Mine Flooding and Water Management at Underground Uranium Mines two Decades after Decommissioning

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Abstract Closure and flooding of five underground uranium mines represent a key component of the Wismut Environmental Remediation Program. By 2013, all mines are abandoned and flooded to a large extent. In order to avoid adverse effects of groundwater rebound, water collection and treatment systems had to be installed at all sites. Monitoring data recorded during more than 20 years allow comparison with earlier model predictions. Evolution of mine water quality suggests that the operation of treatment systems will remain an ultimate requirement over the next decades at most sites. Opportunities and constraints to use and enhance natural attenuation processes in mine water bodies are delineated.

Keywords uranium, arsenic, underground mines, mine flooding, water management, environmental impacts

Introduction

Germany still ranks No. 4 amongst the historical uranium producing countries, as SDAG Wismut had been one of the world's major uranium suppliers from 1946 through 1990. Upon cessation of uranium mining in 1991, Wismut GmbH was commissioned as a government-owned enterprise to establish and run the decommissioning and rehabilitation of the legacy production sites. Roughly 90 % of Wismut's total production of almost 220 kt of uranium came from underground mining. After termination of uranium production, the mines were decommissioned and prepared for flooding which included underground remedial work, removal of materials with the potential to pollute the incoming groundwater, stabilization of shallow mine galleries, and physical closure of shafts and adits. Differences in geology, hydrogeology, and mining technology necessitated site-specific flooding strategies and technological arrangements. First experiences made with flooding the Wismut mines were summarized by Gatzweiler *et al.* (2002), reflecting mainly the conceptual and preparation phases. By 2013, all mines are closed, and more than 97 % of the underground workings are flooded. Hands-on experience and comprehensive monitoring programs, implemented and operated for more than 20 years, deliver insight into the real behaviour of the systems allowing comparison with earlier model predictions. The paper presents a selection of most recent findings regarding mine flooding and post-flooding water management.

Mine characterization

The Wismut Remediation Program comprises, inter alia, the closure of five huge to medium-size underground mines located in the German Saxothuringian uranium province. Deposit types range from "veins in crystalline host rock" (Schlema, Pöhla), to "black shale associated" (Ronneburg), "roll-front sandstone" (Königstein) and "uraniferous coal" (Dresden-Gittersee). Average uranium grades were low (approximately 0.1 % U), and mining methods mainly conventional (room and pillar with backfill, overhand stoping with self-fill, caving, seam mining). The most important production centres were those at Ronneburg and Schlema. The Ronneburg mine field consisted of six interconnected mines with 40 shafts and 3,000 km of mine workings, complemented by a huge, meanwhile completely backfilled open cast mine. The Schlema mine included 80 day and blind shafts with 4,200 km of headings on 62 levels down to a maximum depth of almost 2,000 m. The smaller Pöhla-Tellerhäuser mine close to the Czech border was exclusively accessed by a main adit hosting 2 blind shafts, so that the mine voids were shielded from ground surface by undeveloped overlying country rock. Uranium mining at Gittersee represented the last episode of underground mining in the Döhlen coal basin, which had been ongoing since the 16th century. The activities were dedicated to uraniferous hard coal in three separate mine fields using longwall caving. The only mine with a deviating production scheme was Königstein, where in 1984, as a response to decreasing uranium grades, conventional room and pillar mining was completely replaced by an underground block leach technology using dilute sulphuric acid as leaching agent. Key features of the five mines are summarized in Table 1.

Mine water rebound and water level control

Given the prevailing climatic conditions (annual average precipitation 700…1150 mm, average annual temperature 6…9 °C), the mines were largely flooded due to natural groundwater inflow following cessation or throttling of mine water pumping. With the exception of Pöhla, groundwater rebound was allowed to proceed stepwise and in a controlled manner, in order to ensure proper mine abandonment, but also to gain hands-on experience with the flooding process. Since mine flooding was strongly interrelated with other remedial measures and initially characterized by significant uncertainties, flooding strategies had to be laid out with flexibility including back-up options. Although mine flooding aims for a wide restoration of close-to-nature groundwater conditions in general, in case of the Wismut mine sites the installation and perpetuation of emission barriers, *i.e.* water collection and treatment systems, was and still is inevitable to avoid adverse effects of groundwater rebound. Of the complete list of potential problems known from the literature (*e.g.* Younger and Robins 2002), the following are the most relevant, in descending order: (a) surface water pollution (all sites except Gittersee), (b) pollution of overlying aquifers (Königstein, Ronneburg), (c) localized flooding of agricultural or residential areas (Ronneburg, Gittersee), (d) surface subsidence (Schlema, Gittersee), and (e) mine gas emission, namely radon-222, into residential buildings (Schlema). With the exception of the Pöhla mine, which is dewatered gravitationally through its access tunnel, mine water level control is basically performed using submersible pumps, installed in shafts or extraction wells.

