CASE STUDY: REMEDIATION OF A FORMER URANIUM MINING/PROCESSING SITE IN HUNGARY

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Abstract

The Hungarian uranium mining activities near Pécs lasted from 1958 to 1997. Approximately 46 Mt of rock were mined, from which 18.8 Mt of upgraded ore were processed. Some ore had been exported prior to the construction of the processing plant at the site. Remediation of the former uranium-related industrial sites is being carried out by the Mecsek Ore Environment Ltd. and started in the 1990's. Today the former mines and their surroundings are rehabilitated, former heap piles and a number of smaller waste rock piles have been relocated to a more protected area (waste rock pile N 3). Ongoing core remediation activities are directed to the remediation of the tailings ponds, and also water treatment issues are most important. Three water treatment facilities are currently in operation:

- A mine water treatment system with the objective to remove uranium and gain a marketable by-product.
- A pump-and-treat system to restore the groundwater quality in the vicinity of the tailing ponds.
- A pilot-scale, experimental passive in-situ groundwater treatment system to avoid migration of uranium contaminated groundwater.

General overview of the world uranium production

World uranium production is summarised in Tab. 1 based on data collected by the OECD and IAEA (OECD-IAEA, 2002). It can be seen that up to the year 2000 approximately 1.9 Mt of uranium were produced in 34 countries. The Hungarian production rate was on the level of 500–600 t/a. At beginning of the new millennium production rates decreased dramatically, and in 2001 only 12 countries operated an industrial-scale uranium production with a total production of approximately 37 kt of uranium. Main producing countries are currently Canada (11 kt/a), Australia (8 kt/a), Niger, Namibia, Russian Federation, Kazakhstan, Uzbekistan (each ~ 3 kt/a). Today in Europe uranium is produced in small quantities only in the Ukraine, Romania and the Czech Republic. Some minor quantities are obtained as by-product from remediation activities (e.g. in Germany, Hungary).

The historical development of the market price for uranium is shown in Fig.1. Since 1980 the price dropped continuously from approximately 150 US$/kg to the current value of 20–30 US$/kg (Pool, 2002). The boom at the end of seventies is attributed to the world energy crises. Most uranium producing countries could not adjust their production costs to the level of the post-cold-war market price and thus terminated their production. This was also the case in Hungary.

Tab. 1: Uranium production in the world (OECD-IAEA, 2002).

Country	Uranium production total to 2000 [t]	Expected production for 2001 [t]
Argentina	2,509	0
Brazil	1,110	250
USA	353,796	1,077
Canada	340,523	11,250
Namibia	72,127	2,702
South-Africa	153,337	1,160
Gabon	27,872	0
Niger	81,853	2,910
Australia	91,157	7,700
Germany	5,462	20
GDR	213,380	0
Czech Republic (1)	107,080	501
France	73,664	120
Bulgaria	16,720	0
Hungary	21,030	10
Romania*	17,729	85
Estonia		0
Sweden	215	0
Spain	4,961	30
Portugal	3,717	3
Belgium	686	0
Finland	30	0
Yugoslavia	380	0
Poland	660	0
Ukraine (since 1992)*	10,000	1,000
Russian Fed.*	114,223	2,910
Uzbekistan	95,758	2,350
Kazakhstan	88,372	2,250
India*	7,273	207
Pakistan*	837	23
China*	7,435	700
Japan		
Total	**1,913,896**	**37,258**

(1) Czech Republic: Aggregated production of the mines MAPE, Hamr, Rozna, Pribram, Neidek, and Elias (Jachimovo).

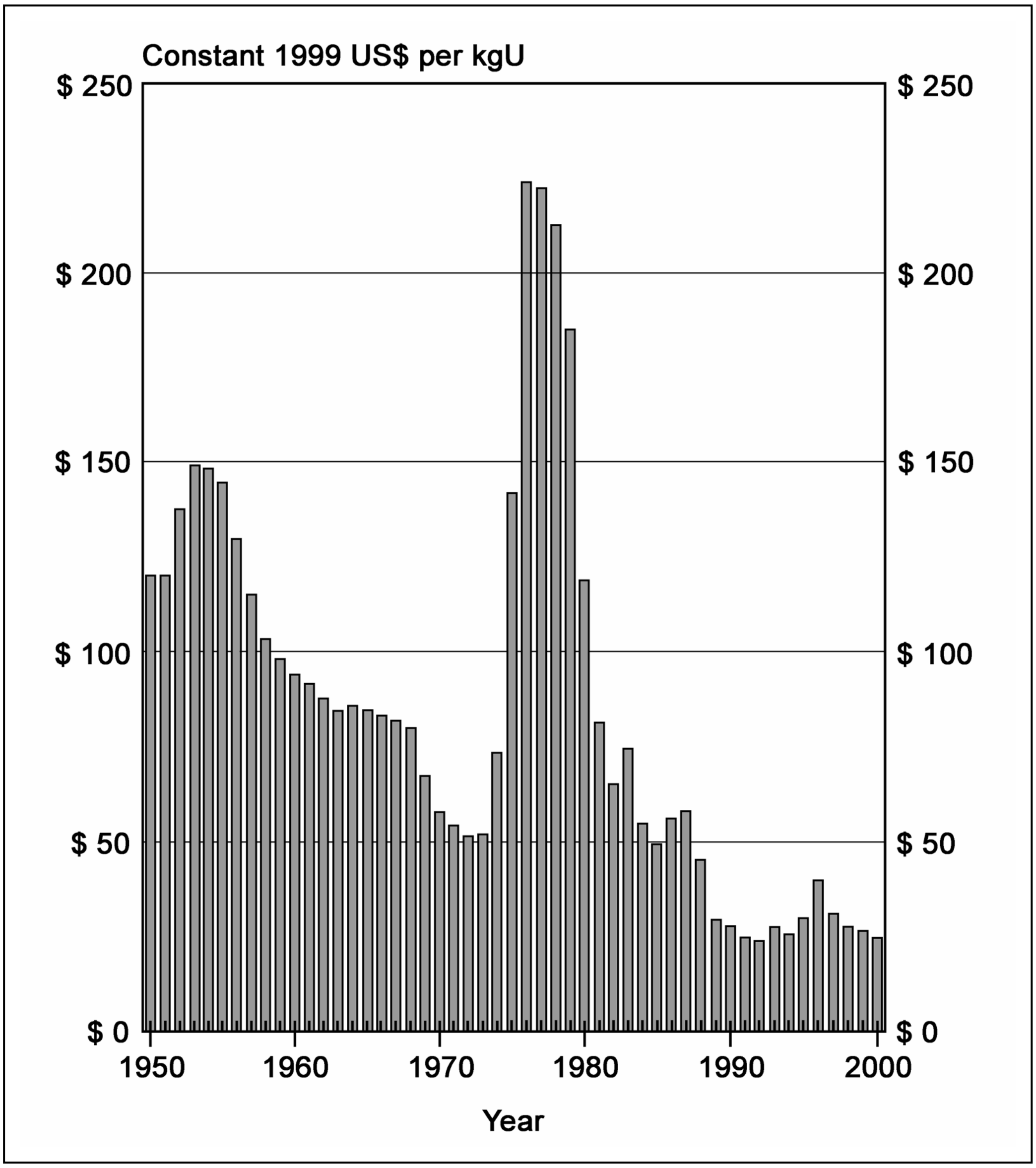

Fig. 1: Historical price for uranium (source: Pool, 2002).

