PROGNOSIS OF THE FLOODING OF URANIUM MINING SITES IN EAST GERMANY WITH THE HELP OF NUMERICAL BOX-MODELING

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ABSTRACT

The uranium mines of Ronneburg and Aue were amongst the largest in the world. About 100.00 tons respectively 70.000 tons were produced.
Both sites are in flooding now. To show the contamination of groundwater and surface water during and after the rising of the water table, caused by contaminants like U, Ra, As, SO_4, or heavy metals, a prognosis of the speed and of local differences of the rising is necessary. This was done for the Ronneburg deposit with the help of a complex box-modell. This includes the estimation of the pore volumes of mine workings, shafts, boreholes, backfilling and of the host rock formations, which are dewatered. Further, all important open and partially backfilled hydraulic connections between the mining fields and the volumes of the surface open pits are defined. The most important inputs into the model are the calculated infiltration of surface precipitation into the mine and the groundwater inflow from surroundings. The modelling shows that the flooding period will be about 10 years and after completion of flooding, an overflow of about 200 m^3/h will occur. The outflowing waters will contain up to 5 mg/l U, 6 g/l $S0_4$ and a pH of about 3.
The flooding of the Schlema-Alberoda mine at Aue with a maximum depth of about 1800 m is in progress since 1991. High temperatures lead to an active hydraulic convective process within the flooded mine. The mine waters contain up to 5 mg/l U, 5 mg/l As and up to 5 Bq/l Ra. The results of a thermodynamic modelling and a prognosis of the chemical processes will be presented.

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INTRODUCTION

Uranium mining in East Germany was terminated in 1990 after more than 40 years of large-scale exploitation producing more than 200.000 t of uranium. These operations had significant impact also on the hydrosphere in the mining regions of Saxony and Thuringia.

In the Gera-Ronneburg region (Thuringia), the legacy left behind by uranium mining comprises a vast system of interconnected underground mines and a large open pit mine. Underground mining voids total 28 Mm^3, the floodable pore volume of the partially backfilled open pit amounts to some 15 Mm^3.

With a mine and ground water pumping rate of between 700 and 1.000 m^3/h, the depression cone from the mines currently extends over an area of more than 70 km^2 and affects a rock mass of some 15 billion m^3.

In the Aue mining district (Saxony) uranium production amounted to approx. 80,000 t uranium from mines developed down to a depth of some 1,800 m.

Underground mining voids that were not backfilled total some 40 Mm^3. These voids are hydraulically connected, both horizontally and vertically, by 62 stoping levels extending over a distance of 4,200 km, 80 shafts, and numerous mining chambers.

To date, two thirds of the Schlema-Alberoda mine have been flooded.

In the Ronneburg mining district, flooding was initiated in mid-1997 following extensive preparations.

OBJECTIVES OF AND CONDITIONS FOR MINE FLOODING IN THE RONNEBURG REGION

Remediation of the legacy left behind by uranium mining is aimed at reducing radiological, chemical and other exposure to the public and the environment to an acceptable level. Remedial action is carried out in full regulatory compliance.

Flooding of the Ronneburg deposit meets long term environmental requirements, e.g. reduction of acid generation from pyrit and subsequent mobilization and discharge of radionuclides, metals, and salts into ground and surface waters and the elimination of radioactive emissions.

Mining voids to be flooded comprise the workings of the former Reust, Schmirchau, Paitzdorf, Drosen, and Korbußen mines. The vertical extension of the flooding zone is about 900 m. The volume to be flooded is in excess of 50 Mm^3.

Hydrogeological conditions and structural and substantial differences between individual mining fields give rise to the following requirements of a general nature that must be met in order to control pre- and post-flooding water qualities:

- avoidance of large-scale circulation of water and active intervention with regard to stratification;
- protection of receiving waters against unacceptable contaminant loads;
- restoration, to the extent feasible, of pre-mining conditions in catchment areas of receiving streams;
- permanent suppression of oxidation processes in drawdown area and improvement of water quality.

The option preferred by WISMUT consists of uninterrupted flooding up to an optimum elevated ground water level in order to reduce natural leaching processes due to infiltrating waters in the long term.

Realistic forecasting of the flooding process and of the flows and currents involved as well as of the anticipated final ground water levels is subject to the availability and reliability of a multitude of parameters describing flooding zones and water ingress.

Floodable mine cavities are not limited to stoping levels, but may extend over long distances following vertical and horizontal mine developments. They would also include open, collapsed, or backfilled voids from the exploration, development and mining activities. The later type of voids represents about 28 Mm^3 and is of specific hydraulic relevance to the dynamics of flooding and subsequent flows and currents.

Due to loosening and deformation, the rock mass directly influenced by mining operations contains in particular in the roof floodable pore voids of 6 Mm^3 and offers priority possibilities for direct infiltration of meteoric waters.In contrast to mine cavities in the rock mass and to cavities under the immediate influence of mining operations, geological voids in the virgin rock mass within the depression cone are anticipated in the order of 4 to 10 Mm^3.

