SOURCE MANIPULATION IN WATER BODIES OF FLOODED UNDERGROUND MINES – EXPERIENCES FROM THE WISMUT REMEDIATION PROGRAM[1]

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Abstract. Following reunification of Germany in 1990 the uranium production in eastern Germany (former GDR) was abandoned. Wismut GmbH was established as a federal company and put in charge of decommissioning and rehabilitating the uranium mining liabilities. The Wismut Remediation Program comprises the full scope of mine environmental remediation activities, i.e. remediation of underground and open pit mines, waste rock dumps, tailings ponds, area cleanup, decommissioning and demolition. As a crucial element of the closure plan the Wismut project includes the flooding of five underground mines which account, after groundwater rebound has been completed, for the bulk of contaminated waters to be treated at the different mine sites over the long-term. In order to optimize long-term water treatment and to minimize annual treatment costs, a set of alternative approaches to directly influence the contaminant loads to be handled at the surface has been investigated at different scales. As a result of these activities Wismut introduced a set of different methods of direct or indirect source manipulation of water bodies in flooded underground mines into the closure plans.

In the Königstein-ISL-mine an immobilisation technology, which is based on the injection of water supersaturated in barite into former leaching blocks has been implemented as part of the closure plan in order to immobilize parts of the contaminant potential. As an alternative a reactive barrier approach had also been tested within the mine, however, this technology did not prove to be feasible under the site specific conditions of the Königstein mine. With the intention to decrease the uranium concentration in mine waters a set of studies has been carried out where the addition of zero valent iron has been investigated as a tool to establish reducing conditions underground.

At the Pöhla mine site a full-scale field test had been applied to evaluate if natural attenuation processes in the mine water column can be enhanced by simple changes in the mine water management scheme. A water management approach is also the basic instrument at the Ronneburg mine site in order to limit the water treatment costs by plugging the mine which induces mine water stratification.

Additional Key Words: mine flooding, uranium mining, natural attenuation, water quality, water management

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Introduction

Uranium (U) mining in the eastern part of Germany was launched in 1946 immediately after the end of World War II, one year later the Soviet state-run company Wismut (SAG Wismut) was established. During the early "wild" years with a workforce of up to 120,000 employees, U mining in Saxony and Thuringia was characterised by destructive exploration of resources and complete disregard for the environmental concerns of these densely populated areas. Between 1954 and 1990, a new bi-national Soviet German company (SDAG) Wismut continued U mining. The total production of about 216,000 t U ranks Wismut as number three in post-war U production, after the USA and Canada.

With the German reunification in 1990 more than 40 years of intensive U mining came to an end. Liabilities left behind included 1,500 km of open mine workings, 311 million m^3 of waste rock, and 160 million m^3 of radioactive tailings.

In 1991, under the provisions of the Wismut Act, the former SDAG Wismut was legally transformed into a remediation company. The Federal Republic of Germany became the only shareholder. The corporate purpose of Wismut GmbH is to decommission its former U mining and milling facilities and to rehabilitate the devastated land for further use. Wismut GmbH is financed by the federal government which is funding this largest environmental project in Europe and has committed a total of up to Euro 6.2bn for its completion. Rehabilitation by Wismut and the German federal government will turn these former mining regions into ecologically intact landscapes and open new promising vistas.

Mine flooding is the most important step in mine closure because of its long-term consequences and its strong relevance to costs. Also, mine flooding has been found to be strongly interrelated to other measures in mine remediation. The environmental impacts of mine flooding on the water, soil and even on the air path can be substantial. Forecasts of water level recovery and water chemistry based on models initially imply major uncertainties when representative monitoring data is not yet at hand. The experience gained so far underlines the need for comprehensive planning for flooding and for a flexible approach as part of the mine closure management plan which allows continuous updating of initial planning and corrective actions on the basis of monitoring data recovered during the flooding process.

Mine flooding as a principle remediation measure

Basic considerations

The safe decommissioning and closeout of the large networks of underground workings, drifts, galleries, and chambers as well as of adits and shafts is a priority task on the Wismut agenda. Final mine remediation can only be achieved by flooding the mines. Endless water management, and associated water treatment, was not a realistic option since the disturbed hydraulic and unsaturated status must not be allowed to persist, and permanent costs arise. Due to the individual conditions at each of the mine sites the development of site specific flooding concepts was necessary. In general flooding of Wismut mines can be summarized as follows (Fig. 1): After termination of U production (a) the mines were prepared for flooding which includes underground remediation work, removal of hazardous materials and closure of shafts and adits. After completion of these operations, water management is reduced and finally terminated. At this stage, inflow of natural ground water starts uncontrolled flooding (b). To avoid damage to the surface and to minimize any environmental impact due to the ground water

