modified [66])

6.3.12 Case studies: Herfa-Neurode (salt), Konrad (iron ore) and WIPP-site (salt)

The following case studies illustrate how underground waste disposal has been implemented at several sites.

Herfa-Neurode site – brief description

The Herfa-Neurode site, the oldest (since 1972) and largest (capacity up to 200,000 t/y) underground disposal site worldwide, represents the 'classical' concept of safe containment of hazardous wastes and their isolation from biosphere by 'dry safe-keeping' in salt-rock. The salt deposit is approximately 240 million years old and constitutes the main geological barrier, with a thickness of up to 350 m. Overlying clay layers, altogether approximately 100 metres thick, serve to seal off the wastes and to protect the rock salt from processes at or near the surface. Disposal of a wide variety of hazardous wastes takes place in a depth of about 600 m, that area being just a minor part of the total mining area.

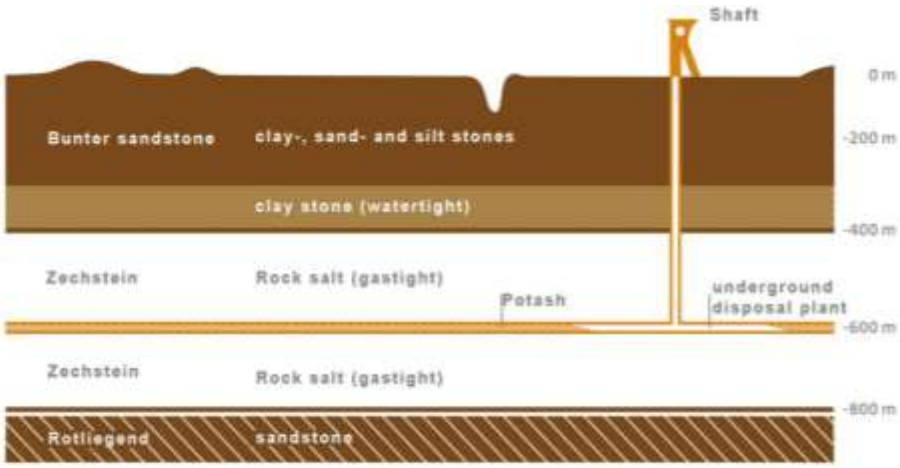


Figure 25 Geological cross section of the Herfa-Neurode site (source: K+S Entsorgung [4])

Transport of the wastes to the underground waste disposal plant of Herfa-Neurode is performed by trucks or by rail. 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. After acceptance control and determination of the conformity, the waste is cleared for storage. It is then unloaded from the delivery vehicle by forklifts and transported to its final destination. At the shaft entrance, the waste enters the underground transport system to the storage area. Underground, the waste is transported by trucks all the way to the destined place of storage. The waste is stacked accordingly at the final place of storage. During the operational phase, technical measures are undertaken to increase the operational safety. This includes waste packaging, closing of the storage chambers against each other and the building of dams between the waste disposal area and other mining fields. 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.

Konrad site – brief description

The Konrad repository represents a future deep geological disposal facility for destined radioactive wastes, which is currently under construction but which doesn’t follow the so-called 'salt-concept', i.e. safe containment of hazardous wastes and their isolation from the biosphere by 'dry safekeeping' in rock salt. Nevertheless, the location of the Konrad repository reveals a geological situation that is extremely favourable for an underground disposal facility.

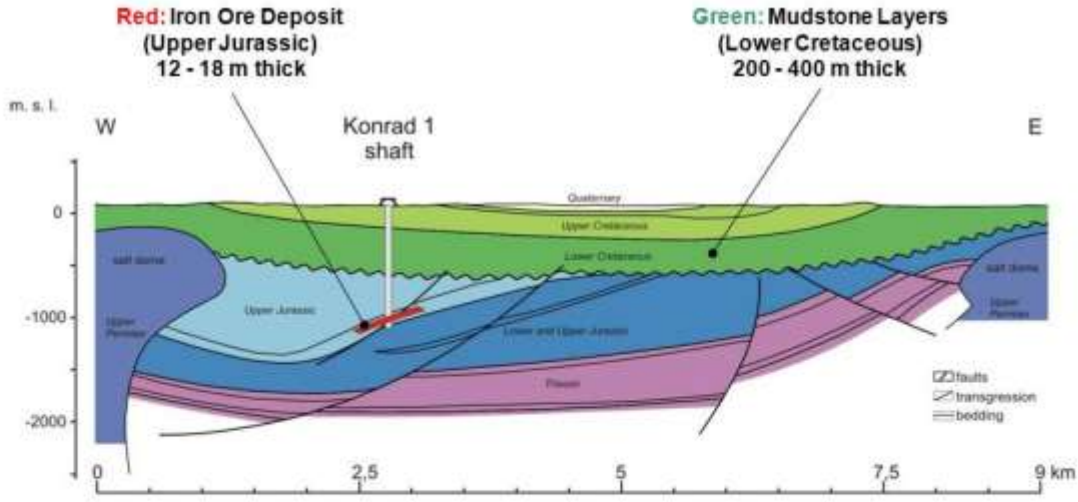


Figure 26 Geological cross section of the Konrad Site (source: Bundesamt für Strahlenschutz, modified [13])

The host rock itself where the future storage fields will be constructed is represented by an iron ore-bearing rock (so-called ‘Coral Oolite’), which has been deposited about 150 million years ago during the Upper Jurassic and is located at a depth of between 800 and 1,300 metres below ground. Konrad site is characterized by the fact that the iron ore layer itself doesn’t feature a very well suited host rock. But the overall geological situation clearly demonstrates that Upper Jurassic sediments (including the iron ore deposit) are appearing in a synclinal (trough-shaped) structure, which is covered discordantly as well as spaciously by an almost 400-metre-thick layer of impervious clayey rocks (transgression). This means that the storage area of the Konrad repository has no hydraulically effective connections to near-surface groundwater. This natural barrier allows for the complete isolation of the waste to be disposed off from the biosphere.

Since the Konrad site is intended to become a final repository for radioactive waste, planned operational details are of no greater relevance for this report. However, it may serve as an example for the manifold geological situations that may provide an isolation of wastes from the biosphere.

Waste Isolation Pilot Plant (WIPP) – brief description

The WIPP-site in Carlsbad, New Mexico (USA) is situated in a Permian rock salt formation (bedded 'Salado Formation') of more than 600 m total thickness and at a depth of approximately 650 m below ground. The main barrier function is fulfilled by the host rock itself. In addition, approximately 300 m of overlying rock is present at the site. The disposal horizon has not have any contact with groundwater for the last 250 million years.

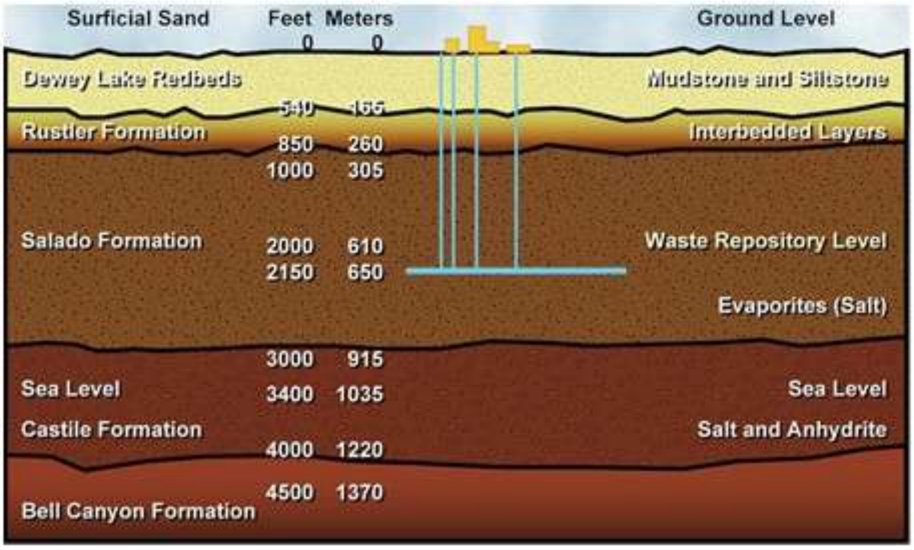


Figure 27 Geological cross section of the WIPP-site, U.S.A. (source: US Department of Energy)

From 1981 on, the site was first constructed as an Underground Research Laboratory (URL) featuring four shafts. Underground experiments started as early as 1984 and included in-situ experiments as well as demonstration tests to prove and upscale lab-results, to examine investigation methods, construction techniques and much more.

Since 1995, the URL has been shut down in several phases and, on March 26, 1999, the WIPP-site went into operation as a final repository for radioactive wastes. The termination of the operational phase is scheduled for 2033. Within this time, the disposal of up to 175,000 m³ of radioactive waste is projected.

The disposal area has been excavated between 1986 and 1988. It consists of altogether eight panels, each one comprising seven chambers. Each chamber has a length of 90 m, a width of 10 m and a height of 4 m. Pillars between the chambers are 30 m wide, between panels of 60 m, which results in an overall excavation degree of 25%.

6.4 Deep well injection

Deep well injection of waste is a common practice of waste disposal in some countries. It is often used for disposing of wastes that are generated through the production of oil or natural gas. In some countries, deep well injection is used to dispose of liquid hazardous waste as well. In the USA there are approximately 550 wells of class I where hazardous and non-hazardous wastes are injected into deep, isolated rock formations that are thousands of feet below the lowermost underground sources of drinking water [87] (Figure 28).

Figure 28 Outline of deep well injection (source: US EPA)

Deep well injection was also proposed for the disposal of slurries containing mercury sulphide [14].

On the other hand, deep well injection may endanger groundwater by uncontrolled transport of hazardous substances [67]. A very careful characterization of the geological and hydrological structures and processes is needed in order to ensure that the hazardous substances do not pose a risk to relevant groundwater levels even in the distant future [83].

6.5 Export of elemental mercury to storage and disposal facilities outside the region

As long as stabilization and storage facilities for elemental mercury or disposal facilities for mercury waste are not available, export to countries outside the region is an option that should also be taken into account (this does not include export for the purpose of later use and possible release into the environment). It should be noted that export of mercury waste is already taking place [34]. According to the principles of the Basel Convention, hazardous wastes should be disposed of in the country where they were generated, as far as this is possible in compatibility with environmentally sound and efficient management. Therefore, it is necessary to support countries in the region to develop their own mercury waste treatment and disposal facilities.

6.6 Summary

During the next decades, between 5,500 and 7,500 tons of mercury will have to be stored or disposed of in the Asia Pacific region. Due to the size of the region, the occurrence of nearly all rock types and the widespread mining practice, it seems highly feasible to search for, to construct and to operate an underground disposal facility. Beside the ‘classical’ concept of using salt mines (as it is practised in Europe), a wide variety of rocks might serve as host rocks for underground disposal of mercury waste if the overall geological structure (especially thick overlaying clay formations) guarantees safe isolation from the biosphere.

In addition, a further concept has been developed and will be proposed with regard to underground mercury disposal in the region. The main feature of this concept is the conditioning of mercury with sulphur to receive mercury (II) sulphide (HgS) and to dispose of mercury sulphide in a metal sulphide mineral deposit. Mercury sulphide, in this case, represents a waste material, which can be characterized as insoluble in water, non-flammable and non-toxic. It can easily be filled into big bags, sealed and handled with forklifts. The big bags will be disposed of in rooms developed from a main drift in a fishbone arrangement in an existing copper / zinc mine.

7 Concept study for above ground storage of elemental mercury

7.1 Overview on environmental hazards in the region[8]

7.1.1 Overview

The Asia-Pacific region is among the most disaster-prone in the world. Natural disasters such as earthquakes, tsunamis, tropical storms, flooding, landslides and volcanic eruptions occur frequently and with such intensity that they affect millions of people every year and cause severe financial losses. Climate change, along with the increasing growth of population and the density thereof, has contributed to worsening the negative impact of these disasters, increasing their frequency and strength (UN OCHA ROAP 2011 [76]).

7.1.2 Earthquakes, volcanic eruptions and tropical storms

Figure 29 shows the areas at risk for earthquakes, volcanic eruptions and tropical storms and places them within established scales of risk. The intensity of earthquake risk is shown according to the effects of an earthquake on the surface. The map shows zones with a 20% probability that the current degrees of intensity will increase in 50 years. Tropical storm intensity is based on the five wind speeds of the Saffir-Simpson Hurricane scale. It is founded on the 'World Map of Natural Hazards' (Munich Re [55]). The map shows zones with a 10% probability of being hit by a storm of the indicated intensity in the next 10 years. Volcanic risk is indicated by the location of Holocene volcanoes, which are defined as those having exhibited activity within approximately the last 11,500 years (UN OCHA ROAP, 2011 [76]). Eastern Asia is routinely menaced by typhoons striking from August to September, while in Southeast Asia monsoons often cause flooding and mudslides.

[8] This part of the report has been prepared by Guilberton Borangan

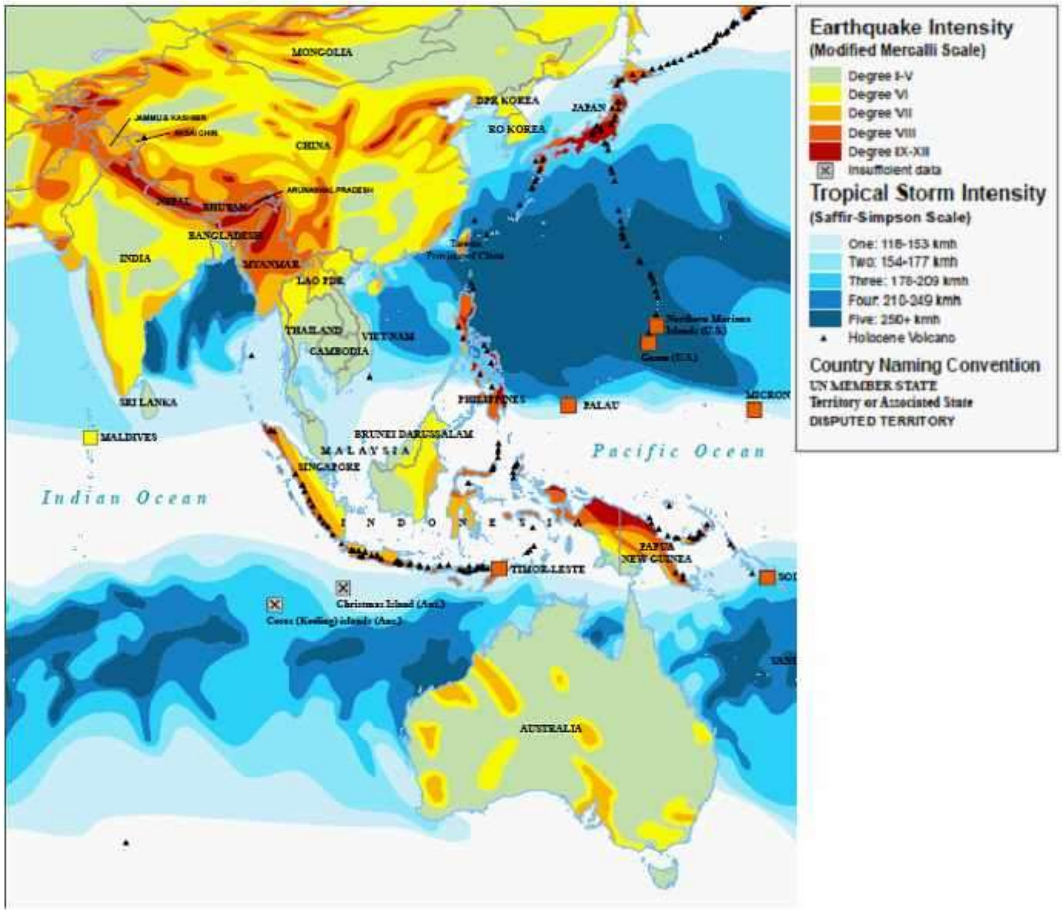


Figure 29 Geographical distribution of hazards in Asia Pacific region (source: UN OCHA ROAP [76])

7.1.3 Flooding

Figure 30 depicts the risk of flooding in the region. Due to the large scale of the map, only areas or countries of high risk may be identified. Information that is more detailed is necessary in order to reveal whether a specific location within the area may be affected. Such information is provided by flood hazard maps that are currently under development for river systems in many countries of the region [74]. An example is given for the Lampang Municipality in Thailand (Figure 31) [3].

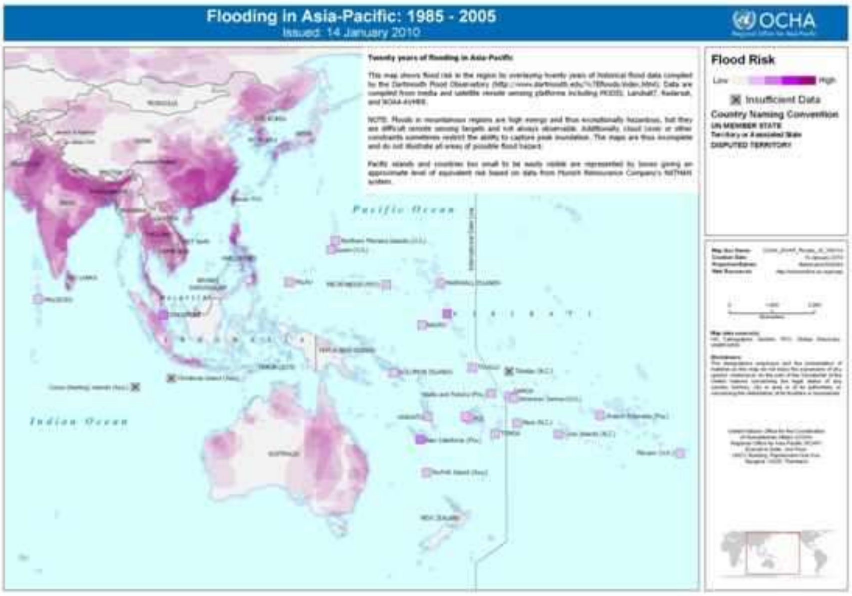


Figure 30 Flooding in Asia Pacific 1985-2005 (source: UN OCHA ROAP [76])

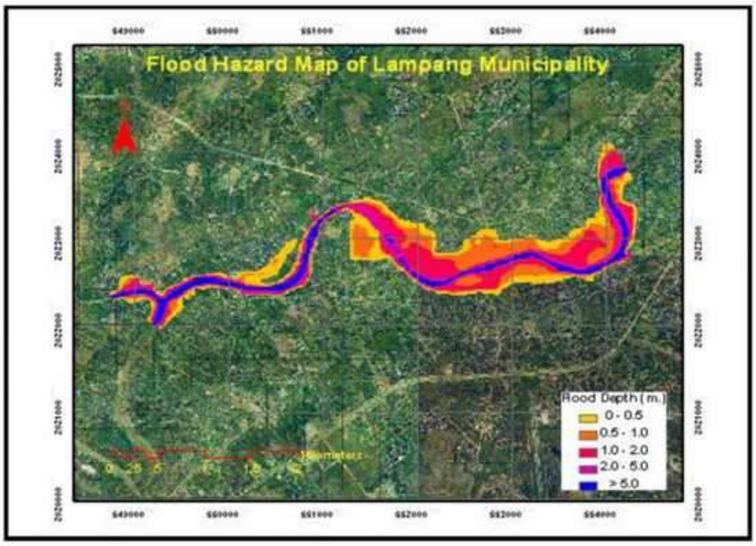


Figure 31 Flood Hazard Map of Lampang Municipality (source: Amnatsan [3])

Taking into account the requirements for the site selection of above ground and underground storage and disposal facilities, the facilities in general must provide for dry storage conditions. A dry climate is favourable, but technical measures that prevent contact of containers with rain, groundwater or floodwater and the use of corrosion resistant containers will probably provide the same level of long-term performance. Moreover, the selected areas should not have unfavourable conditions, such as risk of active disturbances cause by seismic and volcanic activities. The facility should be stable, including safety from flooding, tropical storms and other hazards.