Project structure

The remediation of the former uranium mining and processing area started with defining priority areas and remediation targets. Subprojects were defined and an appropriate time schedule was set up (Tab. 2). The overall remediation plan was split into 10 sub-projects. Most of these sub-projects are today completed. The subprojects “water treatment”, “remediation of tailing ponds” and “monitoring” are still in progress. The remediation of the tailings ponds will take more time than initially anticipated. The expected remediation endpoint is currently defined with the year 2005.

Tab. 2: The main sub-projects of the remediation program.

N^0	Subproject title	Year						
		1998	1999	2000	2001	2002	2003	2004
1	Underground mines	🟩	🟩	🟩				
2	Surficial facilities and areas	🟩	🟩	🟩	🟩	🟩		
3	Waste rock piles and their environment	🟩	🟩	🟩	🟩	🟩		
4	Heap-leaching sites	🟩	🟩	🟩	🟩	🟩		
5	Tailings ponds			🟩	🟩	🟩	🟩	🟩
6	Mine water treatment	🟩	🟩	🟩	🟩	🟩	🟩	🟩
7	Reconstruction of electric network			🟩	🟩	🟩		
8	Reconstruction of water and sewage system		🟩	🟩	🟩			
9	Other infrastructural service	🟩	🟩	🟩	🟩	🟩		
10	Monitoring and miscellaneous activity	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Total							

The total sum estimated for the remediation projects amounts to approximately 18 billion HUF (~ 85 million US$). These expenditures are covered by the Hungarian state budget.

The following chapters provide a short review of those sub-projects directly connected to the surface and groundwater protection.

Processing practice used by Mecsekérc

Dissolution or leaching of the uranium minerals is the most important step in the processing of uranium ores. A major part of the reagents needed for the process is consumed at this stage due to the dissolution of gangue minerals.

Leaching chemistry

Uranium in minerals exists in tetravalent or hexavalent form. In its hexavalent form uranium goes directly into solution according to the equation (1):

$$UO_3 + 2H^+ = UO_2^{\;2+} + H_2O \qquad (1)$$

H^+ is supplied either by acids, or by bicarbonate in alkaline carbonate processes.

When uranium is present in tetravalent form, e.g. in form of uraninite (UO_2) it does not dissolve at an acceptable rate and requires oxidising into hexavalent form:

$$UO_2 - 2\,e^- = UO_2^{2+} \qquad (2)$$

The oxidising reaction is a rather complex process. In acidic condition rapid oxidation can be achieved by the presence of ferric ion in the process solution:

$UO_2 + 2\,Fe^{3+} = UO^2 + Fe^{2+}$ (3)

To maintain the dissolution of UO_2 the Fe^{2+} must be oxidised to Fe^{3+}, e.g. by manganese dioxide. This process requires hydrogen ions, too:

$Fe^{2+} + MnO_2 + 4\,H^+ = 2\,Fe^{3+} + Mn^{2+} + 2H_2O$ (4)

Instead of manganese dioxide sodium, chlorate or Caro's acid (H_2SO_5) can be applied.

The Mecsekérc Company used two kinds of chemical ore treatment practices (Fig. 2):

- acid leaching for radiometrically upgraded ore
- alkaline heap leaching for low-grade ore

Approximately 97 % of the total uranium production (18.1 kt) were obtained in an acid leaching mill process and only 3 % by heap leaching.

The volumes of waste generated in the processes were:

- 7.2 Mt of solid residues and 0.2 Mm^3 of liquid wastes from heap leaching
- 20.3 Mt of solid residues and 32 Mm^3 of liquid wastes from the acid leaching mill process

Alkaline heap leaching was carried out constructing heaps like that shown in Fig. 3. Low-grade ore and partially rejects from a radiometric sorting stage (approximately 33 % of the rock mass were separated from the run-off ore as gangue minerals) were crushed to a size of < 30 mm and dumped to the pad constructed for this purpose. The bottom of the pad was sealed with two layers of plastic foils.

Sodium carbonate and bicarbonate solution (leaching agents) were percolated through the heaps to leach the uranium. The collected leachate was pumped to ion exchange columns, where the uranium was sorbed by an anion exchange resin (Varion AP). The barren solution was circulated back on the top of the piles. The resin loaded with uranium was regenerated and the eluate (U concentration ~ 10 g/l) was then processed to yellow cake. Using this technology approximately 7.2 Mt of low-grade ore was processed, removing 545 t uranium from the ore.

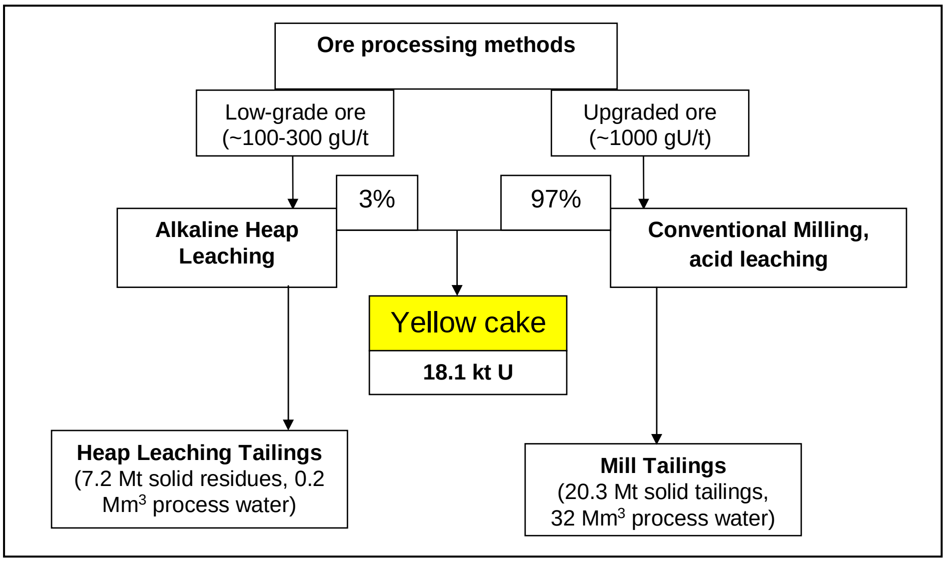

Fig. 2: Processing methods and the volume of generated tailings at the Mecsekérc installations.

