# Technical options for storage and disposal of mercury


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## Introduction

This study has been undertaken under contract with UNEP Chemicals during a temporary leave of absence.

## Definitions used in this document

Mercury: All mention of mercury in this document relates to the management of excess supply of commodity-grade elemental mercury and mercury compounds in their pure form. It is recognised that significant amounts of other materials containing mercury exist that may call for attention in similar respect at later stage.

Storage facility: A facility where mercury is temporarily put under supervised conditions during a limited period of time. The time may be short-term, e.g. some months or a few years, or long-term, e.g. several years or a few decades.

Disposal facility: A facility where mercury is put permanently (during indefinite time), essentially with no or only very limited need for supervision and/or maintenance.

## Storage facility options

- Above ground in storage building, stored in retrievable manner
- Above ground in landfill, stored in retrievable manner
- Near surface below ground in landfill, stored in retrievable manner
- Near surface in shallow rock cavern, stored in retrievable manner
- Near surface in excavated storage location in surface soil, stored in retrievable manner
- Deep rock storage in crystalline rock caverns, stored in retrievable manner
- Deep rock storage in salt rock caverns, stored in retrievable manner
- Deep rock storage in sedimentary rock caverns, stored in retrievable manner

## Options for the physical and chemical form of stored mercury

- Liquid mercury in free form
- Liquid mercury in steel flasks (a few liters size)
- Liquid mercury in containers (up to about 1 $m^3$)
- Physical stabilization of mercury, e.g. cement solidified form and amalgamation
- Chemical stabilization of mercury into solid form, e.g. as mercury sulphide
- Combined physical and chemical stabilization, e.g. cement+sulphide stabilization, the SPSS-method, the MBS-method and the Mersade-method.

## Disposal facility options

- Above ground in storage building
- Above ground in landfill, stored in a manner not depending on supervision and/or maintenance
- Near surface below ground in landfill, stored in a manner not depending on supervision and/or maintenance
- Near surface in shallow rock cavern, stored in a manner not depending on supervision and/or maintenance
- Near surface in excavated storage location in surface soil, stored in a manner not depending on supervision and/or maintenance
- Deep rock storage in crystalline rock caverns, stored in a manner not depending on supervision and/or maintenance
- Deep rock storage in salt rock caverns, stored in a manner not depending on supervision and/or maintenance
- Deep rock storage in sedimentary rock caverns, stored in a manner not depending on supervision and/or maintenance

## Options for the physical and chemical form of disposed mercury

- Liquid mercury in free form
- Liquid mercury in steel flasks (a few liters size)
- Liquid mercury in containers (up to about 1 $m^3$)
- Physical stabilization of mercury, e.g. cement solidified form and amalgamation
- Chemical stabilization of mercury into solid form, e.g. as mercury sulphide
- Combined physical and chemical stabilization, e.g. cement+sulphide stabilization, the SPSS-method and the MBS-method

## Options for additional barriers in disposal facilities

- Tight disposal containers
- Concrete barrier constructions
- Clay sealing layers
- Synthetic sealing layers (e.g. plastic membranes, rubber membranes)
- Hydraulic barriers (e.g. drainage layers, gravel, crushed rock)
- Mechanical support (backfill material to support the host rock, gravel, crushed salt, crushed rock, concrete backfill)

## Short descriptions of the general construction and performance principles of the different storage facility options

From a technical point of view, mercury can be stored over several years in suitable storage facilities. Mercury as such is not inherently different from many other types of chemicals that are commonly stored under well controlled conditions. However, legal issues may call for further measures to be taken regarding mercury.

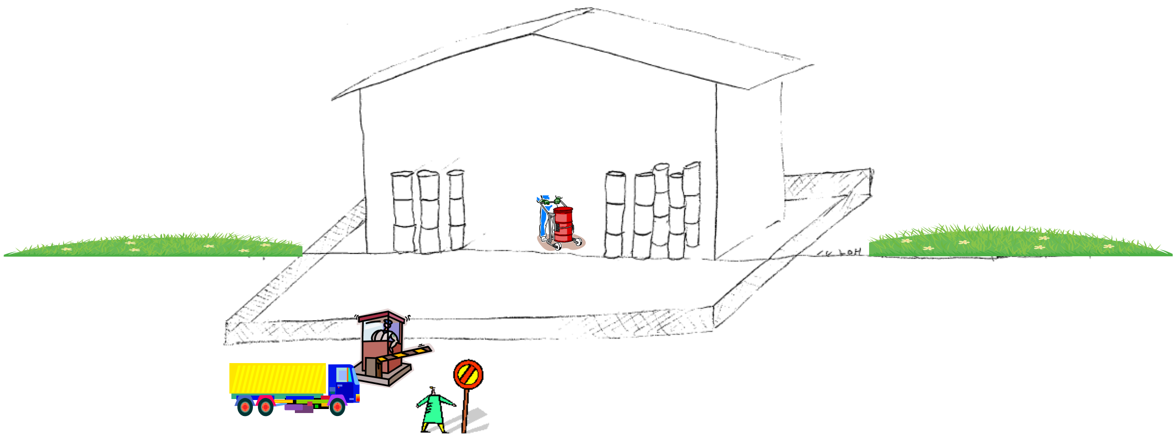
In the following some examples of different options available for storage of mercury are briefly described in text and simple illustrations. To give the reader an overview the different options are first summarized in Table 1.

***Table 1 Overview of different storage options.***

| | Storage facility options | Above ground in storage building | Above ground in landfill | Near surface below ground in landfill | Near surface in shallow rock cavern | Near surface in excavated storage location in surface soil | Deep rock storage in crystalline rock caverns | Deep rock storage in salt rock caverns | Deep rock storage in sedimentary rock caverns |
|---|---|---|---|---|---|---|---|---|---|
| Common demands | Mercury can be stored over a limited period of time. | X | X | X | X | X | X | X | X |
| | Method require supervision and a certain amount of maintenance. | X | X | X | X | X | X | X | X |
| | Mercury can be stored in a retrievable manner. | X | X | X | X | X | X | X | X |
| | Mercury is a toxic element. The storage facility can be protected against intrusion to avoid risk of human health and the environment. | X | X | X | X | X | X | X | X |
| | The stored mercury can be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions etc | X | X | X | X | X | X | X | X |
| | Mercury stored in the storage facility can be kept separate from other contaminants and materials in the storage facility, e.g. by compartmentalization of the storage facility. | X | X | X | X | X | X | X | X |
| | Mercury put into a disposal facility intended as a temporary storage solution can be constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the facility, or that any risk for uncontrolled release of mercury would appear. | X | X | X | X | X | X | X | X |
| | Certain requirements must and can be fulfilled regarding the competence of the storage facilities where the mercury is kept. | X | X | X | X | X | X | X | X |
| Specific demands | The geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility | X | X | X | X | X | X | X | X |
| | Protection against digging and construction work etc | X | X | X | | X | | | |
| | Protection against mining/quarrying etc | | | | X | | X | | X |
| | Protection against digging, salt mining/salt extraction and construction work etc | | | | | | | X | |
| | The rock mechanic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility | | | | X | | X | X | X |
| | These factors can be expected to be well fulfilled | X | X | X | | | X | X | X |
| | Under the condition that the requirements on geotechnical and tectonic stability can be assured, all these factors can be expected to be well fulfilled | | | | | X | | | |
| | Can be excavated in hill slopes or vertically in shallow bed rock | | | | X | | | | |
| | A typical rock overburden required is on the order of a few tens of metres | | | | X | | | | |
| | Cavern may have been excavated and used for other purposes, such as oil storage, military purposes etc. This may call for specific measures before use, e.g. clean-up | | | | X | X | X | X | X |
| | A typical surface soil deposit depth required for an excavated storage facility is on the order of a few tens of metres | | | | | X | | | |
| | Supporting constructions in the excavated facility, e.g. supporting walls may be required to assure mechanical stability | | | X | | X | | | |
| | Excavations may be quite large and finding separate storage locations for mercury would seem possible | | | | X | | X | X | X |
| | Storage facility would typically be located at a depth of several hundred metres below ground | | | | | | X | X | X |
| | Storage facility may be situated below the natural groundwater table and may require pumping of drainage water during operation | | | | (X) | (X) | X | | X |
| | Storage facility may be situated below the natural groundwater table, whereas the salt formation may be quite impermeable to water. However, the construction of the underground facilities, such as excavations, shafts etc, may constitute passages for water into the facility, hence it cannot be ruled out that the facility may require pumping of drainage water during operation | | | | | | | X | |

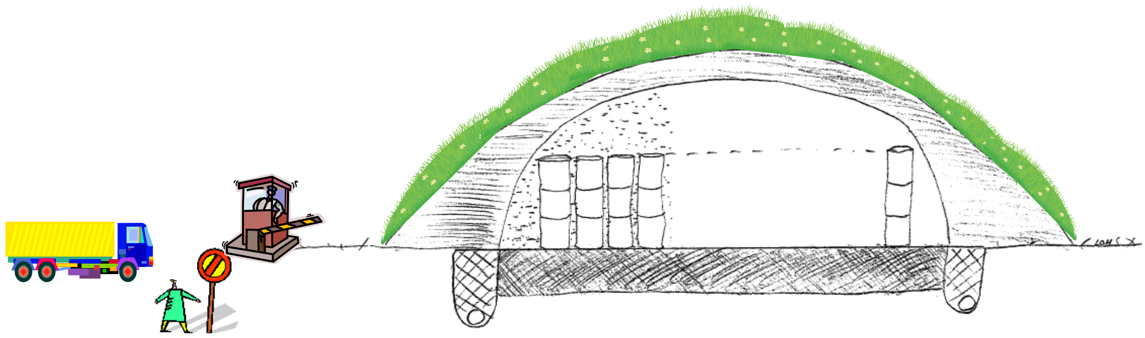
## Above ground in storage building, stored in retrievable manner

Mercury can be stored in conventional storage buildings over a limited period of time. The method requires supervision and a certain amount of maintenance. Mercury being a toxic element requires that the storage building is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions etc. This puts some requirements on the competence of the storage facilities where the mercury is kept. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility.