7.1.4 Environmental hazards in selected countries of the region

The environmental hazards in countries like Thailand, India, Indonesia, the Philippines, and China are described in the following table. Among these countries, China, Thailand and Indonesia have a good potential for above ground and underground storage and disposal of mercury. The bar chart in Table 9 and Table 10 shows the degree of exposure to natural hazards and the percentage of area affected. Tsunamis and storm surges are a threat to coastal regions, particularly gulfs, bays and estuaries. Flood hazard results from river floods and torrential rain [UN OCHA ROAP, 2007].

Table 9 Natural hazards classification of selected Asian countries I

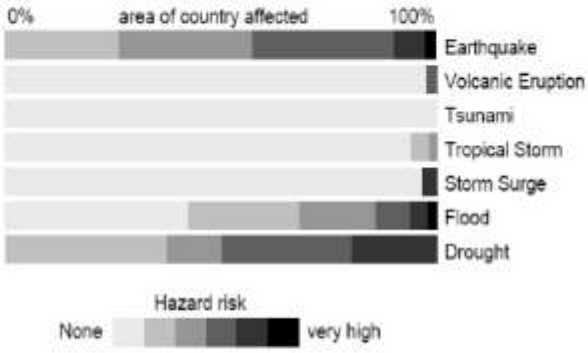
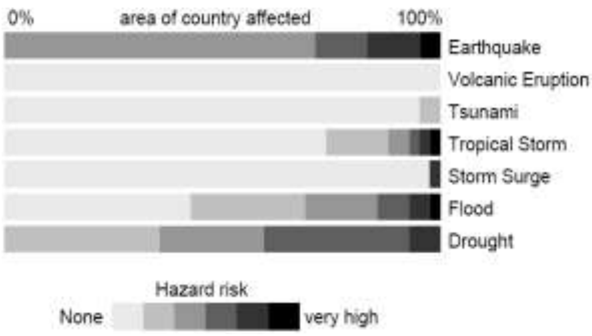
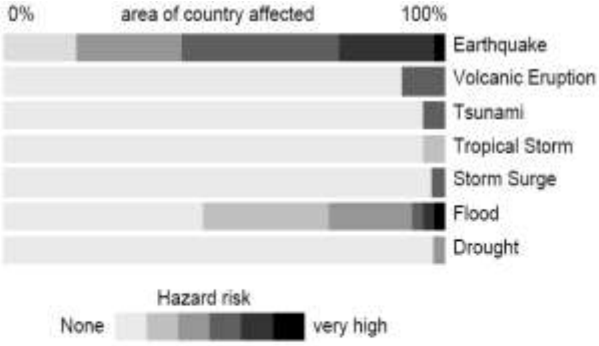
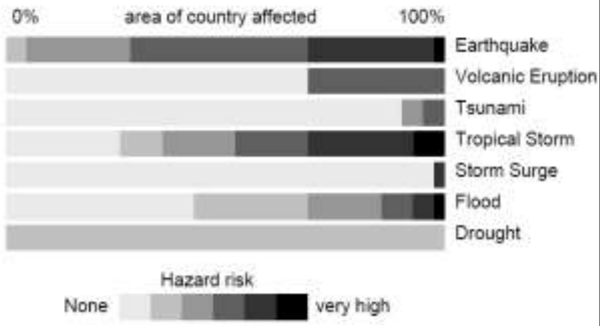
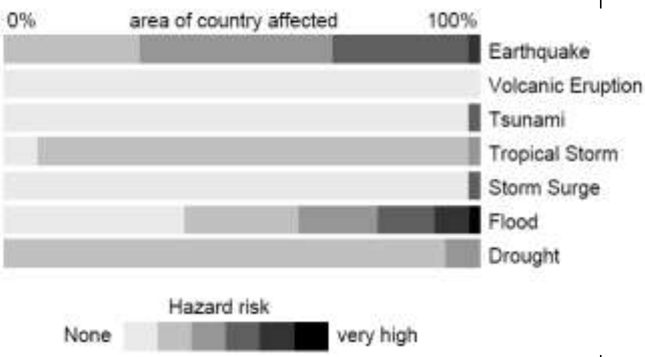
China: The natural hazards that affect most of the area of China are droughts and Earthquakes, with half of its area being exposed to high levels of risk. Floods also affect half of its area, but only relatively small areas are exposed to high risks. In addition, even though high-risk volcanic eruptions and storm surges do occur, they affect only small areas, with tropical storms least affecting China.	
India: The natural hazards that affect most of the area of India are droughts, earthquakes, and floods, with half of the area being exposed to high levels of risk. Moderate storm surges do occur, but affect only small areas, and tropical storms present a relatively moderate level of risk.	

Table 10 Natural hazards classification of selected Asian countries II

Indonesia: The natural hazards that affect most of the area of Indonesia are earthquakes and floods, with half of the area being exposed to high levels of risk. Volcanic eruptions are relatively frequent, but mostly affect only small areas. Tsunamis and storm surges present moderate levels of risk affecting the least of the area, while tropical storms affect Indonesia only lightly.	
Philippines: The natural hazards that affect most of the area of the Philippines are earthquakes, tropical storms, floods and volcanic eruption, with half of the area being exposed to high levels of risk. Storm surges do occur, but they affect only small areas.	
Thailand: The natural hazards that affect most of the area of Thailand are earthquakes and floods, with almost half of the area being exposed to high levels of risk. Tropical storms also affect half of the area, but only relatively small areas are exposed to moderate risks. High-risk storm surges and tsunamis do occur, affecting only small areas.	

7.2 Concept study[9]

7.2.1 Design and conceptual assumptions

The basis of the following analysis was the concept of warehouse storage as it has been described in the US EPA cost estimate study [86]. It was assumed that:

- In the base scenario, between 2029 and 2050, 5,500 t elemental mercury will have to be stored in one facility.
- It was estimated by US EPA that the excess mercury storage would require 200,000 square feet (18,580 m^2) of warehouse space for storage of 7,500 tons of elementary mercury. It has therefore been estimated that the storage construction in Asia needs approximately 14,000 m^2 of warehouse space for storing 5,500 tons of mercury in the above ground ground storage facility. However, it is expected that slightly less space than that needed in the US example will be needed in the Asian warehouse, which should be about 12,000 m^2 in size.
- Mercury is stored in 3-litre – flasks in steel drums with an anticorrosive coating.
- Mercury is delivered directly from the producer or a recycling facility without needing an additional (interim) storage facility.

7.2.2 Capital investment

Besides providing space for storing mercury containers, the warehouse should include the following features:

- Closely controlled access and automatic control system
- Static ventilation
- Heat, smoke and fire detection and alarm system
- Active fire suppression system
- Intrusion detection and alarm
- Buildings constructed of materials resistant to fire such as concrete and steel

[9] This part of the study was taken from the original AIT study, but was slightly amended.

- All doors fitted with suitable containment dikes that are incorporated into the floor sealant system
- Routine monitoring and mercury inspections
- Protective equipment and clothing and
- Spill prevention control and response procedures and on-site clean up equipment

Since there are legislative and institutional requirements, costs for the licensing procedure, such as environmental impact assessments, have to be considered. Moreover, insurance may be necessary.

The following investments will be necessary:

- Civil works cost: assume the total size of the warehouse including offices to be 12,000 m^2. The cost estimates are based on the information of a similar construction project in China.
- Field engineering cost: refers to that of a similar engineering cost in China.
- Facilities and material costs are assumed to be proportional to those applied in the US storage site, because the mercury containers are likely to be imported from the USA.
- Import equipment cost is proportionate to that applied in the USA, with a reduction factor 0.7, because fire suppression system could be manufactured in the host country.
- Transportation cost for the facilities: 6 % of the facilities' cost.
- Other costs:
    - Construction management cost: 3 % of the construction cost.
    - Employee training expense (construction): 3 months, USD 300 (per person per month), 20 persons.
    - Office facilities for the employees: 1% of the facilities' cost.
    - Inspection cost: 0.55 % of the construction cost.
    - Insurance: 0.45 % of the construction cost.

- Design cost: In accordance with the national charging standard, approximately USD 150,000.

- EIA (Environmental Impact Assessment) cost: In accordance with the national standard cost of China, USD 20,000.

The following equipment for above ground storage is considered necessary according to the US experience:

Table 11 Major equipment needed for the above ground storage facility

Name of equipment	Capacity	Number needed	Note
a) Steel cylinders	100-150 kg		With durable, anti-corrosion coating
b) Carbon steel flasks	34 kg over 100 kg	161,770	Width: 13 cm; Height: 33 cm; Capacity: 34 kg
c) Metallic and durable shelves	60m x 10m x 1m		For storage of 6,000 tons
d) Handlers of equipment			To prevent cylinders from falling
e) Cargo containers			For transportation or temporary storage at the interim facility
f) Automobile, truck, train, motorway			For loading / transporting the tanks at special terminals
g) Automatic system			For packing, standardization, purification

Table 12: Estimated investment for the above ground storage facility

Item		Cost (USD)	Notes
Construction costs	Civil work	1,680,000	Warehouses' construction cost
	Field engineering	1,200,000	Cost of the equipment installation
Facilities costs	Domestic facilities and materials' cost	507,470	Cost of the construction materials; Cost of mercury containers
	Import equipments	2,156,000	Cost of monitoring and fire suppression system
Transportation costs	Facilities Transportation	159,810	Transportation costs for the facilities
Other costs	Construction managing cost	86,400	Managing cost for the period of construction
	Employee training expense	18,000	Cost for training the construction and installation workers
	Office facilities	26,640	Cost for the basic facilities for the storage employees
	Inspection cost	15,840	Cost for inspection before construction
	Insurance	12,960	For the construction workers
	Design cost	150,000	Project design and approval
	EIA	20,000	EIA design and approval cost
Net investment costs (rounded)		**6,030,000**	

7.2.3 Human resources

Table 13 shows the personnel needed to operate an above ground storage facility. It is noted that this estimate of staff size is for routine operation of the storage warehouses. Additional staff needed for the preparation stage is not included. The staff should be prepared to perform the following tasks:

- Transportation of mercury to the facility and placing it into the warehouse
- Ensure security and prevent unauthorized access
- Monitoring, inspection of containers, recording and reporting
- Cleaning up and treatment when leakage is found
- In addition, there must be professional training provided to the storage site staff and annual (at least) inspection by a third party.

Table 13 Personnel needed for the above ground storage facility

Item		Number of Persons
Management and logistics service	Manager	2
	Office	4
Operation	Monitoring	2
	Transportation	4
	Guard	6
Maintenance	Facility maintenance	2
Total		**20**

7.2.4 Operation and maintenance costs

The principles in the calculation of the operation and maintenance costs are as follows:

- Annual facility maintenance cost: 10% of the facility costs
- Annual monitoring cost: 1% of the facility costs
- Employee's salary: fixed number of employees is about 20, and the average salary of each person is estimated as USD 1000 (pr person per month). The total cost for salary will be USD 240,000
- Risk cost: 10% of the maintenance cost
- Mercury containers: USD 30 per flask. Alternatively: 1-ton stainless steel container (USD 2000)

Table 14 Annual operation and maintenance costs for the above ground storage facility

Item		Cost (USD/year)	Notes
Maintenance cost	Facility maintenance	266,350	To guarantee all the facilities to be in its ordinary status
	Monitoring	26,635	
Employee's salary		240,000	Average salary: USD 1000/ (person. month); 20 persons
Risk cost (emergency)		29,300	The cost for emergency situation
Total (rounded)		**560,000**	

7.2.5 Comparison of cost calculations for LAC and Asia/Pacific

The calculation of investment and operational costs for both regions shows quite similar results despite the methods of calculation and the assumption being rather different. The investment costs amount to about USD 6 million for one large warehouse. Costs for containers were added to the original calculation in order to make it comparable to underground storage of stabilized mercury, where mercury containers are replaced by plastic bags ('big bags'). Within 20 years of operation, the investment costs, operation costs and costs for containers would amount to USD 22 – 30 million. The following costs have not been taken into account, because they depend extensively on the location of the producer of surplus mercury, the type of mercury produced (elemental mercury/ mercury compounds) to be stored and the timely availability of storage / stabilization and disposal facilities:

- Transport of elemental mercury or mercury compounds to a temporary storage facility and temporary storage (if direct transport to a chemical plant is impossible)
- Transport to a chemical plant
- Chemical conversion of mercury compounds into elemental mercury and / or purification of mercury (in order to meet the purity requirements for storage)
- Transport from the chemical plant to a temporary storage facility (could be at the chemical plant itself) and temporary storage (if direct transport to an above ground storage facility is impossible).
- Transport from the temporary storage to the above ground storage facility.
- Cost after the 20-year period (further storage / disposal)

Table 15 Investment, operational and total costs for storing surplus mercury in above ground warehouses (US$)

Region	Net Investment	Operational cost/year (prices of 2010)	Cost for containers (flasks)	Total cost 20 years of operation (prices of 2010)	Cost/t mercury
Latin America and the Caribbean (Mexico/Brazil) 8,500 t	4,470,000 - 6,090,000	702,000 - 844,000	7,100,000	26,000,000 - 30,000,000	4,700 - 5,500
Asia and the Pacific 5,500 t	6,030,000	560,000	4,600,000 - 11,000,000	22,000,000 - 28,400,000	4,000 - 5,200

7.3 Temporary storage

As long as other management options such as long-term storage in above ground warehouses or final disposal are not available, smaller amounts of surplus mercury could also be temporarily stored at the site of production or at existing waste management facilities if these meet the appropriate environmental, operational and occupational safety requirements. Unfortunately, a cost calculation for storing mercury in such facilities was not possible within this study. Surplus mercury may be generated at many locations in variable amounts. There is currently no reliable model available that would describe which amounts of surplus mercury would have to be stored at which location and for how long. Principally, the costs could be rather low: if storage space in existing facilities could be used, additional costs would mainly be caused by the need to buy containers, transport to and from the facilities and the training of personnel. For elemental mercury, costs start at USD 30 for a three-litre mercury flask and go up to USD 2000 for a one-ton stainless steel container. Solid wastes could be stored in steel or plastic drums or big bags. Typical prices for a 30- or 55-gallon (110 – 200 litre) steel drums with epoxy or rust inhibiting lining are around USD 80 - 120[10] A 30-gallon drum could be filled with about 200 kg of stabilized mercury (powder). If an extension or enhancement of facilities is necessary, these costs would depend to a great extent on the site-specific needs. Such an estimate would be purely speculative at the time.

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[10] Quote from Baytec Containers, http://www.bayteccontainers.com

8 Concept study for underground storage of mercury waste

8.1 Approach

Since there is no operative underground waste storage facility in the Asia Pacific region that could be used as an example for calculating disposal costs, a concept study has been undertaken in order to provide a first cost estimate. Costs for mining activities such as underground disposal are very site specific. Reasonable cost estimates depend on detailed information for every single site, and it was impossible within this study to perform a site selection process in order to identify potential candidates. Therefore, a generic model or scenario has been chosen that represents one possible approach of underground waste storage – disposal of stabilized mercury in an operating zinc or lead mine. As shown before, underground storage of waste may take place in other geological formations as well, but for the purpose of cost calculation a zinc / lead deposit in one Asian country was chosen as a basis.

8.2 Procedures for a pre-investment study

8.2.1 Introduction

Pre-investment studies in conjunction with additional support of functional studies, which are usually conducted separately, are part of the pre-investment phase (see figure below). This phase comprises several stages:

- Identification of opportunities (scoping or opportunity study)
- Analysis of project alternatives and preliminary project selection (pre-feasibility study)
- Project preparation (feasibility study)
- Project appraisal and investment decision (appraisal report)

The resulting analysis and report of such studies are primarily economic in nature, but legal, technological, environmental and socio-political aspects shall be included as well.

Differences between the various studies lie in the accuracy of the study execution in terms of costs and pricing. In general, the following accuracies might be expected:

- Scoping or opportunity study: 40% - 50%
- Prefeasibility study: 20% - 30%
- Feasibility study: 10% - 15%

A feasibility study should come to definitive conclusions on all basic aspects of a project after consideration of various alternatives. The conclusions and any recommendations made with regard to decisions need to be explained and supported by compelling evidence.

Therefore, a feasibility study should be carried out only if the necessary financing facilities, as determined by the studies, can be identified with a fair degree of accuracy. Project financing must be considered as early as the feasibility study stage.

8.2.2 General content of pre-investment studies

The way towards and the putting together of a feasibility study is a significant investment of time and money, and the entrepreneur should hence ensure that no major roadblocks occur on the road to business success. Eventually, the feasibility study will assist in identifying such obstacles and determine the true viability of the business concept.

In this section, the principle main chapters of such pre-investment studies are listed. Areas of special interest are mainly focused on the geology of potential deposits respectively, mines and the market for such a form of disposal. These issues will be detailed in the following chapters. The main parts of pre-investment studies can be described as follows:

- Introduction with background and objectives
- Site conditions
- Legal aspects and regulations
- Geology of the deposit and qualifying factors, criteria as mine and as underground disposal
- Geotechnical aspects
- Access to the mine / disposal from surface

- Mining respectively the development of an underground infrastructure and the preparation of open rooms for disposal and handling of the material underground
- Surface infrastructure and facilities (access to power, water, sanitation and existing infrastructure, buildings) and handling of the material on surface
- Organization and staffing of the operation
- Environmental issues and environmental impact
- Market environment, marketing and sales strategy
- Operating and capital requirements
- Financial projections and business model
- Income statement
- Cash flow projections
- Capital requirements
- Critical risk factors

The result will culminate in a feasibility study. A feasibility study should provide all data necessary for an investment decision. The commercial, technical, economic and environmental prerequisites for an investment project should therefore be defined and critically examined.

