Abandoned mines as hazardous waste repositories in Europe

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Abstract: Hazardous waste disposal is one of the most serious and complicated environmental problems worldwide. More than 400 million tones hazardous waste are produced, worldwide, on a yearly basis and at the same time, not only the quantity is being increased but also the hazardous waste stream must be classified in several sub streams that need a discrete management. The result is a respective increase in the demand for hazardous waste disposal sites. An interesting solution is the prospect of utilizing abandoned underground mines as hazardous waste repositories. Although this solution has been already tested in several cases, there is a need for a more general approach that should provide integrated methodologies for abandoned mines utilization, under different mine conditions and for different waste streams. This paper focuses on the concept of utilizing abandoned mines for hazardous waste disposal in Europe and presents the available mines, the potential waste disposal techniques as well as an outline of potential barriers and modeling procedures.

Key words: Hazardous waste; Disposal; Abandoned mines

1. Introduction

The problem of hazardous waste disposal is a major environmental challenge [1] that has to be faced. In European Union (EU), as in other developed areas, it seems that there is a special emphasis to find out sustainable solutions which should combine medium- long term efficiency and low cost. The current cost of handling hazardous waste is already high and the separation of waste in sub-streams – which deems necessary in order to promote reuse and recycling of certain materials - is going to increase this cost. At the same time the available disposal sites are getting at the end of their life and the new measures that have been introduced by the "Landfill directive" [2] are going to increase the hazardous waste landfilling cost and decrease the landfill sites dramatically.
The use of abandoned mines for hazardous waste disposal has already been tested in several cases as an alternative to typical landfills. Utilization of underground mines is

believed to be an achievable, low-risk and relatively cheap solution for the disposal of hazardous waste. Underground mines, depending on the surrounding rock mass and the mining method applied, are usually 'ready to use' areas as they provide an adequate space in a fairly safe environment. The necessary preparations for the construction of a waste repository are limited to its operational needs, like transportation and isolation of the waste. As a result, the construction cost of this undertaking is expected to be lower than that of any other underground repository that has to be designed from scratch. The concept of using, systematically, abandoned mines for hazardous waste disposal cannot be considered as a general and proven methodology, yet, but it may be, if the following questions are going to be answered:

- Are there abandoned mines that can be utilised in Europe?
- What are the minimum prerequisites that have to be met in order to use an abandoned underground mine?
- Are there low-cost disposal technologies under specific conditions and which is their environmental efficiency?

These are also the main issues discussed hereinafter. A large part of the presented results has been implemented within the framework of the EC funded project "Low Risk Disposal Technology" (LRDT). . Five parts conduct this project, namely the Geodevelopment AB (Sweden), the DURTEC GmbH (Germany), the Computational Mechanics Center (UK), the Wessex Technical Institute (UK) and the School of Mining and Metallurgy of the National Technical University of Athens (Greece).

2. Mine survey and reference cases

The economic growth that has been observed in all developed European countries ever since the industrial revolution relied largely on mining activity. This activity was reflected in a large number of mining exploitations, a lot of which were underground mines. However, the decline of the mining industry during the last decades has lead to the closure of many mining sites throughout most European countries. As a result, there are a lot of abandoned underground mines, which, most of the time remain inactive and practically useless. In addition, due to the continuous decline of the mining industry, a large proportion of the remaining underground mines is expected to cease their operation in the near future. These mines could also be considered as potential disposal sites.

During the study, an inventory of the used mines as hazardous waste repositories, as well as the abandoned underground mines in Europe has been conducted. There are 19 mines that have already been used for hazardous waste disposal in Europe (Table1). Additionally, more than 70 underground mines were registered and their main characteristics were recorded. Most mines are located in Germany, Sweden, Finland and the United Kingdom, as expected due to the intense mining activity in these countries. Figure 1 presents a summary of the results that were achieved.