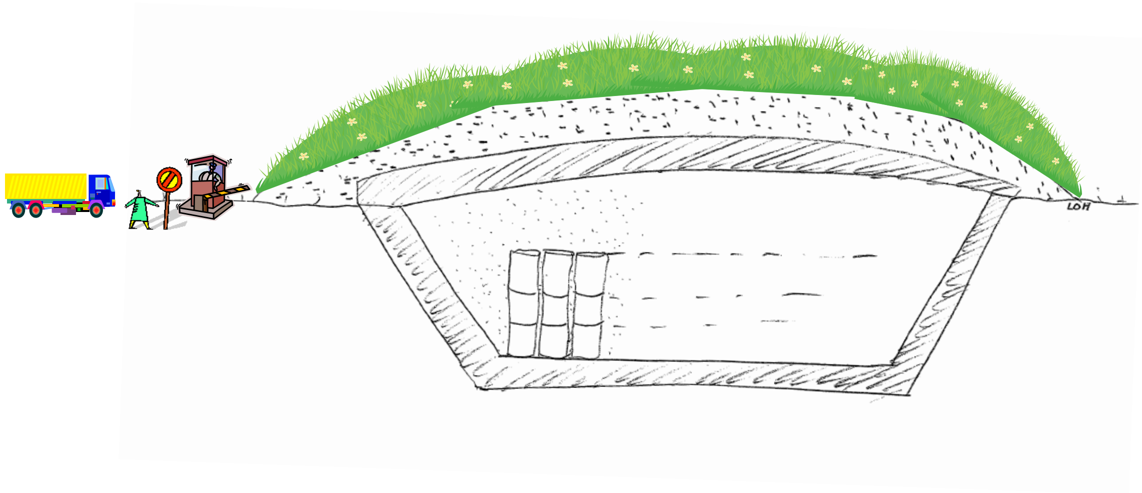
## Above ground in landfill, stored in retrievable manner

Mercury can be stored in an above-ground landfill over a limited period of time. The method requires supervision and a certain amount of maintenance. Mercury being a toxic element requires that the landfill is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the landfill where the mercury is kept. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the landfill. It is also important that mercury put into a landfill intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the landfill facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the landfill is kept separate from other contaminants and materials in the landfill, usually this can be achieved by compartmentalization of the landfill.



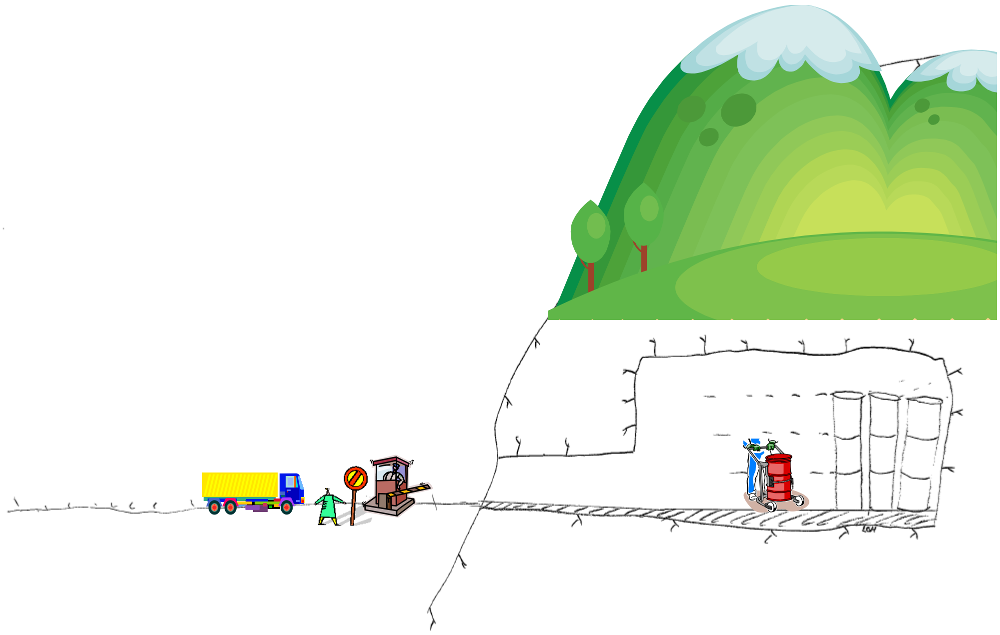
## Near surface below ground in landfill, stored in retrievable manner

Mercury can be stored in a below-ground landfill over a limited period of time. The method requires supervision and a certain amount of maintenance. Mercury being a toxic element requires that the landfill is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the landfill where the mercury is kept. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the landfill. It is also important that mercury put into a landfill intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the landfill facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the landfill is kept separate from other contaminants and materials in the landfill, usually this can be achieved by compartmentalization of the landfill.



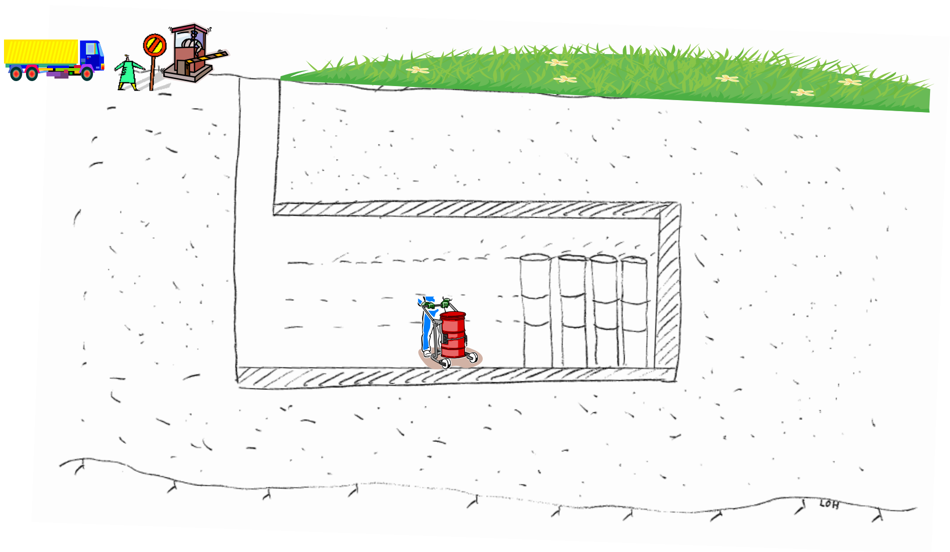
## Near surface in shallow rock cavern, stored in retrievable manner

Mercury can be stored in a shallow rock cavern over a limited period of time. The method requires some supervision and a minor amount of maintenance. Mercury being a toxic element requires that the storage facility is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the rock storage facility where the mercury is kept. Further, the rock mechanic, geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by rock cavern storages. It is also important that mercury put into a rock cavern intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the storage facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the rock cavern is kept separate from other contaminants and materials in the storage facility, usually this can be achieved by compartmentalization of the caverns. Rock caverns can be excavated in hill slopes (as inferred by the illustration) or vertically in shallow bed rock. A typical rock overburden required for a shallow rock storage cavern is on the order of a few tens of metres. A shallow rock cavern may have been excavated and used for other purposes, such as oil storage, military purposes etc. This may call for specific measures before use, e.g. clean-up.



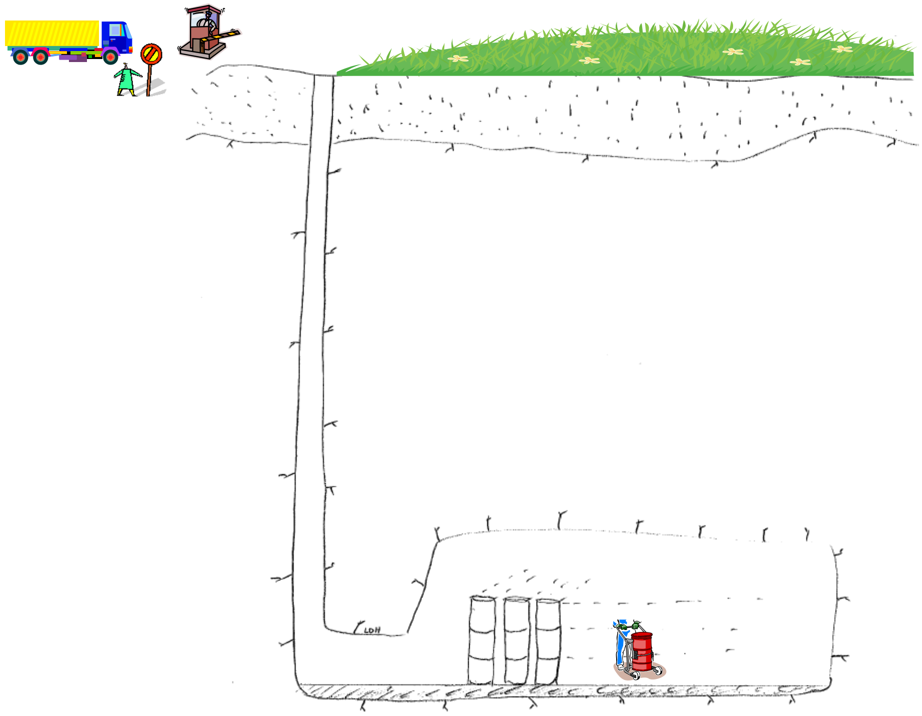
## Near surface in excavated storage location in surface soil, stored in retrievable manner

Mercury can be stored in a excavated storage facilities in surface soils over a limited period of time. The method requires some supervision and a certain amount of maintenance. Mercury being a toxic element requires that the landfill is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the excavated storage facility where the mercury is kept. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. Under the condition that the requirements on geotechnical and tectonic stability can be assured, all these factors can be expected to be well fulfilled by excavated storage facilities in surface soil. It is also important that mercury put into an excavated storage facility in surface soil intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the storage facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the storage facility is kept separate from other contaminants and materials in the storage facility, usually this can be achieved by compartmentalization of the storage facility. Storage facilities can be excavated in hill slopes or vertically in shallow soil deposits (as inferred by the illustration) of sufficient depth. A typical surface soil deposit depth required for an excavated storage facility is on the order of a few tens of metres. Supporting constructions in the excavated facility, e.g. supporting walls may be required to assure mechanical stability.



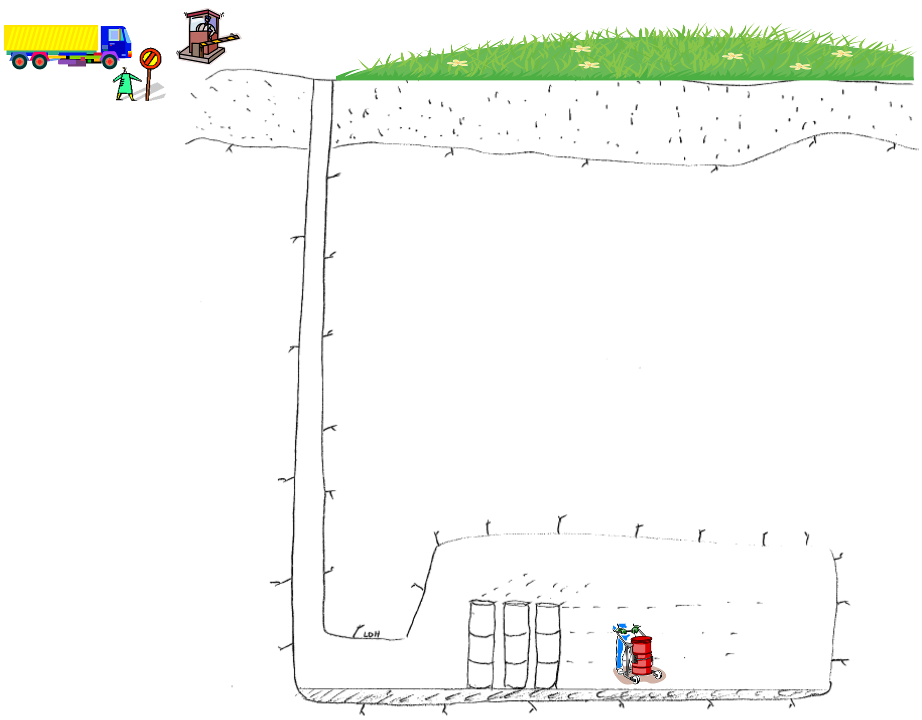
## Deep rock storage in crystalline rock caverns, stored in retrievable manner

Mercury can be stored in a deep crystalline rock cavern over a limited period of time. The method requires a minimum of supervision and maintenance. Mercury being a toxic element requires that the storage facility is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging, mining and construction work etc. This puts some requirements on the competence of the rock storage facility where the mercury is kept. Further, the geotechnical, rock mechanical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by rock cavern storages. It is also important that mercury put into a rock cavern intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the storage facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the rock cavern is kept separate from other contaminants and materials in the storage facility, usually this can be achieved by compartmentalization of the caverns. Deep rock storage facilities are most likely facilities that were built for other purposes, such as mining activities. Therefore, the excavations may be quite large and finding separate storage locations for mercury would seem possible. A deep rock storage facility would typically be located at a depth of several hundred metres below ground. A typical feature of deep crystalline rock storage facility is that it is situated below the natural groundwater table, the facility may therefore require pumping of drainage water during operation.