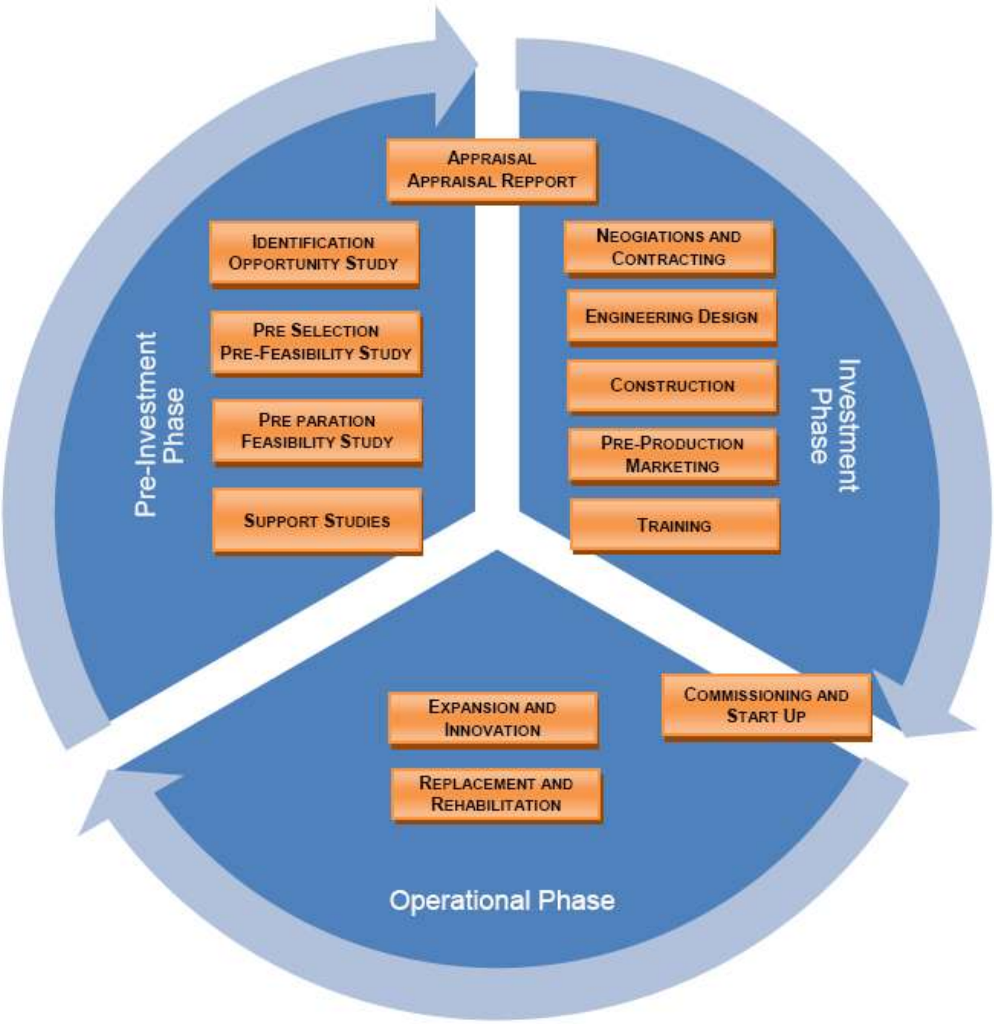

Figure 32 Details of investment phases (source: IMC)

8.3 Important elements for the evaluation of pre-investment studies for an underground disposal

8.3.1 Introduction

An integral part of the planning of underground waste disposals is the proof of safety and stability for underground openings, geological and geotechnical barriers during the operating and the post-closure phase. Therefore, the proof of safety is a tool to guarantee the safety and functionality of the barriers and the stability of the mine throughout the course of the disposal.

In the pre-investment studies of underground disposal, a viable concept has to be developed for the life of the underground disposal. This also includes a concept for sealing the rest of the mine with plugs and backfill if needed. Furthermore, it includes a concept for monitoring the compliance with stability and functionality during the operational and the post-closure phases.

The following chapters will focus on some key elements that should be integral parts of the pre-investment studies and must be evaluated in detail during the process.

8.3.2 Technical concept

The safety goal for underground disposal of hazardous waste is to guarantee the protection of human health and of the environment today and in the future, without imposing unreasonable burdens on future generations [38]. This is achieved by combining two established principals of emplacement:

- The principle of emission neutral emplacement: The pollutant is immobilized within the matrix of the waste. The emplacement of waste does not significantly increase naturally occurring pollutant concentrations.
- The principle of total enclosure: Waste is isolated from the biosphere by natural and engineered barriers.

In general, the applied technical concept has to meet the following requirements in order to guarantee the long-term safety of the disposal [64]:

- Prevent fluids from coming into contact with waste
- Prevent pollutants from being mobilized from the waste
- Preventing pollutants from being transported and entering the biosphere
- Retention of pollutants from contaminated transport fluids

Within the planning of underground waste disposal, the choice of the technical storage concept depends mainly on the risk exposure of the hazardous material and on the local characteristics of the mine.

Besides the technical requirements, the disposal also has to meet all the legal requirements of the country where the waste is to be disposed off, especially regulations regarding the treatment of waste, employee safety and mining operations.

8.3.3 Market

A market study for the selection process of suitable mines should be prioritized. This needs to answer several questions, *inter alia* the following:

- Is there a market for a waste disposal for mercury?
- What is the market area?
- What would the market size, in terms of tonnage per year,be?
- What price will ensure acceptance?
- Will the project be supported or subsidized?

8.3.4 Legal aspects

The underground disposal of waste is only partly covered by international treaties, laws and regulations, and hence national regulations are of higher relevance. The construction of an underground dumpsite and the emplacement of waste involve several aspects that must be regulated by the authorities. Of especially importance is the guarantee of compliance with regulations regarding working conditions and work safety. In addition, regulations regarding the treatment of waste itself have to be taken into consideration. Furthermore, for the time during and after the disposal, environmental laws and water rights are of importance. In addition to national and international laws and treaties, international organizations contribute to the development of environmental protection. They issue general guidelines for the treatment of different kinds of hazardous waste.

Besides the laws and regulations that deal with the operation of the disposal site, the legal structure of the mine disposal is also of importance. Liabilities that result from damages related to the disposal need to be addressed. It is especially important that agreements about sealing costs of the mine and long term risk sharing be reached if the owner of the mine is not the same person as the one establishing the disposal.

8.4 Presence of potential host rocks in Asia and the Pacific

As explained above, no single rock type, whether salt, clay or crystalline rock, can be declared the most suitable host rock. Rather, the consideration whether all safety objectives are met by a given site depends on the overall geological situation. Therefore, there is no foreseeable reason that the area discussed in this report (Asia and the Pacific) should not have suitable rock formations to realize an underground disposal concept. Asia and the Pacific is a huge area in which rocks from all ages, and nearly all rock types, are present (Figure 33).

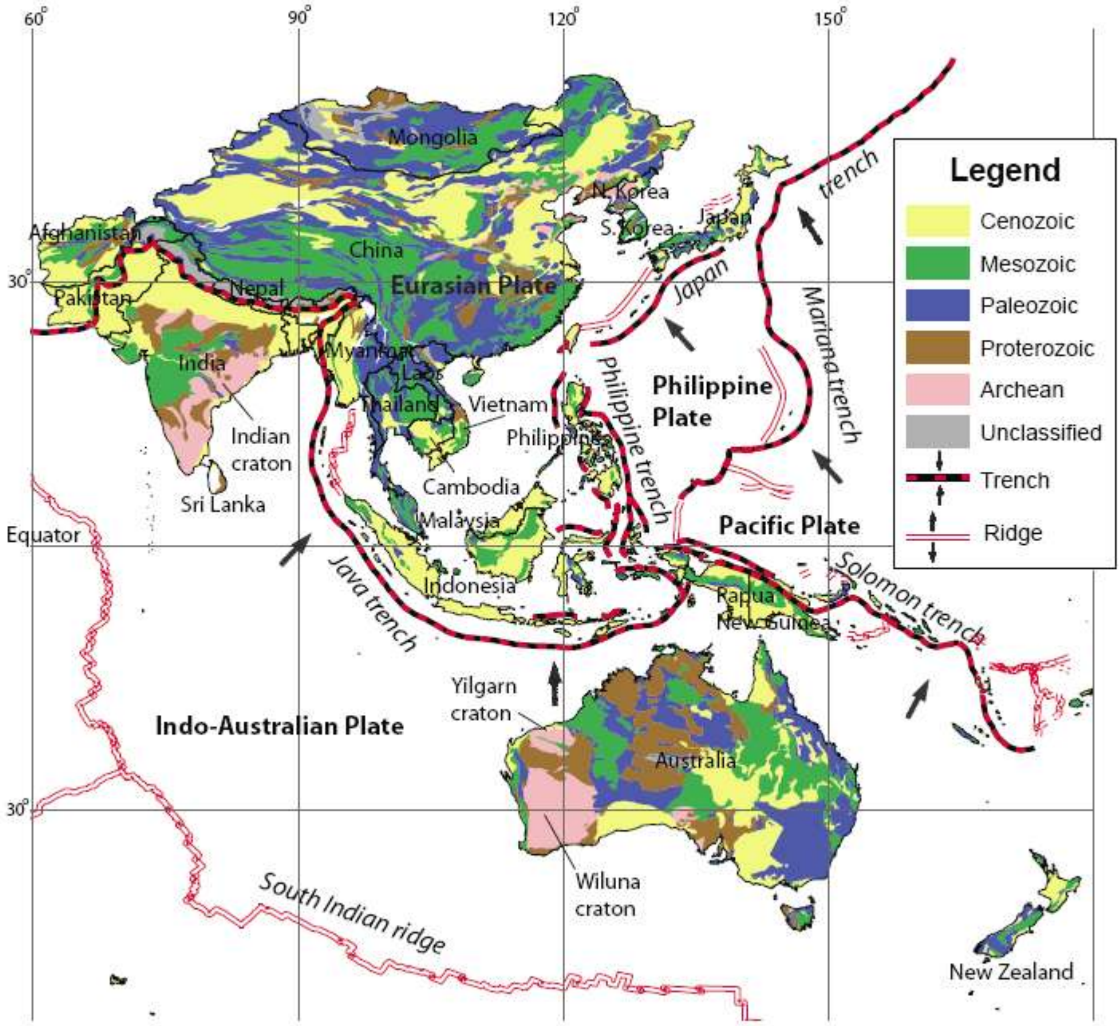

Figure 33 Distribution of rocks divided into the five main ages of Earth's history in the Asia and Pacific region (source: USGS [88])

Data sources

Despite the fact that geological maps primarily show surface conditions, they also allow for an idea of the underground structure. Therefore, a first step in selecting a suitable region or site will always be the search for and the interpretation of geological maps. Geological maps are widely available, mainly by international organizations and national geological surveys. Even large-scale maps allow first statements. An example is given in Figure 34, which depicts the general geological structure of India as an example of how this kind of map may be used and interpreted. The map shows that, in most parts of India, crystalline or volcanic rocks are widespread. These rocks might provide large homogeneous rock bodies, and are possibly suitable as a host rock themselves or when accompanied by mineral deposits. This may call for a search for sulphide mineral deposits, because, as already explained, sulphide mineral deposits may provide highly suitable geochemical conditions to keep stabilized mercury (waste) in its poorly soluble form.

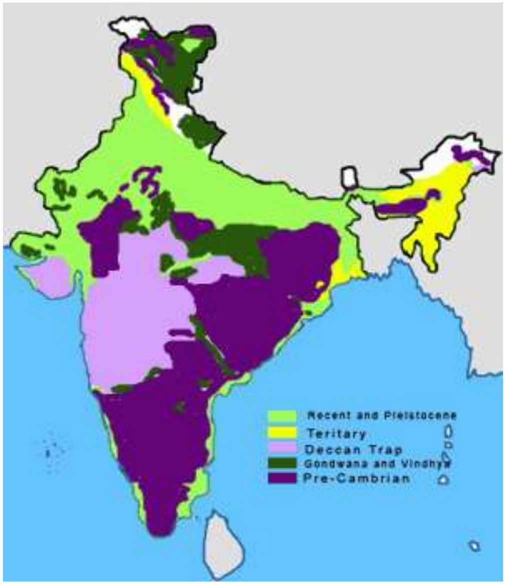

Figure 34 Large-scale geological map of India (source: Nichols[11])

A major part of the area covered by this report is covered by maps showing geology, oil and gas fields and geological provinces of South Asia, edited by USGS [88][90]. The map for South Asia was compiled and synthesized primarily from the UNESCO 1976 and 1990 geological maps of South and East Asia, of scales of 1:10,000,000 and

[11] http://commons.wikimedia.org/wiki/File:India-geology-map.png (GNU Free Documentation License).

1:5,000,000 respectively [75]. Geologic units were combined to simplify the map and to maintain consistency with other maps of the series. Basic literature providing an overview of the geological situation of a country or a region, e.g., India [61] and China [93], is also available.

8.4.1 Salt rock deposits

Since salt rock is the most favoured host rock for underground disposal in Europe, it might be a reasonable procedure to study the distribution of major deposits of salt minerals such as halite and potash in the Asia Pacific region. A recent compilation of global halite and potash deposits has been prepared by Warren (2010 [91] Figure 35, Figure 36). With regard to potash, the study of Garrett (1996 [32]) may also serve as a valuable reference.

In addition, the USGS report ‘Geology and Nonfuel Mineral Deposits of Asia and the Pacific’ enables the first rock-type specific research [88]. It contains (among others) major mineral regions and well-known significant mineral deposits. Referring to evaporates (e.g., rock salt) this USGS-report elucidates that sediment-hosted evaporate deposits are a main source of minerals that have evaporated during accumulation of sediments. The Asia and Pacific regions contains a number of these deposits in the Palaeozoic sedimentary basins of Pakistan, China, Mongolia and Australia. Palaeozoic rocks also contain the major salt deposits Warcha, Kalabagh and Khewr, Pakistan and the salt and gypsum deposits at Davst uul, Mongolia. Mesozoic rocks contain extensive potash and salt deposits and are to be found in north-eastern Thailand at Udon Thani (Khorat Plateau), western Laos (Vientianed and Savannakhet Plains) and parts of Cambodia, and include rocks that also contain gypsum and copper deposits. The salt deposits at Weixi, China, are also contained in similar extensive evaporate sedimentary rocks. Significant Cenozoic age deposits include the salt deposits in Afghanistan and western Pakistan. Other Cenozoic evaporate deposits include Sangiyn Dalay Nuur, Mongolia, and Lake Macleod, Australia (Australia not being worked on in this study). The countries as well as the deposits are listed in detail in [89]. Figure 37 summarizes the details of the USGS-report for the minerals listed in the legend, *inter alia* evaporates (i.e. salt rocks). It should be noted that this map is only one of a series of three maps that show the distribution of many non-fuel mineral deposits in the Asia and Pacific region. The full range of diagrams may be found in the annex.

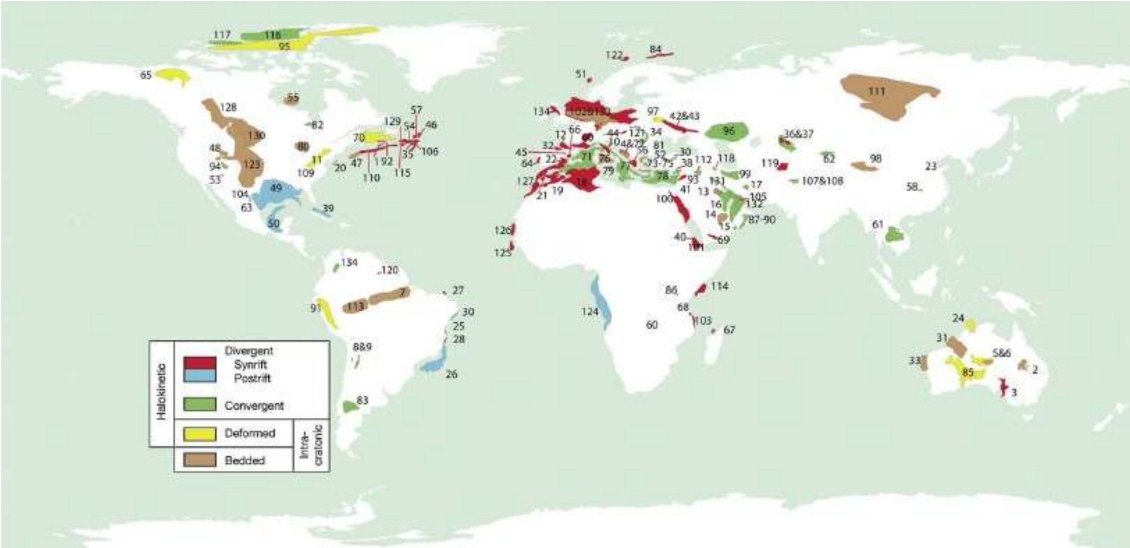

Figure 35 Global distribution of halite-entraining basins; the numbers refer to deposits in the original publication (source: Warren [91])[12]

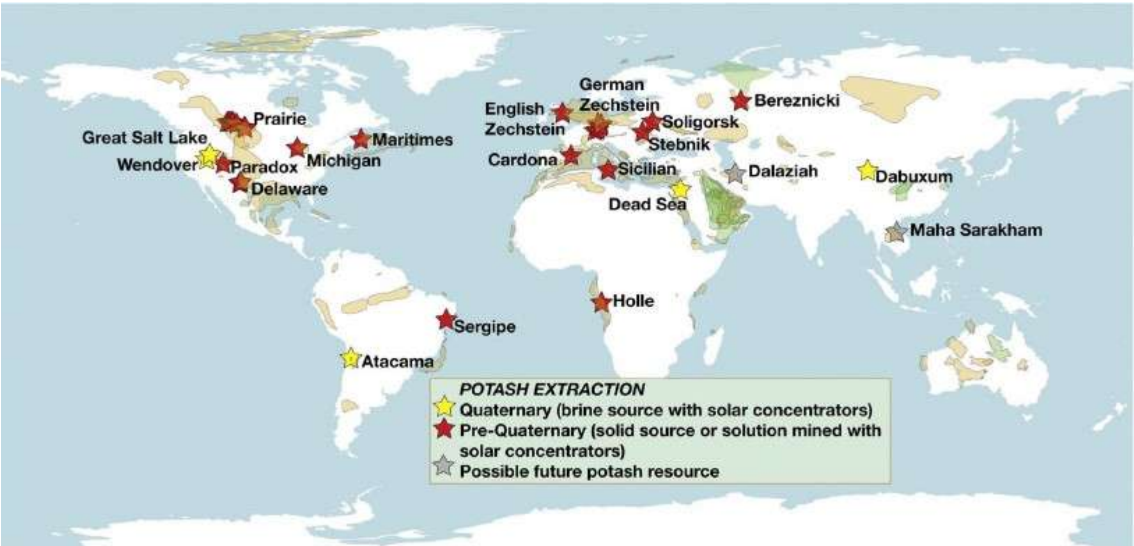

Figure 36 Global potash deposits and extraction (source: Warren [91])[12]

[12] Reprinted from *Earth-Science Reviews, Vol. 98*/ 3-4, John K. Warren, Evaporites through time: Tectonic, climatic and eustatic controls in marine and non-marine deposits, 217-268, Copyright (2010), with permission from Elsevier.