Acid leaching is usually carried out with sulphuric acid in a co-current or counter-current set-up. At the Mecsekérc installations the co-current technology was used. In the leaching system at least two acid concentration steps were maintained with high concentrations (100 g/l or more) at the head and low concentrations (5–10 g/l) at the end of the leaching. Uranium was removed from pulp (density 1.18 kg/l) using an anion exchange resin. The loaded resin was regenerated with solution containing hydrochloric acid and sodium chloride. Uranium was precipitated from the eluate with lime milk. Thus the end-product (yellow cake) was calcium diuranate. One of the two heap leaching areas is shown in Fig. 3.

Fig. 3: Alkaline heap leaching at the former uranium mining and processing site near Pécs.

Remediation

Remediation work is carried out in accordance with the environmental license issued by the local authorities. In the following chapter some important steps of the performed remediation work is presented. Special attention is given to water protection issues. According to the license the limits for discharges are as follows:

Natural uranium in water: 2 mg/l

Radium-226: 1.1 Bq/l

Individual discharge limits are given for discharge of all collected waters:

Total dissolved solids: 5000 mg/l

Specific conductivity in the receiver (at village *Zók*): 2000 µS/cm

Remediation of heap leaching sites

Total area of the heap leaching sites was approximately 47 ha. It was decided to relocate all solid residues to waste rock pile N3, which was thought to be more suitable for long-term repository of wastes. The heaps were washed with mine water for two years prior to the relocation. The collected solution from the heaps was treated, and uranium and radium were removed.

The solid residues were relocated to waste rock pile N3, on which a lime-based reactive barrier was built for retardation of uranium in seepage. The heap residues were placed on lime-containing layers (1.5 kg CaO per t of residues), which proved to be very effective in the retardation of uranium. A detailed description of the reactive barrier is given by Csövári et al. (2002).

Mine water treatment

The geological cross-section of the former mining area is shown in Fig. 4. It can be seen that the mining area is principally divided into two parts: the southern part is closely connected with the drinking water aquifer situated at foot of Mecsek hills, the northern part has no direct connection with that area. During the period of active mining, mine water from both areas has been partly used for milling and other industrial purposes. Water chemistry for the mine waters and seepage from waste rocks is presented in Tab. 3.

Both the mine water and the seepage show an elevated uranium concentration. This means that though the pyrite content of the rock is low (much less than 1 %), some geo-chemical processes take place and uranium has been dissolved. At the same time dolomite and perhaps other gangue minerals are also dissolving. The heavy metal content is low (<< 1 mg/l), and arsenic concentration is approximately 10 µg/l (data not given in the table). It is worth to mention that uranium is still high (above the discharge limit) in the seepage. Therefore the water has to be treated for removing of uranium. Other constituents are acceptable and do not require additional treatment.

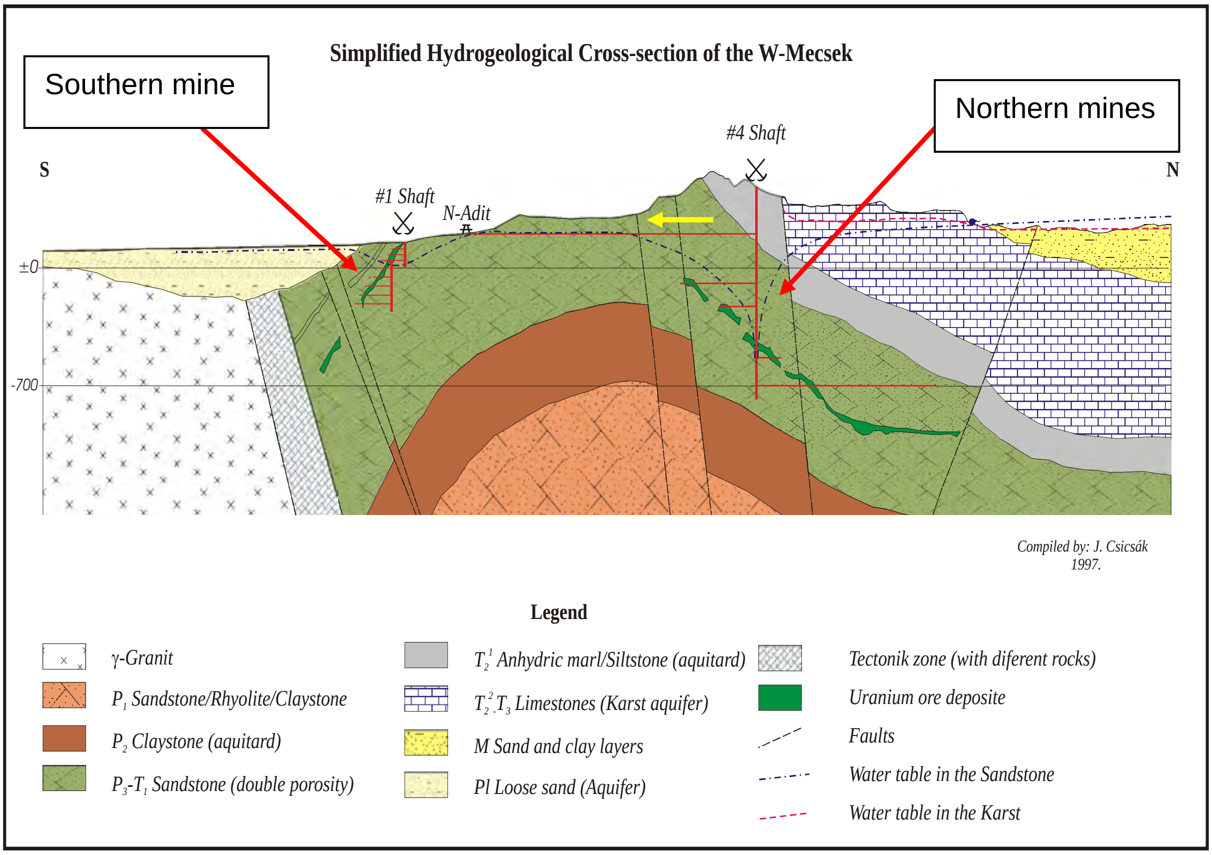

Fig. 4.: Geological cross-section of the mining area.

Uranium mining had started in the Southern part, in mine N1. After closing this mine in 1968 authorities demanded that a depression funnel is kept around the mine (to keep the water level in the mine at 106 m below surface) to protect the drinking water aquifer from the uranium-contaminated mine water. The depression funnel was maintained by pumping. The extracted water had to be treated prior to discharge.

Tab. 3: Composition of mine water and seepage from waste rock piles.