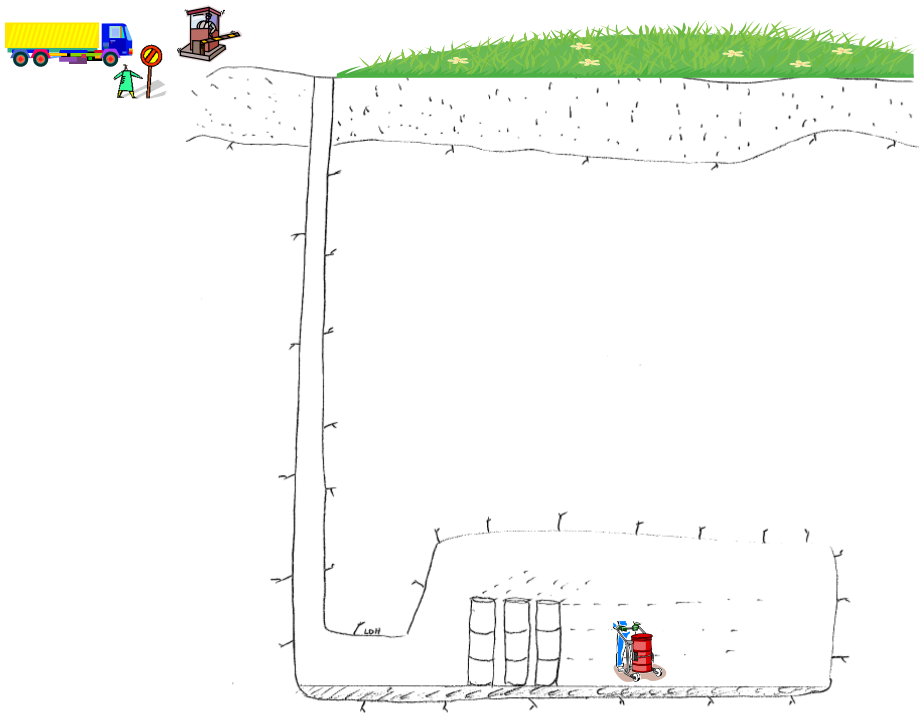
## Deep rock storage in salt rock caverns, stored in retrievable manner

Mercury can be stored in a deep salt rock cavern over a limited period of time. The method requires a minimum of supervision and maintenance. Mercury being a toxic element requires that the storage facility is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging, salt mining/salt extraction and construction work etc. This puts some requirements on the competence of the salt rock storage facility where the mercury is kept. Further, the geotechnical, rock mechanical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by salt rock cavern storages. It is also important that mercury put into a salt rock cavern intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the storage facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the salt rock cavern is kept separate from other contaminants and materials in the storage, usually this can be achieved by compartmentalization of the salt rock caverns. Deep salt rock storage facilities are most likely facilities that were built for other purposes, such as salt mining activities. Therefore, the excavations may be quite large and finding separate storage locations for mercury would seem possible. A deep rock storage facility would typically be located at a depth of several hundred metres below ground. Typical features of deep salt rock storage facility are that it is situated below the natural groundwater table, whereas the salt formation may be quite impermeable to water. However, the construction of the underground facilities, such as excavations, shafts etc, may constitute passages for water into the facility, hence it cannot be ruled out that the facility may require pumping of drainage water during operation.



## Deep rock storage in sedimentary rock caverns, stored in retrievable manner

Mercury can be stored in a deep sedimentary rock cavern over a limited period of time. The method requires a minimum of supervision and maintenance. Mercury being a toxic element requires that the storage facility is protected against intrusion to avoid risk of human health and the environment. The stored mercury should be protected from the direct exposure to rain, sun, wind, flooding, extreme cold conditions, digging, mining/quarrying and construction work etc. This puts some requirements on the competence of the sedimentary rock storage facility where the mercury is kept. Further, the geotechnical, rock mechanical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by sedimentary rock cavern storages. It is also important that mercury put into a rock cavern intended as a temporary storage solution is constructed in such a way that retrieval of the mercury can be done efficiently and without jeopardizing the integrity of the storage facility, or that any risk for uncontrolled release of mercury would appear. It is important that mercury stored in the rock cavern is kept separate from other contaminants and materials in the storage facility, usually this can be achieved by compartmentalization of the caverns. Deep sedimentary rock storage facilities are most likely facilities that were built for other purposes, such as mining activities. Therefore, the excavations may be quite large and finding separate storage locations for mercury would seem possible. A deep sedimentary rock storage facility would typically be located at a depth of several hundred metres below ground. A typical feature of deep sedimentary rock storage facility is that it is situated below the natural groundwater table, the facility may therefore require pumping of drainage water during operation.



## Options for the physical and chemical form of stored mercury

To give the reader a brief overview of different options for converting the physical and chemical form of mercury prior to storage is summarized in Table 2.

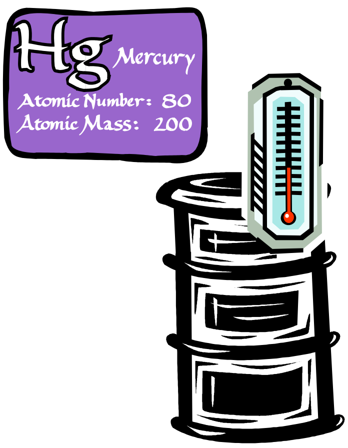
*Table 2 Overview of different stabilization options.*

| Options for the physical and chemical form of stored mercury | Can be handled by conventional methods | Would require additional packaging during storage | Cost | Risks during handling in storage facility | Physical stability of packages |
|---|---|---|---|---|---|
| Liquid mercury in free form | X | X | Low | X | |
| Liquid mercury in steel flasks | X | | High | (X) | X |
| Liquid mercury in containers | X | | Moderate | (X) | X |
| Physical stabilization of mercury | X | | 3000-27000 €/tonne Hg | | X |
| Chemical stabilization of mercury into solid form | X | (X) | 2000-4000 €/tonne Hg | | (X) |
| Combined physical and chemical stabilization | X | | 3500-4000 €/tonne Hg | | X |

## Liquid mercury in free form

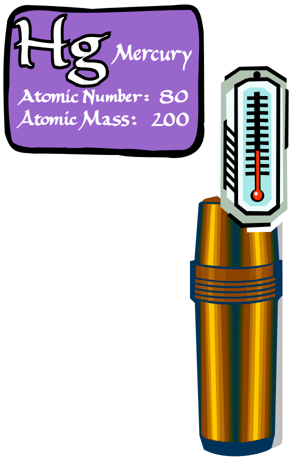
In principle, mercury can be handled as any among a wide variety of chemical compounds that are in common use in society today. Many of these chemicals are hazardous, but can still be managed by appropriate handling according to regulations. Mercury is no exception in this respect. Mercury is also today handled in bulk quantities by industry as a commodity chemical. In essence the same practices can be applied with reasonable safety for storage of mercury in different types of storage facilities. The most common practice today is to store mercury in liquid form in standard steel flasks or steel containers in storage buildings.

However, handling of liquid mercury in free form without appropriate containers must be strongly discouraged.



## Liquid mercury in steel flasks (a few liters size)

Special steel flasks have been developed to contain mercury in a safe way suitable for handling, transport and storage. These steel flasks are very robust and tight. With little doubt would storage of mercury in steel flasks be a viable option. A disadvantage is the high prize.




## Liquid mercury in containers (up to about 1 m$^3$, even up to 50 tonnes)

Mercury is also often handled in different types of steel containers. The steel containers differ in size, the largest may contain up to 1 m$^3$ of liquid mercury. For long term storage purpose a 50 tonnes steel container has been developed (Mersade). Larger containers may become impractical due to the heavy weight when filled by mercury. With little doubt would storage of mercury in steel containers be a viable option. An advantage is the reasonable prize in comparison with steel flasks.

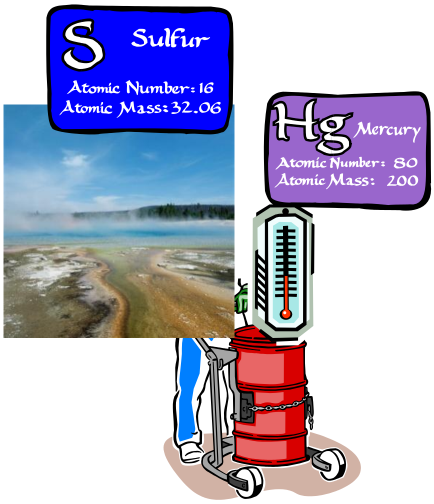

## Physical stabilization of mercury, e.g. cement solidified form and amalgamation

Physical stabilization of mercury can be achieved in different ways. One method is to mix the mercury into cement to produce a solid body where the mercury is contained within the porous internal structure of the hardened cement. While this method may produce a solidified form of mercury, the chemical and toxic properties of mercury remain unchanged. Storage of mercury in cement solidified form may constitute a hazard due to the possibly high vapor pressure of mercury of the product. In combination with other physical containment this problem can be managed.

Amalgamation is a method where metallic mercury is dissolved by a solid metal, forming an alloy. Mercury alloys are commonly named amalgam. Mercury readily forms amalgam with copper, zinc, silver, tin and other metals such as sodium. The strong tendency of mercury to amalgamate gold is the tragic basis of the use of mercury for extraction of gold in small artisanal gold mining. Amalgamation results in a hard solid form of mercury, whereas the chemical and toxic properties are only to a part affected. Storage of mercury in solidified form as amalgam may constitute a hazard due to the possibly high vapor pressure of mercury of the product. In combination with other physical containment this problem can be managed.