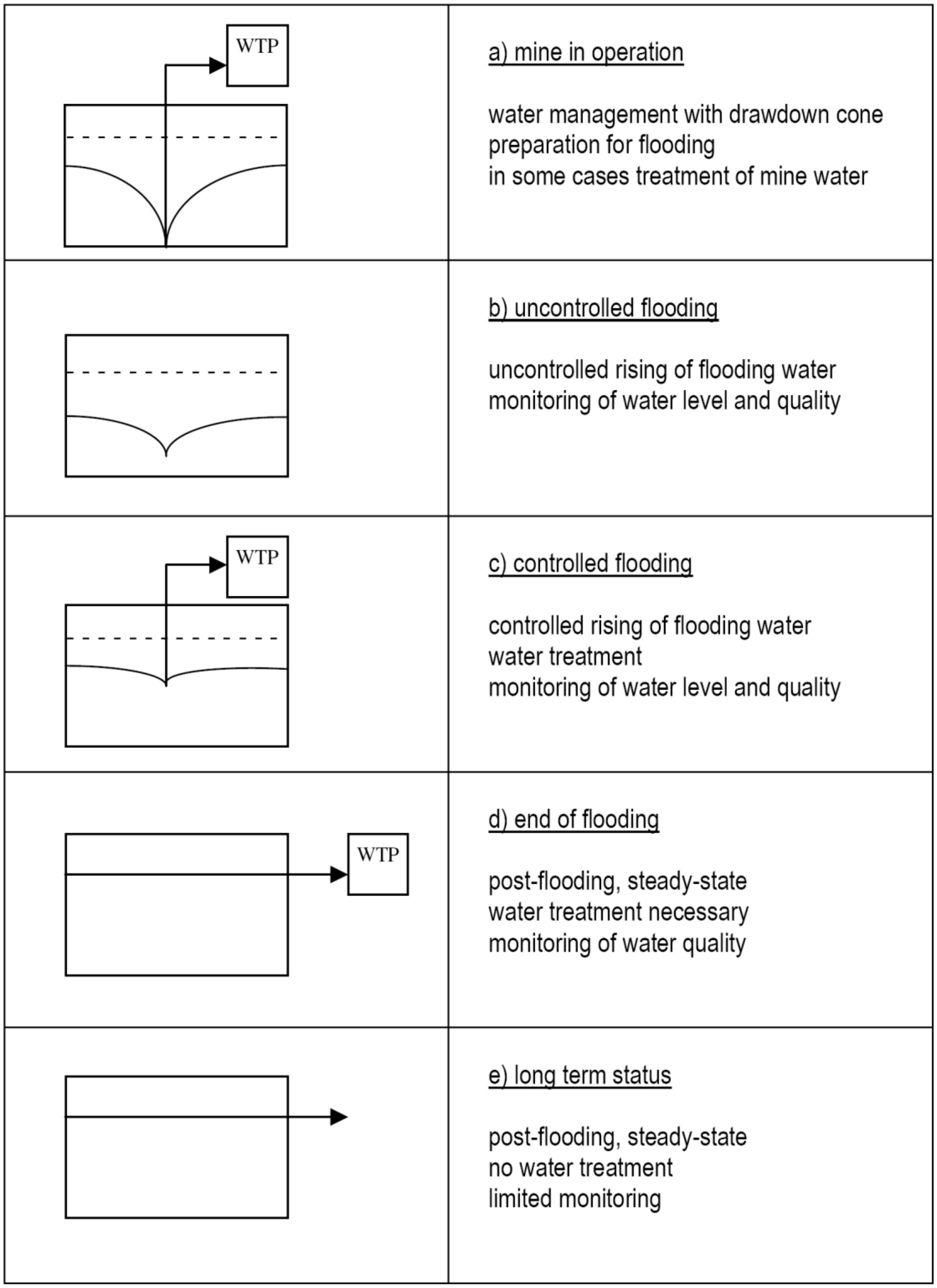


Figure 1. Mine closure. Main steps in terms of mine flooding at Wismut sites, abstracted (WTP = Water treatment plant)

rise, the flooding of the shallow mine levels usually has to be controlled by pump and treat measures (c). Due to the high contamination level of the mine water in this period (first flush), water treatment is necessary. With the controlled flooding the final water level will be reached, and mine waters are released as diffuse groundwater discharge or by adits. After reaching stable hydraulic conditions water quality requires continued water treatment since achieving significant decrease of contaminant levels in the mine water is a long-term process. If water quality meets permitted values or cannot impact ecological systems any longer, water treatment can be terminated (e). From step (b) to (d), the groundwater rise and quality have to be intensively monitored. Over the long term (e), the monitoring effort will be significantly lower.

Site characterization

Wismut has operated a multitude of U mines over the past decades. Five of them which comprise the most important ones in terms of production will be discussed in this paper (see also Fig. 2):

- Ronneburg (111 kt U)
- Schlema (88 kt U)
- Pöhla (1 kt U)
- Königstein (19 kt U)
- Gittersee (4 kt U)

The numbers in brackets indicate the U output from individual mines[1]. The following Table 1 gives an overview of some basic characteristics of these mine sites.

Characteristics of mine water bodies

As the result of the mining activities, geochemical reactions, mainly oxidation processes involving sulfidic ores, occur in the host rock, and the geochemical state of the deposits has been dramatically changed due to the oxygen entry as a result of dewatering. At the end of active mining a near quasi steady-state regime had developed in terms of flow and mass transport. Depending on the mineralogical composition of the mined strata and the mining technology used, a more or less high level of water soluble contaminants is stored within the mine, mainly SO_4^{-2}, heavy metals and natural radionuclides. By flooding the mine this contamination potential is taken up by the inflowing groundwater becoming mine waters with relatively high mineralization and contaminant concentrations. However, oxidation reactions will be reduced by saturation of the rock and exclusion of atmospheric O_2. Later dilution by groundwater inflow predominates, and contaminant levels in the mine water begin to drop. Experience from flooding operations at different mines has shown that the duration of the time span with elevated concentrations, the so called first flush, equals about four times the flooding period (Younger et al. 2002).

[1] According to Lange et al. (1991). Remark: The total output from the mine operations is higher than the total production of SDAG Wismut since the total production refers to the output of the processing plants which accounts for losses in the milling process.