Forecasts of the flooding process and its impact on the local ground and surface water regimes proved to be difficult. Despite the fact, that state-of-the-art modelling techniques were used and highly qualified mine water

Mine	Mine voids subject to flooding, Mm³	Mean annual mine water Inflow, Mm³	Operating Life	Mine flooded From – to	Recent water abstraction method
Schlema	36.5	6.0	1946–1990	1991–2000	Submersible pumps
Ronneburg	25	4.3	1951–1990	1997–2007	Collection drains and submersible pumps
Königstein	4.1	1.0	1967–1990	2001–2013	Submersible pumps
Pöhla	1.0	0.12	1967–1990	1992–1995	Dewatering adit
Gittersee	0.5	1.0	1949–1954 1968–1989	1995–2003	Submersible pumps

Table 1 *Characteristics of Wismut’s flooded Uranium Mines and recent water management regime.*

professionals were involved, some of the predictions failed. The reasons for that are manifold, but chiefly comply with those discussed by Brown (2010) and Younger and Robins (2002): (i) highly variable and poorly defined systems parameters including problems of scale, (ii) analytical complexity and insufficient knowledge of key processes, (iii) inadequate data base, especially poor quality of pre-mining data, (iv) limited possibilities for model calibration prior to flooding, and finally (v) diverging interests of the parties involved when it comes to interpretation and decision-making (stakeholder pressure). Appearance, relevance and consequences of such erroneous predictions shall be illustrated by three examples:

(1) Flooding of the Schlema mine was initiated in 1991, flood water emerged quicker than expected. The volume of mine water at post-flooding state had been originally predicted to be around 450 m^3/h, based on measured mine inflow data prior to flooding, but assuming a head-dependent inflow reduction. When flooding was in progress the actual volume, however, levelled off at an average of about 800 m^3/h, since significant inflow reduction did not occur. In consequence, construction of the planned water treatment plant had to be sped up and its capacity augmented to accommodate a recent maximum rate of 1,150 m^3/h, with regard to storm water events.

(2) In 2003, the Gittersee mine had been allowed to flood up to the natural water level. Contrary to all expert predictions, sufficient subsurface runoff to the local receiving stream as well as an historic dewatering adit, draining a neighbouring abandoned mine field, did not materialise, obviously due to an overestimation of the hydraulic conductivity of the mined ground/goaf. Instead of that, water logging occurred in the Freital urban area. Following repeated hydrogeological investigations, the original dewatering concept had to be discarded, and preference was given to extend the historic Elbstolln drainage gallery by some 3 kilometres, to ensure long-term runoff while safely precluding any surface water emergence.

(3) At Ronneburg, water discharge from the underground mine started in 2006 in line with original plans, feeding a near-surface collection system installed in a local valley. The collection system had been placed and instrumented according to model predictions (Unland *et al.* 2002). The installations, however, proved not to be sufficient in their effectiveness, causing substantial reworking measures. Further rise of mine water heads up to a maximum of some 20 m above the valley bottom did finally cause significant uncontrolled discharges to the local creek, leading to a pollution of downstream water courses in 2010/11. The problems were initially caused by an insufficient hydraulic range of the basic system in high yield areas, but also by water creeping at old boreholes and backfilled raise drifts, due to their insufficient state of preservation. More seriously, pumping and treatment capacities proved to be undersized to cope with the increasing quantities of escaping groundwater and contaminated surface waters during the wet year of 2010. A back-up extraction well, although installed in time, could not be fully used due to the shortage in treatment capacity. In consequence, water treatment and pumping capabilities had to be augmented, and water management strategy is recently under major revision.