## Chemical stabilization of mercury into solid form, e.g. as mercury sulphide

Mercury can be reacted with sulphur to produce a solid mineral consisting of mercury sulphide. Mercury sulphide is a common form for mercury in the nature, where it constitutes many of the mineralisations being mined for extraction of mercury. Mercury sulphide is very stable and has low solubility and low toxicity. However, mercury sulphide is susceptible to oxidation and is therefore suitable for storage under oxygen-free conditions. In practical terms this means emplacement of the stabilized product in air-tight containers during storage.




## Combined physical and chemical stabilization, e.g. cement+sulphide stabilization, the SPSS-method, the MBS-method, the Mersade-method

There exist a variety of different alternative methods for combined physical and chemical stabilization of mercury. The different methods are based on chemical transformation of mercury to a solid form, commonly mercury sulphide, which in turn is trapped in a porous matrix such as cement that forms a solid body. The advantage is that mercury is chemically bond in a form that has low vapor pressure and low solubility in water, further a solid body is formed that is easy to handle and ensures mechanical stability.

# Short descriptions of the general construction and performance principles of the different disposal facility options

The different disposal facility options and options for physical and chemical form of mercury for disposal should be compared with stringent criteria for the function over time. In the first section an example of such criteria set up by the Swedish Environmental Protection Agency (1997) are briefly presented.

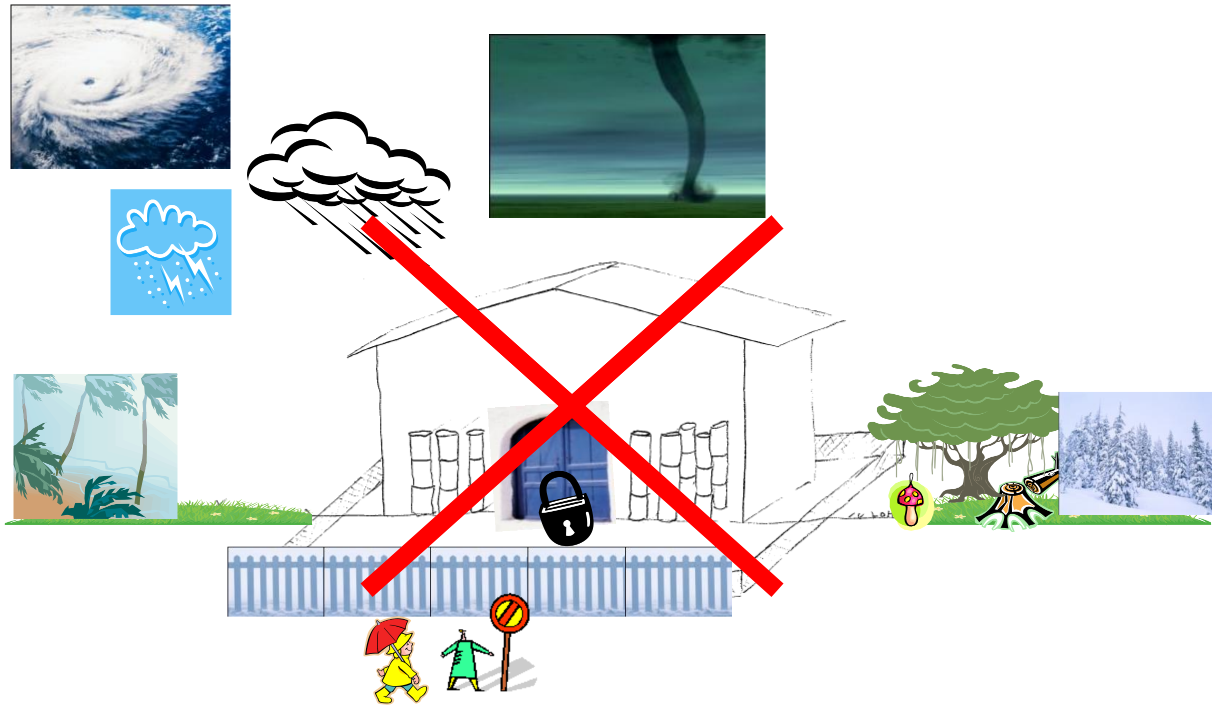
## Demands on a disposal facility for mercury (Swedish EPA, 1997)

- Time aspects
  - Short-term or long-term releases must be within acceptable load to recipients
  - Mercury is a stable element that will not degrade
  - Disposal method - demands on the safety function - very long time
- Protection against accidental human intrusion
  - Active knowledge of a disposal facility cannot be proven over long time
  - A disposal facility must provide protection against e.g. digging, construction work
- Return mercury in suitable form in its natural geochemical cycle
  - Chemical form of mercury - resemble the original ore. Stable form desired.
- Stringent requirements for safety (Principle of multiple, independent barriers)
  - Sufficiently functional - even if unforeseen events happen, such as:
    - Changes of chemical conditions
    - Changes of climate
    - Failure of one or more barriers
- Requirements on restricted release of mercury
  - Below the level that can be accommodated by nature/receiving environment.

In the following some examples of different options available for disposal of mercury are briefly described in text and simple illustrations.

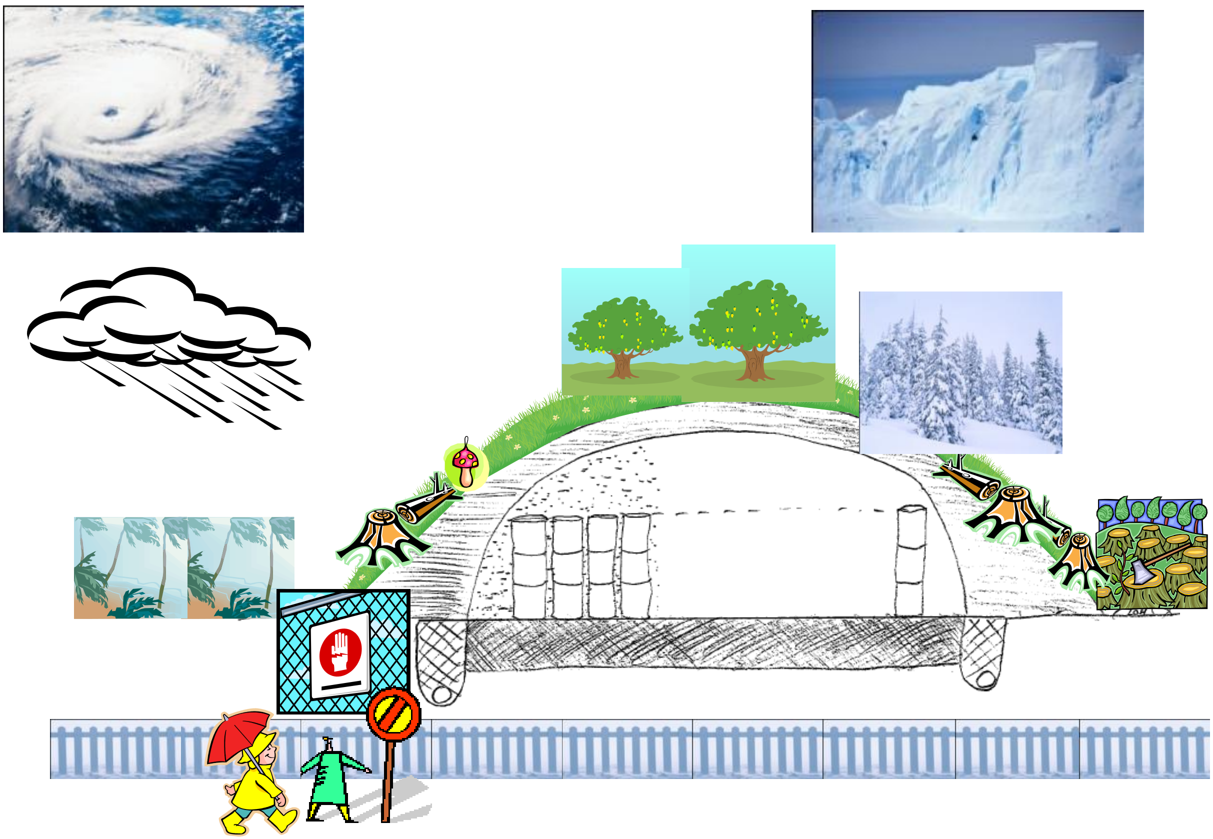
## Above ground disposal in storage building

Mercury may as an idea be disposed in conventional storage buildings over long time. However, in practice this option does not seem viable in the long-term. Significant stress will be put on the integrity of any building at the ground surface left without supervision and maintenance. Mercury being a toxic element requires that the disposal is protected against intrusion to avoid risk of human health and the environment. Further, the disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions etc. This puts some requirements on the competence of the facilities where the mercury is disposed. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the disposal facility. In medium- to long-term it can be expected that a building structure exposed to the forces of nature will not be able to maintain these functions. The implementation of this method for disposal of mercury as a long-term solution must be strongly discouraged.



## Above ground disposal in landfill

Mercury can be disposed in an above-ground landfill over an extended period of time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the landfill is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the landfill where the mercury is kept. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the landfill. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a landfill that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the landfill. It is important that mercury disposed in the landfill is kept separate from other contaminants and materials in the landfill, usually this can be achieved by compartmentalization of the landfill. In the long-term, it remains questionable if an above ground landfill will be able to maintain its barrier functions. The longevity of different landfill designs should be evaluated considering the site specific conditions, e.g. climatic, tectonical, geotechnical. In the very long-term, the integrity of any ground surface structure will limited by such events as glaciations periods. The decision whether a surface landfill would be compliant with desired safety functions need to be taken on a case to case basis.