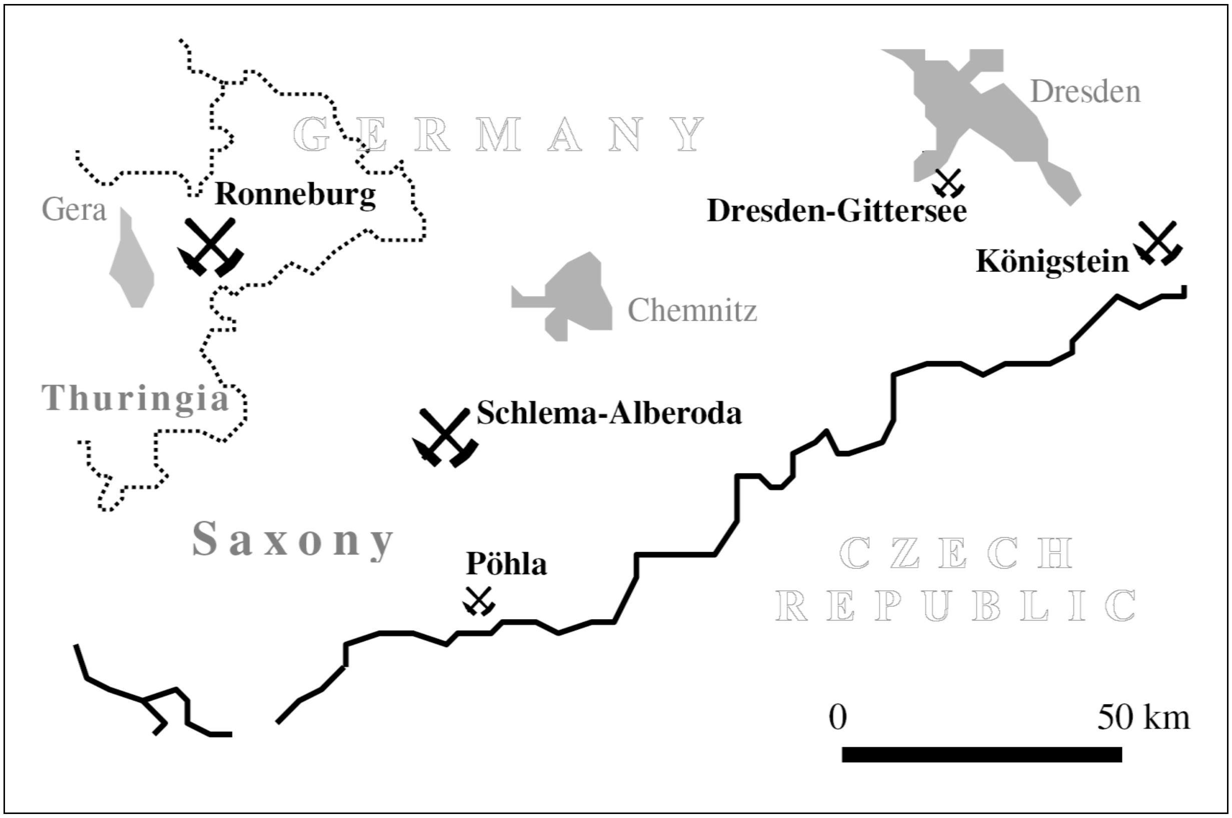


Figure 2. Site sketch showing the locations of Wismut underground mines

Table 1. Characteristics of Wismut mine sites being flooded (WTP = Water treatment plant)

Mine (mining method)	Flooding Volume	Flooding Status November 2005	Prediction	Current water treatment
Ronneburg (conventional ore mining)	25 - 30 M m^3	Water level: 270 m a.s.l., flooded cavity: 20 - 25 M m^3	first water release on surface: 2005/ 2006; final water level: 2007/ 2009	lime addition, 450 m^3/h
Schlema (conventional ore mining)	36.5 M m^3	280 m a.s.l., flooded cavity: 35.8 M m^3	final water level: 320 m a.s.l.	lime + $FeCl_3$ + $BaCl_2$ addition for U + As +Ra precipitation, 500 - 800 m^3/h
Pöhla (conventional ore mining)	1.5 M m^3	flooding finished 11/1995	16 - 20 m^3/h mine water discharging	wetland trial runs (Ra, As) with redundant WTP
Königstein (ISL mine)	water level 190 m a.s.l.: 11.5 M m^3	water level: 110 m a.s.l., flooded cavity: 4.5 M m^3	water level: 140 m a.s.l.: 2007 water level: 190 m a.s.l.: 2013	Up to 190 m a.s.l.: 100… 270 m^3/h, HDS
Gittersee (Coal mine)	2.3 M m^3	Water level: 160 m a.s.l., flooded cavity: 2.2 M m^3	Final water level uncertain; water adit or pumping	lime addition and aeration for iron precipitation, up to 250 m^3/h

Currently all Wismut U mines are in the process of flooding, each with a different degree of completion. The relative time delay of the huge mines at Ronneburg and Königstein is a consequence of the size of the mines but also of the duration of the permitting procedures (see Table 1). The qualities of the mine waters vary depending on the respective characteristics of the mines (Table 2). Table 2 indicates the average composition of the pumped mine water, except in the Ronneburg case, which is derived from about 50 monitoring wells connected to the flooded mine workings.

The Schlema and Pöhla mines are characterized by relatively homogenous mine water bodies as a result of good hydraulic connections within the underground workings and an enforced convection by geothermal processes. The Königstein mine is situated in an aquifer with a technically enforced convection (pump and treat) thus water quality is relatively homogenous, too. The mine water body at the Gittersee mine shows a significant stratification with higher mineralised water at the deeper levels. The Ronneburg mine is a complex system of interconnected, formerly individual mines with different water qualities. Accordingly, a very inhomogeneous flooding water body has developed, and the hydrochemical properties differ substantially within the mine workings.

Table 2. Hydrochemical properties of mine water bodies in former Wismut U mines (status 2005)

	Ronneburg	Schlema	Pöhla	Königstein	Gittersee
pH	2.3 – 11.1	6.8	7.1	2.8	7.0
Redox potential (mV)	10 – 750	164	97	650	200
conductivity (mS/cm)	0.1 – 9	3.2	0.6	2.5	2.5
SO_4 (mg/L)	8 – 7,300	1,390	7	1,700	800
Cl (mg/L)	8 – 1,860	70	5	40	100
HCO_3 (mg/L)	6- 550	760	350	< 5	400
Ca (mg/L)	13 – 600	290	50	150	200
Mg (mg/L)	2 – 1,220	210	20	20	40
Fe (mg/L)	0.3 – 2,800	8	6	500	20
Al (mg/L)	0.05 – 77	< 0.1	< 0.1	60	< 0.1
As (µg/L)	1 – 918	1,520	2,590	500	10
Zn (mg/L)	0.007 – 43.5	10	75	20	0.03
U (mg/L)	0.003 – 19	4.0	0,04	30	0.1
Ra-226 (Bq/L)	0.3 – 1,800	2.6	3.8	8	0.02

Types of alternative approaches to reduce water treatment costs

To date Wismut is operating conventional water treatment plants at each underground mine site with design capacities ranging from 80 m^3/h at Pöhla up to 1150 m^3/h at Schlema-Alberoda. Main contaminants to be removed include U, Ra, As, Fe, Mn, and other heavy metals, such as Ni, Zn, and Cu. Annual water treatment at Wismut's mine sites amounts to more than 10 million m^3 (2004) with costs on the order of Euro 15 million.