Due to geological bedding conditions the rock mass within the depression cone is only partially dewatered. In addition, the void's structure involving depositional porosity and narrowness of joints as well as relatively isolated karst holes reduces the cavity share in limestone which was dewatered by gravity and will be subject to replenishment from flooding.

There is nevertheless potential for a volume of floodable geological voids to be reckoned with and which might affect both the duration of the flooding process as well as potential gradients and isostatic compensation currents as the flooding proceeds.

Waste rock material deposited in the open pit's internal dump and waste rock placed in the pit for backfilling purposes offer a floodable pore volume of 16 Mm^3 which will have considerable impact on the duration of flooding but only minor impact on the dynamics of the flow.

Towards the end of the flooding process, the anticipated ratio of mine cavities to geological voids impacted by mining activities to virgin geological voids to pore volume of open pit fill will be 50 % to 11 % to 11 % to 28 %.

The total volume to be flooded as well as the volume of anticipated alimentation is in the first place dependent on the condition and extension of the depression cone. Therefore, determining the exact volume of the drawdown by monitoring ground water prior to and during the flooding process is an essential condition for predicting flooding behavior.

Alimentation of the flooding volumes is primarily by direct infiltration of meteoric water. In order to monitor varying infiltration rates it will make sense to select a number of infiltrotopes, i.e. zones overlain by geomechanically disturbed rock and outcropping aquifers. Total infiltration into the flooding voids will average some 725 m^3/h in a normal year, in a wet year it will approximately be 1,000 m^3/h.

RESULTS OF BOX-MODELING TO PREDICT THE FLOODING PROCESS

Discretization of the flooding voids into boxes (20 mining fields and specific areas of easy infiltration) and cells (up to 22 levels) was required to allow three-dimensional and unsteady modeling of the flooding process in a complicated rock mass characterized by the folded Silurian joint aquifer and numerous interconnections between mining fields and blocks via drift systems, rise drifts, and boreholes.

This gave rise to a total of more than 300 spatial units to which volumes of mining cavities and geological voids, amounts of water ingress and discharge as well as alimentation volumes were assigned.

Box-specific volumes of infiltration, calculated for dry, normal, and wet years and the effects on infiltration rates by future surface remedial activities can be used to predict the flooding procedure and subsequent dynamics of ground water as well as to predict local ground water levels in specific mining fields.

Conventional simulators fail to model the flooding process within this system and the flow fields in the post-flooding stage. Therefore, a new program code was developed that allows the free structuring of flow balance boxes within the flooding voids thus operating with a minimum of problem-related balance boxes. For the first time, dynamics of flooding were calculated using that code.

For the calculation of the post-flooding stage the box-model was linked to a conventional pore model.

Water balancing does not merely consider flood waters in the saturated zone but also includes all operational artificial water transfers between mining fields.

Major results of the modeling include:

Uneven distribution of cavities and ground water restoration rates generate currents between mining fields during the flooding process. Unstable process description identifies dynamic sources and sinks.

Predictions of changes in the ground water regime during the flooding process is also possible in cases where the water balance is controlled by technical intervention.

In the post-flooding stage, hydraulic shortcuts via the drift systems cause dominating currents between the mining fields to occur rather in the drifts than in the geological body. This would cause, among others, the ground water to flow through the mine areas surrounding the backfilled open pit.

Once the flood volume will be reached, flood waters will flow out almost entirely in a single valley which is characterized by its hydrogeological connection to the pore aquifer, its valley situation and location close to mine workings.

The box-model produced to allow balancing and forecasting of flooding processes also permits predictions of water table levels in individual mining fields and of volumes and directions of flow between boxes and cells. It is anticipated that it will take a minimum of 11 to 13 years for the flooding waters to flow out into the Gessental valley.

During the flooding process, ground water restoration will be slow in high-cavity mining fields such as the Lichtenberg open pit. Compensation currents may occur between sources and sinks and the latter be impacted by artificial tapping or alimentation.

In the light of partial test floodings and laboratory investigations as well as of geochemical modeling it is anticipated that flooding waters flowing out at the surface, in particular into the Gessental and Wipsetal valleys, will show the following initial concentrations:

Parameter	Unit	Gessental valley forecast (mg/l)	Wipsetal valley forecast (mg/l)
Water volume	m^3/h	approx. 250	< 50
pH		3-4	3-4
U_{nat}	mg/l	< 6	< 4
Ra-226	mBq/l	< 500	< 500
Fe_{tot}	mg/l	< 400	< 400
SO_4	mg/l	< 10000	< 4000
hardness	°dH	< 300	< 200

During the first years following the flooding stage, discharge into the Gessental valley is anticipated to contain approximately 6 mg/l uranium. Discharge to this extent will continue for at least 10 years.