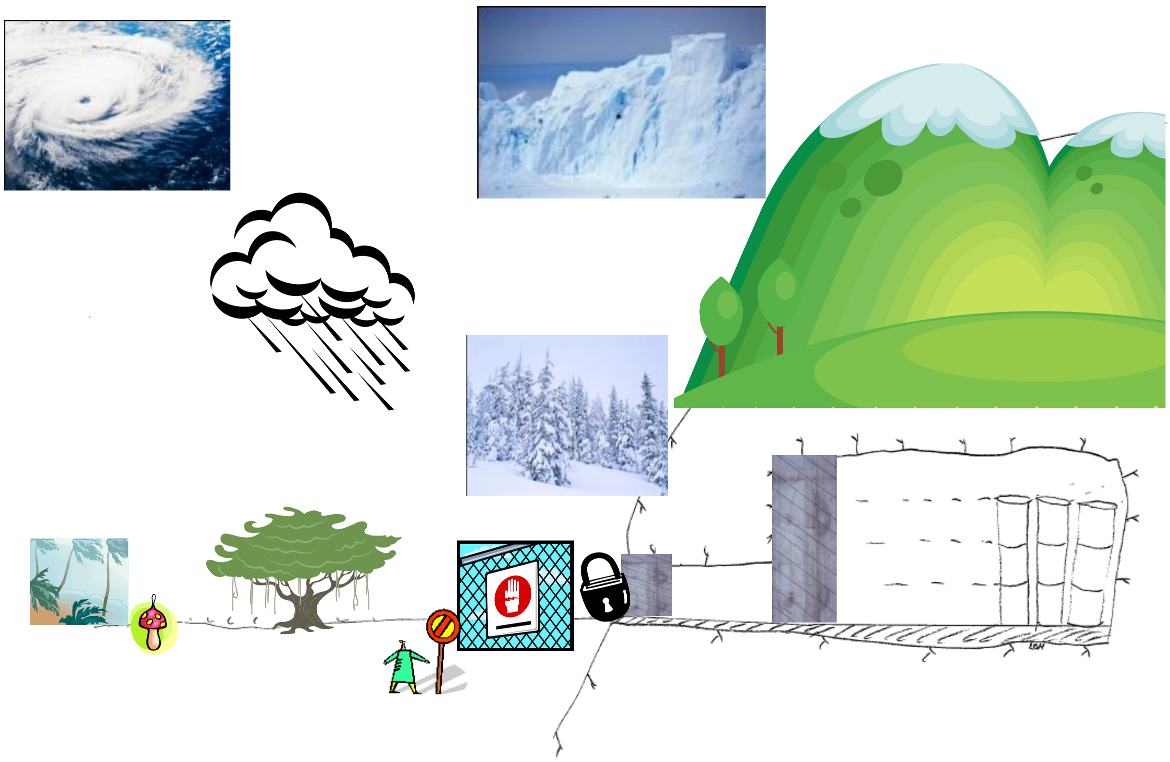


## Near surface below ground disposal in landfill

Mercury can be disposed in a below-ground landfill over an extended period of time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the landfill is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the landfill where the mercury is kept. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the landfill. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a landfill that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the landfill. It is important that mercury disposed in the landfill is kept separate from other contaminants and materials in the landfill, usually this can be achieved by compartmentalization of the landfill. In the long-term, it remains questionable if an above ground landfill will be able to maintain its barrier functions. The longevity of different landfill designs should be evaluated considering the site specific conditions, e.g. climatic, tectonical, geotechnical. In the very long-term, the integrity of any ground surface structure will limited by such events as glaciations periods. The decision whether a below ground landfill would be compliant with desired safety functions need to be taken on a case to case basis.

## Near surface disposal in shallow rock cavern

Mercury can be disposed in a shallow rock cavern over an extended period of time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the disposal facility is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the rock disposal facility where the mercury is disposed. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a disposal facility that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the disposal facility. It is important that mercury disposed in the rock cavern is kept separate from other contaminants and materials in the disposal facility, usually this can be achieved by compartmentalization of the caverns. Rock caverns can be excavated in hill slopes (as inferred by the illustration) or vertically in shallow bed rock. A typical rock overburden required for a shallow rock storage cavern is on the order of a few tens of metres. The longevity of different shallow rock disposal facility designs should be evaluated considering the site specific conditions, e.g. climatic, tectonical, geomechanical. In the very long-term, the integrity of even such robust structures as a shallow rock disposal facility may be limited by such events as glaciations periods. However, in comparison with surface landfill disposal facilities the safety functions of a shallow rock disposal facility would appear to be superior in the long-term. The decision whether a shallow rock disposal facility would be compliant with desired safety functions need to be taken on a case to case basis.

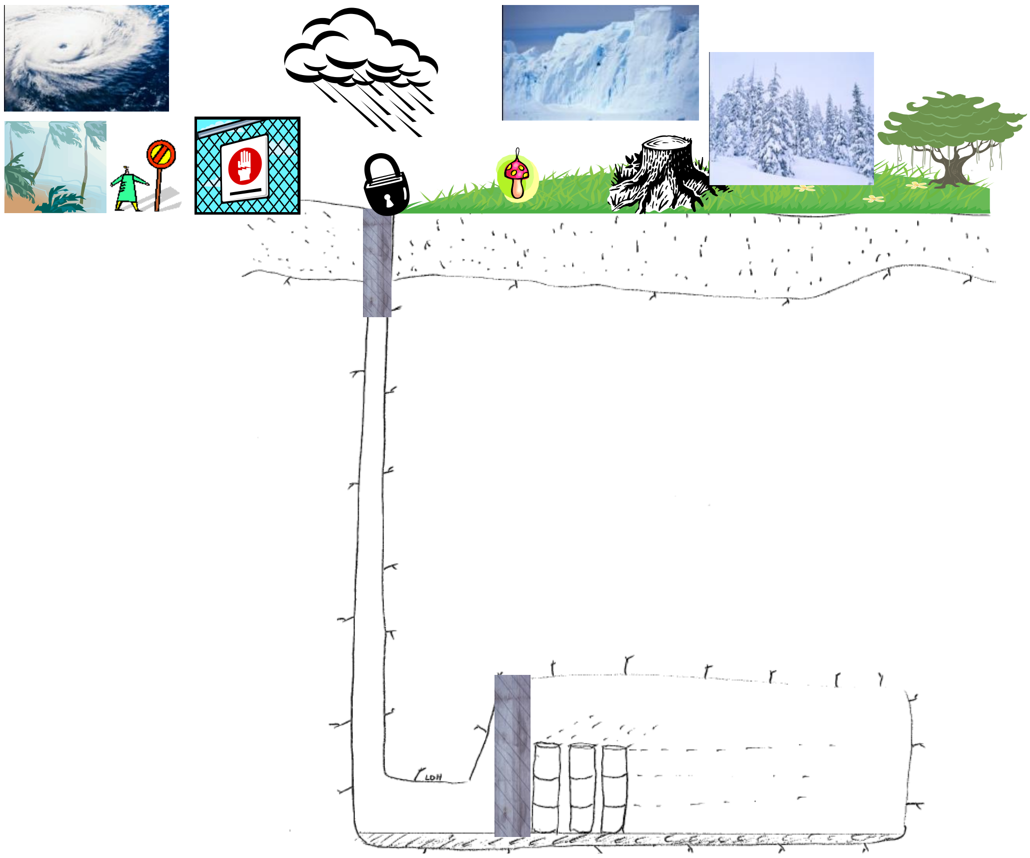


## Near surface disposal in excavated disposal location in surface soil

Mercury can be disposed in excavated storage facilities in surface soils over an extended period of time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the disposal facility is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of the excavated disposal facility in surface soil where the mercury is disposed. Further, the geotechnical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a disposal facility that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the disposal facility. It is important that mercury disposed in the excavated disposal facility is kept separate from other contaminants and materials in the disposal facility, usually this can be achieved by compartmentalization of the disposal facility. Disposal caverns can be excavated in hill slopes or vertically in surface soil (as inferred by the illustration A typical surface soil deposit depth required for an excavated disposal facility is on the order of a few tens of metres. Supporting constructions in the excavated facility, e.g. supporting walls may be required to assure mechanical stability. The longevity of different excavated disposal facility designs in surface soils should be evaluated considering the site specific conditions, e.g. climatic, tectonical, geotechnical. In the very long-term, the integrity of an excavated disposal facility in surface soil will be limited by such events as glaciations periods. In comparison with surface landfill disposal facilities the safety functions of an excavated disposal facility in surface soil would appear to be better in the short- to mid-term. However, the long-term integrity of an excavated disposal facility in surface soil is likely to be inferior compared to a shallow rock disposal facility. The decision whether an excavated disposal facility in surface soil would be compliant with desired safety functions need to be taken on a case to case basis.

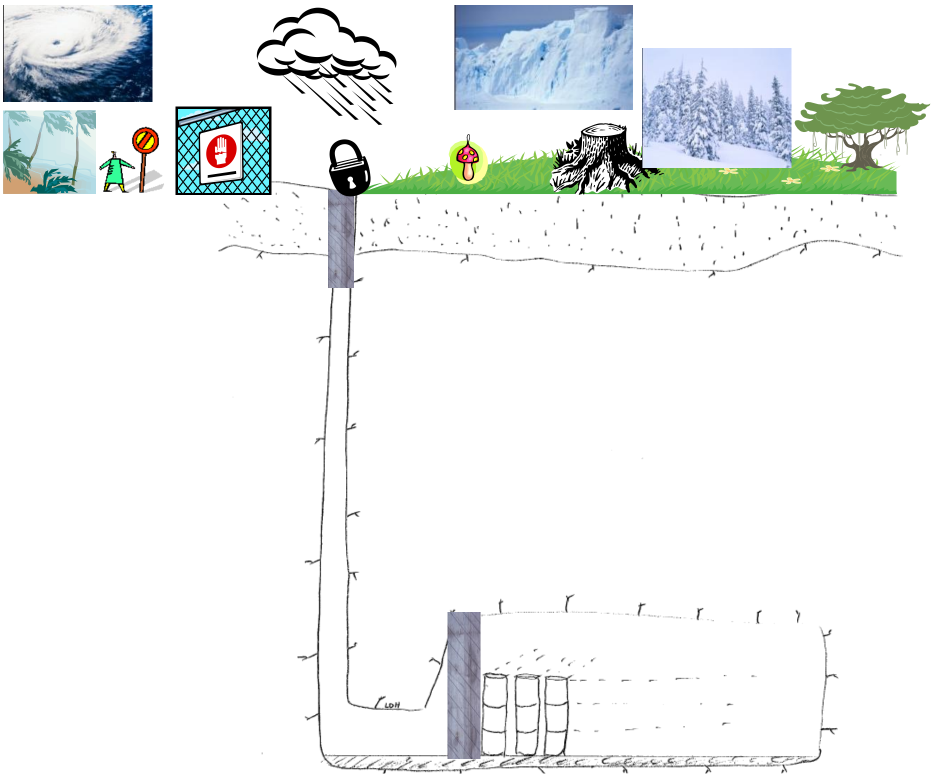
## Deep disposal in crystalline rock caverns

Mercury can be disposed in a deep crystalline rock cavern over long time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the disposal facility is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of deep rock disposal facility in crystalline rock where the mercury is disposed. Further, the geotechnical, rock mechanical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by deep disposal facilities in crystalline rock. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a disposal facility that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the disposal facility.  It is important that mercury disposed in the deep disposal facility in crystalline rock is kept separate from other contaminants and materials in the disposal facility, usually this can be achieved by compartmentalization of the disposal facility. Deep rock disposal facilities are most likely facilities that were built for other purposes, such as mining activities. Therefore, the excavations may be quite large and finding separate disposal locations for mercury would seem possible. A deep disposal facility in crystalline rock would typically be located at a depth of several hundred metres below ground. Typical features of deep crystalline rock storage facility are that it is situated below the natural groundwater table, with geochemical conditions that are favorable for maintaining the thermodynamic stability of mercury disposed in sulphide-stabilized form. It is interesting to note that deep disposal in crystalline rock has been the considered the safest disposal option for spent nuclear fuel in many countries around the world.