Given the high level of mobile and readily leachable contaminants in the flooded mines, it is obvious that mine water will be contaminated for an extended period of time, requiring that the mine water would have to be treated over a period of up to decades. Both from an ecological as well as from an economic point of view, it is crucial to reduce the time span required to achieve compliance with water standards and to minimize levels of released contaminants. In order to achieve this a variety of alternative approaches has already been considered and/or are being evaluated. The basic principles of these approaches are summarized in Table 3.

They have been investigated and developed to different degrees. Approaches which have reached a full scale application and were already implemented under the closure plans of the individual deep mines will be described in the following section.

Table 3. Alternative principles and approaches to reduce water treatment costs

Basic principle	Attempts	Approach
Control of hydraulic conditions	Control of inflow/outflow	Catching of groundwater and separate discharge, reduce of flooding water flow rate
	Isolating of certain minefields	Isolating of minefields with high contaminant potential by dams, backfill
	Control of mine water convection in the water body	Sealing of hydraulically active shafts, galleries by dams, backfill
Source manipulation	pH-buffering	Backfill of mine openings with buffering material
		Injection of buffering liquids Na(OH), $Ca(OH)_2$
	Eh-Lowering	Injection of reducing liquids Na_2SO_3, Fe(0)
		Injection of nutrients and organic matter to enforce microbiological activity
	Controlled precipitation	Injection of stabilized supersaturated solution in mine openings, clastic rock or porous rock
Down stream control	Passive water treatment	Natural iron and heavy metal precipitation in dewatering adits
		Backfill of downstream galleries with reactive material

State of implementation under the closure plans of the individual mine sites

Ronneburg mine field

The Ronneburg site is an excellent example of a flooding operation at which hydraulic measures were used to positively affect the water treatment efforts in the post-flooding state (see Fig. 1 d). The very complex Ronneburg mine consisted of six formerly separate mines comprising 14 mine fields with 40 shafts (Fig. 3). Total mine water discharge averaged > 1000 m^3/h for the whole mining district. Because of the huge area of the mine (ca. 70 ha) and its very complicated structure with different geochemical and hydraulic conditions water quality differed substantially in the various mine fields and mine levels.

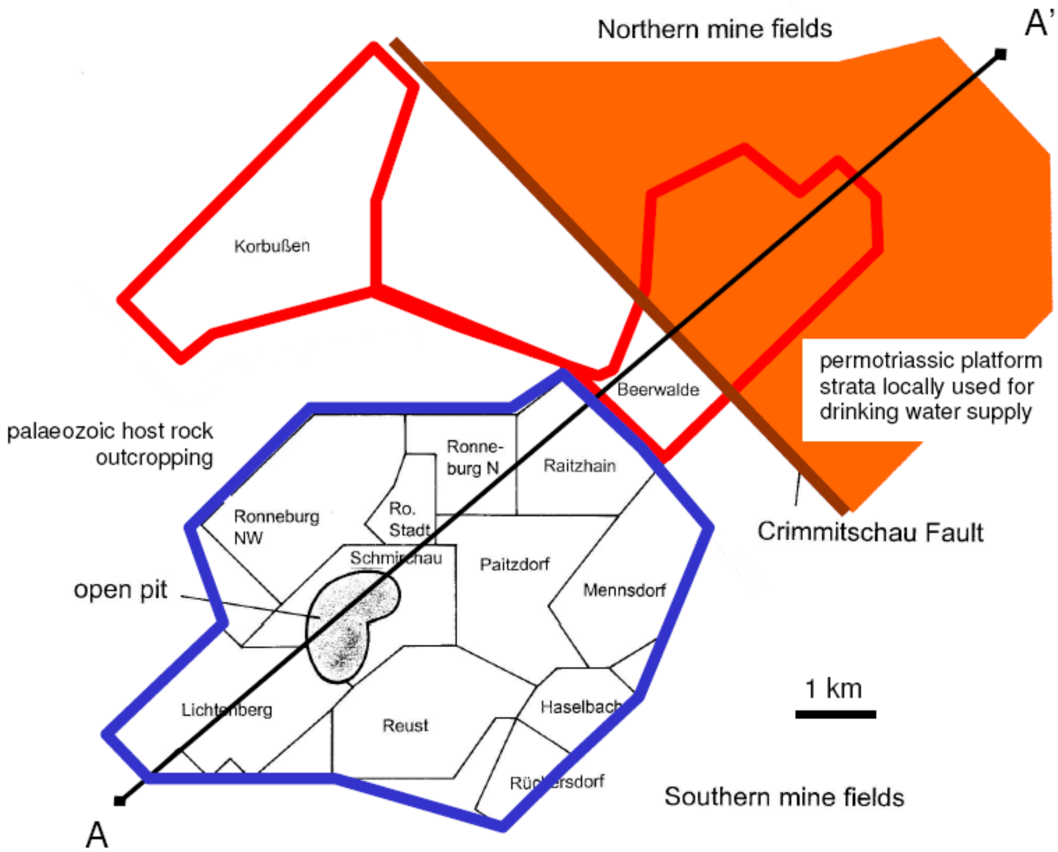
This variation in water quality of the Ronneburg mine waters chiefly reflects the different conditions in the various mine fields. Prior to flooding the main contaminant sources for the mine waters were a multitude of waste rock piles with a total volume of about 200 million m^3. Due to the lack of impermeable liners under these piles and because of the location of most of them within the drawdown area of the underground mine most of the seepage, high in radionuclides, heavy metals and sulfate, was draining to the underground galleries. The most important dumps in terms of seepage characteristics were the Absetzerhalde (65 Mm^3), the Nordhalde (30 Mm^3), and about 76 Mm^3 of waste dumped within the Lichtenberg open pit as an internal dump. So the seepage from these sources became the most important contaminating streams, and because of their location the mine waters of the Lichtenberg and Schmirchau mine fields were characterized by the poorest water quality. On the other hand mine waters from mine fields located close to the edge of the drawdown cone showed only low contamination.

