Integrated water protection approaches under the WISMUT project: The Ronneburg case

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Abstract. At WISMUT's Ronneburg mine site since 1991 a combined remediation strategy has been realised, which consists of the following central elements: clean-up of operational areas, backfilling of the open pit mine with waste rock from the surrounding piles, flooding of the underground mine and construction/ operation of technical water management systems. This remediation approach can be characterized by a number of environmental benefits which include the termination of water quality problems caused by the waste rock piles which were originally spread over a large area, the immobilization of toxic substances in the area of the underground and the open pit mine and the termination of surface water pollution by the discharge of effluents from the mine drainage system. These effects enabled WISMUT to minimize the additional construction and operational costs for technical water management and treatment systems which are, however indispensable for the successful completion of the closure work.

Introduction

WISMUT GmbH is carrying out the closure of the entire East German uranium mining industry which makes this remediation program to one of the largest mine closure projects in the world. Among WISMUT's former mining sites the Ronneburg mining district which produced from both underground and open pit operations was the most important with a production of approximately 113 kt U between 1951 and 1990. Mineralisation was present as lenses and stockworks within a package of slates, magmatites and limestones, approximately 250 m thick, reaching from upper Ordovician to lower Devonian with an average uranium content of less than 0.1 percent.

By the end of production in 1990 the mining legacy at the Ronneburg site consisted of: (1) a complex underground mine with 40 shafts, about 3000 km of mine workings and an open volume of about 24 million m^3 to be closed, (2) Waste rock material with an overall volume of about 200 Mm^3 to be remediated, (3) Operational areas of 1670 ha to be cleaned up and prepared for reuse, (4) an open pit mine with a total volume of about 160 Mm^3 and a maximum depth of 240 m to be stabilized. Due to partial backfilling during the operational phase the volume of the pit decreased from the original 160 Mm^3 to about 84 Mm^3 before the remediation activities commenced.

The paper gives an overview on the conceptual and remediation activities since 1991 and their specific role concerning the integrated water protection approach which has been realized at the Ronneburg site.

Hydrogeological setting

The Ronneburg uranium mining district in Eastern Thuringia is located on both sides of the water divide between the Weiße Elster and the Pleiße rivers, which are both tributary to the Elbe river basin. The southern part of the district is situated at the so-called Ronneburger Horst, the north-eastern part of the Berga anticline of the Thuringian shale highlands, where the host rocks of the mineralized zones are directly outcropping. In the northern part of the district, which consists of the mine fields of Beerwalde, Drosen and Korbußen, the productive palaeozoic rocks are partly covered by permotriassic platform series.

The mean annual precipitation rate in the district amounts to ca. 680 mm/a according to time series evaluations based on the Gera-Leumnitz station values (German federal weather service) covering the 40-year-period between 1964 and 2003. Groundwater drawdown as a consequence of operating the mine drainage system of the southern mine fields covered an area of about 40 square kilometers. Before flooding the average inflow into the drainage system amounted to about 650 m^3/h with variations from < 500 m^3/h up to 800 m^3/h (based on monthly values, time series between 1991 and 1997). Mine water inflow and area can be used to evaluate the mean groundwater recharge rate of about 140 mm/a or 4,5 $l/s*km^2$.

In terms of water quality conditions it is characteristic for the Ronneburg district that due to the iron sulfide concentrations of up to 5 % in the palaeozoic rocks the mine waters as well as the seepages from the waste rock dumps were carrying very high concentrations of dissolved iron, sulphate, heavy metals (Mn, Ni, Co, Cu, Zn, Cd) and radionuclides (Table 1). Since the prevailing rock forming carbonate mineral in the deposit is dolomite extreme sulphate concentrations of up to 40 g/L were occuring in waste rock seepage, accompanied by hardnesses of up to 2000 °dH dominated by magnesium.

Prior to remediation the impact on the freshwater reservoirs downstream the mine was dominated by the mine water discharge which was performed both to the Wipse creek (tributary to the Weiße Elster, southern mine fields, see Table 1) and to the Sprotte system (tributary to Pleiße river, northern mine fields). Total

Table 1. Water quality typical for waste rock dumps in comparison to mine water of the southern mine fields prior to flooding (arithmetic mean, 1992-1997).