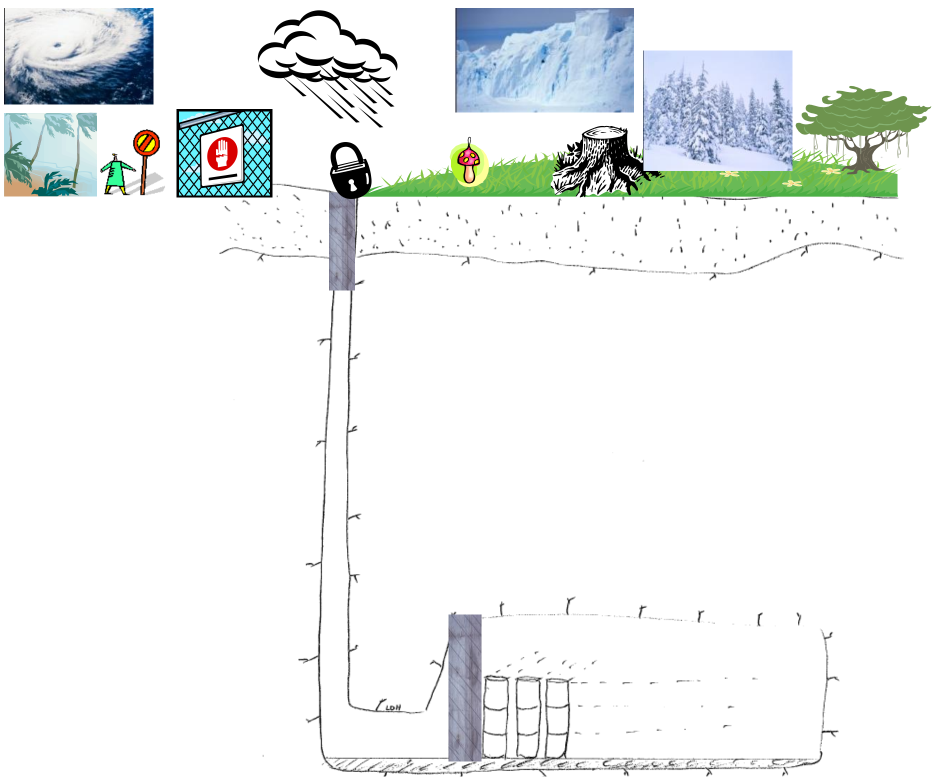
## Deep disposal in salt rock caverns

Mercury can be disposed in a deep salt rock cavern over long time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the disposal facility is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of deep disposal facility in salt rock where the mercury is disposed. Further, the geotechnical, rock mechanical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by deep disposal facilities in salt rock. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a disposal facility that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the disposal facility.  It is important that mercury disposed in the deep disposal facility in salt rock is kept separate from other contaminants and materials in the disposal facility, usually this can be achieved by compartmentalization of the disposal facility. Deep rock disposal facilities are most likely facilities that were built for other purposes, such as salt mining. Therefore, the excavations may be quite large and finding separate disposal locations for mercury would seem possible. A deep disposal facility in salt rock would typically be located at a depth of several hundred metres below ground. Typical features of a deep salt rock storage facility are that it is situated below the natural groundwater table, whereas the salt formation may be quite impermeable to water. However, the construction of the underground facilities, such as excavations, shafts etc, may constitute passages for water into the facility, hence it cannot be ruled out that the facility may require pumping of drainage water during operation. It is interesting to note that deep disposal in salt rock has not yet been the considered a feasible disposal option for spent nuclear fuel in any country in the world.



## Deep disposal in sedimentary rock caverns

Mercury can be disposed in a deep sedimentary rock cavern over long time. To be effective in the long-term the disposal facility must be fully passive and not depend on supervision and maintenance. Mercury being a toxic element requires that the disposal facility is protected against intrusion to avoid risk of human health and the environment. The disposed mercury should be protected from the direct exposure to rain, sun, extreme cold conditions, digging and construction work etc. This puts some requirements on the competence of deep rock disposal facility in sedimentary rock where the mercury is disposed. Further, the geotechnical, rock mechanical and tectonic conditions at the site must be thoroughly evaluated to ensure physical stability of the storage facility. All these factors can be expected to be well fulfilled by deep disposal facilities in sedimentary rock. While keeping with the requirement that a disposal facility should be a passive structure not depending on maintenance, it is recommended that mercury is disposed in a disposal facility that is constructed in such a way that retrieval of the mercury is not made impossible if future generations would find this necessary, e.g. in order to upgrade the safety measures of the disposal facility.  It is important that mercury disposed in the deep disposal facility in sedimentary rock is kept separate from other contaminants and materials in the disposal facility, usually this can be achieved by compartmentalization of the disposal facility. Deep rock disposal facilities are most likely facilities that were built for other purposes, such as mining activities. Therefore, the excavations may be quite large and finding separate disposal locations for mercury would seem possible. A deep disposal facility in sedimentary rock would typically be located at a depth of several hundred metres below ground. Typical features of deep sedimentary rock storage facility are that it is situated below the natural groundwater table, with geochemical conditions that may be favorable for maintaining the thermodynamic stability of mercury disposed in sulphide-stabilized form.

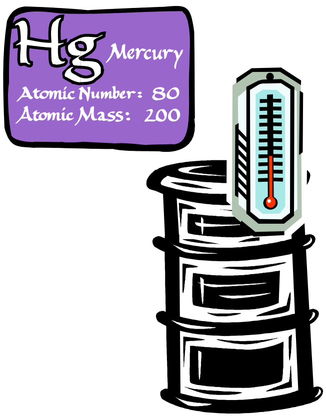


# Options for the physical and chemical form of disposed mercury

## Liquid mercury in free form

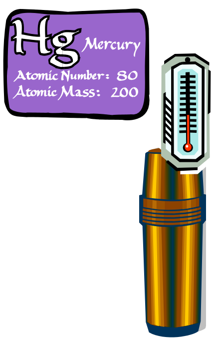
In principle, mercury can be handled as any among a wide variety of chemical compounds that are in common use in society today. Many of these chemicals are hazardous, but can still be managed by appropriate handling according to regulations. Mercury is no exception in this respect. Mercury is also today handled in bulk quantities by industry as a commodity chemical. In essence the same practices can be applied with reasonable safety for storage of mercury in different types of storage facilities. The most common practice today is to store mercury in liquid form in standard steel flasks or steel containers in storage buildings.

However, when turning the attraction to disposal of mercury, it must be considered that the supervision and maintenance would not anymore be an option. Therefore higher demands must be put on the physical and chemical form of mercury to be disposed. Mercury in liquid form without any containment is certainly not a feasible form for disposal and must be ruled out as an option for the disposal phase.




## Liquid mercury in steel flasks (a few liters size)

Special steel flasks have been developed to contain mercury in a safe way suitable for handling, transport and storage. These steel flasks are very robust and tight. However, the risk for leakage of liquid mercury will remain over time with this option. Whether or not disposal of liquid mercury in steel flasks is a viable option must be evaluated for each considered disposal option, taking into consideration the desired level of long-term safety.



## Liquid mercury in containers (up to about 1 $m^3$)

Mercury is also often handled in different types of steel containers. The steel containers differ in size, the largest may contain up to 1 $m^3$ of liquid mercury. Larger containers may become impractical due to the heavy weight when filled by mercury. However, the risk for leakage of liquid mercury will remain over time with this option. Whether or not disposal of liquid mercury in steel flasks is a viable option must be evaluated for each considered disposal option, taking into consideration the desired level of long-term safety.

## Physical stabilization of mercury, e.g. cement solidified form and amalgamation

Physical stabilization of mercury can be achieved in different ways. One method is to mix the mercury into cement to produce a solid body where the mercury is contained within the porous internal structure of the hardened cement. While this method may produce a solidified form of mercury, the chemical and toxic properties of mercury remain unchanged. Disposal of mercury in cement solidified form may constitute a hazard due to the possibly high vapor pressure of mercury of the product. In combination with other physical containment this problem can be managed.

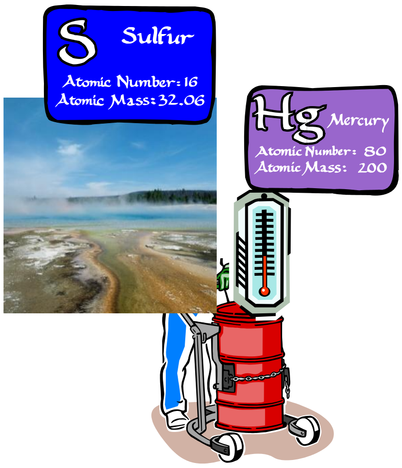
Amalgamation is a method where metallic mercury is dissolved by a solid metal, forming an alloy. Mercury alloys are commonly named amalgam. Mercury readily forms amalgam with copper, zinc, silver, tin and other metals such as sodium. The strong tendency of mercury to amalgamate gold is the tragic basis of the use of mercury for extraction of gold in small artisanal gold mining. Amalgamation results in a hard solid form of mercury, whereas the chemical and toxic properties are only to a part affected. Disposal of mercury in solidified form as amalgam may constitute a hazard due to the possibly high vapor pressure of mercury of the product. In combination with other physical containment this problem can be managed.

For both types of physical stabilization the risk for uncontrolled leakage of mercury in the disposal facility is greatly reduced. However, the relatively high vapor pressure and solubility in water would still constitute a concern for the long-term function of the disposal facility with respect to release of mercury to the environment. Whether or not disposal of physically stabilized mercury is a viable option must be evaluated for each considered disposal option, taking into consideration the desired level of long-term safety.

## Chemical stabilization of mercury into solid form, e.g. as mercury sulphide

Mercury can be reacted with sulphur to produce a solid mineral consisting of mercury sulphide. Mercury sulphide is a common form for mercury in the nature, where it constitutes many of the mineralisations being mined for extraction of mercury. Mercury sulphide is very stable and has low solubility and low toxicity. However, mercury sulphide is susceptible to oxidation and is therefore suitable for storage under oxygen-free conditions. In practical terms this means emplacement of the stabilized product in air-tight containers during storage.

For chemical stabilization the risk for uncontrolled leakage of mercury in the disposal facility is practically eliminated. The vapor pressure and the solubility in water are very low and would offer a viable long-term function when disposed in a feasible type of disposal facility. Sulphide stabilized mercury would ensure that mercury is returned into its geochemical cycle in a chemical form that is compatible with naturally occurring mercury mineralizations. Mercury sulphide is however only thermodynamically stable under oxygen-free conditions, hence would be suitable in the first hand for deep disposal in crystalline rock and sedimentary rock where the rock material would buffer the redox conditions, whereas it would be difficult to ensure for landfill disposal facilities at or near the ground surface where oxygen ingress from atmosphere is likely to occur. Whether or not disposal of chemically stabilized mercury is a viable option must be evaluated for each considered disposal option, taking into consideration the desired level of long-term safety.



## Combined physical and chemical stabilization, e.g. cement+sulphide stabilization, the SPSS-method, the MBS-method, the Mersade-method

There exist a variety of different alternative methods for combined physical and chemical stabilization of mercury. The different methods are based on chemical transformation of mercury to a solid form, commonly mercury sulphide, which in turn is trapped in a porous matrix such as cement or some polymer that forms a solid body. The advantage is that mercury is chemically bond in a form that has low vapor pressure and low solubility in water, further a solid body is formed that is easy to handle and ensures mechanical stability.