These circumstances led to a specific closure strategy for the Ronneburg mine field which included (a) the spatial concentration of the majority of the mine waste within the Lichtenberg open pit and (b) the construction of hydraulic barriers of different types in order to minimize the mixing of waters with different water quality and to diminish the water flow through the mine to the downstream catchments and ground water reservoirs (Hockley et al. 1997, Paul et al. 2005).

The concept for mine flooding included four major types of hydraulic barriers:

1. Hydraulic separation of the southern and northern mine fields, separation of the Korbußen mine field,
2. Plugging of all shafts and adits, complete backfill of shallow mine workings,
3. Minimization of the water exchange rate between individual mine fields of the southern part of the mine, and
4. Selective plugging of preferred flow paths in exfiltration areas where mine water discharge is expected after the groundwater rebound has finished.

So prior to mine flooding intensive preparation measures were implemented to remove contaminants (e.g. oils, lubricants) from the mine, to stabilize/ backfill mine openings and shallow workings. In order to separate mine fields with different water quality altogether 117 hydraulic barriers have been erected. All existing connections between the mine fields of Raitzhain and Beerwalde (7 drifts at 5 levels) as well as Korbußen and Beerwalde (1 drift) were blocked with concrete plugs dimensioned for pressure differences of up to 35 bar.



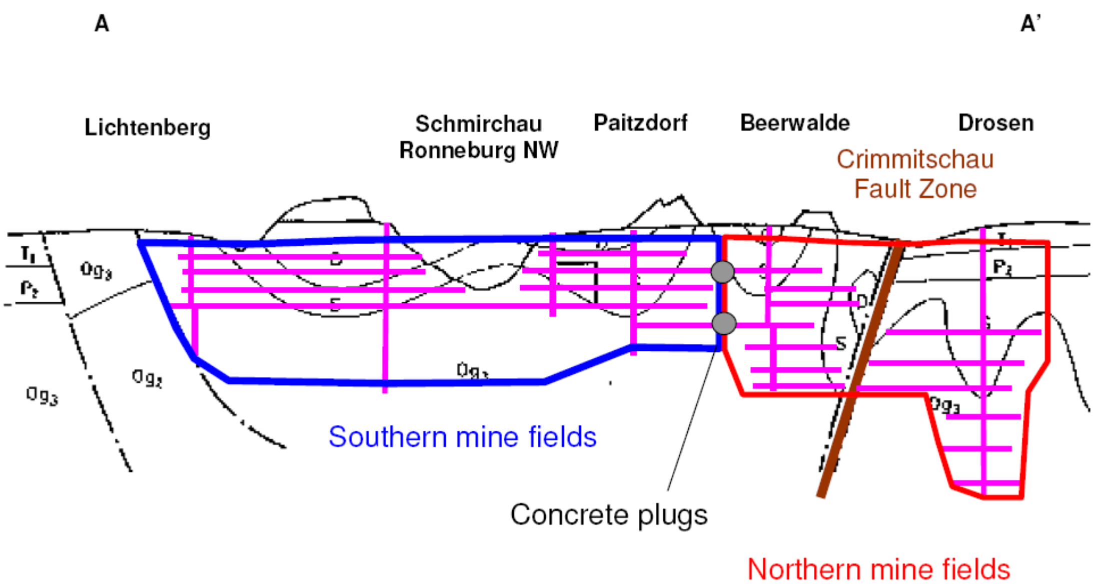


Figure 3. Plan view and cross section showing the separate mine fields and the basic structure of the Ronneburg mine, schematic (Og_2/ Og_3…Ordovician, S…Silurian, D…Devonian, P_2…Upper Permian “Zechstein”, T1…Lower Triassic “Buntsandstein”)

As a consequence of the complete separation of the southern, the northern, and the Korbußen mine fields, flooding of the underground mine could be initiated independently. Whereas fully fledged flooding of the southern mine fields was initiated at the turn of 1997/1998 after a four-year-permitting and preparation phase, flooding of the northern mine fields started in 2000 (Paul et al. 2002, Gatzweiler et al. 2002).

Since the whole underground mine is completely backfilled in its uppermost 100 meters and no draining adits or other preferred elements for mine water discharge exist the flood waters are expected to eventually exfiltrate into local receiving streams. As the mine water quality in the central part of the southern mine fields does not allow untreated discharge, the mine water has to be collected and treated. Water collection will be mainly realised in the Gessental valley which is expected to be the main water discharge area of the contaminated groundwater after the groundwater rebound has finished. A system of drainage elements installed inside permeable Quaternary sediments overlaying Silurian bedrock will collect ascending waters under anaerobic conditions. A pump station downstream will convey the water to the Ronneburg water treatment plant (WTP) with a design capacity of 450 m^3/h. First exfiltrations in the Gessental area are predicted for mid 2006. Alternatively the water supply from the southern mine fields to the WTP can also be realized from a deep well which is connected to the underground galleries of the Schmirchau mine field. Both opportunities of water supply are necessary, since there must be the possibility to influence the flood water rise in the mine directly using the deep well (fall-back option). However, the water level in the mine shall be adjusted over the long term without any water pumping directly from the open mine voids in order to reach a high inundation level and to minimize the catchment area of the mine. This will also limit the thickness of the unsaturated zone which is subject to further acid generation. As a consequence of this "collect-and-treat" instead of "pump-and-treat" strategy density stratification within the mine water column is expected to appear. Since the inflow rate to the mine is clearly head-dependent, this concept aims to minimize the amount of water which has to be treated as well as the contaminant loads which have to be handled in order to diminish operational costs for water management, water treatment and sludge disposal.