Source	Year	Na	K	Ca	Mg	Cl	SO_4	HCO_3	TDS	El. cond.	pH	U	Ra
						mg/l				µS/cm		mg/l	Bq/l
Mine N^{0}I	1999	260	<5	205	139	117	890	677	2000	2404	7.1	8.5	0.6
(south mine)	2002**	191	13	181	104	84	610	808	1605	2135	7.1	3.22	0.23
Mines N2,3,4,5	1999	75	11	112	68	37	298	284	780	1142	8.2	1.40	0.6
(northern & deep mines)	2002						under flooding						
Adits*	1999	19	<5	82	78	28	209	369	790	975	7.3	0.7	0.6
	2002					28	145		660		7.35	0.18	0.22
Seepage from waste rock													
(pile N1)	2002											1–20(1)	
(pile N2)	1995(1)	100	5	282	186	28	1041	494	2500	3860	7.8	27.0	0.14
	2002***	116	22	374	279	37	1440	573	3070	3230	7.2	31.39	0.2
(pile N3)	2002****	200	22	251	199	63	860	567	2704	3090	8.4	8.79	0.35

** North + East adit, ** 12.09.2002, *** 30.10.2002, **** 5.8.2002*

(1) depending on the seasons

In the case of the Northern mine there was no necessity to extract the contaminated mine water because this area has no connection with the above mentioned drinking water aquifer. Therefore, after termination of the mining activity and closing of the Northern mines, water from this region was no longer pumped. It is supposed that in approximately 20 years the mining cavities will be flooded and the mine water will leave the area through the adit. Water can be treated on the existing water treatment station if necessary. It should be mentioned that a small volume of water is flowing out even at present from the adit (seepage from the top of adit).

So at present only mine water extracted from shaft N1 (approximately 500,000 m^3/a) needs to be treated for uranium removal. The treatment process is based on anion exchange, which has been used since 1968, and some tons of uranium are removed yearly from the mine water. The whole process of mine water treatment is aiming at a commercial-grade end-product, which is sold. This option was chosen to avoid the generation of new wastes. The principal flow sheet consists of following steps:

- water pumping to the treatment facility
- sorption of uranium on anion exchange resin
- desorption of uranium from the resin with sodium chloride and sodium carbonate containing solution
- precipitation of uranium with hydrogen peroxide
- thickening and drying
- packing of the yellow cake

The main chemical processes of the treatment are:

Sorption-desorption:

Uranium exists in mine water in form of carbonate complexes, therefore it can be sorbed by anion exchange resin:

$$4\ R\text{-}Cl + [UO_2(CO_3)_3]^{4-} = R_4[UO_2(CO_3)_3] + 4\ Cl$$

with R-Cl representing the resin in chloride form. Sorbed uranium complexes can be desorbed with sodium chloride (50–80 g/l), containing some g/l (~ 5 g/l) sodium carbonate:

$$R_4[UO_2(CO_3)_3] + 4NaCl = R\text{-}Cl + [UO_2(CO_3)_3]^{4-}$$

The obtained solution contains approximately 10 g/l of dissolved uranium.

Precipitation of uranium:

Uranium can be precipitated from solution obtained in the sorption-desorption process in alkaline medium by ammonia, magnesium oxide, sodium hydroxide, etc. or from acidic medium (pH ~ 3–4) by hydrogen peroxide solution.

At Mecsekérc, hydrogen peroxide is used since it is more acceptable from environmental point of view and provides a yellow cake of high purity. In a first step the carbonate complexes are decomposed by hydrochloric acid:

$$[UO_2(CO_3)_3]^{4-} + 6\ HCl = UO_2^{2+} + 3\ CO_2 + 3\ H_2O + 6\ Cl^-$$

In the second step the uranium is precipitated in form of uranium peroxide:

$$UO_2^{2+} + H_2O_2 + 2\ H_2O = UO_4 \cdot 2\ H_2O + 2\ H^+$$

Fig. 5: Facility for yellow cake by-production.

The treated water is led to the discharge point (nearby the tailings ponds), where it is mixed with treated groundwater. The mixed water is discharged into the receiver.

Earlier, the loaded anion exchange resin was further processed in the mill. After termination of the uranium mining activities and decommissioning of the mill a new small yellow cake production facility has been built in which a commercial-grade yellow cake is produced as a by-product of the water treatment efforts. The facilities for thickening and packing of uranium peroxide in the new plant is shown in Fig. 5.

Also the seepage from waste rock piles contains elevated uranium; therefore these waters are treated together with the mine water.

At present it is not known how long the mine water treatment process will have to last. Up to now altogether more than 130 t of uranium have been removed from mine water (1968–2002). The current uranium concentration in the mine water is still high, approximately 3–5 mg/l, while it reached 7–8 mg/l in the past.

Remediation of tailings ponds and their surroundings

The main part of the uranium ore was processed by the conventional milling process. The generated tailings were deposited in ponds constructed without or with very poor sealing. Therefore process water from the tailings ponds partly seeped into the underlying subsoil.

TDS was in average approximately 22 g/l in the process water. It has been estimated that approximately 23 Mm^3 of process water seeped into the surrounding soils, causing a huge chemical contamination of groundwater. The average concentration of different constituents of the process water is presented in Tab. 4.

Main polluting components are magnesium sulphate (originated from dolomite in the processed ore) and sodium chloride (originated from the ion exchange process). Nitrate is originated from the explosives used in the mines.

Therefore, tailings ponds remediation is connected with solving two main problems:

- groundwater quality restoration,
- long-term stabilisation of tailings ponds.

A general overview of the tasks to be solved at the tailings ponds is given in Fig. 6.

Tab. 4: Water chemistry of the seepage on tailings ponds.

Na	K	Ca	Mg	Mn	SO_4	Cl	NO_3	TDS	U	Ra
mg/l									mg/l	Bq/l
1.1	0.18	0.6	2.8	0.8	12.8	2.4	0.2	~22	~0.05	~5

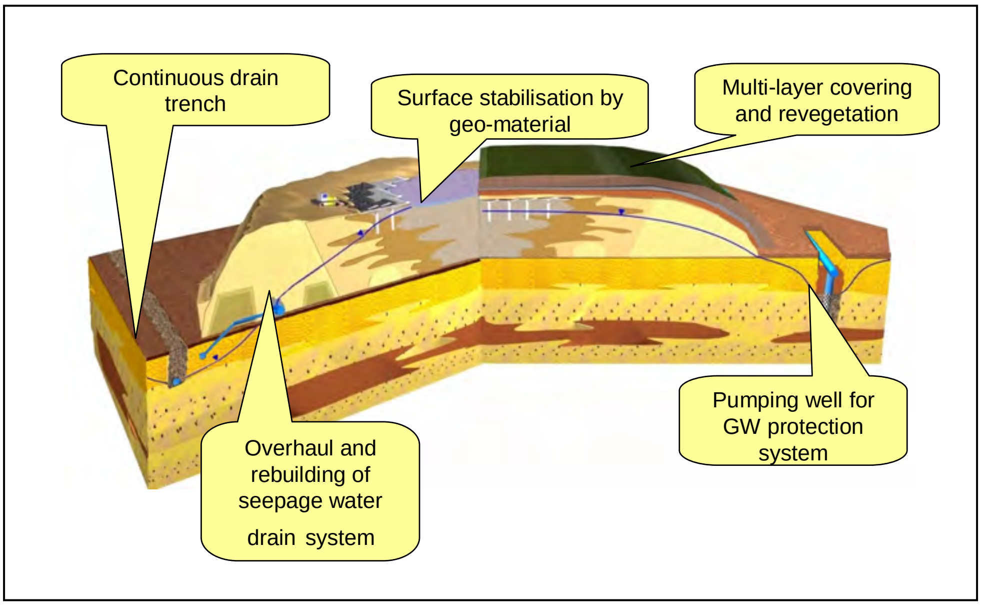

Fig. 6: General overview of tasks at the tailings ponds.