	Waste rock seepage, Acid type (Nordhalde, e-443)	Waste rock seepage, Neutral type (H. Paitzdorf, e-508)	Mine water discharge to Wipse creek (e-404)
Flow rate (m^3/h)	0.6	1.6	778
PH	2.9	7.6	6.9
Mg (mg/L)	1390	3443	389
Ca (mg/L)	354	402	339
SO_4 (mg/L)	12,970	14,140	2,354
Total Fe (mg/L)	2,126	1.6	4.3
Total Mn (mg/L)	128	0.8	5.4
Cu (µg/L)	3,835	14	93
Ni (µg/L)	30,610	138	1,252
Co (µg/L)	11,735	14	327
Zn (µg/L)	23,870	79	625
Cd (µg/L)	293	2.2	7.5
As (µg/L)	40	4.0	2.8
U (mg/L)	1.2	1.7	0.3
Diss. ^{226}Ra (mBq/L)	12	32	134

mine water discharge averaged to > 1000 m^3/h for the whole mine district. The only treatment measure consisted of simple aeration/ precipiation in settlement ponds to primarily minimize the iron contents of the discharged mine waters.

Seepage water flow rates from the waste rock dumps amounted to some m^3/h for the smaller objects but up to some tens of m^3/h for the biggest waste rock dumps, such as the former Absetzerhalde with a total area of 225 ha. However, due to the lack of impermeable base liners under the piles and because of the location of most of the piles within the drawdown area of the underground mine most of the seepage water was draining to the underground galleries. So the seepage from the Absetzerhalde and the internal dumps of the open pit became the most important polluters of the mine waters of the Lichtenberg and Schmirchau mine fields.

Basic elements of the remediation strategy

Individual remediation measures at the Ronneburg site are basically grouped into two main complexes:

a) Closure and clean-up of the underground mine including mine flooding,
b) Remediation of the waste rock dumps in combination with the stabilization of the open pit, including area clean-up.

From the viewpoint of water protection the individual remediation measures can be classified into three groups of approaches: (1) Source control, (2) migration control, (3) water treatment.

Beginning with the first remediation concept in 1991 great importance has been attached on applying a broad variety of source and migration control measures to enhance the sustainability of the whole remediation work but also to minimize the efforts necessary in terms of water treatment which will be the most important and cost intensive long term burden of the entire project. The most important item to be mentioned here is that both the strategies for mine flooding and waste rock dump remediation/ pit backfilling have been developed and implemented in a co-ordinated way to make use of synergetic effects.

The source and migration control concepts applied will be discussed in the following chapters, an overview on the different measures is given in Table 2.

Table 2. Measures applied in terms of water rehabilitation.

category	remediation measures	under-ground mine	open pit	waste rock	conta-minated areas
Source control	flooding	x	x		
	subaquatic deposition	x	x	x	
	alcali addition/ injection	x	x		x
migration control	minimization of the area		x	x	x
	dry covers/ revegetation		x	x	x
	plugging of migration pathways	x			
	geochemical barriers	x	x		
water treatment		x	x	x	x

Management of AMD-generating waste rock

Dumped mine wastes from the open pit and the underground mines amounted to about 200 million m³ (Weise et al 1996) at 17 single locations. The biggest piles of the district were the Absetzerhalde (65 Mm^3) and the Nordhalde (30 Mm^3), the smallest were containing some 100,000 m^3 only. About 64 Mm^3 of mine waste had been deposited in the open pit mine during active mining (Innenkippe, Schmirchau balcony). The wastes comprised for the most part shales, limestones and diabases with a high tendency to AMD (see Table 1).

Extensive investigations were carried out between 1992 and 1996 on waste rock material to determine crucial geochemical and soil physical parameters. The investigations included the review of historical and geological informations, drilling of boreholes, excavation of test pits, static laboratory tests and kinetic column and lime addition tests (Weise et al 1996, Hockley et al 1997).