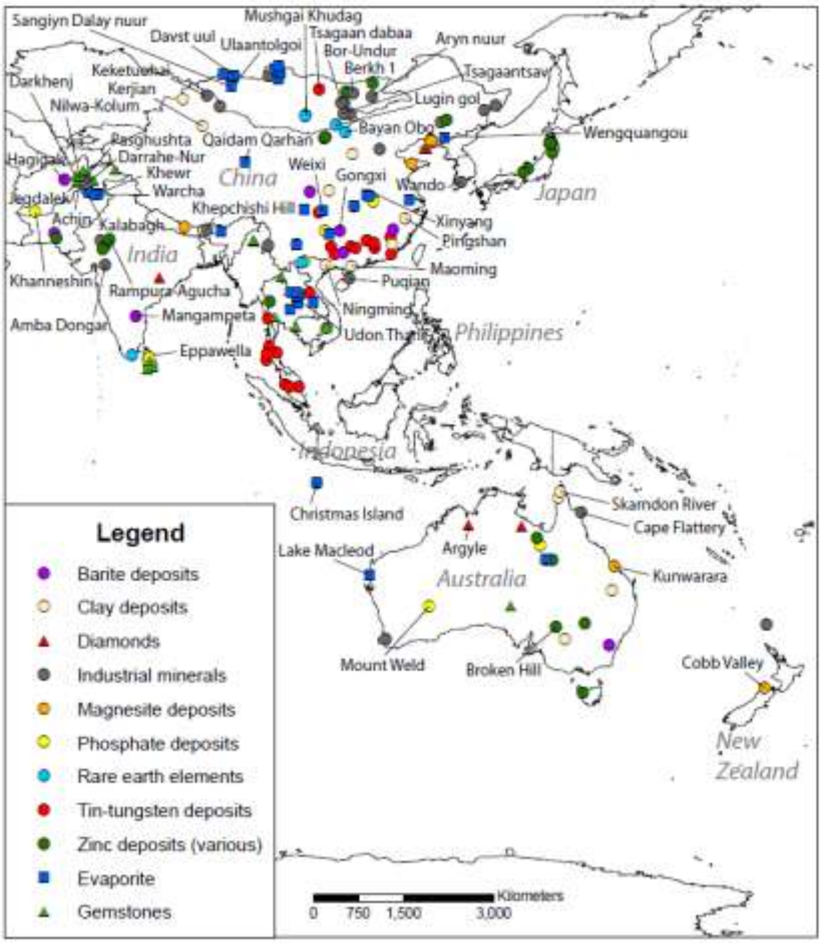

Figure 37 Main non-fuel mineral deposits in the Asia and Pacific region (source: USGS [88])

8.4.2 Crystalline rocks and clay formations

In the discussion of underground disposal of radioactive waste, clay formations and crystalline rock play the most important role beside salt rock. They are widespread in the Asia Pacific region [54]. However, it should be noted that the underground disposal of high level radioactive waste is always intended to become realized in newly excavated mines. In contrast, and mainly for economic reasons, the underground disposal of hazardous wastes is practised in already existing mines. Typically, mining of clay and crystalline rock is done by open pit mining, in quarry or in near-surface mines. Such mining operations do not produce cavities deep enough to ensure sufficient isolation. Therefore, the option of disposing hazardous wastes in crystalline rocks or clay formations is no longer pursued in this report. Nevertheless – as explained with the depiction of the Konrad mine (Germany) – overlying clay layers might represent a highly effective natural, geological barrier that might help to isolate hazardous wastes from the biosphere when disposed of below them. In any case, the effectiveness of the overall disposal system must be investigated and proved.

8.4.3 Metal sulphide deposits

Another option for disposing of stabilized mercury could be the use of metal ore mines. These could provide suitable geochemical reducing conditions under which mercury sulphide remains thermodynamically stable and immobile. Metal sulphide deposits such as zinc sulphide often contain mercury sulphide as a minor component. Returning mercury sulphide into a zinc mine could be considered ‘environmentally neutral’, given that the overall geological situation of such a mine, in combination with technical barriers (as far as needed or indicated), guarantees a sufficient level of isolation from the biosphere.

A good overview of metal ore deposits and their mining in the Asia region is given in the USGS’ 2008 Minerals Yearbook [89]. The tables in this yearbook outline which metal is being exploited in which country of the region. Much more detailed information is provided by, e.g., [69], in which distinct deposits in certain districts of numerous countries are compiled, including which metal is found and exploited at a given site. These include underground zinc, lead copper and iron mines eventually suitable for disposing of Hg-sulphide that, in that distinct compound, would fulfil even the requirements of above ground landfills. Metal deposits described in [69] are also compiled in worldwide maps, with one of them given as an example of the mode of representation (Figure 38).

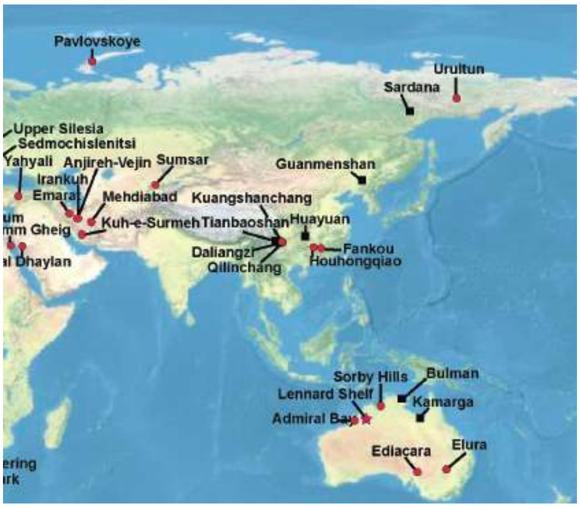

Figure 38 Distribution of Mississippi Valley-type lead-zinc deposits in the Asia and Pacific region (section of Figure B2, source: Sims [69])

Another map (Figure 39) points out the distribution of ore deposits in South-East Asia [58] in more detail. Similar maps are available for other sub-regions or countries (e.g., China). Additional and more specific information may be taken from the literature cited or the tables in the country-information Annex. Further information on metal ore deposits may be found in:

- USGS (2005) report on the geology and non-fuel mineral deposits of Asia and the Pacific [88];
- Hutchison (1996) South-East Asian oil, gas, coal and mineral deposits [41] ;
- Moores and Fairbridge (1997) Encyclopedia of European and Asian Regional Geology [54].

The occurrence of ore deposits, as shown in the figures, is often related to historic tectonic processes, volcanism, etc. Such processes might still be active and represent an exclusion criterion with regard to an underground disposal site. Site-specific investigations are necessary in order to assess the potential impact of active geological processes on the long-term safety of an underground disposal facility.

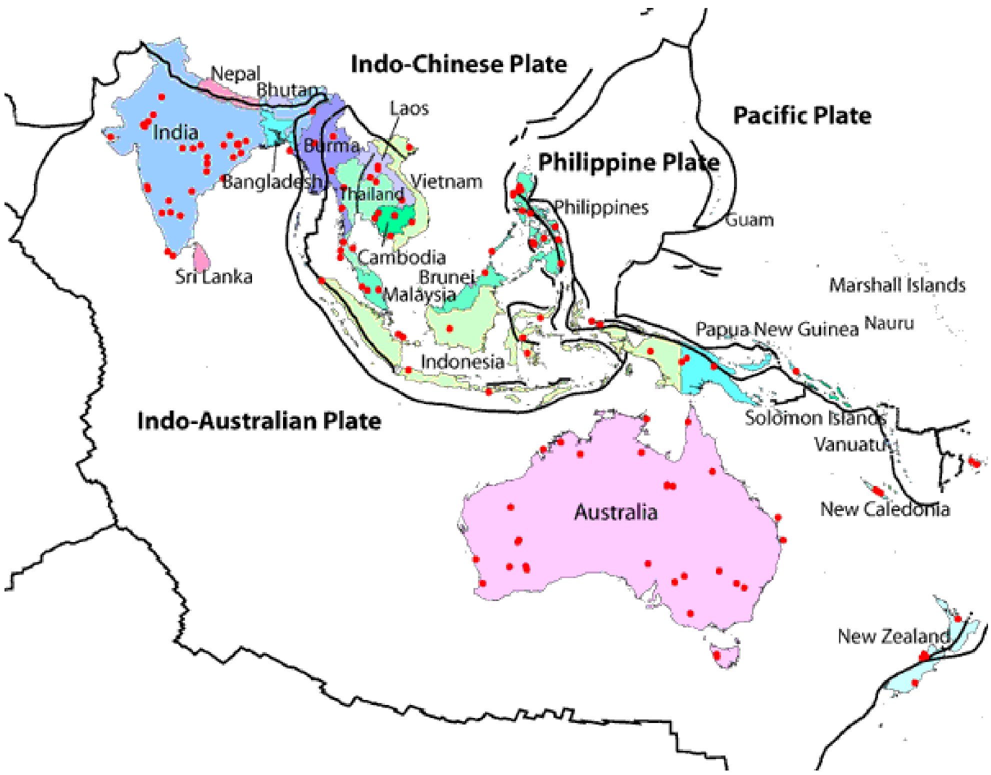

Figure 39 Distribution of ore deposits in SE-Asia (source: Peters and Back, USGS [58]).

8.4.4 Conclusions

The explanations given in the previous subchapters clearly point out that site selection, construction and operation of an underground disposal facility might be possible under a number of varying geological conditions. In general, potentially suitable geological conditions seem to be present in numerous countries in the Asia Pacific region. As this statement is currently only based on general geological maps and synoptical tables of country-specific information, the practical availability and suitability of underground mines can only be assessed on site-specific investigations.

8.5 Cost estimate for disposing of stabilized mercury in a sulphide mine

8.5.1 Scenario

The underlying principle for the concept of underground mercury disposal in the Asia region is the stabilization of elemental mercury with sulphur to receive mercury (II) sulphide (HgS), a chemical compound virtually insoluble in water. Compared to other chemical compounds of mercury, HgS is much less toxic. The relevant amount of mercury to be disposed of within 20 years is estimated to be up to 7,500 t, resulting in an annual capacity of 375 t of mercury. For the purpose of this calculation, it was assumed that surplus mercury would occur in the form of elemental mercury. Adding the proposed stabilization, the annual waste has a tonnage of 435 t. The volume of the sulphur stabilized mercury is 6 times higher than that of the initial elemental mercury, and amounts to a volume of 166 m^3, which can be regarded as the annual required storage space.

8.5.2 Mine selection

The selection of a suitable underground disposal will be part of a pre-investment process outlined in the previous section. In a first attempt for such studies, the evaluation process considers existing and operating underground mines for sulphide ores, mainly copper / lead / zinc mines, to fulfil the goal of disposing a sulphide compound in a sulphide mineralization. Secondly, the evaluation process aims at minimizing the capital expenditures by, e.g., identifying sites where the necessary infrastructure for disposal are already present.

For calculating potential costs for underground storage, the following scenario was developed.

- The underground storage facility is located in a certain country with a large number of operating metal ore mines. This country was selected for the mere purpose of making a consistent cost calculation for the hypothetical case of having an underground facility in one country in Asia. The selection does not imply that mines in this country are especially qualified or that this country should host an underground disposal site for other reasons.
- One mine in this country was arbitrarily chosen as an example for a mine that could in principle host a storage facility. Elemental mercury is shipped from Asian countries to a sea harbour near the mine. Here or in close vicinity a stabilization plant is available that transforms elemental mercury into mercury sulphide.
- The stabilized mercury is shipped to a nearby mine were it is permanently stored underground.

The chosen country has a variety of operating copper and / or zinc mines with a sulphide mineralization. They vary greatly in production capacity and distance to the next seaport as well as geological settings. For cost calculations, one mine has been chosen, located approximately 250 km from a large port. It hosts a well-developed infrastructure and the geology in which the mine stands is well explored.

In the following, the work that needs to be carried out and the technical parameters of the disposal site are briefly described.

8.5.3 Waste handling and emplacement

The waste is to be shipped to a port in the selected country where it will be stabilized using sulphur and packed into big bags with sealing. The stabilized mercury is then loaded onto a regular highway truck with regular forklifts and transported to the mine site.

At the mine, the waste material is unloaded using a forklift and later loaded onto the hoisting rack. On the level of the disposal site, the rack will be unloaded by a forklift again and the waste is loaded onto an underground transport vehicle, which transports the waste to the emplacement site. There it will be unloaded again and placed in the room.

During the placement of the waste, backfill will also be added. Assuming that the backfill is delivered over-ground, it also has to be transported down to the disposal site where it will be moved to the rooms by wheel loader and placed using a backfill centrifuge. Each room is of dimensions able to hold a tonnage equal to twice the annual delivery rate. When the tonnage of one year is placed, a brick wall will be erected to retain the backfill and the waste of the first year. After the waste of the second year is placed and the backfill is brought in, a concrete retention dam is constructed to seal the room.

8.5.4 Layout of the disposals and emplacement

Along with the placement process, several pre- and post-processes have to take place. The main drift and the rooms are driven in and completed with rock bolts and a liner of shotcrete. It has been assumed that all drifts and rooms need to be newly driven.

The development of the openings also includes the installation of ventilation, drainage pumps (ideally, it is unnecessary), water supply and power supply. Another considerable part of the work before and during the emplacement is material transport, especially backfill and concrete transport. Furthermore, it is assumed that the batching of the concrete will be done underground and distributed by a transmixer.

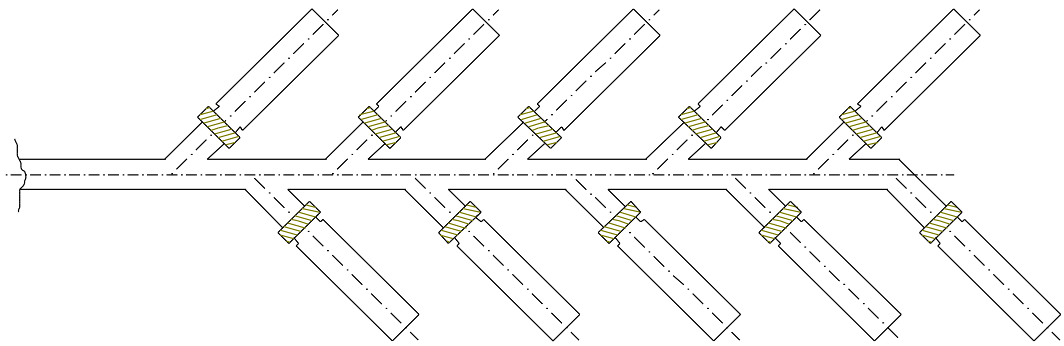

Figure 40 Layout of underground disposal rooms in a fishbone arrangement branching from a main drift (source: IMC)

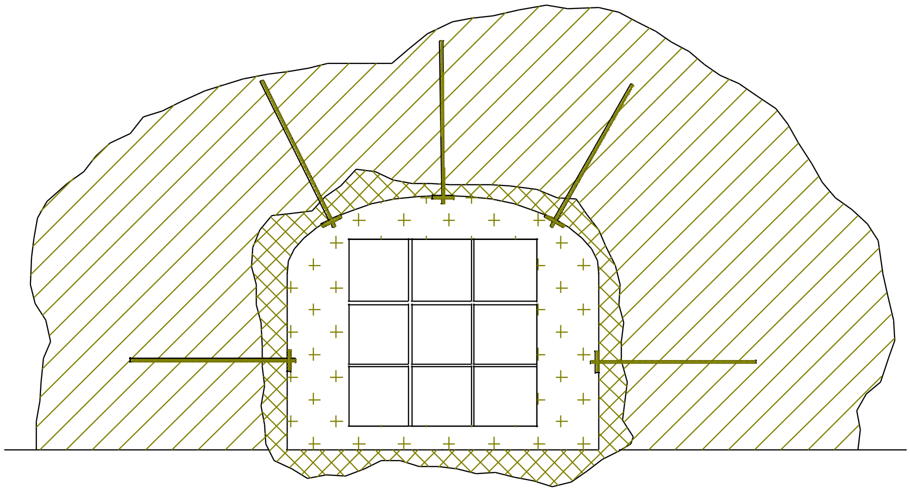

Figure 41 Emplacement of HgS big-bags within a prepared disposal room; stability is supported by rock bolts and shotcrete, void space is backfilled (source: IMC)

The layout of the underground disposal consists of 10 rooms in a fishbone arrangement and a main drift. Each adjacent room is 10 m apart and branches off the main drift at an angle of 45°. The rooms have a length of 26 m and begin 11 m off the main drift. The main drift has a face area of 15 m², whereas the rooms have a face area of 36 m².

Figure 40 and Figure 41 show drawings of the described layout and the emplacement of the big bags. The cost calculations have been based on the assumption that a single concrete retention dam is sufficient to seal every room. Since the mercury is stabilized and insoluble in water, no more isolating liners or backfill need to be applied. Therefore, only regular backfill was considered in the calculations.

8.5.5 Capital expenditure

The table below (Table 16) illustrates the overall capital expenditure. It is assumed that all the equipment is bought by the executing entity and that no contracting is carried out. This would result in capital costs of about USD 4.8 million, or USD 550 per ton. Only the possibility of using a contractor for the transport to the mine site has been evaluated. When using a contractor, the overall capital expenditure will decrease to USD 530 per ton waste. In any case, the low utilization of the equipment due to the small amount of waste placed results in a high capital expenditure per ton of waste disposed.

Table 16 Capital expenditures for the development of an underground storage facility for stabilized mercury in a zinc / lead mine.