Groundwater restoration consists of extracting the contaminated water by deep drainage and wells. Long-term stabilisation of tailings ponds can be carried out by dewatering of the inner slime core, covering the reshaped surface with a low permeable multi-layer cover system and finally with re-vegetating the newly formed surface of the tailings.

Because of a lack of sealing layers and inadequate neutralisation of the barren pulp at the end of the mill process (neutralisation was carried out to pH ~ 7–7.5), app. 400 kt of chemical compounds seeped into the groundwater with process water causing a huge contamination around the tailings ponds. The seepage of highly contaminated process water caused a huge groundwater contamination in the surrounding of the tailings ponds. This contamination can be seen in Fig. 7, where the distribution of TDS in groundwater is presented.

Groundwater restoration

Hydrological modelling showed that the contaminated groundwater could reach the drinking water wells built near the tailings ponds (some of them in a distance of only 1 km). Therefore measures had to be taken for the protection of the drinking water quality. After evaluating different options a pump-and-treat system was adopted for groundwater restoration. The system was implemented in 2000.

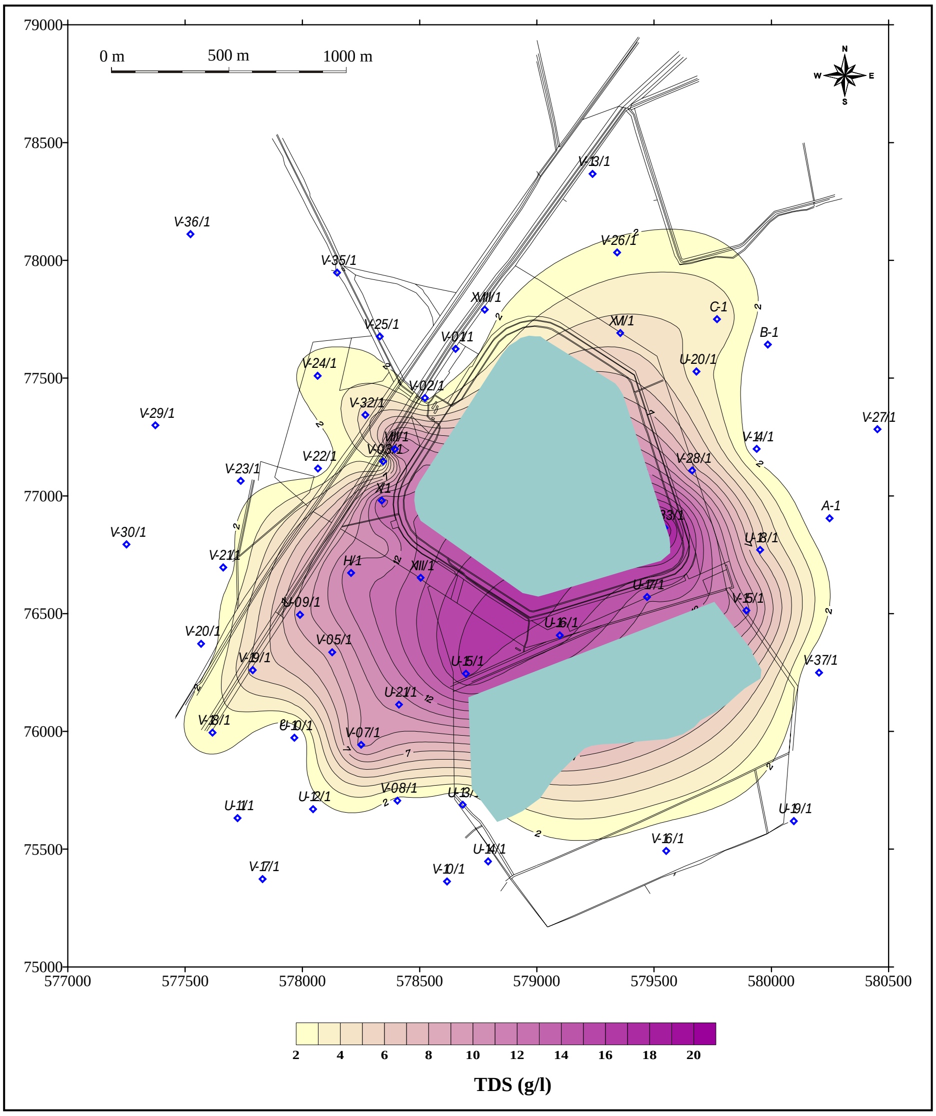

Fig. 7: Contamination of the shallow groundwater around the tailings ponds.

Groundwater extraction

The monitoring data showed that the shallow groundwater aquifer (0–10 m) was most heavily polluted and was therefore the priority target of the remediation measures. Based on modelling data and worldwide experience a drainage system was constructed and extraction wells were built.

Total length of the drainage (which is placed in approximately 9 m depth) is 2.9 km. 7 extraction wells for shallow groundwater and 7 for contaminated deeper water are at present in operation, too. It is supposed that after evaluation of the operation of the existing extraction system additional drainage and wells will be built for the still escaping contaminated water. The locations of the drainage and wells are presented in Fig. 8. The system is capable of extracting approximately 1500 m^3 of contaminated water per day.

Treatment of the extracted water

Composition of extracted water in individual wells depends on the location of the wells and drainage. In average the TDS is 13 g/l in the collected water. It contains mainly magnesium in form of magnesium sulphate (5–6 g/l), and sodium chloride (2–3 g/l). Such water has to be treated prior to discharge it into the local receiver. Uranium concentration in groundwater is generally low, with some exceptions less than 30 µg/l. This low uranium concentration is most likely due to the sorption processes taking place in the soil. Therefore only the salinity of the water is regarded as polluting component, which has to be decreased prior to the discharge of the water into the receiver.

Effective desalination of such water can be achieved by reverse osmosis, as it was demonstrated in our laboratories. But this method is not reasonable from economic point of view. Instead, a commonly used lime process had been chosen for the removal of magnesium sulphate:

$$MgSO_4 + Ca(OH)_2 = Mg(OH)_2 + CaSO_4$$

Of course uranium present in the water also precipitates in this process, though its concentration is much below the discharge limit even in the original extracted water.