Table 1: *Mines that are being used for hazardous waste disposal in Europe*

Country	Number of mines
Germany	10
Italy	3
United Kingdom	2
Sweden	1
France	1
Former Soviet Union	1
Slovenia	1

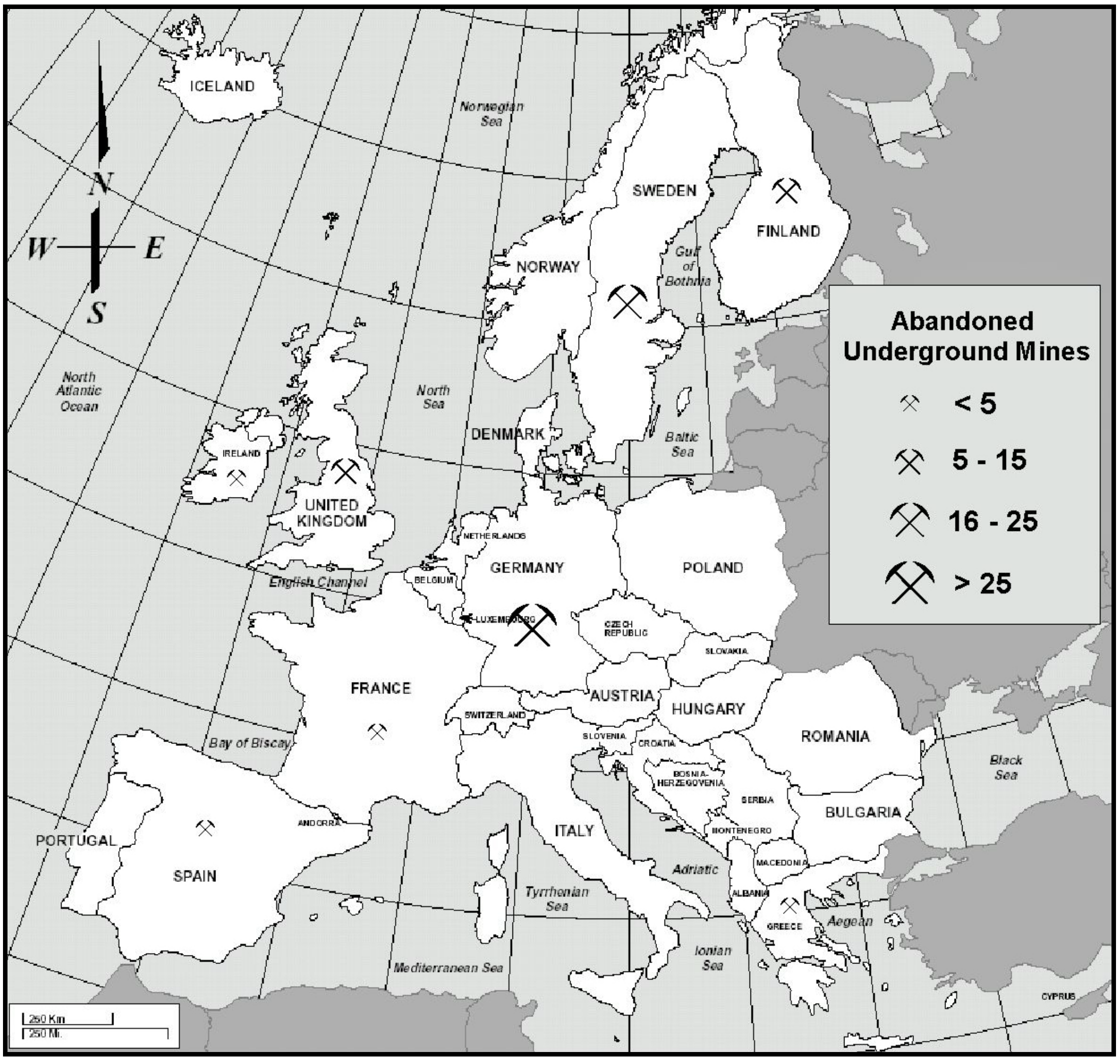

Figure 1: *Abandoned underground mines distribution [3]*

In order to examine the concept of underground hazardous waste disposal in different conditions and host mediums, four different categories of underground mines were formulated and a representative mine was selected for each category. The most important criteria applied are permeability and stability behavior of the host rock, as well as the suitability of the mine's drifts and rooms for the storage of waste packages. Thus, only mines excavated by a method that leaves adequate free space, like the "room and pillar" method are under consideration.