Item	Cost estimate (USD)
Highway Truck	150,000.00
Forklift 2x	40,800.00
Rear-dump Truck	632,000.00
Transmixer	258,000.00
Drilling Rig	620,000.00
Wheel Loader	479,000.00
Backfill Centrifuge	200,000.00
Crew Transporter	35,900.00
Shotcrete system (includes truck)	422,500.00
Concrete Batching Plant	81,400.00
Development Drift & Rooms	1,183,500.00
Ventilation Fan	14,800.00
Air Duct	2,211.00
Pumps 2x	2,660.00
Pipes	832.00
Switchboard	4,010.00
Cables	2,980.90
Other Equipment	25,000.00
Equipment Transport	8,000.00
Planning	624,539.09
Sum Capital Expenditure	4,788,132.99
Capital Expenditure per ton waste	550.36

8.5.6 Operating expenditure

The table below (Table 17) illustrates the total operating costs for disposing the waste in the underground mine. It is based on the labour costs in the selected country. When using a contractor for the transport of the waste to the mine site, the total operational expenditure increases slightly from USD 185 to 189 per ton of waste. Within the calculation of the total operating expenditure, a usage fee of USD 100 per ton waste has been included. This can be regarded as a royalty to contribute to the closure costs of the mine as well as a service charge for the provision of the infrastructure and power supply.

Table 17 Operating expenditures for an underground waste disposal

Task	Cost estimate (USD/t)
Transport to Mine	21.26
Transport Underground	3.01
Emplacement	36.87
Administration & Management	24.17
Usage Fee	100.00
Sum Operating Expenditure	185.32

8.5.7 Costs for stabilization

It is assumed that one of the stabilization technologies discussed above would be available for installation in the selected country. It is further assumed that the plant could offer the service of stabilization at a price of USD 2,300 per ton[13]. Costs per ton could be significantly lower if the plant is operated with a constantly high annual throughput. However, it was not possible to make a more detailed calculation since detailed financial data for the DELA plant were not available.

8.5.8 Other costs

The following cost types are not taken into account, because they depend heavily on where and in which chemical form surplus mercury is produced and when stabilization and disposal facilities become available:

- Transport of elemental mercury or mercury compounds to a temporary storage facility and temporary storage: could be decentralized at the production sites or carried out at a centralized site (if direct transport to a stabilization plant is impossible)
- Transport to a stabilization plant
- Chemical conversion of mercury compounds into elemental mercury
- Transport from the chemical plant to a temporary storage facility and temporary storage (if direct transport to an underground storage facility is impossible)

[13] DELA (Germany) currently charges USD 2700 for the same service, but it includes the costs for final disposal (about EUR 300 or USD 400 per ton, details unknown).

- Transport from the temporary storage to a harbour, located near an underground storage facility.

8.5.9 Costs for existing underground storage facilities

Little information is available on the investment and operation costs for existing underground storage facilities. A German report estimated that the reconstruction of the salt mines in Zielitz and Heilbronn incurred investment costs (including funds for closure expenditures) in the order of EUR 16 to 28,5 million (costs of 2002) [19]. Based on these data, the costs for disposing of hazardous waste in salt mines would be around EUR 32 to 76 per ton (USD 43 to 103) if the assumed annual capacity of these facilities (100,000 and 200,000 t/y, respectively) were to be fully achieved.[14]

Table 18 Estimated investment and operational costs for German underground disposal facilities

	Zielitz	Heilbronn	Borth)*
Annual capacity [t]	100,000	200,000	350,000
Preparation and closure [million EUR]	28,5	16	35
Operation [million EUR / year]	6,7	6	12,5
Costs per ton of waste stored (lifetime of facility 40 years [EUR / t]	76	32	41
)* never went into operation			

The costs are much lower than calculated above for storage of mercury sulphide in an ore mine because the annual throughput in the operating underground storage facilities in Germany is much higher (100,000 to 350,000 t). It should be noted that these are only cost estimates, and that actual costs may differ. The current prices for underground waste disposal in Germany are in the order of EUR 260 to 900 (USD 350 to 1200) per ton [11].

[14] According to industry sources, the annual amounts are lower.

8.6 Export of elemental mercury for disposal outside the region

In case of there being no stabilization and disposal facilities available in the region, export to a country outside the region might be a potential means for the environmentally sound management of surplus mercury. This does not include export for the purpose of later use and possible release into the environment. In the past, the EU and the USA imported raw mercury from different sources in order to purify and re-export it. When the EU and the US export bans come into force, export will no longer be allowed. As the declining domestic demand in the EU and the USA will presumably already be met by domestic sources (e.g., recycling of waste, gold production), there will be little need for additional imported elemental mercury and the only possible fate of such imports would be disposal (in the EU) or long-term storage (in the USA). For the EU, the requirements, and consequently costs, of final disposal of mercury are still completely unclear, so that a cost estimate is impossible now. For the USA, the total costs for storing 7.500 t of elemental mercury for 40 years were estimated to be between USD 59.5 and 144.2 million. The annualized costs per ton are expected to be at USD 0.084 to 0.181 per pound (USD 185 to 400 per ton per year), including further storage or stabilization and disposal after this time. In a simplified approach, this value was applied to the scenario of storing 5,500 t for 20 years. The resulting total costs for storing would amount to USD 20.4 to 43.9 million. Costs, however, would most probably be higher because investment cost would have to be split over fewer years.

For the transport of by-product mercury from Peru to the USA, costs are in the order of USD 850 to 1140 per ton [45]. The figure is based on industry experience. According to first estimates, transport costs from Asia to the USA or EU would probably be in the same order of magnitude, but no attempt was made to prepare a better estimate. In summary, export to and long-term storage in the USA, if legally feasible, would produce costs in the order of USD 7,200 to 16,100 per ton for a 40-year period and additional unknown costs after this time.

8.7 Summary

In the next decades, between 5,500 and 7,500 tons of mercury will have to be stored or disposed of. The investigated concept for an underground mercury disposal facility in the Asia region is based on the assumption that surplus mercury will be stored in a stabilized form, mercury sulphide. It can easily be filled into big bags, sealed and handled with forklifts. The big bags will be disposed of in rooms developed from a main drift in a fishbone arrangement in an existing copper / zinc mine.

The capital expenditures were estimated at USD 4.8 million, and the operating expenditures at around USD 185 per ton, considering a usage fee of USD 100 per ton for the mine operator. The total costs for stabilization and disposal of 7,500 t elemental mercury are estimated to be between USD 23.4 million and USD 3,100 per ton. Calculated costs would be only slightly lower for 5,500 t, the base scenario in the mercury excess study, because the most important factor, the stabilization costs per ton, would remain constant and the investment costs for the mine would decrease only slightly. Assuming that investment costs remain the same, stabilization of 5,500 t elemental mercury and subsequent disposal would cost USD 18.8 Mio. These costs could be significantly reduced if an underground storage facility could be operated for other waste types as well. However, a quantification of this was not possible within this project.

Table 19 Costs for stabilization of elemental mercury and subsequent underground storage of mercury sulphide

	Cost per ton elemental mercury (USD)	**Total costs (USD)**
Stabilization	2,300	17,250,000
Investment costs, mine	638	4,788,132
Operational costs, mine	185	1,389,900
Total costs (rounded)	**3,100**	**23,400,000**

The disposal of stabilized mercury is assumed to be a viable method to remove mercury from the market and from the biosphere. For the further development of the project, two initial studies are proposed. The first study should evaluate the market for the future underground disposal of mercury together with the market area and the financing of the project. The second study should investigate in sufficient detail the geological conditions of suitable underground mines in the region and chose three to five suitable candidates. A scoping or prefeasibility study can then be conducted based on the achieved knowledge.

9 Legal framework

Before any of the above-mentioned technical concepts could be implemented in any country, adequate, effective and conclusive legislation should be in place in order to provide a sufficient regulatory base for the environmentally sound management of elemental and stabilized mercury. Legislation should cover all aspects of the mercury life cycle. Regarding surplus mercury management, regulation is needed that

- Increases the effectiveness of mercury collection and channels surplus mercury to storage and disposal: obligations to deliver mercury and restrict its import / export
- Ensures a high level of environmental safety when planning and operating mercury management facilities (storage / treatment / stabilization / disposal)
- Ensures a high level of transparency throughout the mercury management process (public involvement / monitoring / reporting / data access)
- Defines, who will bear the costs for storage, stabilization and disposal

Table 20 lists a number of aspects that may need further regulation.

Table 20 Fields for potential regulation for different elements of mercury management

Element	Regulation needed
Trade / Supply	• Harmonize the region's trade restrictions of elemental mercury / national export bans • Prohibit imports of goods for which there are mercury-free options available in the region • Natl. Inventory / Traceability of trade: request reports on production / use / import / export / storage / disposal / source / destination • Natl. inventory of potential producers of Hg surplus • Restrict import / export to licensed dealers or restrict export for purpose of disposal • Restrict sale to licensed dealers / producers
Use	• Phase-out mercury in products and processes, where its replacement by mercury–free alternatives is feasible
Collection of surplus mercury / mercury waste	• Require delivery of surplus mercury to waste-collection centres • Require separate surplus mercury / mercury waste collection • Deposit system for Hg added products
Management	• Technical standards for handling, treatment, packaging and transport, storage of mercury and mercury waste • Cost sharing • Liability
Storage / Disposal	• Require stabilization (optional) • Above-ground storage / underground storage: Site requirements, site selection process, acceptance criteria, operational safety, long-term safety, monitoring, inspection, liability

10 Conclusions and recommendations

10.1 Challenges

A regional excess of 5,500 t mercury supply is expected for the years 2029 - 2050. An excess supply may occur sooner if countries decide to implement measures to reduce mercury demand or to increase mercury recovery from industrial process gases or wastes. On a national level, mercury surpluses are possible as soon as a country decides to stop exports.

Inefficient collection systems for hazardous waste in general, and for mercury waste in particular, combined with inadequate capacities of countries to store, treat and dispose of elemental mercury and mercury waste, lead to disposal of mercury under unsafe conditions and potential release from landfills and open dumps.

10.2 Available concepts for the management of surplus mercury

There are different concepts available that could be utilized to manage surplus mercury in the region. Among these are:

- Temporary storage: as interim measures, temporary storage of elemental mercury, stabilized mercury and by-product mercury compounds may take place at hazardous waste management centres, although the specific requirements still have to be developed;
- Above ground storage of elemental mercury in warehouses;
- Permanent storage (disposal) of stabilized mercury or by-product mercury compounds in underground mines, possibly in combination with (other) hazardous waste;
- Disposal of stabilized mercury in specially engineered landfills;
- Deep well injection.

These concepts are already in use elsewhere in the world or are legally possible in many countries (disposal in landfills). Permanent storage of elemental mercury in underground mines is a concept envisioned by EU legislation, but is currently not allowed and not practised. Export to another region for storage or disposal could also be an option if there are no adequate management options available in the region.

There is a high probability that each of these concepts could be applied in the Asia Pacific region as well. Their technical feasibility does not mean that these concepts provide the same level of environmental safety. Each concept has its own advantages and disadvantages and only a site-specific safety assessment may show if occupational and (long-term) environmental standards are likely to be fulfilled. Nevertheless, a general discussion of the above ground storage and permanent storage should be given here.

Above ground storage in warehouses

Constructing and operating an above ground warehouse for elemental mercury in accordance with the US concept is probably a feasible option. Finding suitable sites or even already existing warehouses that could be reinforced is not expected to pose serious technical problems. If there is an urgent need for storing considerable amounts of elemental mercury, this concept should be taken into account. The biggest drawback of warehouse storage is the fact that surplus mercury remains in the biosphere and could be subject to unexpected incidents in the future. The concept requires a high level of political, economic and institutional stability that is not present in all countries. If institutional oversight and law enforcement weakens, unauthorized access to the mercury may lead to theft and subsequent use and inadequate maintenance to the failure of container or construction material and subsequent release into the environment. If other options are unavailable, warehouse storage could play an interim role.

Stabilization and underground storage

Taking into account recent research and development, stabilization of elemental mercury must now be acknowledged to be available, proven technology for full-scale industrial application. Stabilized mercury could be much more safely handled, transported and stored. Due to the availability of stabilization technologies that convert liquid elemental mercury into a non- or at least much less hazardous solid, a new disposal option has been opened for surplus elemental mercury. In contrast to liquid elemental mercury, stabilized mercury and solid by-product mercury compounds may be and are already permanently stored (disposed) in underground waste storage facilities. Disposal of stabilized mercury waste, stabilized mercury and possibly other hazardous waste types could in principle be done in one facility, thus opening a way for the general need for hazardous waste disposal as well.

The main advantage of underground storage is the high level of environmental safety that it could provide – up to several hundred thousand years or even more. Potential sites could be underground mines with suitable geochemical conditions. These include salt and hard rock formations. Returning mercury sulphide to the place of origin or similar mineralogy such as zinc, lead, gold or copper mines could be an option for the Asia Pacific region, where such deposits are abundant. The implementation of underground storage concepts requires considerable time for site selection and site-specific long-term safety assessment. Experience in this field is becoming more and more available in the region as many countries in the region are now engaged in similar underground disposal projects for nuclear waste.

10.3 Surplus mercury management costs

Based on the information in Table 21, above ground storage, stabilization / underground storage and export to above ground storage in a different region all seem to represent comparable costs. However, the data from the concepts studied in this report still have a significant uncertainty. In the case of above ground storage, the fate of elemental mercury after 20 years of storage is not considered in the calculation. Additional costs will definitely be caused by extended storage or disposal. In contrast, placing mercury sulphide containers in a mine incurs costs only once, whereas maintenance and surveillance of above ground storage facilities is required for as long as the facility is actively operated.

For underground storage, the location of the mine and its specific characteristics, such as mine layout and mine operation, have an important impact on the resulting costs. For example, in one mine, excavation of new drafts might be necessary, in others not. Only a site-specific feasibility study taking into account all local and national requirements would then be able to generate figures that allow for an investment decision.

Most surplus mercury is expected to be produced by industrial facilities such as zinc smelters, natural gas producers and gold mines. If the ‘polluter pays principle’ were applied to surplus mercury, industrial producers would have to bear the full costs of managing surplus mercury, as will be the case in the EU and the USA after the coming into force of their export bans. It is interesting to note that, according to industry sources, companies prefer management concepts such as environmentally sound final disposal, as it constitutes a one-time cost factor, but also, more importantly, transfers the ownership and liability to the operator of the disposal facility.

Table 21 Comparison of the three major storage concepts excluding transport costs (rounded)

	Above ground storage in Asia and the Pacific	Stabilization and disposal in underground storage facility	Export to above ground storage facility outside the region
Investment costs	6,030,000	4,790,000	0
Container costs	4,600,000	110,000	(included in operational costs)
Stabilization	-	12,650,000	-
Operational costs for 20 years	11,200,000	1,020,000	20,400,000 - 43,900,000
Total	21,830,000)*	18,800,000	20,400,000 - 43,900,000
Cost per ton	3,970	3,100	3,700 - 8,000
)* Additional costs after 20 years:	Disposal: 20,800,000 Storage (20 years): 11,830,000	0	Partly included

10.4 Legal requirements

Before any of the discussed storage and disposal concepts can be implemented, countries should have an adequate regulatory framework that describes requirements and procedures for their environmentally safe operation in place. Because neither the above ground nor the underground storage concept has ever been implemented in the region, appropriate specific legislation does not exist in the region.

10.5 Suggested surplus mercury management strategy

Guiding principles and key elements

Based on the findings and discussions above, a suggested management strategy was developed that could possibly be implemented on a national level, but would benefit from regional cooperation between surplus mercury producers and entities that operate storage, stabilization and disposal facilities.

It is a well-accepted fact that elemental mercury, due to its liquid state, vapour pressure and toxicity, is a hazardous material that needs special care when being transported, handled and stored. Thus, a guiding principle for environmentally sound management of mercury should be to reduce its hazardousness as soon and as much as possible in order to make the safe management more feasible and the fulfilment of occupational and environmental safety requirements more achievable. Stabilization and isolation from the biosphere are the key elements within this concept. The sooner mercury that is no longer needed for accepted purposes is removed irreversibly and safely from the biosphere, the lower is the risk of unwanted releases or contaminations.

A management strategy that follows such prescriptions would consist of three steps:

- Effective Collection
- Early Stabilization
- Safe Disposal

Effective collection means to remove elemental mercury and mercury compounds that are not needed for accepted uses from the market. This would include an obligation for producers of surplus elemental mercury and mercury compounds to register and deliver elemental mercury and mercury compounds to mercury storage or disposal facilities. Moreover, effective collection is needed to separate mercury waste such as mercury added products from the general waste stream. Such a measure would reduce its hazardous content and allow for the specific management of mercury containing waste. Stabilization of mercury is now a commercially available technology. Temporary storage of elemental mercury will be necessary for managing surplus mercury on an interim basis. Nevertheless, the duration of temporary storage should be kept as short as possible. Stabilization of elemental mercury converts elemental mercury into non- or at least much less hazardous material that can more easily be managed, transported, stored and disposed of. Currently, disposal of liquid elemental mercury is forbidden in most, if not all, countries, but in many countries, stabilized mercury may be disposed of in existing disposal facilities.

Finally, it is necessary to make available safe disposal facilities for stabilized mercury. Underground storage is considered a safe concept that could isolate stabilized mercury from the biosphere, if the site fulfils the appropriate safety requirements. On the other hand, near-surface disposal in landfills may produce a source of mercury releases in the far future. Whether by-product mercury compounds like calomel could be directly disposed of in underground mines depends on the mine type and its isolation potential. Due to their higher solubility and thermodynamic instability, mercury compounds should not be disposed of in landfills.