For combined physical and chemical stabilization the risk for uncontrolled leakage of mercury in the disposal facility is practically eliminated. The vapor pressure and the solubility in water are very low and would offer a viable long-term function when disposed in a feasible type of disposal facility. The additional feature of the mercury sulphide entrapped in a solid matrix would not significantly add to the safety functions of the disposal system, but would on the other hand not be any disadvantage. Sulphide stabilized mercury would ensure that mercury is returned into its geochemical cycle in a chemical form that is compatible with naturally occurring mercury mineralizations. Mercury sulphide is however only thermodynamically stable under oxygen-free conditions, hence would be suitable in the first hand for deep disposal in crystalline rock and sedimentary rock where the rock material would buffer the redox conditions, whereas it would be difficult to ensure for landfill disposal facilities at or near the ground surface where oxygen ingress from atmosphere is likely to occur. Whether or not disposal of combined physically and chemically stabilized mercury is a viable option must be evaluated for each considered disposal option, taking into consideration the desired level of long-term safety.

## Options for additional barriers in disposal facilities

Only very brief descriptions are included here. More elaborate descriptions on the functionality of different individual barrier or multi-barrier systems in disposal facilities can be found in literature related to disposal of radioactive waste where these issues have been studied intensively over the last decades.

### Tight disposal containers

Disposal of mercury in tight disposal containers would certainly be an option. However, the long-term integrity of such tight containers questionable and it may be difficult to prove the long-term function.

### Concrete barrier constructions

Concrete barrier constructions can be implemented in all types of disposal facilities and would act as a mechanical support, a resistance to air and groundwater, as well as a resistance against mercury vapor and mercury dissolved in water. Concrete barrier systems are commonly used in nuclear waste disposal facilities and evaluations show that the integrity may last for several thousand years. However, concrete barriers are also brittle and may form cracks e.g. as a result of earthquakes or uneven settlement in surface soil.

### Clay sealing layers

Clay materials are soft materials when in contact with water. The permeability is usually very low which means that clays can be excellent sealing layers to restrict the flow of air, water, mercury vapor and mercury dissolved in water. Certain types of clay exhibit swelling properties which means that they can fill up empty spaces around disposed waste e.g. steel flasks or containers. Swelling clays such as bentonite also have very low permeability. Bentonite clays are commonly used in nuclear waste disposal facilities. Clays are however, susceptible to erosion processes and should be used in combination with other barriers that can protect the clay from direct contact with streaming water, strong winds etc.

### Synthetic sealing layers (e.g. plastic membranes, rubber membranes)

Different types of synthetic sealing layers are in common use today when constructing landfills, preventing water intrusion into buildings etc. Both plastic materials and rubber are in extensive use and exhibit very good sealing properties, i.e. they are practically impermeable to water and would restrict the flow of air, mercury vapor and dissolved mercury to very low levels. The drawback of synthetic materials is that their longevity is difficult to assess. Since these materials have been invented during the last 50 years, there is for obvious reasons a lack of long-term experience of the integrity of these materials over time. Synthetic sealing layers can be used in combination with other types of barriers.

## Hydraulic barriers (e.g. drainage layers, gravel, crushed rock)

While sealing layers and concrete constructions aim at reducing the flow of water by constructing a barrier with low permeability, the concept of a hydraulic barrier is to divert the flowing water into a constructed zone having a very high permeability. If a hydraulic barrier is constructed around a disposal system the effective driving force for water flow through the disposal system will be reduced to essentially zero. A hydraulic barrier system can be constructed using different types of permeable materials, e.g. gravel, crushed rock, and crushed concrete. Hydraulic barriers can be used in combination with other types of barriers.

## Mechanical support (backfill material to support the host rock, gravel, crushed salt, crushed rock, concrete backfill)

Different types of mechanical support can be necessary in a disposal system. Here is meant different types of backfill with the purpose to reduce the mechanical stress to other parts of the disposal system, e.g. concrete barrier constructions, rock walls in underground disposal facilities. Backfill can made with different types of crushed rock, salt rock (only in salt rock disposal facilities), sand, gravel, clay, concrete and other materials. Backfill can be used in combination with other types of barriers.

## Technical options for storage and disposal of mercury

**Lars Olof Höglund, Consultant**

# Annex 1 –

# Summary of storage and disposal options and chemical stabilization and solidification options reported in the literature

A brief summary of reported literature data on different options for storage, disposal, chemical stabilization and physical/chemical solidification of mercury is presented in Tables 1 and 2. References are summarized in Table 3.

*Table 1 Summary of storage and disposal options reported in literature.*

| Country | Type | Development status | Description | Economics | Ref | Page |
|---|---|---|---|---|---|---|
| **UK** | Salt mine deposit | In use for storage of hazardous waste since 2005 | Minosus rock salt mine in Winsford, Cheshire, UK. The hazardous waste is disposed in a depth of 170 m. Storage capacity of the mine is 2 million tonnes of hazardous waste over the next 20 years. Licensed to handle e.g. hazardous waste such as air pollution control residues and ashes with dangerous substances which might be mercury. Currently not permitted to take mercury wastes. | | A | 64 |
| **Germany** | Underground salt mine | In use for hazardous waste since 1972 | Herfa-Neurode. Authorised to permanently store mercury containing waste in depths of several hundred meters. Official long term safety and risk analysis studies exist. | Cost for disposal of 1 tonne hazardous waste: 260-900 €, irrespective of the hazardousness of the waste. | A | 65 |
| **Germany** | Underground salt mine | In use for hazardous waste since 1995 | Zielitz. Authorised to permanently store mercury containing waste in depths of several hundred meters. Official long term safety and risk analysis studies exist. | Cost for disposal of 1 tonne hazardous waste: 260-900 €, irrespective of the hazardousness of the waste. | A | 65 |
| **Germany** | Underground salt mine | In use for hazardous waste since | Borth. Authorised to permanently store mercury containing waste in depths of several hundred meters. Official long term safety and risk analysis studies exist. | | A | 65 |
| **Germany** | Underground salt mine | In use for hazardous waste since 1972 | Heilbronn. Authorised to permanently store mercury containing waste in depths of several hundred meters. Official long term safety and risk analysis studies exist. | | A | 65 |
| **Germany** | Underground salt mine | In use for hazardous waste since 2006 | Sondershausen. Authorised to permanently store mercury containing waste in depths of several hundred meters. Official long term safety and risk analysis studies exist. | Cost for disposal of 1 tonne hazardous waste: 260-900 €, irrespective of the hazardousness of the waste. | A | 65 |
| **Sweden** | Deep bedrock storage | Investigated for mercury-containing industrial waste | Final report 31 January 2008 | | A | 74 |

| Country | Type | Development status | Description | Economics | Ref | Page |
|---|---|---|---|---|---|---|
| **Norway** | Disposal facility for hazardous waste | In use. | NOAH AS, situated on the island of Langoya. Permitted for disposal of mercury waste (10% Hg) | | A | 75 |
| **Norway** | Disposal facility for hazardous waste | In use. | Disposal in the rock caverns of the former steel works in Mo i Rana. | | A | 75 |
| **Sweden** | Concept study | Report to the Swedish Government [SOU 1997] | The study includes deep rock repositories in hard rock, disposal in shallow rock repositories as well as surface deposits | | | |
| **Sweden** | Concept study of deep rock repositories | Report to the Swedish Government | The study focuses on hard rock repositories | The report [SOU 2001] estimated the cost of a deep bedrock repository to 250,000-650,000 SEK per tonne of pure Hg. | | |
| **Sweden** | Concept study | Report to the Swedish Government [SOU 2008] | Study covers both salt repositories and hard rock repositories in deep rock formations as well as near-surface facility | | | |
| **Spain** | Above-ground storage | In use. | Storage of liquid mercury in a reconverted auxiliary above ground building above a former mercury mine. (MAYASA) | | A | 85 |
| **Spain** | Deep rock facility | In study. | Storage of mercury stabilized by the Mersade-process in old mine mercury mine (MAYASA). | 3500 – 4000 €/tonne of pure Hg (Mersade-Life project) including stabilization etc. | E | |
| **USA** | Above-ground storage | In use since ca 1960 | Storage of liquid mercury in above ground warehouses. (DNSC) | Estimated cost for storage of liquid mercury: $.0515 per lb per year | A | 86 |

| Country | Type | Development status | Description | Economics | Ref | Page |
|---|---|---|---|---|---|---|
| **USA** | | | DOE has been directed to designate a facility or facilities for the long-term management and storage of elemental mercury generated within the United States. DOE is analyzing the storage of up to 10,000 metric tons (11,000 tons) of elemental mercury in a facility(ies). DOE has prepared this Mercury Storage EIS to evaluate the reasonable alternatives for a facility(ies) for the long-term management and storage of elemental mercury. This Mercury Storage EIS analyzes the potential environmental, human health, and socioeconomic impacts of elemental mercury storage at seven candidate locations: Grand Junction Disposal Site near Grand Junction, Colorado; Hanford Site near Richland, Washington; Hawthorne Army Depot near Hawthorne, Nevada; Idaho National Laboratory near Idaho Falls, Idaho; Kansas City Plant in Kansas City, Missouri; Savannah River Site near Aiken, South Carolina; and Waste Control Specialists, LLC, near Andrews, Texas. As required by CEQ NEPA regulations, the No Action Alternative is also analyzed as a basis for comparison. DOE intends to decide (1) where to locate the elemental mercury storage facility(ies) and (2) whether to use existing buildings, new buildings, or a combination of existing and new buildings. DOE's Preferred Alternative is storage in a combination of an existing facility and a new facility at Waste Control Specialists, LLC, near Andrews, Texas. | | B | |