In contrast, monitoring time series from the northern mine fields including Korbußen show water quality conditions, which allow groundwater rebound to occur without extensive technical water management facilities as a prerequisite. However, as part of a fall-back option the main shaft of the Beerwalde mine has been equipped with a well, and plans are at hand to install a water treatment facility should this be required. The flooding operation is expected to be completed between 2007 and 2009.

Schlema-Alberoda mine

Controlled flooding of the Schlema-Alberoda U mining site, comprising ca. 36.5 million m^3 of voids and reaching down to a depth of 1,800 m, began in 1991 under the mine closure program. Flooding progress is monitored for its environmental effects in terms of geomechanics, radiology and hydrology/hydrochemistry.

The process of flooding was influenced by the

- Operation of the water treatment plant (treatment rate, downtimes for maintenance/ rebuilding/ extension);
- Ground water recharge or inflow rate into the mine;
- Vertical distribution of the mine voids.

By mid-2005 about 95 % of the floodable voids at the site had been flooded, and the mine water level rose to about 50 m below the natural spill point to the Zwickauer Mulde river. This was accompanied by a slowdown in the continuous rapid rise and the transition to a discontinued, step-by-step flooding progress. Flooding of the remaining near-surface voids is closely monitored with a view to ensuring targeted control of flooding impacts on this densely populated area. Five shafts are being surveyed by the monitoring system. Temperature, conductivity, pH-value and redox-potential are measured at regular intervals. Furthermore the quality of flooding water and the water level are observed.

Slowed down final flooding is a good prospect for getting first-hand information from the analysis of contaminated flood water and for establishing detailed prognoses of long-term water characteristics. In the medium term, such prognosis will help to optimise the cost-intensive operation of the water treatment plant which came on line in 1999. At the present moment, the storage capacity of near surface voids is being checked. This “buffer volume” serves to compensate for extreme inflow rates which exceed the capacity of the water treatment plant.

Control of mine water convection in the water body by sealing of shafts, and blocking of galleries by dams and backfill has been checked. Due to the very intensive perforation of rock mass over a wide area it was found that it is not possible to block mine water convection significantly. It is expected that water convection and homogenous water quality will occur over the long-term, in particular due to the high temperature gradient down to a depth of nearly 2 km.

Current trends in water quality are characterised by declining concentrations. The convection-driven transfer of constituents still continues in the flooded mine. To comply with standards, the water treatment will last at least ten years, thus investigation have been carried out to manipulate the hydrochemical conditions. Like at the Pöhla site (see below) it is expected that the water body will reach pH-neutral and reducing conditions in the long-term. With a view to accelerating such a trend different iron materials have been tested on a lab scale. Current results show that fine iron powder and nano-size Fe particles are able to lower the redox potential and to immobilize U from solution. Sedimentation tests are carried out to calculate the mobility of the Fe particles in shafts and galleries. Following the laboratory tests, a field test is planned in a main shaft of the Schlema mine. The idea is to use relatively intensive water convection to convey reducing substances into the water body.

<u>Pöhla mine</u>

Remediation at the comparatively small Pöhla U mine began in 1991, flooding was carried out from early 1992 until autumn 1995. Due to a head-dependency of the mine water inflow into the mine and to additional floodable pore volume, mine flooding took longer to complete than originally predicted.

Flooding progress had been monitored for its environmental effects, too, but the aspects of geomechanics and radiology are not that important in comparison to the Schlema-Alberoda mine. Flooding water rising to the anticipated spill-over level is mixed or homogenised, respectively, by convection due to natural hydrogeological and geothermal processes.

The Pöhla case is a good example of natural attenuation processes that occur in a flooded mine. In 1995, contaminated flooding water reached the level of natural overflow to the surface via the former main haulage adit, at a rate of about 15-20 m^3/h. A conventional water treatment plant was commissioned in 1995. According to the trends in mine water chemistry it became obvious after spill over, that only Fe, As and Ra required treatment (Fig. 4). After only about three years, SO_4^{-2} and U levels in the discharging mine water were found to be significantly decreased below the discharge limits. Favourable conditions like a deep, isolated and relatively small flooding water body, low influx of O_2 rich ground water and microbiological activity lead to strong reductive conditions and demobilisation of redox-sensitive compounds. However, in contrast to this the recent development of Ra and As concentrations shows no decreasing trend, and continued mid- to long-term water treatment appears to be necessary for those compounds.

To replace the conventional water treatment plant Wismut's first full scale constructed wetland was implemented after a successful pilot scale test which started in 1998 (Küchler et al., 2005). The two-line facility designed for the As and Ra removal from 20 m^3/h of mine water was put into experimental operation in 2004. The performance of the wetland is still improving; however the decommissioning of the conventional WTP is not yet possible, since the performance robustness of the whole process is still insufficient and calls for further adjustments.