Implementation strategy

For a successful implementation of this strategy, it is suggested that progress be sought in the following fields (Figure 42):

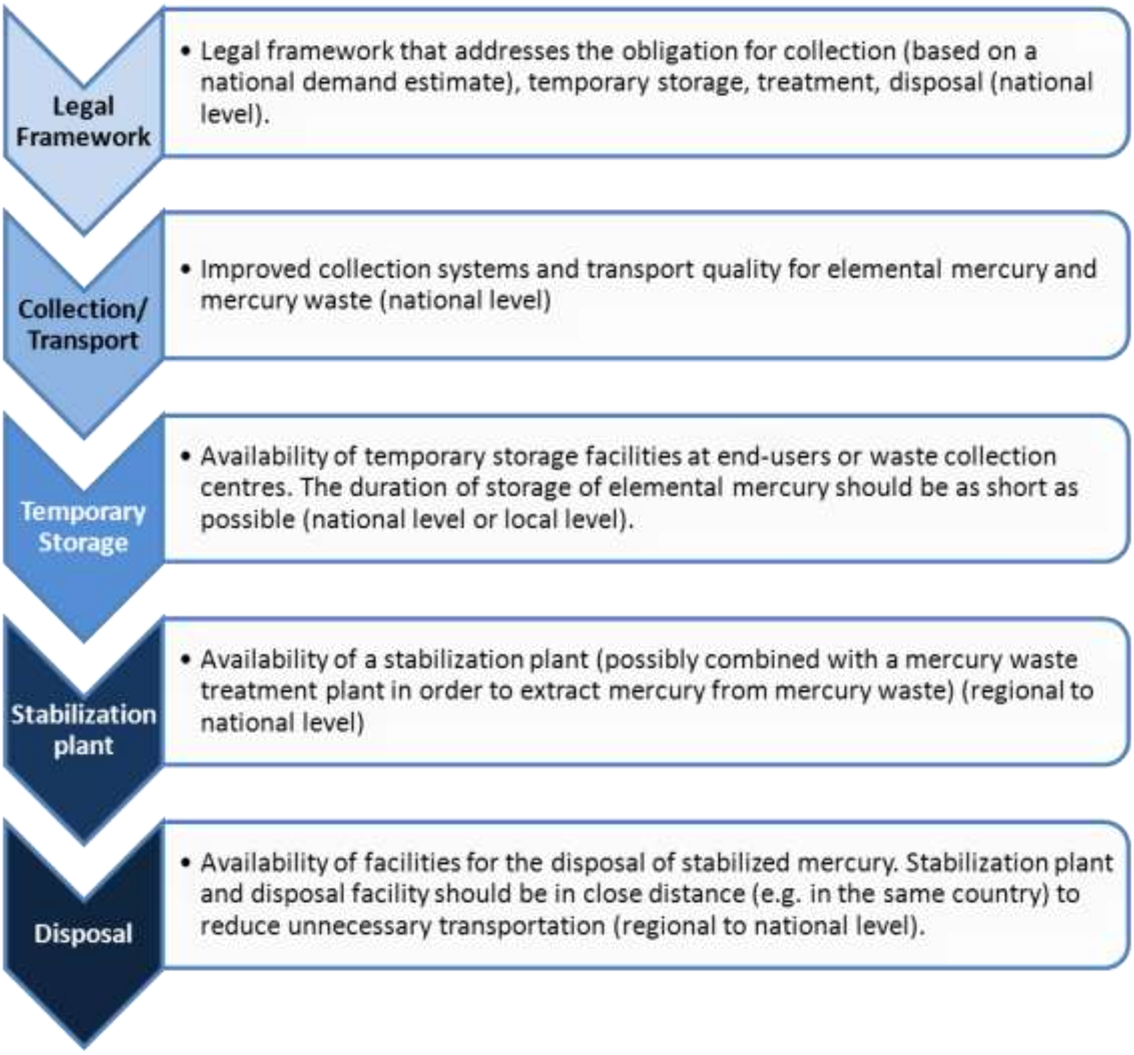

Figure 42 Milestones in implementing a storage strategy

Table 22 and Table 23 show a list of activities that could be undertaken to achieve progress in these fields. The concept aims at an early and irreversible isolation of mercury from the biosphere as this is considered the safest long-term concept for dealing with a hazardous and non-degradable substance like mercury. The safety of the discussed disposal concepts relies on geological and engineered barriers and not on organisational measures like security, monitoring or inspection. However, the full implementation of such a concept may need some time, so that interim measures will probably be necessary. These include temporary storage facilities for the management of elemental mercury, mercury compounds and stabilized mercury. For a transitional period, if storage, treatment and disposal facilities are not available in the region, export of elemental mercury and mercury compounds for storage and disposal outside the region may be an option.

Table 22 Potential activities to support progress in the field of mercury storage, stabilization and disposal I

Field	Potential activities
Legal framework	• Development of a legislative toolbox that contains proposals for legislative structures and core elements of legislation / regulation to address: • Management of (non-waste) elemental mercury, mercury compounds and mercury-added products (labelling, storage, producer responsibility, labelling etc.) • Management of mercury waste (collection, transport, temporary storage treatment, disposal, labelling, tracking, cost sharing) • Based on the example of a few countries: Elaboration of proposals to improve/ adapt existing national legislation • Capacity building and assistance in developing appropriate legislation (in cooperation with Basel regional centres)
Collection systems	• Support of countries in identifying large scale producers of by-product mercury • Exploration of possibilities to make delivery of by-product mercury (elemental or compound) obligatory • Development of an inventory of national mercury waste collection practices in the region • Assessment of efficiency of existing collection systems and exploration of ways to improve them • Assistance of countries in improving collection systems

Table 23 Potential activities to support progress in the field of mercury storage, stabilization and disposal II

Stabilization plant	• Development of inventory of mercury treatment / recycling plants in region • Analysis of feasibility of applying existing stabilization technologies in the Asia Pacific region • Investigation of approaches such as: mobile stabilization plant (incl. legal aspects), regional plant to accept elemental mercury from different countries (incl. elaboration of proposal for legal and financial arrangements), combined treatment (extraction) and stabilization plant • Development of guidance on site selection criteria (exclusion and selection criteria) • Arrangement for a regional agreement on having a regional plant that offers service to countries in the region • Site selection (possibly after identification of disposal site), site-specific feasibility study
Disposal facility	• Analysis of the long-term behaviour of stabilized mercury in above-ground landfills • Development of short guidance on site selection criteria for specially engineered landfills (exclusion and selection criteria) • Identification of specially engineered landfills that could be used for the disposal of stabilized mercury • Development of guidance on site selection criteria for underground mines (exclusion and selection criteria) • Site selection: Identification of potential sites, pre-selection, site-specific long-term safety assessment, site specific feasibility study (incl. public participation)
Temporary storage facilities	• Development of guidance on temporary storage facilities at waste collection centres and possibly industry • Support adoption of existing guidelines regarding temporary storage of mercury waste in health care facilities • Development of guidance on the temporary storage of stabilized mercury and other mercury compounds

Not all necessary structures and facilities could be in place immediately, and not all activities to improve the situation will produce results in short time. To address these challenges, activities could be grouped into three implementation phases:

- **First phase:** Begin activities to improve situation in the fields mentioned above and gather necessary information. Improve separate collection schemes and temporary storage facilities for elemental mercury, mercury compounds and mercury containing waste. Explore possibilities for treatment (chemical conversion / purification / stabilization) of elemental mercury, mercury compounds and mercury waste in the region and foster investments in this sector. If such treatment facilities are not available in the region, temporarily store surplus elemental mercury and mercury compounds. If such storage is not yet feasible, export for disposal in countries outside the region may be a possibility.
- **Second phase:** If treatment facilities exist, extract and stabilize mercury. If such disposal facilities are not available, put stabilized mercury and stabilized mercury waste in temporary storage.
- **Third phase:** Collect, extract and stabilize mercury and dispose it in disposal facilities in the region.

10.6 Outlook

Surplus mercury management poses a serious challenge to countries in the Asia Pacific region. If unwanted uses and releases of mercury into the environment are to be avoided, measures are needed on a national basis to reduce the market availability of mercury and to find national solutions to manage surplus mercury and mercury compounds. A safe final solution for surplus mercury is probably its final disposal and its permanent isolation from the biosphere. Such solutions are currently not available in the region, but the report shows a number of options that should be further investigated in the future, such as underground storage, specially engineered landfills and deep well injection. In the meantime, above ground storage of elemental mercury, stabilized mercury and mercury compounds should be taken into account.

The largest share of surplus mercury is likely to be produced in a few countries in the region: those with intensive mining, gas and oil production. For some of them, the expected production of surplus mercury may justify national solutions, but for many others the expected amounts are much too low, so that national facilities for storage, stabilization and disposal make little sense. For these countries, cooperation with other countries will be more efficient.

Such cooperation will only occur if national legal frameworks are in place that oblige industrial producers to manage mercury environmentally safely, including provisions on what has to be done with surplus mercury (storage, stabilization, disposal). Thus, the first step for Asian countries would be to develop such legal provisions and at the same time cooperate with industry and international partners to develop mercury management facilities in their countries or in the region.

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Annex A - Regional inventory of mercury waste

Currently, there is no inventory of mercury waste produced in the Asia Pacific region. Nevertheless, it is possible to derive some rough estimates based on related information. The sources of mercury in waste may be:

- Manufacturing, use, collection and recycling of products (batteries, lamps, thermometers)
- Use of mercury in processes (vinyl chloride production, chlor-alkali production, artisanal small scale mining)
- Mining and processing of mercury containing natural resources (metal ores, natural gas, crude oil)

According to the Concorde Study, the total regional demand in 2010 was expected to amount to 2,243 t, including 837 t for the manufacturing of products. These products include:

- Batteries
- Dental applications
- Measuring and control devices (e.g. thermometers, pressure measuring devices)
- Lamps
- Electrical and electronic equipment
- Other (including pesticides, fungicides, catalysts, paints, chemical intermediates)

A part of these products was exported to consumers outside the region. On the other hand, the region imported end-of-life products, especially old electronic equipment from developed countries. The mercury content of these exports and imports is unknown. The few figures available indicate that the major part of mercury added products that have been produced in Asia were exported (e.g., two-thirds of batteries produced in China were exported in 2003, [71]). It could be expected that a considerable part of exported mercury-added products is treated, recycled or disposed of in developed countries and only a minor part is ‘sent back’ to the region of origin.

The product-recycling rate in Asia is currently very low (3%) and for 2010 it was expected that only about 59 t could be recovered from products. The intentional use of products caused approximately 50-100 t of atmospheric emissions (AMAP/UNEP 2008). It might be expected that maximal 750 to 800 t of mercury could end up in some waste stream.

The fate of mercury in processes is not well understood. For the chlor-alkali sector, it was estimated that about 20 to 30 t of mercury ended up in waste, part of which was internally recycled (2005, [22]). In the vinyl chloride sector, mercury (I) chloride is used as a catalyst. During the process a part of the mercury dissolves in the by-product hydrochloric acid (about 37 %, [71]), most of the remainder could be recovered from the depleted catalyst.

About 47% of the mercury that was fed into the process as catalyst was recovered through recycling [22], whereas in Russia up to 62% is recovered [71]. The difference of 15% could be an indication that part of depleted catalysts are not recycled but directly disposed of. If 1,000 t of mercury are consumed each year, this would mean about 150 t of mercury was not recycled from catalysts.

Mining and processing of natural resources represents another potential source of mercury waste. Depending on their geographical origin, natural resources may contain considerable concentrations of mercury. The most important sources are coal, natural gas, zinc and gold ores. Mercury is often released into the atmosphere when the resources are heated (metallurgy) or incinerated (power plants). If flue gas cleaning technologies are applied, mercury may be captured in one of the gas cleaning products like fly ash or activated carbon. Sometimes the mercury content is so high that mercury could be recovered. However, it seems that outside of Japan (76 t of mercury per year) recovery does not take place. Mercury may also form an impurity in other waste types, including waste rock and tailings from mineral processing.

Several Asian countries export mercury waste (e.g., fluorescent lamps waste, natural gas cleaning waste) to OECD countries like Japan, EU countries or USA for treatment and incineration. A recent overview reported about 1000 t of difficult-to-treat wastes, including mercury wastes, that were exported [34].

Annex B - Technologies for the stabilization of mercury waste (except elemental mercury)

Encapsulation techniques without pre-stabilization

Encapsulation techniques for mercury-containing solid waste are well known and established on the market. They are based on the use of asphalt, cement, ladle furnace slag, Portland cement or polyethylene as matrix material. Encapsulation of liquids such as elemental mercury is, however, a more challenging task. Even if the encapsulation of liquid mercury is successful, cracks due to aging or mechanical loads can lead to leaching of mercury. The product would pose the same environmental and human risks as elemental mercury without encapsulation. Due to the shortcomings of this technique, no tests for the encapsulation of elemental mercury have to date been done.

In the USA, encapsulation without pre-stabilization is recommended for low mercury waste. Materials used in this process are: synthetic elastomers, polysiloxane or ceramic silicon foam, sol gels, Dolocrete™, calcium carbonate and magnesium oxide ($CaCO_3$-MgO). The hazardous waste material is mixed with the stabilizing material to a settable composition forming slurry. Subsequently, the slurry hardens and encapsulates the waste material. The settable composition most commonly has a powdered cement composition, containing calcium carbonate and a caustic magnesium oxide. Different additives such as aluminium sulphate of citric acid can be added to increase the performance. Encapsulation with ladle furnace slag is realized in an alkali-activated process with thermal treatment.

Encapsulation with pre-stabilization

Any type of stabilization can be used as a first step before encapsulation. The combination of both techniques often leads to acceptable leaching values and low vapour pressures. The sequence of stabilization and then encapsulation of mercury waste has several benefits. One of these benefits is the reduced surface to volume ratio compared to the pre-treated powdery product and, therefore, a lower leaching value. Another benefit is the usually increased physical strength and bearing capacity of the encapsulated product. One major disadvantage of the combined process, however, is the reduced concentration of mercury in the final product, which in turn increases the total amount of waste to be disposed of. Furthermore, additional steps in the combined process have the disadvantage of increasing production costs. Therefore, an encapsulation step should only be taken into account when the first pre-treatment step did not fulfil the criteria for safe disposal.

Other non-commercial investigations on mercury stabilization and solidification (S/S) processes

There are some modifications of the main standardized techniques trying to improve the mercury S/S processes. The text below shows a brief review on these improvements.

Zhang and Bishop (2001) have investigated a novel approach taking into account the very low solubility of mercury phosphates [94]. In the preliminary stage of the study, soluble phosphate (Na_2HPO_4) was proved to stabilize mercury, both in pure solution and in surrogates, successfully. Phosphate / mercury molar ratios of 3-5 were found to be effective for mercury stabilization and an optimal pH range for the phosphate process was found to be pH 2-5, with stabilization efficiency higher than 99%. At higher pH values, less mercury was precipitated, decreasing the stabilization efficiency to 80%. For mercury-doped surrogate samples, Bentonite was found to improve mercury stabilization. However, the phosphate process alone was unable to stabilize mercury-containing surrogate well enough to pass TCLP test.

Other stabilization / solidification (S/S) processes were suggested by Zhang and Bishop (2003) for high mercury wastes [95]. These processes consisted in stabilizing mercury using low-cost powder re-activated carbon (PAC) before its solidification with cement. To improve the mercury adsorption capacity, PAC may be impregnated with sulphide. The authors concluded that the S/S process by reactivated carbon and cement is a robust and effective technology for immobilization treatment of high mercury wastes.

Xin-Yan et al. (2009) investigated stabilization / solidification (S/S) of mercury-containing solid wastes using thiol-functionalized zeolite (TFZ) and cement [92]. TFZ was used to stabilize mercury in solid wastes, and then the stabilized wastes were subjected to cement solidification to test the effectiveness of the whole S/S process. The results show that TFZ has a high level of –SH content, and this species seems to be responsible for the mercury stabilization. The mercury adsorption capacity is greatly enhanced by thiol grafting, the maximum of which is increased about ten times. Though

Cl^{-} and PO_4^{3-} have negative effects on mercury adsorption by TFZ, the Portland cement solidification of TFZ stabilized surrogates containing 1000 mg mercury/kg can successfully pass the TCLP leaching test. The authors concluded that the stabilization / solidification process using TFZ and Portland cement is an effective technology to treat and dispose of mercury-containing wastes.

Annex C - Site descriptions

In the following annex, two sites for underground disposal in Germany will be described and explained in more detail:

a) Herfa-Neurode site

b) Konrad site

Moreover, examples of how the safety concept has been improved by learning from events in no longer operating underground waste storage facilities are given.

Figure 43 Location of Herfa-Neurode and Konrad sites (●) within Germany. (source: Bundesamt für Kartographie und Geodäsie (Note: scale refers only to original map size).

Herfa-Neurode is an underground disposal facility for hazardous waste (operating since 1972). The Konrad mine is a licensed facility for the final disposal of low- and medium-level radioactive waste. Operations are expected to start from app. 2017 onwards. Although their purposes are different, both sites may illustrate the fundamental safety philosophy, the basic safety concept as well as different ways to realize it, taking into account different overall geological conditions and also different host rocks.

In different sections of this text, the authors refer to geological ages. To understand these data, a geologic time scale is given below.

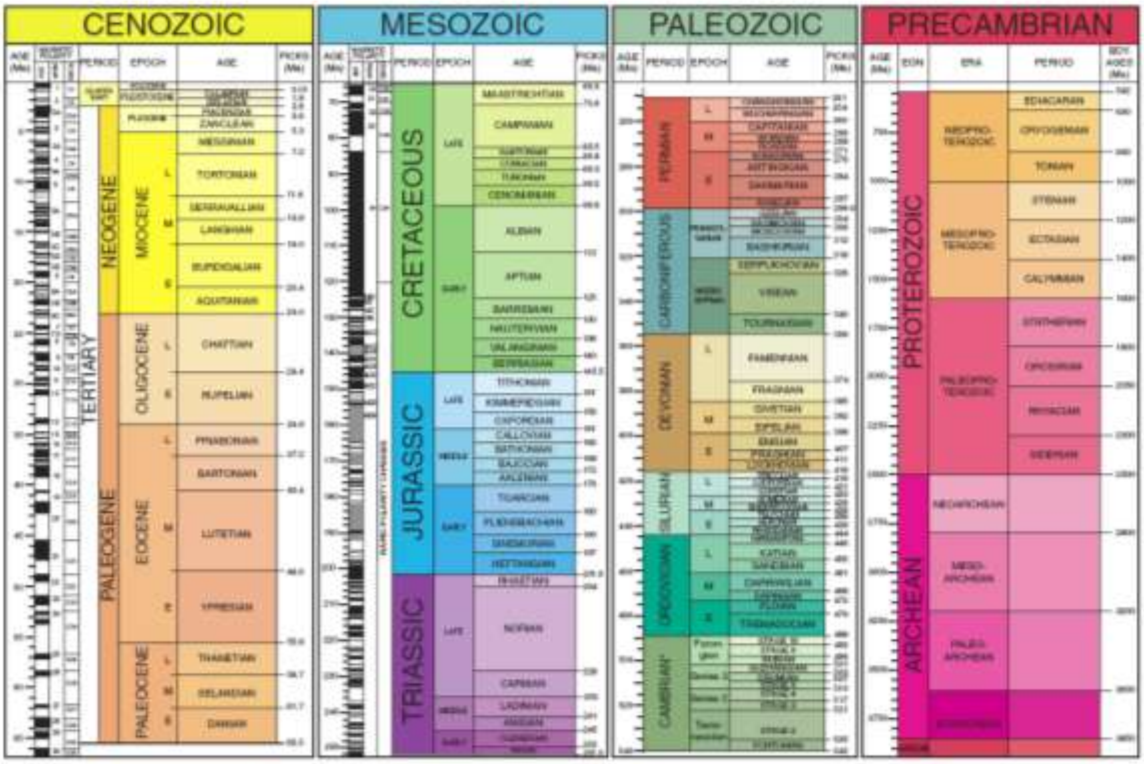

Figure 44 Geologic time scale. Note: instead of ‘late’ and ‘early’ in column ’epoch’, the synonymous terms ‘upper’, resp. ‘lower’ are often used (source: [77] The Geological Society of America [70]).