Based on intensive cost-benefit-analyses of different remediation options the relocation of the waste rock into the Lichtenberg open pit was chosen as the preferred remediation option for more than 90 % of the waste rock. This basic decision makes the controlled backfilling of the Lichtenberg open pit the most important single restoration project of the whole WISMUT program. To minimize the long-term impact of the waste rock material to the ground and surface water bodies waste rock relocation is implementing the following remediation principles:

1) spatial concentration of the waste rock,
2) minimization of the mobility of the contaminants of concern by means of geochemically controlled relocation (separation), alcali and ash addition
3) decrease of the rate of contaminant transport from the backfill to the groundwater due to high compaction of the waste rock and bypassing of the groundwater stream (open drift system in the vicinity of the pit)
4) dry cover construction for infiltration control and minimization of the oxygen ingress including an optimized re-use (predominantly forest)

Since the mobility of radionuclides and heavy metals essentially depends on the degree of acid generation of the waste rock the prediction of long-term geochemical material behaviour was highly significant for remediation planning. The ABA test on drill core samples was chosen for the long-term planning of waste dump relocation, since this test allows rapid assessment of the acid mine drainage risk from sulphide-bearing waste. As the spatial variability of material properties cannot be ascertained in sufficient detail from drilling data (obtained on a 100 m grid) for the purposes of waste pile relocation, long-term planning is supported by a program of short-term excavation control. Under this program, test pit samples are taken on a 25 m grid from the excavation face one to three months ahead of relocation. The material is then classified by a combination of paste pH and NAP pH/conductivity methods (Weise et al. 1996, Hockley et al. 1997). Due to their simplicity, paste and NAP tests, calibrated against ABA data and kinetic test results, are particularly well suited to provide readily available guidance for mining and rehabilitation planning.

Targeted placement in the pit allows the minimization of contaminant release into the groundwater. Acid or acid generating class A material is mixed with quicklime and placed in the deepest zone of the open pit which will be watersatured by rising ground water and hence become anoxic. Class C material placed in the upper zone of the backfilled open pit is to consume incoming oxygen by sulphide oxidation and at the same time impede seepage acidification by neutralisation. Class B material which includes mixtures of A- and C-Material is beeing relocated in between.

Following completion of the backfill that will be up to 60 m above the initial ground level, a dry cover will be placed on top of the backfilled mine wastes. The area to be covered amounts to about 220 ha. As a result of comprehensive studies and investigations, a combined cover of cohesive soil material from on-site excavation (1.6 m) overlain by a 0.4 m thick storage layer to restore natural soil functions for revegetation was derived and submitted for approval (Paul et al. 2003). Together with hydraulic measures, this approach is to meet any requirement in terms of radiology, water protection, stability, erosion protection, and reuse. Waste rock relocation is planned to be finished in 2007.

Waste rock of the northern mine fields has been concentrated at the location of the Halde Beerwalde waste rock dump with a total volume of 8.8 Mm^3 after aggregation of the former Drosen and Korbußen piles. The pile has been covered with a two layer cover system consisting of a 0.4 m thick compacted sealing layer overlain by 1.5 m of recultivation layer. Seepage water (1-2 m^3/h in average) is being treated together with the contaminated surface and seepage waters of the southern part of the district.

Area clean-up

Operational areas in the Ronneburg region amounted to about 1670 ha from which about 460 ha had been covered by waste rock dumps. Remediation of contaminated areas i.s.s. is being realised basically in two steps: (1) demolition of operational facilities respectively decontamination and (2) reconstruction respectively rehabilitation for future public use or specific needs.

Decontamination includes removal and relocation of mining and production facilities, of organic, inorganic and radioactive contaminated soil and waste rock to stop or minimise the dispersion of toxic agents. Waste disposal activities take place in the Lichtenberg open pit or to a controlled landfill site, respectively.

Remediation measures to be applied have to be conform to the federal mining act as well as to current soil and water regulations, but must also be optimised in terms of costs for both implementation and maintenance.