*Table 2 Summary of chemical stabilization and solidification options reported in literature.*

| Country | Type | Development status | Description | Economics | Ref | Page |
|---|---|---|---|---|---|---|
| | Sulphur stabilization | | Mercury and sulphur is blended under ambient conditions for a certain time, until Hg(II)S is formed. | Cost for stabilization and disposal are expected to be ca 2,000 €/metric tonne. | A | 112 |
| **Sweden/ Germany** | The Dela process [DELA April 2011] | Pilot plant exists. Up-scaling has been completed. Successful processing of 100 tonnes of metallic mercury to mercury sulphide reported. | Mixing of metallic mercury and sulphur to form cinnabar (red, alpha phase). Pilot plant capacity 500 kg per day, but can be increased to 3-6 tonnes per day. The annual capacity is 1000 tonnes of mercury, which would cover the needs for stabilization of excess mercury in EU up to 2020. | Cost for stabilization and disposal is approximately 2,000 €/metric tonne. | A<br>D | 113, 115 |
| | Mercury and sulphur reaction by milling [Lopez 2008] | Laboratory scale | A reaction between elemental Hg and S is obtained by milling with stainless steel balls. Laboratory scale, capacity: 25 g elemental Hg. | | A | 113 |
| | Sulphur stabilization patents [Sakab] | Laboratory scale | A number of patents are available related to the sulphur stabilization process, see reference. | | A | 114 |
| **USA** | Sulphur stabilization according to Bethlehem Apparatus | Patent pending but have developed a running stable process. | Batch size: 45 kg. Plans to attach 10 or 20 units to a single Hg feed which will enable processing of 500 to 1000 kg of Hg per day. | | A | 116 |
| | Sulphur Polymer Stabilization/Solidification SPSS | | Elemental mercury reacts with sulphur to Hg(II)S and simultaneously, the HgS ic encapsulated in sulphur polymer cement (SPC). | Cost: 2-12 €/kg of treated elemental Hg. | A | 120 |

| Country | Type | Development status | Description | Economics | Ref | Page |
| --- | --- | --- | --- | --- | --- | --- |
| | SPSS according to ADA Technology | Established process | Batch size: 75 kg. Scale up possible to 375 kg/batch. 10 metric tonnes of radioactive mercury has been stabilized. | | A | 123 |
| | SPSS according to DOE | Further investigations are on hold (economic reasons) | Capacity: 20 kg of Hg per shift. | | A | 125 |
| | Amalgamation | | Mercury is dissoluted and solidified on other metals such as copper, selenium, nickel, zinc and tin, resulting in a solid, non-volatile product. | Cost (depending on metal used): 3-27 €/kg treated Hg | A | 127 |
| | Phosphate ceramic/glass stabilization (CBPC) | | Chemically bonded phosphate ceramics (CBPCs) are manufactured by mixing calcined MgO and KH2PO4 in solution to form a hard dense ceramic of magnesium potassium phosphate hydrate (MKP). MKP is then combined with Hg. | Total cost (including raw materials, labour and disposal): 10 €/ kg elemental Hg | A | 132 |

| Country | Type | Development status | Description | Economics | Ref | Page |
|---|---|---|---|---|---|---|
| **Germany** | Process for stabilization of metallic mercury (DELA) | Pilot plant exists. Up-scaling has been completed. Successful processing of 100 tonnes of metallic mercury to mercury sulphide reported. | Elemental sulphur is vaporized in a heated vacuum mixer and reacts in the gas phase with added elemental mercury to mercury sulphide. The final product is a mixture of black metacinnabar (β-HgS) and red cinnabar (α-HgS). Efforts are undertaken to produce red cinnabar only. A pilot plant has been operated batch-wise with a capacity of 500 kg per day [56]. Operational full scale unit at the beginning of 2010. The maximum treatment capacity will be in the range of 3 to 6 t per day The annual capacity is 1000 tonnes of mercury, which would cover the needs for stabilization of excess mercury in EU up to 2020. | Cost for stabilization and disposal is approximately 2,000 €/metric tonne. | C<br>D | 12 |
| **France** | Stabilization of metallic mercury using sulphur (STMI, Gif sur Yvettes, | Semi-pilot scale | Liquid mercury and elemental sulphur are brought to reaction in a glass apparatus by stirring the mixture at elevated temperature. Background: The process has been developed with the aim of stabilizing radioactively contaminated elemental mercury with the purpose of later storage. According to available information the method in its semi-pilot stage is limited to batches with 1 kg mercury. | | C | 14 |
| **Spain** | Conversion to mercury sulphide by milling (CENIM) | | Conversion of elemental mercury to mercury sulphide by milling at room temperature. | | C | 15 |

| Country | Type | Development status | Description | Economics | Ref | Page |
|---|---|---|---|---|---|---|
| | MERSADE - A two-step process to convert liquid mercury first to metacinnabar, then to polymeric sulphur cement solid form | Full scale plant is in development. Successful tests by CENIN reported. | Capacity of full scale plant will be 2.5 tonnes Hg/day. | Estimated cost 3500 – 4000 €/tonne of pure mercury, including collection, transport, stabilization, disposal | E | |
| **USA** | Mercury stabilization as mercury sulphide (Bethlehem Apparatus) | Testing. | A process that converts liquid mercury into mercury sulphide and encapsulates them in a polymer matrix. When brought to full-scale the process is planned to have an annual conversion capacity of 1.000 t. The current scaling is unknown. | | C | 16 |
| | Synthesis of mercury sulphide by shaking | 1 kg batches. | Powdered sulphur is mixed with elemental mercury at ambient temperature to give mercury sulphide. Several methods were investigated to stabilize radioactive mixed waste that contains mercury. The method was demonstrated in 1 kg batches. As far as known no scale-up to larger dimensions was made. | | C | 17 |

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| | Stabilization of radioactive mercury as sulphide or selenide (FZJ) | | Mercury is dissolved in nitric acid and then precipitated as mercury sulphide by adding ammonium sulphide. It has been shown that under hot cell conditions it was not possible to achieve a complete conversion of elemental mercury to mercury sulphide using a dry process on the basis of powdered sulphur. Therefore a wet process in a closed glass apparatus was developed, in which mercury was first dissolved in concentrated nitric acid ($HNO_3$). Then aqueous ammonium sulphide (and hydrogen sulphide if necessary) was added to precipitate mercury as mercury sulphide. Reactions took place in a 2000 $cm^3$ glass reactor with external temperature control (circulating water). Maximum load per batch was 1000 $cm^3$. In a later stage it was investigated whether embedding of mercury sulphide in a polysiloxane matrix would further reduce the leachability of mercury. At the moment the process was only demonstrated with inactive mercury in an experimental setup with 2 litre capacity. Up-scaling for a process that is able to handle tons of irradiated mercury under hot-cell conditions was considered as a challenging task. | | C | 18 |

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| | Sulphur Polymer Cement (Brookhaven National Laboratory) | | Mercury, powdered sulphur and polymerizing additives are mixed at room temperature and then heated until the mixture melts. The product is mercury sulphide encapsulated in a sulphur polymer matrix. Pilot-scale (55-gal drums of mixed-waste soil). 62 kg (approximately 137 lb) of radioactively contaminated elemental mercury were successfully treated.<br>A similar process (SULKO) has been developed in the 1990 by the Austrian Forschungszentrum Seibersdorf (ÖFZS, now part of the Austrian Institute of Technology) for the treatment of hazardous waste (e.g. sludges), but not specifically for mercury-containing waste.<br>Pildysh Technologies Inc. (Calgary, Alberta, Canada) has developed a technology named TerraBondTM, which is based on mixing waste with molten sulphur without the addition of polymerizing agents but with suitable stabilizers and fillers. Waste load is reported to be around 65 %. After cooling the material is pelletized and eventually coated with a hydrophobic sealing. | The SPC material costs around 0.12 USD/lb (0,27 USD/kg). For mixed mercurycontaining waste the life cycle treatment costs for a 1000 lb/h operation unit was estimated to be in the order of 2.30 USD/kg (without transportation) 89 % of which is for disposal.<br>In another study the costs for the treatment of 5000 t liquid mercury (annual throughput: 1000 t) were estimated to be around 15 USD/kg including disposal in a new monofill landfill. It was not possible to separate the treatment cost from the calculation. | C | 20 |

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| | Process for stabilization of mercury (ADA Technologies) | | Mercury and powdered sulphur as well as polysulphides and sand are vigorously mixed. The process was up-scaled after licensing it to Perma-Fix Environmental Services. Itcould handle batches up to 100 kg, including a mixer that was purged with a nitrogen gas stream in order to prevent the formation of mercury oxides. Perma-Fix was licensed to treat 235 t of a mercury-containing waste from one US nuclear complex. The throughput is > 100kg in 8 hours. The process may be deployed as a mobile unit. It was estimated that in future implementations up to 375 kg mercury could be treated in one batch. | Process costs to treat 1.500 kg of mercury were estimated to be in the order of 300 USD/kg (1999). In another study (2005) costs for annually stabilizing 1000 t mercury (5000 t in total) were estimated to be in the order of 4.9 to 8.2 USD/kg including disposal in a new monofill landfill. It was not possible to separate the treatment cost from the calculation. | C | 23 |
| | Mercury sulphide by shearing (Westinghouse Savannah River Co.) | | Mercury is brought to reaction with sulphur by a high-shear mixer. | | C | 25 |
| **Sweden** | Stabilization of mercury as mercury selenide (Boliden Mineral, Sweden) | | Mercury is thermally extracted from waste and allowed to react with gaseous selenium to react to solid mercury selenide. The process has been demonstrated in a furnace of 1 m length. The throughput per hour was 100 g batteries. It is unknown whether the process has been up-scaled. | The process costs are unknown. But it may be mentioned that in the case of treated batteries 10g/h Selenium were needed to bind 2 g/h mercury in 100 g/h batteries (weight ratio 5:1, molar ratio 12.5:1). With respect to current metal prices (selenium: 40 - 60 USD/kg) the costs for selenium alone would amount to 200 - 300 USD/ kg Hg. | C | 26 |

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| **USA** | Mercury Amalgamation (Ecoflo, Greensboro, NC, USA) | | Mercury reacts with powdered metals to form solid amalgams. Liquid mercury is mixed in a disposable bottle or container with a powdered amalgamating agent in ratio of 1:1 to 1:3, but preferably 1:3. Proposed agents are copper, nickel, zinc or sulphur powder. Shaking is performed by means of a paint mixer for at least 5 - 15 minutes, but 40 minutes (metals powders) and 20 minutes (sulphur) are recommended, respectively | | C | 27 |
| | Stabilization of liquid mercury (Institute of Gas Technology, Des Plaines, IL, USA) | | Mercury is stabilized as copper amalgam. The obtained product is a hard metallic alloy. There is no information about leaching results or volatility. In comparison with the Ecoflo process the amalgams produced by this method contain more than 50 wt % mercury. | | C | 27 |
| | Amalgamation with zinc or copper | | Decontamination and decommissioning of certain nuclear facilities result in the production of radioactive mercury and mercury containing waste. In the USA amalgamation is one of the standard procedures to treat such residues. | | C | 28 |

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| | Two-stage stabilization/solidification with copper powder and Portlandcement (British Nuclear Fuels) | | Amalgamation with copper powder and subsequent solidification with Portland cement and blast furnace slag. The process was developed with the aim of stabilization and disposal of radioactively contaminated waste. The product is a concrete-like homogenous monolith. A similar approach has been proposed and successfully tested by Oak Ridge NationalLaboratory. | | C | 29 |

*Table 3 References*

| Ref. | Reference | |
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| A | Requirements for facilities and acceptance criteria for the disposal of metallic mercury | BiPRO for European Commission, Brussels, 3 November 2009 |
| B | Draft Long-Term Management and Storage of Elemental Mercury Environmental Impact Statement (Mercury Storage EIS) | U.S. Department of Energy (DOE) |
| C | Technologies for the stabilization of elemental mercury and mercury-containing wastes | Gesellschaft für Anlagen und Reaktorsicherheit (GRS) mbH, Sven Hagermann, October 2009 |
| D | Safe disposal of liquid mercury by formation of mercury sulphide. | Susanne Kummel -DELA GmbH, Presentation-Budapest-April 2011 |
| E | Looking for Solutions for a Sound Management of Metallic Mercury + Looking for a Possible Permanent Storage for Mercury. | M. Ramos – MAYASA, Presentation March 2011 + June 2011 |