The geological host medium is of primary importance. Based on the current experience, most underground waste repositories have been developed in crystalline rock, salt rock and clayey sediments. Crystalline rock offers an excellent stability of the drifts and rooms, while salt contains no free water and hence offers very good isolation of the waste. Clayey sediments have a very low hydraulic conductivity but poor stability. The possibility of having limestone rock as the fourth reference type host medium seems particularly interesting as a worst-case scenario, regarding permeability. Limestone has a medium stability and is pervious, but presents a high pH.

The ideal geometrical shape of rooms for waste storage is represented by drifts and tunnels with horse-shoe cross section of 20-50 m^2 and a length of 50 to 200 m. Big rooms with a width and height of 20-30 m and a length of 50-100 m can be considered as well, but they often require significant stabilization and sealing of the rock.

Table 2 presents the four different categories, with an assessment of their characteristics.

Table 2: *The four categories of host mediums and an assessment of major characteristics [4]*

	Crystalline rock	*Salt*	*Clayey sedimentary rock*	*Limestone*
Available room	Very big rooms are offered	Very big rooms can be obtained	Small and moderately big rooms can be obtained	Small and moderately big rooms can be obtained
Rock structure	Well defined structure that can be determined by boring and geophysics	Poorly defined structure	Well defined structure that can be determined by boring and geophysics	Bedded limestone: Well-defined structure that can be determined by boring and geophysics. Reef-type limestone: Poorly defined structure
Stability	Usually good at least for drifts and small rooms	Often good except if brine flow takes place	Poor	Usually poor
Discontinuities and hydraulic conductivity	Usually rather high. Discrete fracture zones are of particular importance.	Only major discontinuities are conductive	Usually insignificant but the excavation disturbed zone is of great importance	Usually high
Chemical conditions	pH around 7. Low to high salt content	pH around 7. Very high salt content	pH around 7. Moderate salt content	pH>10. Moderate to high salt content

Based on these criteria and the data availability, the four mines selected, as reference cases are [4]:

- Stripa mine (Sweden) for crystalline rock.
- _Asse mine (Germany) for salt.
- Opalinus Clay (Switzerland) for clayey sedimentary rock.
- Bauxite Parnasse mine (Greece) for limestone.

3. Hazardous waste in Europe

Hazardous waste generation, key waste streams and chemical dispersion in Europe and especially in EU countries have been examined. This work aimed to provide the waste streams of interest for underground mine disposal and the potential pollutants that should be into consideration. The key-findings are [1,5,6,7]:

- ✓ The European Environmental Agency member countries generate about 36 million tones of hazardous waste per year and estimations predict an increase 10-15% until 2010.
- ✓ Hazardous waste amounts are increased, but it is difficult to quantify the rate of increase, due to lack of relevant data or due to no compatibility. For Austria, Spain/Catalonia and Denmark, the data show increasing quantities of hazardous waste, with smaller rates for Denmark. For Germany and UK it is believed that there is a small decline of hazardous waste, due to introduction of cleaner technologies.
- ✓ Increasing amounts of hazardous waste can be even the result of positive developments such as better collection and registration of waste.

A general profile of the hazardous waste in EU countries can be outlined as shown at Figure 2.