The footprint areas of the relocated waste rock dumps are represented by often unfertile, sometimes acidic and biological dead raw soil substrates of high compaction and low water storage capacity. Especially the exhumed footprint areas of the Absetzerhalde and the Nordhalde which account for about 80 percent of the waste rock to be relocated and ca. 300 ha of land to be reclaimed, make high demands on the remediation measures. The soils are still carrying substantial amounts of soluble contaminants such as Al, heavy metals, SO_4 and others due to former infiltration of waste rock seepage. As a consequence remediation measures which are strictly beeing adapted to local conditions typically include lime addition to stabilize soil pH and to minimize the mobility of heavy metals. Lime dosage calculated for 4 dm operation depth accounts for clay, gravel and humus content, average lime quantities are 8 t/ha $CaCO_3$. Dispersion of lime is combined with loosening the ground after reshaping of the surface. Depending on the physical characteristics and the state of bedrock up to 0.5 m inert soil will be applied. Thickness of inert soil depends chiefly on future use. Erosion control is guaranteed mainly by sowing a grass-herbage-mixture. In cases of later forestation, which has to be carried out at an area of 200 ha as a compensation measure for clearing of former woodland, good experience has been made with vegetation in strips across to the dip of slopes, keeping soil strips free for tree scions. Fertilizing is adopted to local conditions, fencing against game has been proven to be indispensable. Contaminated run-off from the rehabilitated areas will be treated as long as necessary. Over the medium term the water balance will recover, and pollutant transfer to the receiving streams will drop under a critical limit as a result of the remediation measures performed.

Closure of the underground mine and mine flooding

Prior to mine flooding intensive preparation measures had been realized to remove water contaminants (e.g. oils, lubricants) from the mine, to stabilize/ backfill mine openings and shallow workings and to separate mine fields with different water quality.

Flooding of the underground mine is taking place within two hydraulically isolated areas: (1) Mine fields south of the federal motorway A 4, (2) Mine fields north of the motorway A 4. Both parts of the mine are hydraulically separated. The southern mine fields also include the Lichtenberg open pit mine, which is under backfilling with material from the surrounding waste rock piles since 1991.

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 mine is completely backfilled in its uppermost 100 meters and no dewatering adits are available the flood waters are expected to eventually discharge as natural exfiltration 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 catched and treated. Due to the orographic and geologic conditions such discharges can arise at the earliest at a flooding level of approx. 240 m above sea level. Thus an extensive water management system had to be designed to avoid an intolerable impact of the mine closure on the environment with special reference to ground and surface waters in the central part of the southern mine fields.

Both model based predictions and monitoring time series from the northern mine fields show much better water quality conditions; so there is no necessity for extensive technical water management facilities as a prerequisite for reaching the final flooding water level.

By May 2005 the water levels in the southern and northern mine fields have reached levels of approx. 220…250 m above sea level. The flooding operation is expected to complete between 2007 and 2009 by reaching a quasi-steady state. First mine water discharge in valley regions could appear in 2006.

In general the Ronneburg mine flooding strategy reflects the philosophy of a rehabilitation process following the extensive impact concerning water balance conditions as a result of active mining operations. Considering this any further technical interferences have to be designed following the specific necessities evaluated from the water quality conditions with their wide variability in the region. From the economic point of view any relevant overcapacities of water catchment, transport and treatment facilities have to be avoided. Extensive monitoring activities are an indispensable prerequisite for following that strategic approach.

Water treatment

Despite of all activities of source and migration control water treatment is an indispensable component of the closure plan, at least for the southern mine fields. Due to the expected water volume in the flooded mine and the preferred flooding strategy the water management system for the southern mine fields consists of installations for water collection, transport, treatment and discharge.

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. Ascending water consists of mainly mine water bearing groundwater contaminated with typical inorganic pollutants like radionuclides and heavy metals. A basic system of drainage elements installed inside hydraulic conductible quarternary sediments overlaying preferred silurian bedrock is going to collect ascending waters under anaerobic conditions. A pump station downstream will convey the water to the central component of the system, the Ronneburg water treatment plant (WTP). First exfiltrations are predicted for 2006.

The WTP completed in 2001 was the basic precondition for active control of the flooding process and to prevent a hazardous impact to the environment at the end of mine flooding. To meet these requirements, the WTP had been designed for a capacity of 450 m^3/h, which is only about 70 % of the mean mine water inflow rate during active mining. This limitation in design capacity could be reached since the inflow rate to the contaminated area has been found to be clearly head-dependent. The decrease of the flow rate has been proven during the initial runs of the WTP in late 2003, where flow rates of ca. 280 m^3/h had been observed.