<u>Herfa-Neurode site</u>

Geological aspects

The Herfa-Neurode site represents the ‘classical’ concept of safe containment of hazardous wastes and their isolation from biosphere by ‘dry safekeeping’ in salt-rock. The host-rock in the narrower sense consists of two rather thin potash seams (each just 2.5 - 3.0 metres thick) which have been exploited before for industrial purposes. They do not represent a major geological barrier by themselves. The main geological barrier at the site are the overlying and underlying rock salt strata that both have a thickness of approximately 350 m and a lateral extension of about 1,100 km². The salt deposit is almost flat. It was formed by sedimentation during the 'Zechstein' age, approximately 240 million years ago. At the Herfa-Neurode site, the rock salt deposit is covered by layers of clay stone, which again is buried under app. 300 - 600 metres of so-called Bunter sandstone sequence, consisting of clay-, sand-, and silt-stones. The clay layers, altogether approximately 100 metres thick, serve to safely seal off the wastes against the water-bearing Bunter sandstone, a) by protecting the underlying rock salt from any impairment of its properties and b) by provision of additional retention capacities for contaminants that might become released from the disposal mine under certain circumstances.

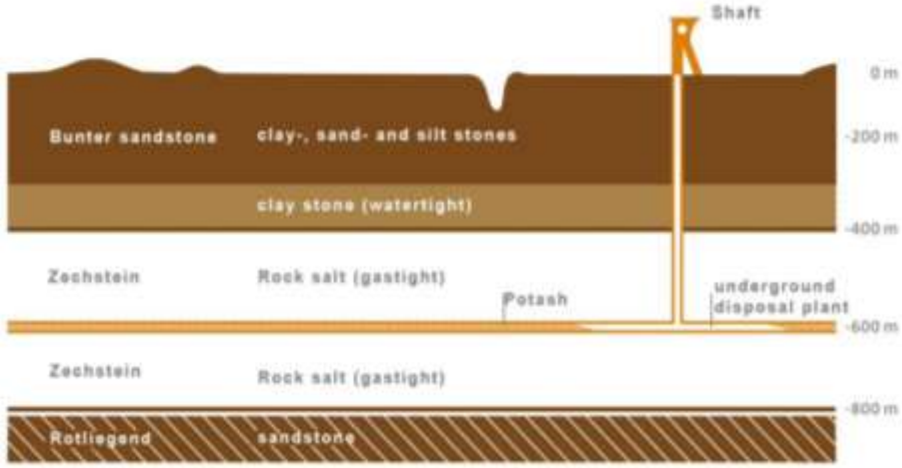

Figure 45 UTD[15] Herfa-Neurode, geological cross section of the site (source: K+S Entsorgung [4])

Even during previous geological developments (e.g. the folding of the Thüringen Forest) the clay layers maintained their sealing qualities. They guarantee reliable and enduring protection for the rock salt deposit and the enclosed waste.

Additionally, the salt deposit was penetrated by basaltic dykes during the Miocene (about 20 million years ago) but remained nearly unaltered, despite the locally very high thermic and tectonic stress. CO_2-intrusions from that time are still enclosed in the rock salt under high pressure. This fact serves as practical proof of the tightness of the rock salt over geological time frames.

[15] UTD = 'Untertagedeponie' (Underground Disposal Facility)

These extremely beneficial geological conditions have been the main reason to operate an underground waste disposal plant at Herfa-Neurode.

Operational aspects[16]

The total mining area, from which only a minor part has been used for disposal purposes since 1972, has been developed with the help of a total of four shafts sunk between 1900 and 1913.

Transport of the wastes to the underground waste disposal plant of Herfa-Neurode may be performed by truck or by rail. 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.

Figure 46 UTD Herfa-Neurode, big-bag disposal operation in an underground chamber (source: K+S Entsorgung [4])

[16] Mainly according to /BAA 10/

After the acceptance controls and the determination of conformity, the waste is cleared for storage. It is then unloaded from the delivery vehicle by forklifts and transported to its final destination (Figure 46). At the shaft entrance, the waste enters the underground transport system to the storage area. Underground, the waste is transported by trucks, all the way to the destined place of storage. The waste is stacked accordingly at final place of storage.

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 to ensure 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.

Safety and licensing aspects[17]

The rock salt beds need to be large enough and also particularly thick in the area selected for disposal. 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 the disposal area must be dry and free of water.

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.

The basis for the issuing of the necessary license is a long-term safety analysis. Its goal is the asite-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.

[17] Mainly according to /BAA 10/

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. Wastes that are explosive may not be accepted for storage. Wastes may also not react detrimentally with the rock salt environment. For details of the mining system, prerequisites for disposal, disposal conditions and the specific disposal concept it referred to /BAA 10/.

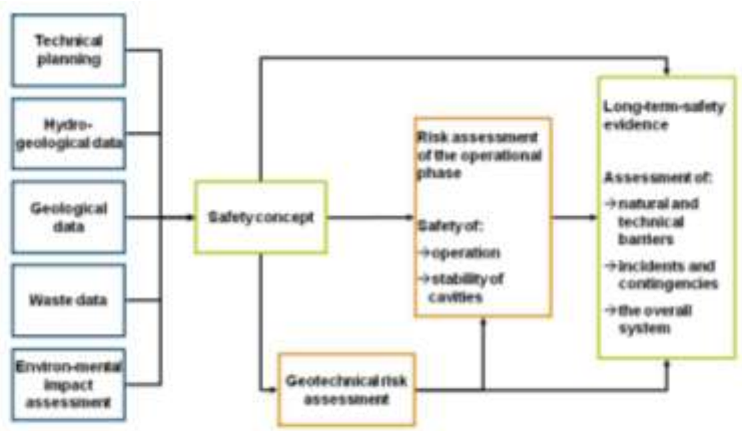

Figure 47 UTD Herfa-Neurode, flowchart of specific safety assessment (source: K+S Entsorgung [4])

Practice, so far, has shown that the use of already existing mines for disposal purposes holds several advantages (e.g. broad knowledge of geological situation, existing infrastructure that might allow operating the disposal mine very cost-efficiently). In such cases, very specific attention must be paid to the fact that the former mining of raw material has normally not 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.

Prerequisites for underground waste disposal

- Waste storage takes place only in excavated, disused areas of the mine
- Storage area has to be remote from still operating extraction areas; there must be the possibility to seal off both areas
- Cavities remain open and have no backfill obligation
- Cavities have to be stable and must remain accessible even after a long time

- Mine has to be dry and free of water
- Storage areas have to be sealed off from water-bearing layers by geological barriers

Wastes excluded from underground disposal

- Explosive
- Self-inflammable
- Spontaneously combustible
- Infectious
- Radioactive
- Releasing hazardous gases
- Liquid
- Increasing in volume

Approved and accepted waste types

- Alkaline wastes
- Acid wastes
- Cyanides (acid / alkaline)
- Mercury (acid / alkaline)
- Organic wastes (acid / alkaline)
- Hydroxide sludges
- Capacitors
- Transformers (Cu / Fe)
- Parts of transformers (Cu / Fe)
- Other wastes

Konrad site

Geological aspects[18]

The Konrad repository represents a future underground disposal facility (for destined radioactive wastes), which is currently under construction, but which does not follow the so-called ‘salt-concept’ (safe containment of hazardous wastes and their isolation from biosphere by ‘dry safekeeping’). Nevertheless, the location of the Konrad repository reveals a geological situation that is extremely favourable for an underground disposal facility.

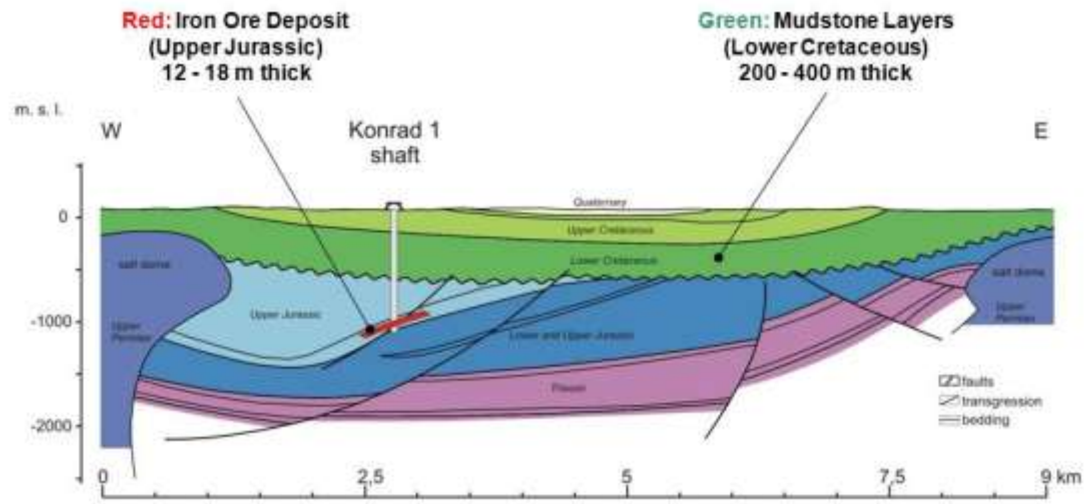

Figure 48 Geological Cross Section of the Konrad Site (source: Bundesamt für Strahlenschutz BfS, slightly modified [13])

Iron ore-bearing rocks (so-called ‘Coral Oolite’), which have been deposited about 150 millennia ago during the Upper Jurassic, are located at a depth of between 800 and 1,300 metres below ground. This iron ore deposit is the geological horizon in which the storage fields of the repository will be created. Due to some porosity and permeability, the iron ore layer itself does not feature a particularly well-suited host rock. But the overall geological situation clearly demonstrates that Upper Jurassic sediments (including the iron ore deposit) are appearing in a synclinal (trough-shaped) structure, which is covered discordantly as well as spaciously by an almost 400 metre-thick layer of impervious clayey rocks (transgression). This means that the storage area of the Konrad

[18] Mainly according to /BFS 10/

repository has no hydraulically effective connections to near-surface groundwater. This natural barrier serves for the complete isolation from the biosphere of the waste to be disposed of.

Figure 49 Model of the Konrad site showing the repository horizons and the overburden layers (source: Bundesamt für Strahlenschutz BfS [16]).

Historic and licensing aspects

Last century, in the 1930s, an extensive iron ore deposit was discovered in the area during exploratory drilling for oil. However, the mining company only commissioned the sinking of Konrad Shaft 1 in 9157, followed in 1960 by Shaft 2. Iron ore mining began in 1965, but by 1976 had already ceased as it became unprofitable. In 1975, the Radiation and Environmental Research Institute (now Helmholtz Centre) began to investigate the suitability of the mine as a repository for radioactive waste. In 1982, the Federal Institute for Metrology (Physikalisch-Technische Bundesanstalt – PTB), as the authority responsible for final storage before the founding of the Federal Office for Radiation Protection, submitted an application for the commencement of planning approval procedures. Approval of the main operational plan by the Lower Saxony State Authority for Mining, Energy and Geology in January 2008, enabled the commencement of essential mining work, which in turn represented a decisive step forward on the way to the transformation of the Konrad mine into a repository for low- and medium-level radioactive waste.

Safety aspects

The approval mentioned above is largely based on long-term safety assessments. As there are no hydraulic connections between the uppermost groundwater storey (biosphere) and the repository horizon, the conditions for a repository in the Konrad mine are very favourable. Any artificially created connections from earlier exploratory drilling have long been effectively sealed. The shafts themselves will also be suitably sealed once the operation is complete.

To verify the long-term safety of the site, simulations were performed on worst-case scenarios of conditions and processes to assess any potential transportation of radionuclides from the repository to the biosphere. Because the thick argillaceous barrier of the Lower Cretaceous completely seals off the top of the storage horizon, the probability of the existence of natural paths to groundwater-bearing layers close to the surface is extremely low.

Fundamentally, experience with regard to the negligible amounts of water found in the mine workings shows that the dangers of an uncontrollable influx of water during the operational life cycle of the repository may be completely ruled out.

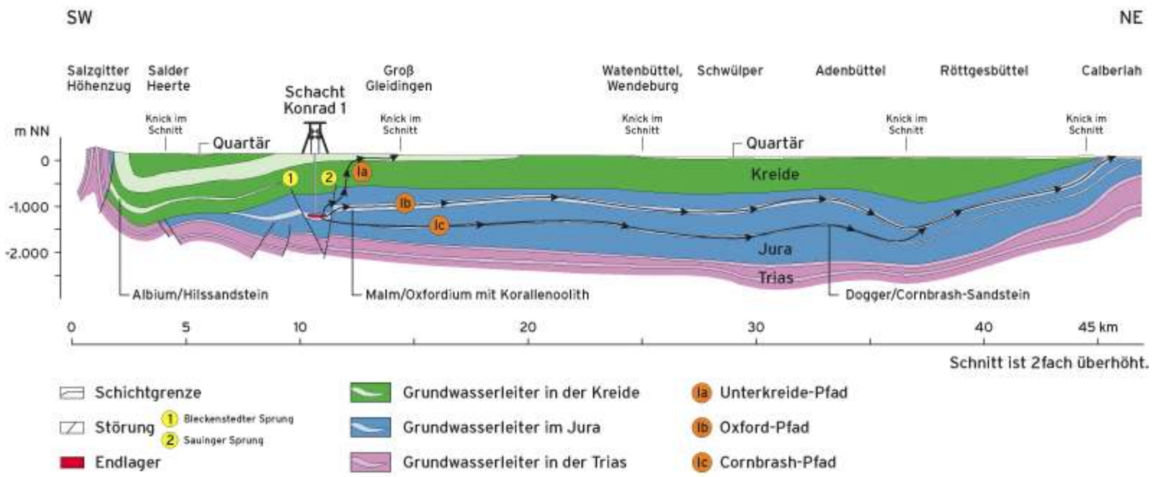

Figure 50 Cross section through the modelled area, with a depiction of the modelled (hypothetical) migration paths (1a, 1b, 1c). The location of the underground disposal facility is marked in red (source: Bundesamt für Strahlenschutz BfS [16])

Learning from the past

Underground disposal is a suitable option for isolation of hazardous wastes from the biosphere if the overall geological situation provides for sufficient isolating potential. A favourable geological situation consists of the host rock itself and / or overlying and underlying strata supporting the isolation. To a certain extent, the natural, geological barriers might be complemented by technical measures. Moreover, compliance with safety requirements during the operational phase is necessary to ensure that events that may have a serious impact on the operational and possibly long-term safety of the facility are avoided. Two examples shall demonstrate the challenges that may occur if fundamental safety principles are not respected in a due manner:

- Salt mine in Germany: Due to the inner structure of a salt dome, the salt has been mined in close proximity to the flanks of the salt deposit. As a result, the remaining thickness of salt rock, necessary to prevent the isolation of the facility from water bearing overlying rock, is not present in all parts of the former mining area. As a consequence, salt solution from outside the salt dome enters the mine. There is a risk that this solution will come into contact with the disposed waste and mobilizes waste components [15]. A remediation concept, which could also comprise retrieval of the wastes, is currently under development. For future facilities, such a situation can be avoided by choosing underground mines with a host rock of sufficient remaining thickness and mechanical stability.

- Salt mine in France: Insufficient control of waste acceptance criteria caused disposal of insufficiently characterized waste types underground. Part of the waste ignited spontaneously. It was impossible to control the fire and eventually the whole mine had to be closed [37]. Such a risk is not expected to be caused by elemental mercury or stabilized mercury, but may be of relevance if other waste types are accepted as well. For future facilities, such a situation may be avoided by strict compliance with waste acceptance criteria.