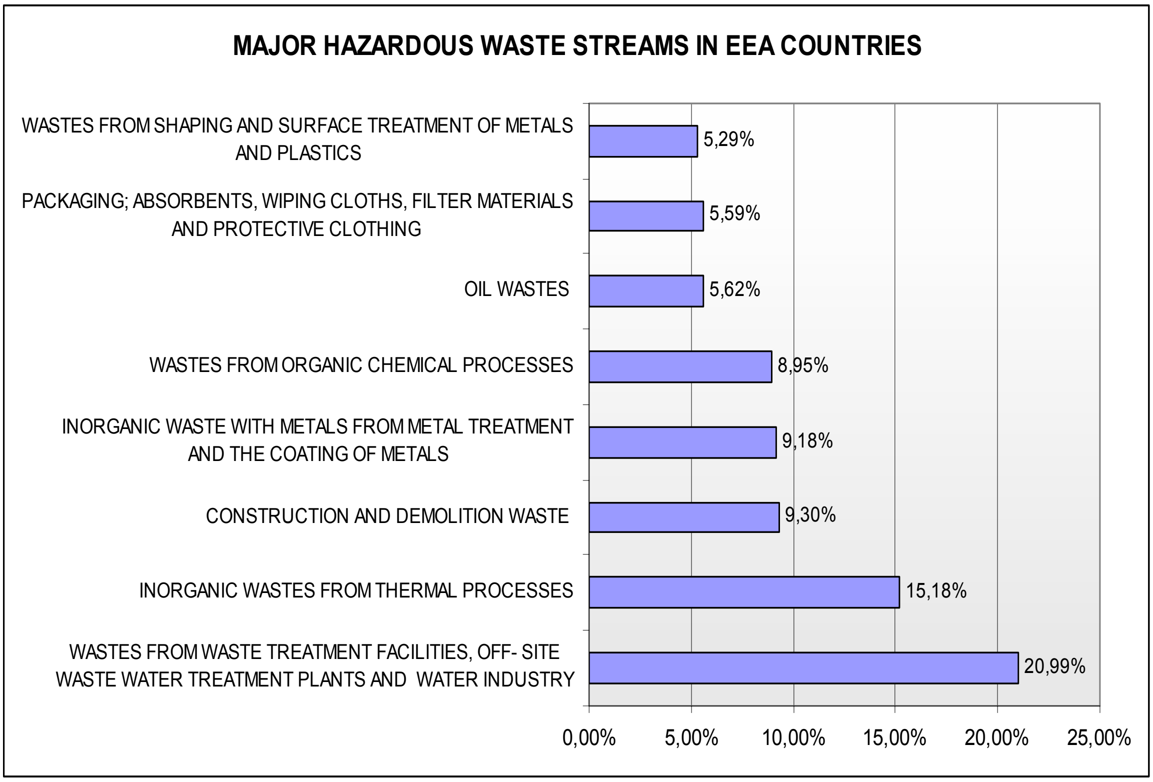

Figure 2: *Main Hazardous Waste streams in EU countries [8].*

Almost 80% of the hazardous wastes become from the seven activities shown in Figure 2. Waste from waste management industry and inorganic waste from thermal processes consist more than 36%. Waste from organic chemical processes, inorganic waste from metal treatment and coating of metals and hazardous waste from construction and demolition waste have an equal contribution of almost 9% each.
Table 3 provides the results of a survey carried out by OECD, in 1999, where 10 European countries were asked to give information about their present and future waste problems.

Table 3: *Present and future key waste streams in selected European Countries [7]*

Country	Key Waste Stream	
	present	future
Austria	Waste oil, lubricants, photochemical	WEEE, waste medicines, end-of-life vehicles
Denmark	no information	no information
Finland	sewage sludge	WEEE, end-of-life vehicles
France	waste oils, end-of-life vehicles	waste oils, end-of-life vehicles, PCB, WEEE, medical waste
Germany	Paint sludges, WEEE, sewage sludge	WEEE, end-of-life vehicles, sewage sludge
Italy	no information	no information
Netherlands	Waste oil, dredging spoil, CD waste, phosphorgypsum	dredging spoil, phosphorgypsum
Norway	Hazardous waste in general	WEEE, Scrapped oil installations
Switzerland	Packing, beverage containers, metalplating sludges	Packing, beverage containers, metalplating sludges
UK	WEEE, end-of life-vehicles, waste oil	Clinical waste, PCB
WEEE: waste from electrical and electronic equipment		

It is clear that one of the most important waste streams is Waste from Electrical and Electronic Equipment (WEEE), while a lot of the other mentioned waste streams are included in hazardous waste streams.

One more parameter of interest is the chemical substances dispersion in Europe [6,7]. The main conclusion is that a growth of 30-50% in emissions (compared to 1990) will take place if current trends and policies will not change. Cadmium and mercury emissions will be increased between 26-30%, while emissions from pesticides and persistent organic pollutants are expected to remain a major environmental threat.

The main conclusions from the above are [8]:

- Waste coming from the waste management industry is the main hazardous waste sub stream. The biggest waste stream is aqueous liquid waste from gas treatment and other aqueous liquid waste. This waste includes a lot of heavy metals and the physical form of this waste makes it appropriate for storage within artificial barriers.
- WEEE is one of the future key waste streams. This stream includes a lot of heavy metals also and there are a lot of difficulties in recovering materials due to lack of appropriate technological advances. Since it is considered sure that within next 5-10 years, the appropriate technologies will be established, underground mines can provide a perfect medium – term storage option, with very low cost and negligible environmental hazards. The same can be concluded regarding the old batteries stream.