Mine water quality and water treatment

The well-known "first flush" phenomenon (Younger *et al.* 2002), characterized by an increase of dissolved matter concentrations in the mine water as water table rises, followed by a steady decline after flooding is complete, was observed at all Wismut mines. Its occurrence, however, differed from mine to mine, was element specific, but also modified by contaminant's discharge from other sources into the mine water, such as above ground objects (*e.g.* waste dumps), mine sections above the water table, or re-flooded host rock. Moreover, temporal variations in mine inflow, water table fluctuations and changes in the water management regime were complicating the picture. With respect to environmental aspects, the monitoring of mine water quality was focussed on U, ^{226}Ra, Fe, Mn, As, Ni, Zn, Cu, Cd, SO_4^{2-} and total hardness, complemented by components with relevance to treatment issues and process understanding, including temperature, pH, redox potential, electric conductivity, O_2, HCO_3^- and others. Table 2 summarizes the recent mine water quality at Wismut’s different mine sites.

In order to outline some typical phenomena, Fig. 1 is illustrating the uranium and arsenic concentrations in the Schlema and Pöhla mine waters over a 15 or 20 years time span, respectively. Both mines are characterized by a wide homogeneity within the mine water column, mainly due to thermal convection. Mine waters are circum-neutral in pH and show intermediate to reducing redox potential. Related to low sulfide and high carbonate contents, acidification can be ruled out. Under these conditions mine water is only moderately mineralized, and mobilization of pollutants is limited to U, ^{226}Ra, As, Fe and Mn (Table 2). After flooding at Schlema was chiefly complete in 2000, the following decline of uranium concentrations could be satisfactorily explained by dilution over a period of about 7 years. This finding is indicated by the reasonable fit between the measured uranium concentrations and those deduced by an ideal dilution estimate based on a mean hydraulic residence time of 6.1 years and a uranium concentration of 0.3 mg/L in the mine inflow (Paul *et al.* 2011). However, a change of the mine water abstraction point back in 2006 and, even with a bigger response, a temporary water table drawdown/re-inundation cycle in 2011 triggered a noticeable deviation from the ideal dilution curve. This observation and the most recent quasi-stagnant uranium values are a clear indication of uranium mobilization from a mine internal source, probably sludges which were precipitated earlier at upper mine levels. At Pöhla, by contrast, uranium showed a rapid decrease even before the mine reached steady-state flow conditions, most likely driven by microbiologically catalysed sulphate reduction leading to uranium precipitation as immobile uranium (IV), since sulphate levels dropped also rapidly with a distinct lead time compared to uranium. Arsenic concentrations, on the other hand, reveal for both Schlema and Pöhla a significant arsenic mobilization within the flooded mines, clearly over-compensating the dilution by meteoric waters. There is

		Schlema	Pöhla	Königstein	Ronneburg	Gittersee
pH		7.0	7.2	3.1	5.7	6.8
Ca	mg/L	180	50	110	470	240
Mg	mg/L	120	20	10	485	45
HCO_3^-	mg/L	590	330	<5	75	530
SO_4^{2-}	mg/L	660	<5	760	3,530	1,010
Fe	mg/L	4.2	5.5	100	230	18
Mn	mg/L	2.5	0.2	2.9	11	1.8
U	mg/L	1.8	<0.02	10.1	<0.2	0.07
Ra-226	Bq/L	1.7	4.2	10.0	0.1	0.025
As	mg/L	1.0	2.1	0.3	<0.04	0.02
Cu	µg/L	<5	<5	32	810	<20
Cd	µg/L	<1	<1	49	32	<1
Ni	µg/L	<7	<5	330	1,580	<10
Zn	µg/L	<5	15	4,370	1,100	35

Table 2 *Mine water qualities at Wismut’s flooded underground mines, 2011 mean values*

strong evidence, that native arsenic which is very common in both deposits and contains elevated levels of arsenolite As_2O_3 due to partial oxidation during mine operation, is the key driver of this process, similarly under oxidising or reducing conditions (Paul *et al.* 2010).