Annex D – Compilation of country related information on mining and mineral resources

Table 24 Mineral resources of countries of the Asia and Pacific region

Country / Region	[54]	[88]
Afghanistan	• Some 20 coal deposits • Largest iron ore deposit • Chromite ore reserves • Cretaceous rock salt deposits	
Bangladesh	• Large deposits of deep-lying coal	
Cambodia	• Iron, tin and bauxite deposits • Phosphorite in Permian lime-stone	• Smaller deposits of iron around igneous bodies • Large evaporate deposits in sedimentary rocks
China	• Underground salt extraction for centuries (drilling techniques) • World largest coal producer (Carboniferous – Cretaceous) • World largest RE-, W-, Sb-deposits, 2nd largest Ni-, 3rd largest Fe-, important Cr- and Cu-deposits	• Salt deposits
India	• Good resources of coal, Fe-, Mn-, Cr-, Ti-ores • Limited resources of Au, Ag, Cu, Pb, Zn, P, S, U • Clay deposits	• Large iron deposits in sedi-mentary rocks
Indonesia	• Well-known tin-belt • Cu- and Au-deposits • Clay deposits	
Kazakhstan	• Huge Fe-resources • Mn-, Cr-, Ni-, Co-, Ti-, V-, Al-, W-, Au-, Cu-, Mo-, Sn-, RE-, Pb-, Zn-deposits • Abundant NaCl-deposits, Salt diapirs • One of the world's largest pot-ash deposits	
Kyrgyzstan	• Rich in Hg-, Sb-, Au- and Sn-deposits, Fe-ores • Coal basins	
Laos	• Small amounts of Sn-ore, gyp-sum, coal and limestone • Immense reserves of rock salt, rich potash deposit	• Extensive large deposits of potash and halite • Smaller deposits of iron around igneous bodies
Malaysia	• Western and eastern tin-belt, central and eastern gold-belt • Important Fe-deposits • Widespread clay production	
Mongolia	• Many granites • Fe-deposits in all provinces • Cu-, Pb-, Zn-, Au-deposits • Rich in coal deposits	• Salt and gypsum deposits
Nepal	• Prospecting of Fe and Cu	

Pakistan	• Known deposits of Fe, Sb, Al, Pb, Mn, Au, Sr, As • Important limestone, gypsum and clay deposits • Need for geological and geo-chemical exploration	• Major salt deposits
Philippines	• Important Au-, Ag- and Cr-deposits	
Sri Lanka	• Rich in industrial clays	
Taiwan	• Tertiary coal • Cu-deposits	
Thailand	• One of world's major Sn-producers • Other important mineral products: W, Mn, Sb, Zn, Pb, Fe, barite fluorite, gypsum, rock salt, lignite, sulphides • Clay production • Granite batholiths	• Extensive deposits of potash and halite
Turkmenistan	• Abundant I- and Br-deposits • Abundant salt reserves • Clay deposits	
Uzbekistan	• Cu-, Au-, Ag-occurrences • Pb-, Zn-deposits	
Vietnam	• Large reserves of coal, Fe-ore, Cr, kaolin, phosphate	
Asia and the Pacific		• Rocks of all geologic ages • Significant deposits of clay

Table 25 Main known non-fuel commodities of mineral deposits in the Asia and Pacific region (excerpt from [88])

Country	Mineral Resources
Afghanistan	Aluminium, barite, beryllium, copper, chromium, gold, iron, lead, mercury, zinc, phosphorous, talc, sulphur, salt, and gemstones
Bangladesh	Titanium
Bhutan	Calcium carbide, dolomite, graphite, gypsum
Burma	Antimony, copper, nickel, lead, tin, tungsten, zinc, limestone, marble, precious stones
Cambodia	Iron, gemstones, manganese, phosphorous
China	Aluminium, antimony, arsenic, barite, copper, gold, iron, lead, magnesite, manganese, mercury, molybdenum, silver, strontium, tin, tungsten, vanadium, magnetite, zinc, uranium, cement, graphite, gypsum, garnet, lime, lithium, perlite, rare earth elements, phosphorous, potash, salt, strontium, sulphur, talc, fluorite
East Timor	Gold, manganese, marble
Fiji	Gold, copper
India	Aluminium, iron, titanium, chrome, copper, gold, lead, zinc, diamonds, limestone-dolomite-marble, barite, manganese, mica, cement, garnet, graphite, rare earth metals, salt, talc, wollastonite
Indonesia	Aluminum, copper, gold, silver, tin, nickel
Korea, North	Copper, gold, lead, tungsten, zinc, graphite, manganese, iron, sulphur, salt, fluorite, magnesite
Korea, South	Tungsten, graphite, molybdenum, lead
Laos	Aluminium, gold, iron, molybdenum, tin, gemstones, gypsum, potash, rock salt
Malaysia	Tin, copper, iron, bauxite, rare earth elements
Mongolia	Copper, gold, iron, molybdenum, silver, tantalum, tungsten, phosphate, tin, nickel, lead, zinc, fluorite, manganese, phosphate, salt, gypsum, zeolite
Marshall Islands	Deep seabed minerals
Nauru	Phosphate
Nepal	Quartz, limestone, copper, cobalt, iron, magnesite
New Caledonia	Copper, cobalt, chromium, iron, gold, manganese, silver, lead, nickel
Pakistan	Copper, iron, lead, zinc, chromium, barite, salt, phosphorous, limestone, gemstones
Papua New Guinea	Gold, copper, silver
Philippines	Copper, cobalt, silver, gold, nickel, salt
Pitcairn Islands	Manganese, iron, copper, gold, silver, zinc
Solomon Islands	Gold, bauxite, phosphate, lead, zinc, nickel
Sri Lanka	Gemstones, titanium, phosphate, graphite
Thailand	Tin, tungsten, tantalum, lead, gypsum, fluorite, cement, dolomite, feldspar, salt, kaolin, ball clay, limestone, potash, diatomite
Vietnam	Aluminium, copper, chromium, manganese, phosphorous, kaolin, silica sand, limestone, rare earth elements

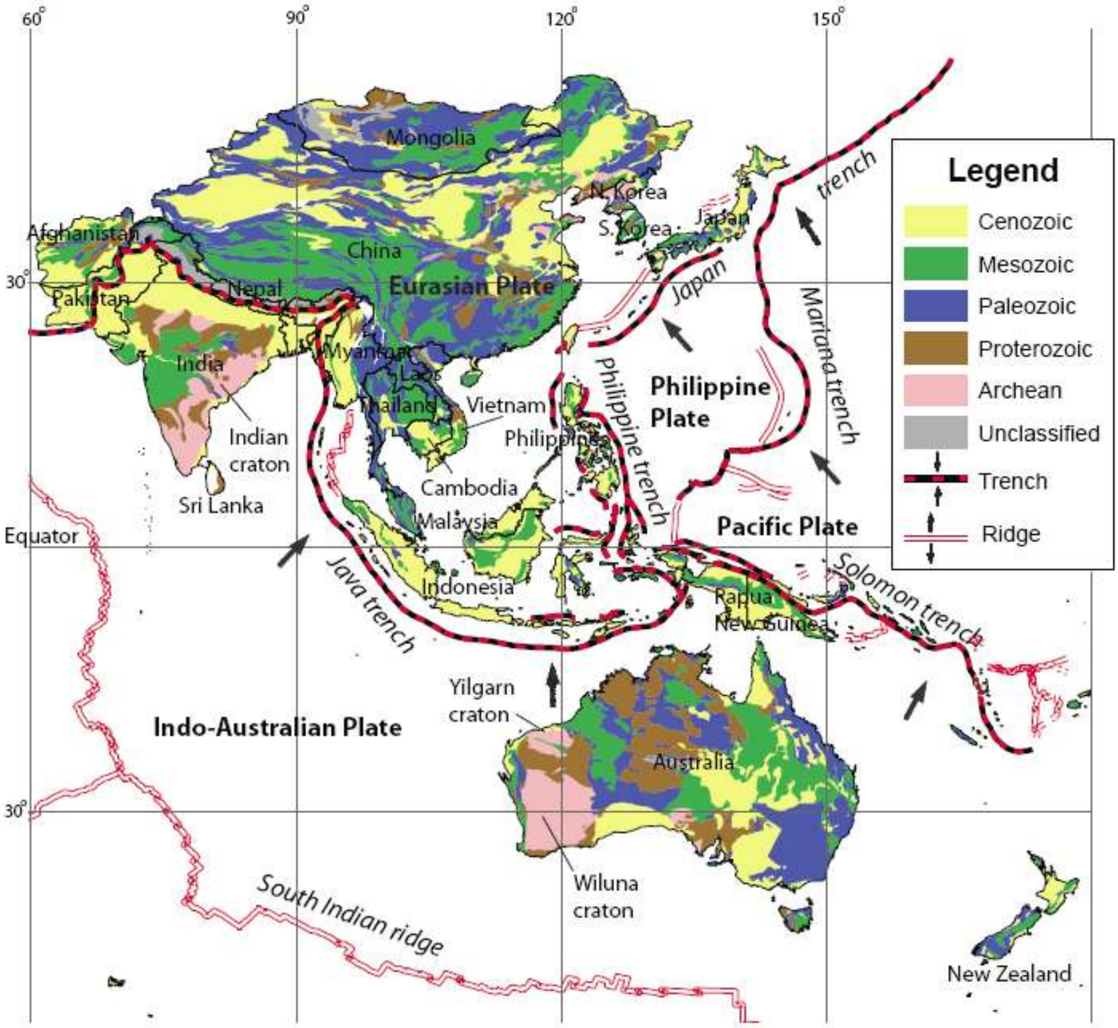

Figure 51 Distribution of rocks divided into the five main ages of earth history in the Asia and Pacific region (source: USGS [88])

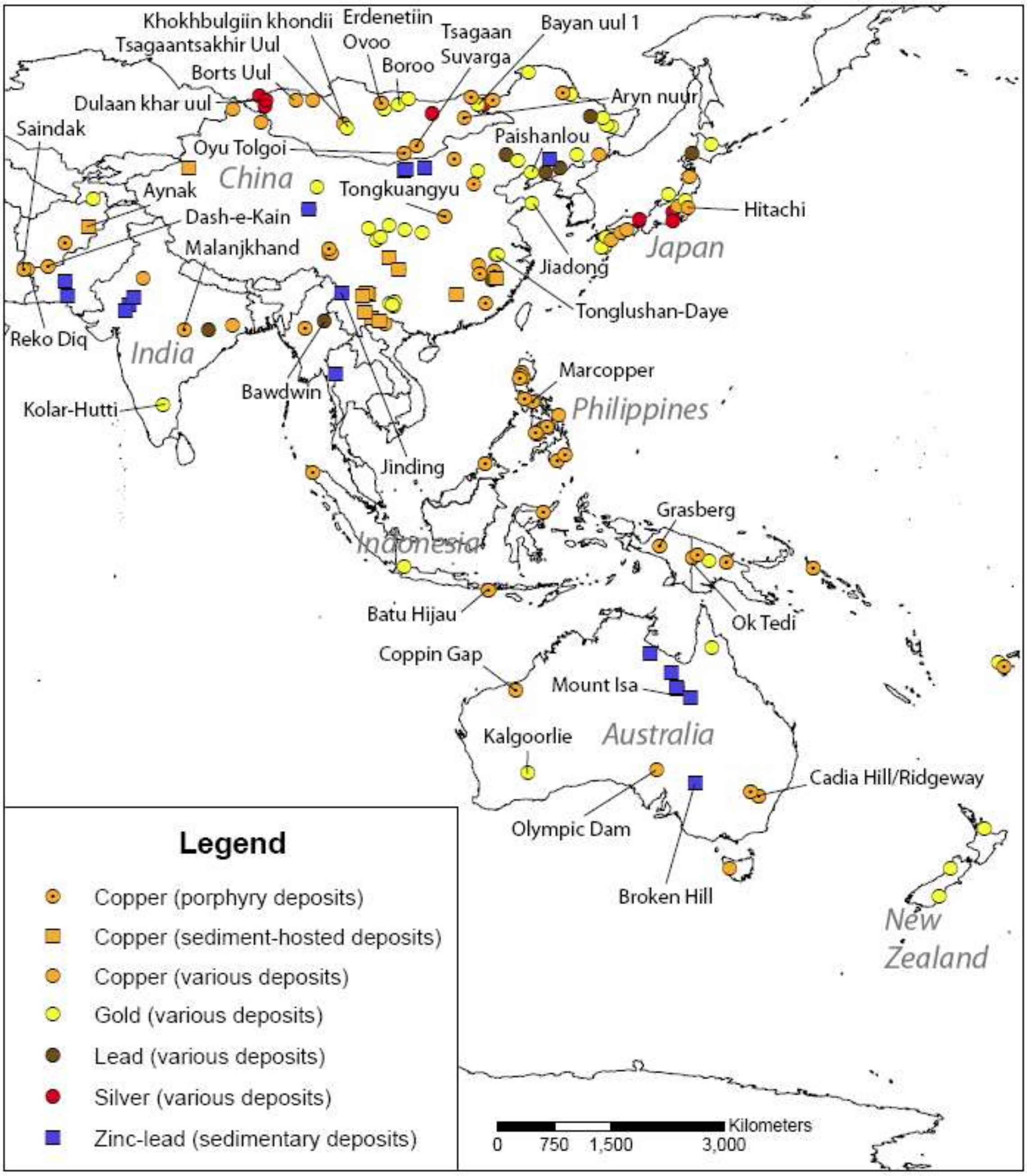

Figure 52 Main non-fuel mineral deposits in the Asia and Pacific region (1) (source: USGS [88])

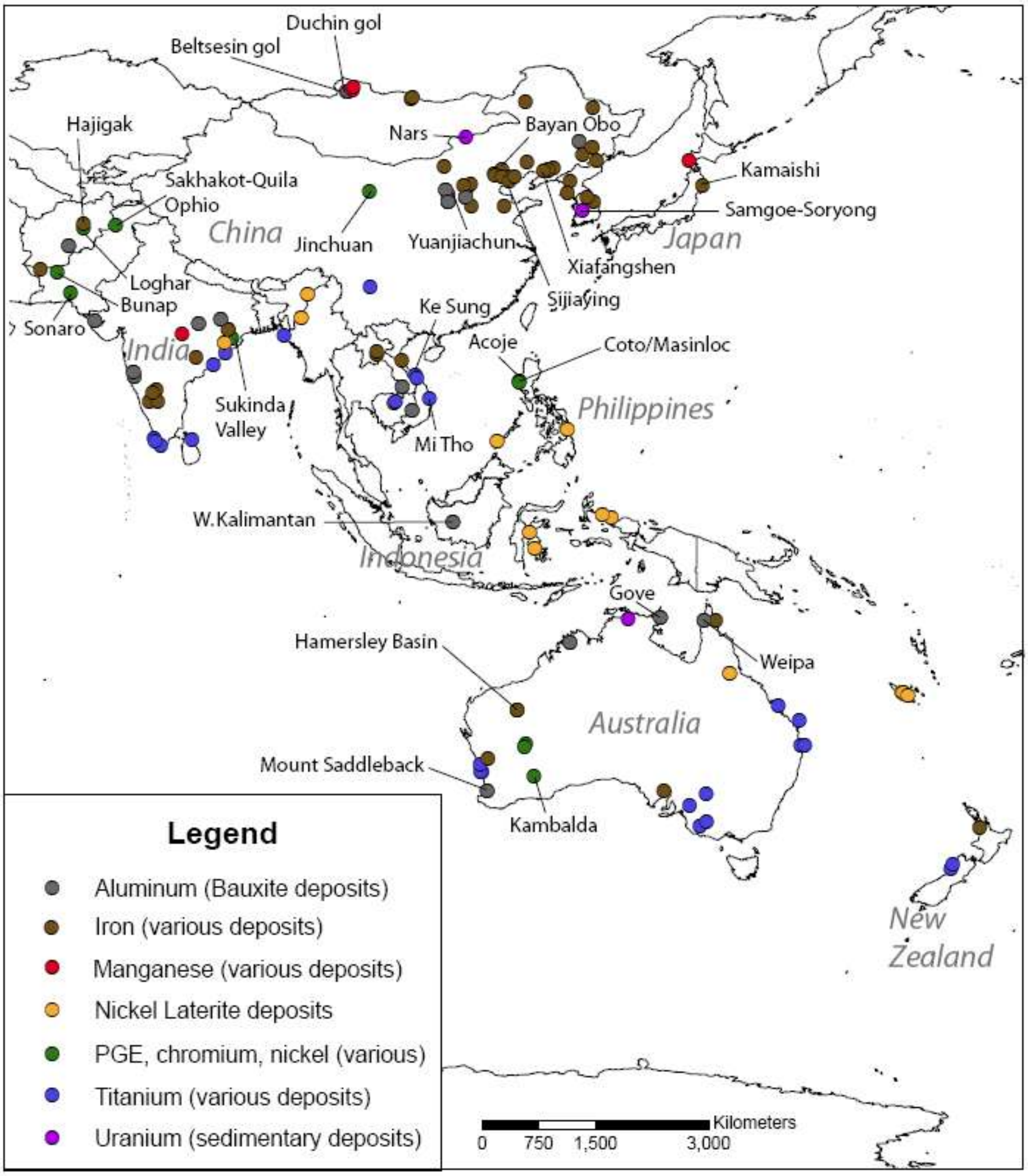

Figure 53 Main non-fuel mineral deposits in the Asia and Pacific region (2) (source: USGS [88])

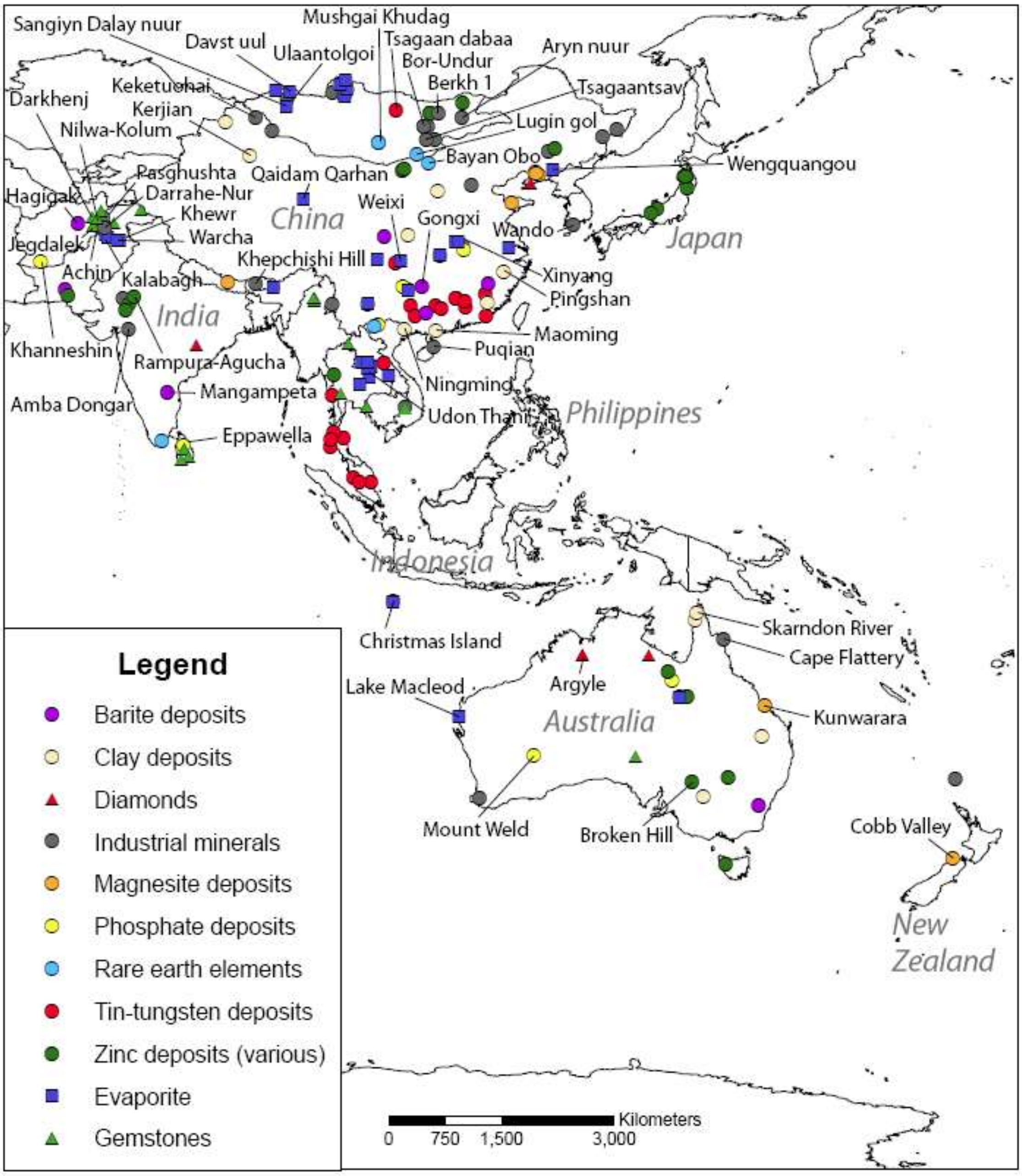

Figure 54 Main non-fuel mineral deposits in the Asia and Pacific region (3) (source: USGS [88])