PREDICTED FLOODING PROCEDURE IN THE SCHLEMA-ALBERODA MINE

The rehabilitation strategy for the Schlema-Alberoda mine provides for the hydraulically controlled flooding of underground mine workings along with the filling of shafts and near surface mining voids and continued ventilation of some upper mine workings.

Flooding of the mine workings will reduce contaminant discharge of environmental relevance via the atmospheric and aquatic pathways in the medium and long term. Exclusion of air in the wake of flooding the workings is predicted to reduce physical and chemical mobilization processes in particular of arsenic, uranium, and radium.

When flooding waters will reach the level of elevation 390 m asl, i.e. about 60 m below the level of the receiving stream, control of the flooding becomes a necessity to limit surface damage. This supposes construction and operation of a water treatment plant designed to cope with up to 400 m^3/h of pumped mine waters. Operating life of the plant may vary between 20 and 30 years..

Three-dimensional modeling was used to predict the hydrodynamics of the flooding procedure and of thermodynamic convection processes in the flooding zone.

First, the mine workings were discretized using AutoCAD, assigning parameters such as geometry, voids, and conductivity to the respective levels and mining fields.

Filling of the flooding zone is the result of approx. 4 Mm^3/a of direct infiltration through near surface mining areas and of up to 3 Mm^3/a from geological sources via the flanks.

Major input data included the geothermal gradient, conductivity rates of shafts, drifts, mining zones and virgin rock, thermal conductivity, specific thermal capacity as well as volumes and location of inflow. Cooling-down of the rock mass as a result of mine ventilation was a thermal boundary condition to be considered.

The transmission constant or k-value is a parameter of specific sensitivity when it comes to predict realistic convection processes. This concerns in particular the permeability of shafts and drifts as well as of mining zones. Evaluations have indicated that shafts and those development drifts which constitute hydraulic connections between shafts determine the permeability of mining zones. Given the presence of numerous shafts, drifts and mining blocks, the mine as a whole is a perfectly communicating system in hydraulic terms.

Density differences of the water due to geothermal water temperatures are the driving force for the generation of convection boxes.

The first step in the modeling process was to calculate various design models to be used for phenomenological considerations to explain modes of action. It became apparent that permeability coefficients, mine geometry as well as hydraulic and thermal boundary conditions are relevant parameters that influence the generation and intensity, respectively, of convection cells.

Modeling of thermo-hydraulic processes was by 3D models designed for that purpose.

Extremely time-consuming calculations showed that convection processes will inevitably occur and even persist at average water temperatures of more than 30 °C once the flooding has come to an end.

In the case of the Schlema-Alberoda mine, modeling results show that warm waters will rise in the shafts to cool down in the upper levels of the mine and subsequently sink down via the mining zones and the disturbed rock surrounding the shafts. Therefore, it can be anticipated that cold infiltration waters and warm waters will mix in greater depths. Stratification and limitation of convection to defined mine areas would presuppose large-scale hydraulic sealing of vertical connections at all levels. This is not feasible due to time and economic constraints.

Investigations are under way to determine the extent to which convection might promote contaminant mobilization in drifts, sumps, mining blocks, and the disturbed surrounding rock or whether rapid exchanges will rather reduce concentrations in the flooding water following discharge of mineralized pore waters and contaminants from the mining zones. For the time being it is anticipated that concentrations in the flooding water which is currently at the 600 m level below the surface will remain stable for some years after the end of the flooding process and will then gradually decrease to natural background levels.

The following concentrations are predicted for the flooding water flowing out at the surface:

Parameter	Unit	Quality
pH		7.0
Dry matter	g/l	4
Filterable matter	g/l	0.02
Ca	g/l	0.3
Mg	g/l	0.3
Na	g/l	0.5
K	g/l	0.05
SO_4	g/l	1.8
HCO_3	g/l	1.1
Cl	g/l	0.1
U	mg/l	5.4
Ra	Bq/l	3.5
As	mg/l	3.5
Fe	mg/l	7.9
Mn	mg/l	4.6
Cu	mg/l	0.02
Pb	mg/l	0.002
Zn	mg/l	0.1
Ni	mg/l	0.02

CONCLUSIONS

With regard to potential emissions and to preventive and active water conservation by the timely construction and operation of water treatment plants and to in situ measures to be taken in the mines, reliable forecasts concerning the duration of the flooding process and the evolution of the flooding media are indispensable.

Numerical models are suited for this job to the extent that the sufficiently represent the complexity of mine workings and disturbed rock.

For simulation calculations to provide reliable results, input data from monitoring must be collected at an early stage.

During the flooding process, models must be calibrated on the basis of monitoring results so that results might be upgraded with regard to the end of flooding situation which is of environmental relevance.

This might also give rise to technical measures to be taken at an early stage to modify dynamics of flooding by dam construction or injections or to influence water quality by in situ treatment with a view of limiting the subsequent contaminant discharge.