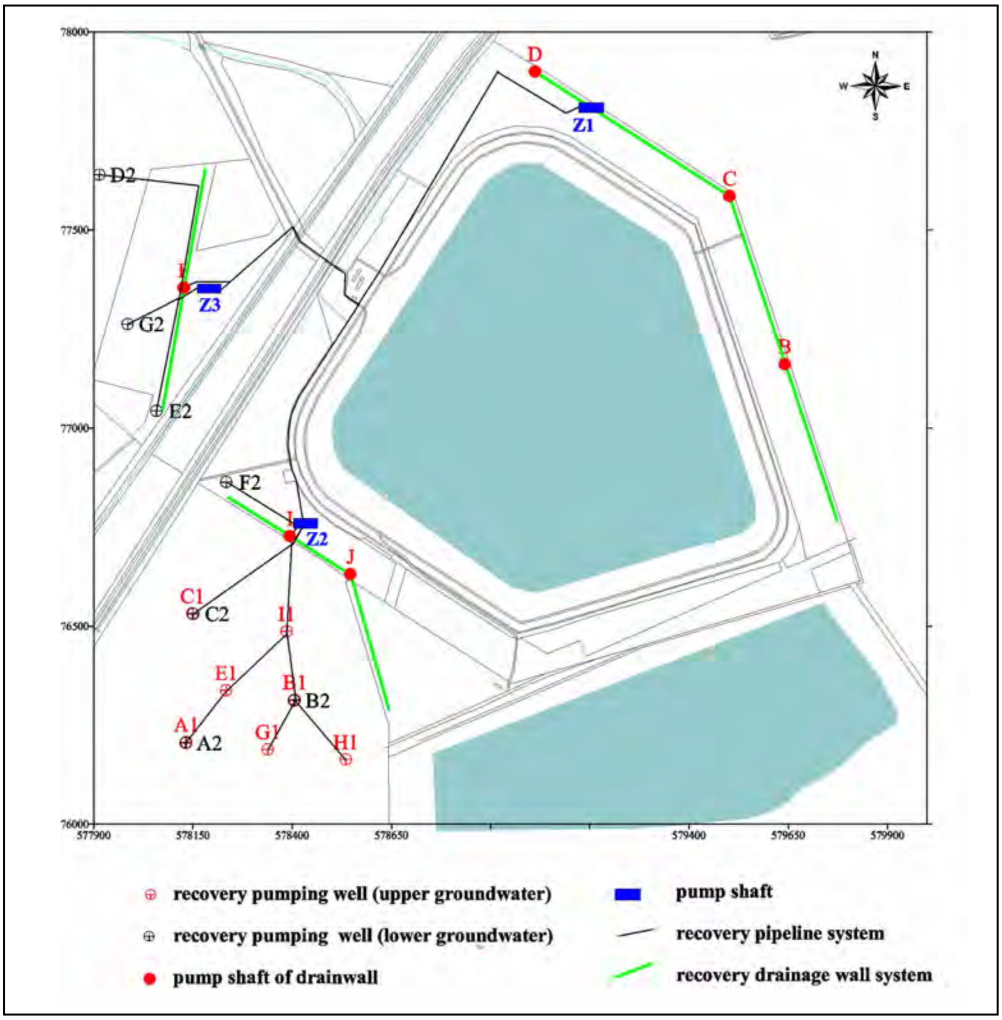

Fig. 8: Location of the groundwater extraction system.

The International Atomic Energy Agency (IAEA) sponsored the development of the water treatment technology. The facility was built on the area situated between the receiver *Pécsi Víz* and the northern foot of the tailings ponds N1.

Main steps of the water treatment are:

- Collecting and mixing the water from the extracting wells in a basin
- Removal of radium (if necessary) in a mixing tank by adding a $BaCl_2$ solution (10 g $BaCl_2$/l)
- Mixing with $Ca(OH)_2$
- Thickening using HDT-process (high density thickening, recirculation some portion of underflow)
- Filtration in continuous press filters
- Deposition of sludge (mixture of $Mg(OH)_2$ and gypsum)

The above process is suitable for the removal of magnesium in form of hydroxide and sulphate in form of gypsum. Two years of experience show that the gypsum precipitation is a slow process, therefore some amounts of the gypsum escape the facility in soluble form. Nevertheless in average the TDS in the treated water decreases significantly from 10–12 g/l to 6–7 g/l. For the treatment approximately 4 kg $Ca(OH)_2/m^3$ is needed.

The water content of the sludge is approximately 50–55 %. The sludge is hauled in containers to waste rock pile N3, where an appropriate storage area has been shaped. Further decreasing of the TDS could be reached only by using physical methods, e.g. reverse osmosis. At the time being such expensive methods are not planned in the near future. Some photos of the water treatment station can be seen in Fig. 9.

Fig. 9: Groundwater treatment station near the tailing ponds.

The water treatment station has been planned for ten years of operation but the real need for water treatment is not known at present.

Stabilization of tailings ponds

Two tailings ponds were built by the company for mill tailings (Fig. 10). The total area covered with tailings is approximately 156 ha.

Fig. 10: Tailings ponds (one is in operation).

The tailings were disposed by hydrocyclones therefore the solid tailings had been segregated: in the central inner part the slime while in the dam the coarse sand had been sedimented. Therefore the water content of the solids and as a result the sear strength of the deposited material changes over a wide range.

Remediation of the tailings ponds means first of all their stabilisation to minimise the releases solid, liquid or airborne material from the tailings ponds. This can be achieved by covering the ponds. To do this the surface of the tailings ponds has to be stable enough to support the covering material. As a matter of fact the surface of the tailings ponds has appropriate stability only on the dam and in its close vicinity. The inner part of the tailings ponds which is often referred to as the 'slime core' has a very weak stability, expressed by low shear strength. Therefore the slime core has to be stabilised prior to covering.

The main tasks regarding the remediation of the tailings ponds were summarised in Fig. 6. The area of the tailings ponds (slime core) needs stabilisation using geomaterials. The method for stabilisation has been developed in the frame of a Phare project with participation of the German companies Wismut GmbH and C&E (Phare project, 1998).

Remediation of the tailings ponds is still underway. Remediation of tailings ponds N2 is near completion while the remediation of the tailings ponds N1 is in progress.

Some steps of the stabilisation of soft tailings are presented in Fig. 11. The soft tailings are covered with geotextiles, geogrid. Vertical drainage is used to accelerate the dewatering process. Next step is placing an interim cover with a good water conductivity. For this sand from reshaping of the dam is used. Role of this layer is loading of the water containing slime to initiate some dewatering under pressure and increase the shear strength of the slime, and at the same time to direct the pressed out water to the collecting well.

Multi-layer soil cover

For long-term stabilisation (usually this means stabilisation at least for two hundred years) the reshaped and dewatered tailings have to be covered with non-radioactive material. The role of the covering material is to isolate the tailings from the environment, first of all to protect the airspace from Radon-222 and its progeny and the groundwater from liquid releases.

The licensing authorities usually determine the radon maximum flux and maximum water infiltration rate allowed in a given location. In our case for radon flux the limit is 0.74 Bq/m^2/s (internationally recommended value). On the uncovered tailings the radon flux is approximately 4 Bq/m^2/s. The external gamma-dose rate has to be decreased below background. For water infiltration the target value is 40 mm/a (precipitation is in average 660 mm/a).

There are many different options for multi-layer covering. As a matter of fact both for radon retardation and the minimisation of water infiltration rate a clay sealing layer is the most promising approach.