In consequence of what was stated above, water treatment units had to be commissioned at any mine site. Key target parameters include radionuclides (U, ^{226}Ra), Fe and Mn, As (most relevant at Schlema and Pöhla), and base metals like Zn, Cd, Cu, and Ni (crucial at Ronneburg and Königstein). Against this background, all facilities are currently operated as modified or HDS-lime precipitation plants, with capacities ranging from 60 m^3/h (Pöhla, under construction) to 1,150 m^3/h (Schlema). The new Pöhla unit will replace a semi-passive treatment facility, being in full-scale trial operation since 2005, which could not achieve the design expectations regarding performance, maintenance efforts and, hence, operational cost. At Königstein, an ion-exchange process step prior to HDS-lime treatment is being operated, recovering uranium as a saleable concentrate to gain revenue partially covering treatment expenditures. At any site, treatment residues have to be immobilized and disposed of into engineered disposal cells, mainly situated on top of waste dumps.

Specifics of the Königstein mine

Amongst Wismut's former production sites the Königstein mine is exceedingly special due to the underground acid leach technology applied, namely in an ecologically very sensitive area close to the Elbe river. The ore body located in the lowest of four sandstone aquifers had been dewatered during mine operation over an area of some 6 km^2, and about 100

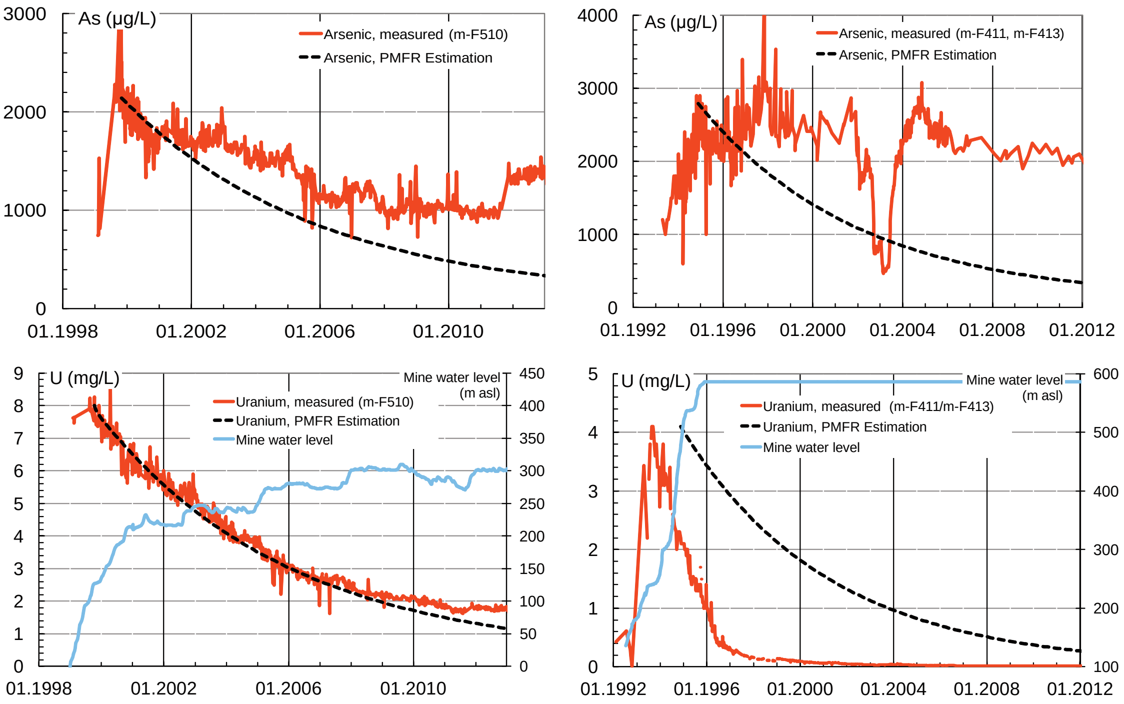

Fig. 1 *Uranium and arsenic concentrations in the Schlema (left) and Pöhla (right) mine waters, in relation to the mine water level. Comparison of measured vs. estimated (Perfectly Mixed Flow Reactor approach, Paul et al. 2011) values after First Flush Peak concentrations. Arsenic values for Pöhla between 2002 and 2004 were influenced by a field test with temporary change in mine water management (see Paul et al. 2006).*