The plant operates according to the High Density Sludge (HDS) lime precipitation technology, following the principle steps: acidification for decarbonization, neutralisation and aeration for lime precipitation, sedimentation and clear water overflow, thickening of sludge and conditioning for disposal, filtration of clear water for discharge. The main treatment purpose is the separation of heavy metals and radionuclides from the mine water.

The water supply from the mine to the WTP is realized optionally both from the central pumping station of the water drainage system in Gessental valley, and from a well (Well No. 1) which is connected to the underground mine workings in central mine field Schmirchau.

Table 3. WTP discharge limits for heavy metals, As and Ra-226.

Pollutant		Discharge limit	Pollutant		Discharge limit
As	[µg/l]	20	Ni	[µg/l]	100
Cd	[µg/l]	3	Zn	[µg/l]	200
Co	[µg/l]	100	U	[µg/l]	500
Cu	[µg/l]	50	Ra-226	[mBq/l]	400

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. 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, to minimize the catchment area of the mine, to limit the thickness of the unsaturated zone which is subject to further acid generation and finally to lower operational costs for water management, including water treatment and sludge disposal. After reaching the final flooding level the water will be collected in the Gessental water collection system only. At present it is predicted that the water treatment must be carried out over a period of 15 to 25 years without any interruption. The WTP must also treat the remaining contaminated surface seepage in the transition period, as long as the rehabilitation progress does not allow the surface runoff to be directly discharged into the receiving creeks and streams. At present the contaminated surface runoff is highly variable in terms of flow rate and contaminant loads, and options are under investigation to inject these waters into the underground mine to blend them with the mine waters before treatment. Treatment goals for the WTP are given in Table 3. The treated waters from the WTP will be discharged into the Wipse creek flowing to the Weiße Elster river, where additional standards especially concerning sulphate and water hardness must be keeped.

Remediation Effects with respect to ground and surface waters

The active mining and mine remediation activities as a whole can be subdivided with regard to impact on ground and surface waters into the following periods:

1) **Active mining period**, characterized by a steady state groundwater depression cone as a consequence of the mine drainage operation, accompanied by water shortage in receiving streams, water quality deterioration as a consequence of water discharge and diffuse seepage from waste rock piles
2) **Period of mine closure and remediation** with a gradual transformation of the water conditions, groundwater rebound in the wake of the discontinuance of mine water discharge, beginning improvement of the water quality in ground and surface waters

3) **Post-closure phase** after the completion of entire mine remediation measures, accompanied with final steady state groundwater conditions, operation of water treatment facilities and discharge of the treated waters, ongoing rehabilitation of water balance and quality.

Since the start of the remediation activities the most evident step in terms of improving the water quality of the receiving streams is marked by the start of the fully fledged mine flooding process associated with the cessation of mine water discharge, which happened in early 1998 for the southern mine fields and in June 2000 for the northern mine fields, respectively. Evaluations based on the extensive monitoring activities show load reductions in the recipient streams in an order of > 90 % regarding radionuclide concentrations like uranium and radium.

Further improvement of the water quality in the catchments of the local receiving streams are closely related to the waste rock relocation program which has lead for instance to the removal of the former Gessenhalde and Nordhalde piles from the Gessenbach catchment area. Mine remediation activities concerning these waste rock piles included by early 2003 the complete excavation and transportation to the Lichtenberg open pit mine backfill operations. Meanwhile the pH-values in the Gessenbach have stabilized in a neutral zone between about 6 and 8, also heavy metal concentrations show noticeable improvement but have not yet reached a satisfactory level so far. Similar observations can be reported concerning the groundwater contamination downstream of relocated waste rock piles like the Drosen pile. The removal of the waste rock pile material had been finished in 1999, and meanwhile the groundwater monitoring results show significant decreases regarding sulphate, heavy metal and radionuclide concentrations.

In terms of the future water management at the Ronneburg site WISMUT is going to be committed by the Thuringian permitting authorities within the scope of the licensing procedures for the final design of the open pit backfill, the completion of the flooding process and the operation of the WTP to keep water quality standards for the Wipse, Gessenbach and Sprotte creeks as well as the Weiße Elster river, which are in conjunction with the aims of the EU water framework directive, but account for the specific history of the area, which hosted the biggest European uranium deposit.

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