Fig. 11: Covering of soft tailings using geomaterial and vertical drains.

For calculation of radon emissions from the pile the following equation is recommended (IAEA, 1992):

$$F_t = R \cdot \rho \cdot E \cdot (\lambda D_t)^{1/2}$$

R is the radium-226 concentration in the tailings, Bq/kg,

ρ is the bulk density of tailings, kg/m^3,

E is the emanation coefficient (dimensionless),

λ is the decay constant for radon-222 ($2.06 \cdot 10^{-6}$ s^{-1}), and

D_t is the diffusion coefficient for radon-222 in tailings, m^2/s.

The lower the diffusion coefficient the lower is the radon flux from the pile. Because the radon flux highly depends on the water content of the media (the higher the water content the lower is the diffusion coefficient), the covering system has to incorporate water-retarding layers. Such layers are most frequently made from clay or loess upgraded with bentonite. In our case (after field-testing) clay proved to be the most suitable material for sealing.

The parameters for the cover system were calculated using the HELP model, which proved to be very useful for the estimation of the effects resulting from changing the different input parameters (thickness of layers, vegetation, properties of soils, etc.) for infiltration rate. The calculations have been made at Wismut GmbH and Golder-Hungary Ltd. Finally the sequence of the covering layers as presented in Tab. 5 was accepted.

Tab. 5: Cover system on tailings pond N1.

	Layer type	**Material**
🌿	Vegetation	Grass and bushes
0.45 m	Storage layer 1	Loess (degree of compaction ≤ 90 %)
0.45 m	Storage layer 2	Loess (degree of compaction 90 to 93 %)
0.4 (0.3) m	Protection layer	Compacted loess (degree of compaction ~ 95 %)
0.3 m	Sealing layer	Compacted clay (degree of compaction 95 to 97 %)

Total thickness of the cover is 1.6 m (on the slopes: 1.5 m). The first layer is the sealing layer composed of compacted clay (0.3 m). Above the sealing layer a protection layer from loess is built, also compacted to a thickness of 0.4 m. The next two layers are practically storage layers for vegetation which is extremely important for evaporation of the bulk of precipitation and erosion protection of the covered surface.

The compacted loess above the sealing layer protects the clay from penetration by plant roots. According to the model calculations it is expected that the infiltration rate will be at a level of 30–40 mm/a.

The partly remediated tailings pond N2 is shown in the Fig. 12. It can be seen that the tailings pond has been partly re-vegetated. The erosion galley needs maintenance in the first years.

Fig. 12: Remediation of tailings ponds (TP2).

Research and development projects (PEREBAR project)

The Mecsekérc company has well equipped laboratories. Therefore the company participates in different research projects. One of the latest projects is the investigation of long-term behaviour of permeable reactive barriers in frame of an EU sponsored project (5th Framework Programme, project acronym PEREBAR). This work was led by the Department of Applied Geology of Karlsruhe University, Germany. Scientific leader was Prof. Dr. Dr. Kurt Czurda. The result of the project is an experimental reactive barrier built for in situ treatment of uranium contaminated groundwater. General information on the project can be found at its website at http://www.perebar.bam.de.

The experimental permeable reactive barrier (PRB) was built in 2002. Some construction steps are shown in Fig. 13. The dimensions of the PRB are: 6.8 m long, 3.9 m deep, 2 m wide. For the PRB a total of 38 t of elemental iron was used. The PRB was built using supporting frames.

The location of the experimental PRB in the valley *Zsid* (test field), with newly installed monitoring wells, is presented in Fig. 14. The cross-section of the experimental PRB is presented in Fig. 15.

In the last half-year detail monitoring was carried out on the test site. It was found that the experimental PRB is extremely effective in removing uranium from the local groundwater. Uranium concentration decreased in the PRB from the original concentration of approximately 1000 µg/l to below 10 µg/l.

A highly unfavourable effect observed in the experimental barrier is the formation of precipitates, caused by the increase of pH from 7 to 9–10. As a result the calcium concentration in the groundwater passing through the iron barrier drops significantly, as demonstrated in Fig. 16.

Fig. 13: Construction of the experimental PRB in Zsid valley near Pécs.

Fig. 14: Position of PRB with monitoring wells

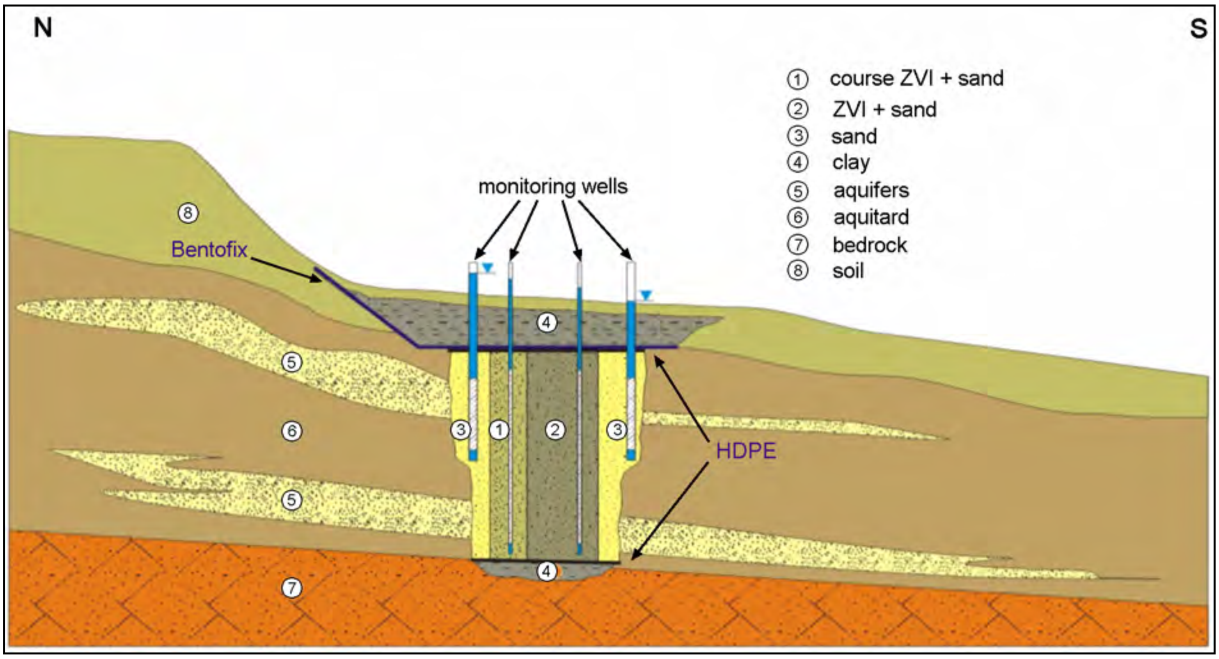

Fig. 15: Cross-section of the experimental PRB (Pécs, Hungary).