In both cases, underground mine disposal takes advantage of the very slow groundwater flow at depth and of the very long transport paths for heavy metals that can be released.

4. Engineered barriers and disposal techniques

Different barriers should be used in underground disposal according:

- The mine characteristics (as specified by the reference types)
- The waste disposed
- The estimated environmental risk.

Regarding the last issue, the barrier should be designed in a way that no major effects could be detected at the nearest aquifer that may be affected. Practically, that means that pollutants of interest should be always below certain quality limits specified according the current or potential use of the aquifer.

Two different disposal techniques are under study [9]. The first way is to embed waste within clay blocks, as presented in Figure 3.

If the geometry is suitable the filling of the gap between the block assembly and the rock with clay slurry can be omitted. Expansion of the blocks consolidates the slurry that ultimately becomes as dense as the blocks, which can have an initial dry density of 1500-2000 kg/m^3. The compacted clay packages form a very effective engineered barrier. This is because of the extremely low hydraulic conductivity and low content of movable porewater. Therefore, the average percolation rate down in the backfilled mine is only about 0.01 mm per year and the other migration processes like diffusion are extremely slow as well.

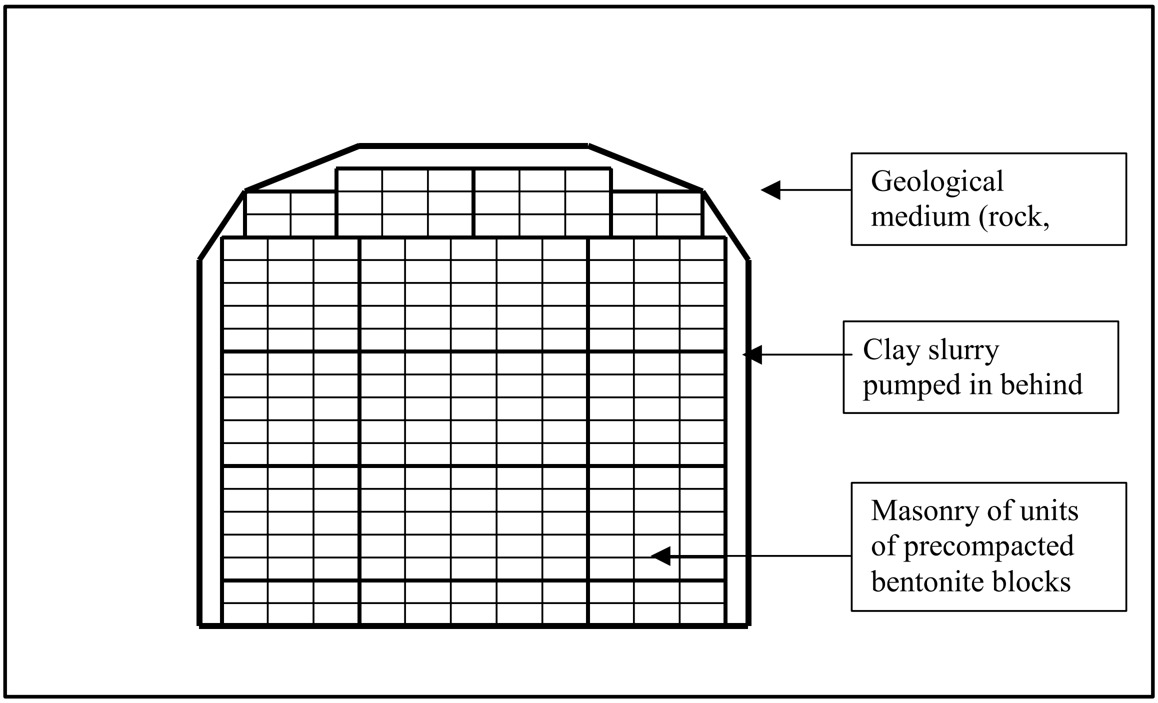

Figure 3: *Clay block masonry with clay slurry filling gap to surroundings [9].*

A possible technique for backfilling of the drifts and tunnels that has been tried in practice is to blow in pellets. The net dry density is too low (800-1200 kg/m^3) for providing effective isolation of the waste but the technique can be used as an alternative to the slurry injection of the gap between block masonries and the rock.
Backfilling of tunnels by using blocks requires very rational procedures and since no large-scale application of block filling has been made so far, the optimum technique is not yet known. A combination of several techniques may turn out to be at optimum.
The second technique is to prepare clay / ballast / waste mixtures. The technique for preparing and applying such mixtures may well be the same as for backfills with no waste and both applications in horizontal and inclined layers are possible.
Figure 4 provides an outline about this second technique.