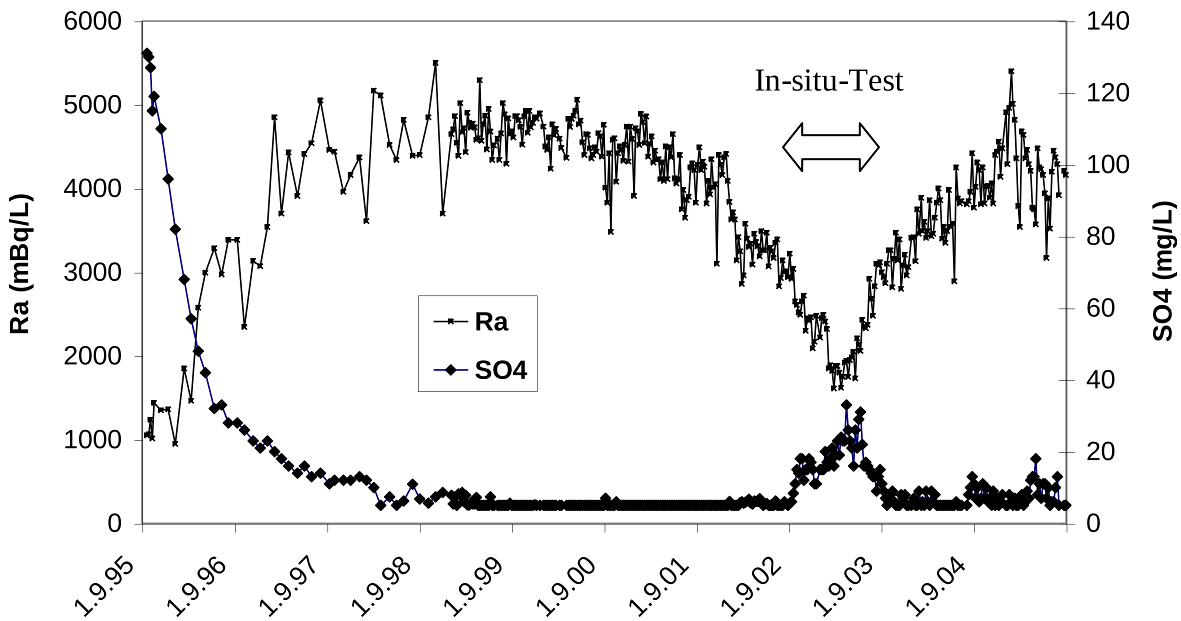
In addition to the switch from conventional to alternative biological passive water treatment, results have been obtained from a test carried out on a method to influence flooding water characteristics in situ and which demonstrated the feasibility of partial contaminant separation by partial flooding water oxidation.

In connection with this test, different fractions of infiltration water, which is rich in O_2, but has low concentrations of radioactive and toxic compounds, was added to the mine water from 2002 to 2003. This experiment led to a limited oxidation of flooding water and a partial separation of Fe and As as shown in Fig. 4. However, the exclusive application to the whole mine to separate the contaminants below the discharge limits is not possible, because there is not enough volume of infiltration water available. Furthermore the Fe/As-ratio is tending to smaller a value which complicates a sufficient AS separation due to co-precipitation with Fe hydroxides (see Fig. 4). Nevertheless investigations are under way to implement a joint solution which makes use of the self purification capacity of the mine as a first treatment step in order to alleviate the treatment capacity of the constructed wetland.

<u>Königstein Mine</u>

The remediation of the Königstein mine near Dresden is a unique case because (1) it is situated within an aquifer in an ecologically sensitive and highly populated area and (2) an in-situ-leaching (ISL) technology was applied. The ore body is located in the 4th sandstone aquifer, the deepest of four hydraulically isolated aquifers in a Cretaceous sandstone basin. The 3rd aquifer is an important water reservoir for the Dresden region and is environmentally and economically very significant.

The U was extracted initially using conventional mining methods, but later an underground in situ leaching method using H_2SO_4 was implemented. The in-situ-leaching was performed on sandstone blocks with volumes of 100,000 to 1,000,000 m³. In all, 104 blocks were leached with solutions containing 2 to 3 g/l of H_2SO_4. During the in situ leaching period, about 130,000 t of H_2SO_4 were applied within the deposit. Additionally, an unknown amount of H_2SO_4 produced by pyrite oxidation was released within the mine. Especially due to the reactions of the oxidizing H_2SO_4, the geochemical nature of the deposit was substantially modified, with a high level of contamination remaining within the deposit, mainly SO_4^{-2}, heavy metals, and natural radionuclides. In the case of uncontrolled flooding (a walk-away option) it was expected that highly contaminated groundwater would rise up into the overlying aquifer through natural or man-made hydraulic connections.



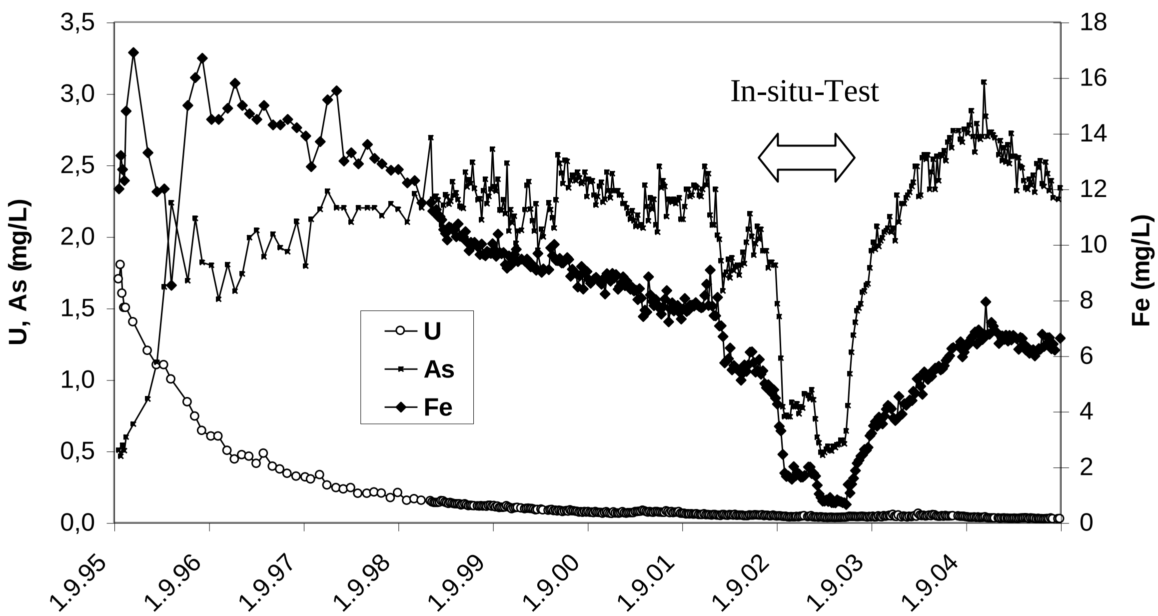


Figure 4. Concentration versus time plots of relevant parameters in the flooding water of the Pöhla mine. The time span of the in-situ test executed in 2002/03 has been indicated.