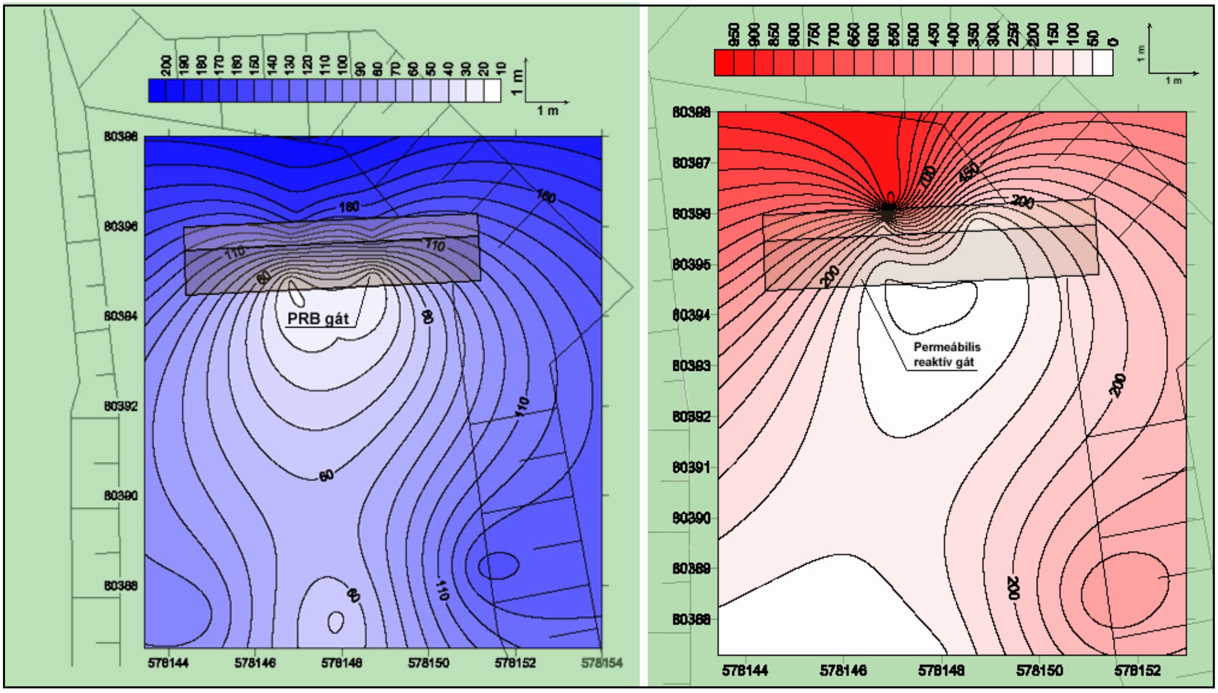

Fig.16: Effect of the experimental PRB on calcium and uranium concentrations in groundwater.

Calcium and partly magnesium, as well as iron dissolved from the iron filling of the PRB are precipitated in form of carbonates. According to the calculation approximately 600–700 g of precipitates are formed when one cubic meter of water passes through the PRB. Question is how will these precipitates effect the long-term permeability of the PRB? It is expected that further monitoring will help to answer this question.

Monitoring

All former uranium mining and processing related objects are being monitored. Also special monitoring stations in the nearby villages carry out continuous monitoring. In Fig. 17 monitoring data measured in village *Pellérd* (in close vicinity of the tailings ponds) are presented. It can be seen that the radon concentration sometimes reaches very high values (250 Bq/m^3 instead of the general 20–30 Bq/m^3 value). This is likely connected with changing of the air pressure, temperature, etc. Inhabitants of the village regularly are informed on the results of the measurements.

Summary

1) For protection of groundwater and surface water the following water treatment methods are used:

- mine water treatment with removal of uranium in form of commercial-grade uranium concentrate which is sold
- pump-and-treat system for groundwater restoration in the vicinity of tailings ponds
- permeable reactive barrier for attenuation of uranium in seepage from waste rock pile

2) Experimental PRB with metallic iron sponge is installed for studying in situ treatment of contaminated groundwater.

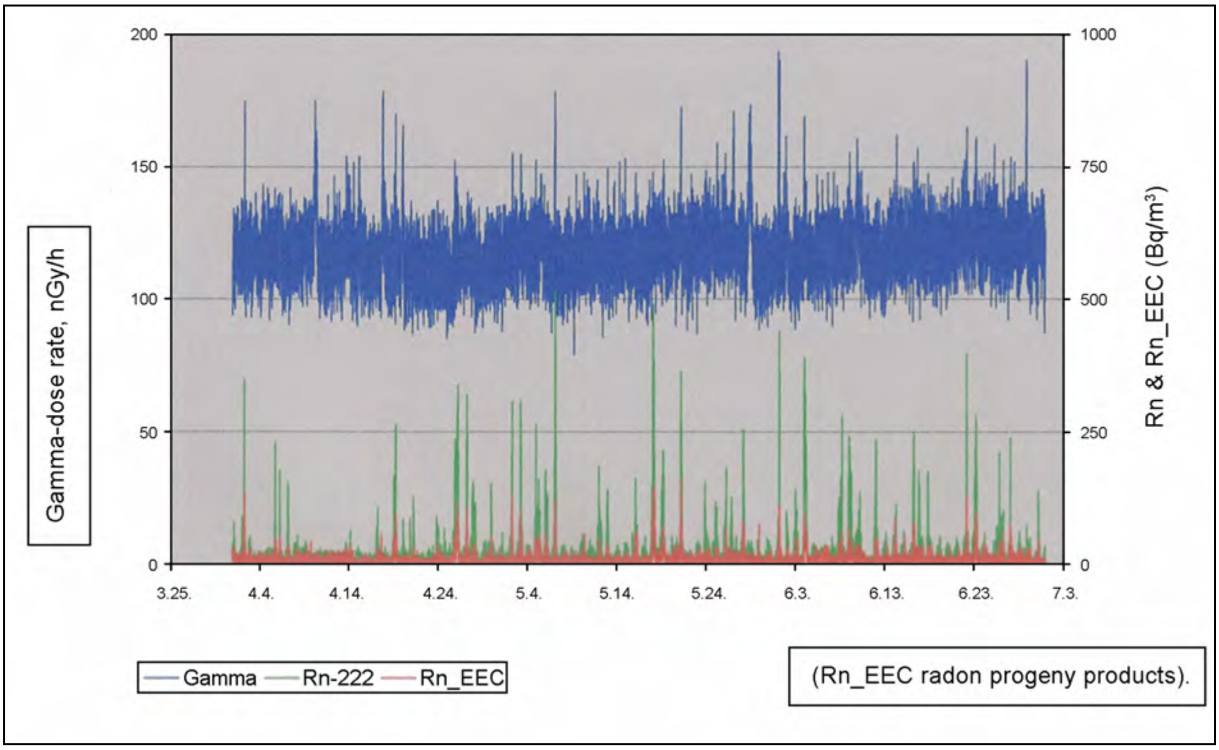

Fig.17: Radiological parameters measured in village Pellerd (1 km from tailings ponds) (Hungary, March–July 2002)

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