sandstone blocks with volumes of 0.1…1 Mm^3 each were leached with solutions containing 2 to 3 g/L of H_2SO_4. In consequence, the geochemical status of the rock was substantially modified, with high levels of acidity, sulphate, radionuclides, and (semi)-metals remaining within the deposit after the stop of production. The mine closure and rehabilitation plan involves flooding of the mine workings up to the natural level of groundwater rise. Following comprehensive preparation, stepwise controlled flooding was initiated in 2001, resulting in a significant flush with maximum uranium concentrations of more than 200 mg/L in the mine water. Contrary to any other Wismut mine, remediation of the contaminated mine water pool is actively accelerated by additional injection of groundwater and treated discharge of the water treatment facility, respectively. Recent mine water quality is also shown in Table 2. While flooding proceeded, the general challenge consists in maintaining control of water-soluble contaminants in the context of restoring natural groundwater conditions. By the end of 2012, the mine was completely abandoned. Water level control to ensure hydraulic isolation of the mine from the surrounding and overlying groundwater resources is implemented by means of two pumping wells, which are connected to the northernmost and deepest mine workings known as control drifts. Mine water is completely captured and treated. Predictions point to probable flood water qualities that will require water treatment to continue for decades to come.

Towards a walk-away status – natural attenuation potential and *in situ* treatment

Wismut's general approach for a sustainable remediation aims for reduction of present and future environmental impacts with reasonable spending to a socially accepted level, preparing the former mine sites for a value-added re-use. Insofar, achievement of a walk-away status should be the ultimate goal for any remediated object. With regard to most flooded underground mines this seems, however, unattainable at least in the short run, mainly for two reasons: (i) the necessity for long term maintenance of drainage installations, to safely preclude any surface water emergence, and, even more importantly (ii) the insufficient water quality. In order to comply with maximum concentration limits for mine water discharge as defined by the regulatory bodies, the operation of active systems to collect and treat contaminated mine water will remain an ultimate requirement over the next decades. The only exception is the Gittersee mine, where with the new drainage tunnel being complete, flood water quality will allow direct discharge into the Elbe River (see Table 2), since residual iron is assumed to precipitate along the 9 km passage along the tunnel.

Apart from that, mine water treatment will be the most cost-intensive long-term task related to the entire Wismut Remediation Program. Besides uranium, iron and (semi)-metals, the most challenging contaminants are radium and arsenic. A lot of research has been conducted to understand, use and enhance possible natural attenuation processes in flooded mine water reservoirs. First experiences with the investigation and testing of supporting *in situ* technologies to improve the mine water quality have been outlined earlier (Paul *et al.* 2006). As a key result, an immobilization technology for non-flooded leach blocks was developed and implemented at Königstein, as long as those mine areas were still accessible (Jenk *et al.* 2004). Full scale applications of in-situ-approaches can, however, only be conceived as supporting measures to conventional technologies, since they are hampered by a multitude of difficulties. The most serious are: (i) incomplete knowledge regarding the overall systems' behaviour, (ii) restricted accessibility of the mine system for reagent input, monitoring and process control, (iii) insufficient or uncertain efficiency, uncertainties regarding potential reversibility of target processes, (iv) reverse reactions of contaminants with diverging geochemical behaviour, and resulting from all that (v) limited acceptance by the regulatory bodies.

Most recently, R&D work was carried out with the objective to improve mine water quality by injecting reactive substances via boreholes. To this end, two alternative approaches were considered: (1) Stimulation of natural sulphate reduction, taking the Pöhla case as a natural analogue, and (2) Neutralisation of acid flood waters by injection of buffer substances (Wismut 2010, Jenk *et al.* 2013). Based on the discoveries made during a field experiment carried out at Königstein, a technology applicable to the Königstein mine as a whole was designed and conceived as a supportive measure to enhance further mine flooding.

Conclusions

Real data from five flooded underground mines revealed, that flooding predictions have not been matched by reality in any case. Therefore, technological arrangements must be flexible and robust to cope with deviations from what was expected. In the context of the lessons learned and with regard to the predicted further mine water quality evolution under the site situations described above, mine water treatment will remain indispensable at the Königstein, Schlema, Pöhla, and Ronneburg mine sites for the foreseeable future. Key contaminants include U, ^{226}Ra, As, Fe, Ni, Zn and Cd. In the context of European Water Legislation and its further implementation at national level it is to be assumed that even stricter environmental standards will come into force in the longer term. In order to avoid burdens in perpetuity, however, careful balancing of ecological, economic and social interests will be necessary.

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