To prevent contamination of the overlying aquifers, a concept of controlled flooding was developed. A major element of this approach is a control drift system which allows collection of draining flooding water down-gradient of the deepest part of the mine. The flooding water collected in this control drift system can be treated and discharged to the Elbe River.

To reduce the long term costs of conventional water treatment, alternative principles to reduce contaminant potential and emission have been considered. Two approaches have been developed up to full-scale application

I. Direct source immobilization

II. Using of reactive material deposited in open mine cavities as a reactive barrier.

Direct source immobilization. Direct source immobilisation is based on the injection of supersaturated $BaSO_4$ and SiO_2 containing solutions to precipitate dissolved contaminants and to cover reactive mineral surfaces (Jenk et al., 2005). The $BaSO_4$ and SiO_2 layers filled pores and covered reactive mineral surfaces and secondary precipitates, such as hydroxides or hydroxysulfates. Because of the extremely low solubility of barite, long-term stable immobilization was achieved. First, laboratory experiments were carried out to create suitable solutions. Barium sulfate supersaturated solutions were prepared by mixing solutions containing $Ba(OH)_2$ with sulphate-containing solutions in the presence of various types of precipitation inhibitors. In a second step, column tests were used to determine the immobilization capacity of $BaSO_4$ producing solutions and to investigate crystallisation products inside the sandstone. In order to increase the immobilization capacity, various amounts of sodium silicate were added. Field tests were carried out on blocks in the southern part of the Königstein mine.

In light of the results from the laboratory, column and field tests, the decision was made to apply the newly developed immobilization technology (direct source immobilization) to selected areas of the Königstein mine as part of the closure plan. Between December 2001 and May 2005, 1.1 million m^3 of sandstone have been treated in the southern part of the mine. To this end, an improved grout plant was installed in the southern mine field. To avoid long pipelines, the plant was disassembled and moved to two different locations. There were no technical problems to reuse the components (Fig. 5). It is expected that this approach will minimize the source in the final flooding process which will significantly reduce the costs for conventional water treatment over the long term after ground water rebound has been completed.

Reactive Barrier. Extensive research has been conducted over several years to establish the extent to which reduction of contaminant concentrations can be positively influenced and accelerated by storage of reactive materials in mine cavities (Jenk et al., 2003). Investigations were carried out at different scales to test and select materials with respect to a maximum immobilisation of contaminants (underground column tests), to examine hydraulic effects (underground large-scale column tests), and to optimise material properties (laboratory tests).

The investigations have shown that a mixture of Fe-chips and lignite is capable of efficiently remediating contaminated acidic mine water. The material studied is easily available and compatible with the environment. A number of feasibility studies were carried out assessing the feasibility of a large-scale application of such a reactive barrier using the control drift down-gradient of the mine. However, the construction of a reactive barrier in open drifts of the control

Figure 5. Immobilization grout plant 2005

drift system proved not to be feasible. The main problems encountered were:

- Emplacement of the reactive material would require single face and auxiliary ventilation systems but the dimensions of the mine workings inhibit use of sufficiently sized ventilation equipment (vent pipes); waste air return (and Rn in particular) was not ensured (radiation protection measures).
- The control drift acts as a drainage element for the flooding water. Safe drainage of this flooding water (ca. 300 m^3/h) would not be ensured when backfilling of the barrier material takes place.
- Upon contact with reactive material, acidic flooding water may produce hydrogen. This could lead to potential risks (firedamp), given the possibility of limited ventilation and the resulting lack of workplace protection.
- Since placement of reactive materials from above ground once flooding of the control drift is completed would inevitably incur disproportionately high costs, this option did not materialise at the Königstein mine site.

Currently a research project for source manipulation is under way. The aim is to accelerate hydrochemical changes in the mine water to achieve a long-term stable status. The approach is designed for the post-flooding period when the flooded water body will have reached its final dimension. The attempt is the injection of milieu influencing chemicals and nutrients from surface to enforce microbiological activity. Natural water convection inside the refilled aquifer supported by pumping provides a possibility for wide dispersion of the injected substances.

Dresden-Gittersee U-bearing coal mine

The former U-bearing coal mine of Dresden-Gittersee is part of a historic coal mining district. Coal mining goes back to the 16th century. The coal contained up to 2000 ppm of U, and consequently Wismut mined coal for U extraction. Flooding started in October 1995. The initial concept was based on a hydraulic connection between the U mine and an old dewatering adit which would drain the overflowing mine water into the Elbe River. However, the overflow did not entirely happen as anticipated. In the summer of 2003, at a flooding level of about 180 m a.s.l., a residential area near Gittersee became wet. Investigations identified mine water being the reason for this effect. As the flooding level can be controlled through pumping from two wells, the response was to have it lowered down to a noncritical level (160 m a.s.l.).

Currently, the minewater is kept at a level of 160 m a.s.l., and investigations for alternative local dewatering possibilities for this area are carried out. Depending on the outcome of those investigations, the final flooding level and the final dewatering system will be selected. Should it turn out to be necessary to pump and treat for an unforeseeable period of time it is anticipated to establish an artificial underground hydraulic connection between the flooded mine field and the above mentioned existing pervious dewatering adit discharging to the Elbe River.

The flooding water at Dresden-Gittersee carries a high Fe and SO_4^{-2} load, thus water treatment is necessary. It is expected that Fe will precipitate in the dewatering adit along the flow length of some 9 km. Supporting arrangements like cascades for aeration or a limited lime addition are under investigation.

Conclusions

Experience with mine flooding in the framework of the Wismut project shows that flooding waters contain contaminants over a long period of time. Contaminant composition and behaviour over time depend on several chief characteristics of the mine. The understanding of flooding processes and of the behaviour of the water body such as hydraulic behaviour, processes of contaminant release and chemical reactions opens ways to influence long term contaminant release rates. A couple of principles have been investigated, and some approaches have been developed up to a full-scale application. It must be stated very clearly, that there is no universal approach, and every mine closure calls for a separate and tailor-made approach. Further research and development is necessary for a better understanding of the very complex processes in flooding water bodies, since long term contaminant release is a burden to nature and economic resources.

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