However, since the density of backfills applied in inclined layers is relatively low close the walls and roof of drifts – the dry density appears to vary between 1600 to 1900 kg/m^3 – more effective compaction yielding dry densities of up to 2100 kg/m^3 can be achieved by compaction of horizontal layers with vibratory rollers and heavy vibratory plates, making at least 10 runs on layers with a thickness of 20 to 30 cm.
A problem in both cases can be caused by water flowing in from hydraulically active fractures and fracture zones. They may have to be sealed by injecting clay or clay/cement grouts or by applying drains at the walls and floor through which water is let out during the construction time.
The drains can consist of perforated pipes, ~~that are~~ filled with highly compacted smectite clay at the completion of the waste application, when also the rooms and drifts are separated by transport tunnels by concrete plugs or systems of clay block masonries, concrete bulkheads and crushed rock.
Inflowing water in drifts, where compacted blocks are put, causes less problems since the construction time is shorter and drainage of the described type can be made in a simpler way.

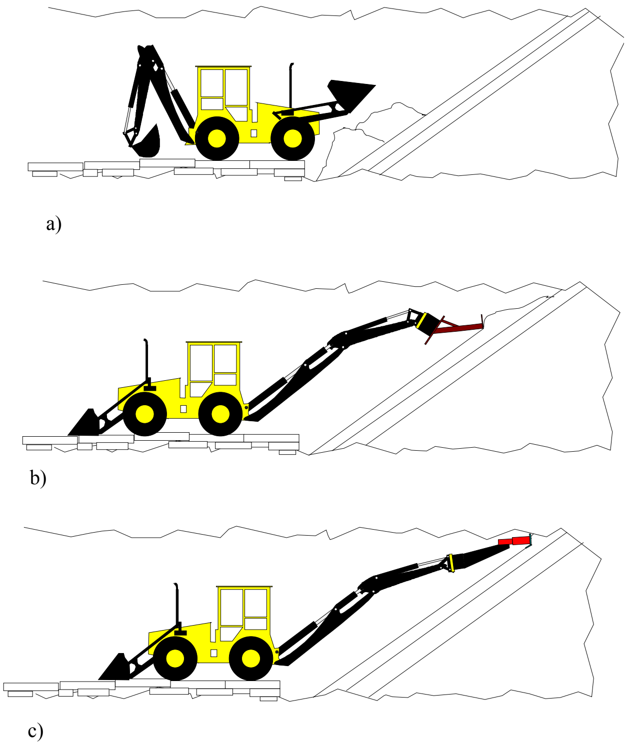

Figure 4: *Backfill cycle for one layer. a) Emplacement of the backfill. b) Pushing the backfill in position. c) Compaction at the roof (After Clay Technology AB) [9].*

5. Modeling

According the reference mine type, the hazardous waste stream and the barriers applied, a modeling procedure will be implemented in order to evaluate the environmental risk, on terms of water pollution

The importance of the flow and transport processes through fractured porous media has influenced development of different approaches to predict the outcome of these phenomena. The most often used approach is the continuum approach, which employs a transformation from microscopic level to macroscopic level by averaging the microscopic field variables [10].

The model developed in this study includes the continuum approach for the near-field rock. The disturbed rock in the vicinity of the repository contains a large number of fractures, which makes it impossible for the modeling part to take into account the flow and the transport through each one of them, because of the enormous computer memory and CPU requirements and difficulties in preparation of input data. In the continuum approach, representative values for the continuum parameters have to be used.

The numerical technique, that is used to solve the partial differential equations defined by the models, is the dual reciprocity method – multi domain (DRM–MD). The method belongs to the boundary element techniques that transform the original partial differential equation into an equivalent integral equation, by means of the corresponding Green’s theorem and its fundamental solution.

The model developed uses the following data to define the flow and transport [11]:

- hydraulic conductivity of rock
- porosity of rock
- diffusion coefficient in rock matrix

- bulk rock density
- geometry of fractures
- hydraulic conductivity of fractures
- porosity of fractures
- dispersivity in fractures
- hydraulic conductivity, porosity and dispersivity of discontinuities cross sections
- dispersion coefficients
- the chemical reactions
- source term of the pollutant
- boundary conditions.

A typical output of the model is presented in Figure 5.

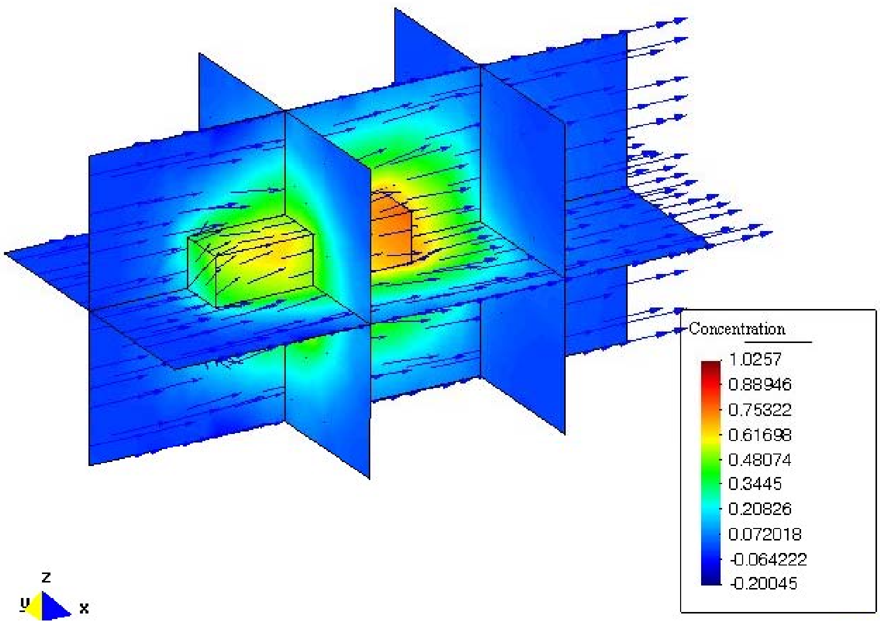

Figure 5: *Dispersion of hazardous chemicals at t=400 years [11].*

Up to now, the model results in a time scale of 400-500 years of safe disposal, with no major influence on the quality of water, if the hydraulic conductivity of the artificial barrier is below to E-10 m/s.

6. Conclusions

The utilization of abandoned underground mines as hazardous waste repositories seems to be a feasible alternative to the construction of waste disposal sites. There is a significant number (more than 70) of abandoned mines in Europe. Moreover, most of the sites are in the developed European countries, which have the biggest industry and consequently the biggest hazardous waste production.
Four reference mines have been determined, corresponding to different host medium, hydrogeological conditions and stability in order to test the concept of underground mines disposal in general terms.
As long as the compatibility of specific waste types with underground disposal is concerned, there are a lot of waste streams that could be driven to underground disposal, either for medium term storage or for a long-term disposal.

The disposal technique seems to be of particular interest, because its selection should be based on the physical state of waste streams, mine geometry and hydrogeology. At the same time the selected technique will affect significantly the disposal cost and the environmental efficiency.
Up to now, the modeling procedure proves that underground mines, with the use of the appropriate barriers, can provide hundreds of years of safe storage or disposal, with low cost.
This is due to the fact that:

- Deep underground disposal provides natural protection with very slow groundwater flow and very long transport paths for pollutants.
- Isolation materials based on clay have been proved efficient barriers in both techniques (clay/ ballast/ waste mixtures and high-density clay blocks).

An issue that requires further study is the long-term chemical stability of clays interacting with waste. This is a major question since the waste materials considered in this project retain their toxicity for any period of time in contrast to radioactive waste, which become significantly less dangerous with time.
In the next stages of the project, using rock characterization methods and numerical techniques calculations will be made for the stability of the rock structure.

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