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Flooding of the Underground Uranium Leach Operation at Königstein (Germany) – A Multidisciplinary Report

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Abstract Mine Flooding of the heavily contaminated Uranium leach operation Königstein has been initiated in 2001. Within the last 12 years the mine water level was raised up in a controlled manner to a permitted interim level of 140 m a.s.l. with about two third of mine volume being filled. Reaching the target water level in January 2013 key findings regarding technological and scientific aspects have been evaluated and reported in a comprehensive manner including a reflection regarding earlier model predictions. The paper provides an extensive compilation of the general technological, hydraulic and geochemical findings of the flooding process over 12 years, including site wide water management and treatment.
Keywords Uranium leach operation, mine flooding, Königstein mine

Introduction

The Königstein Uranium mine is situated in an ecologically sensitive and densely populated area near Dresden, Germany (fig. 1). From the early sixties through 1990, approximately 19,000 t of uranium were produced. Remediation of the Königstein mine is a very special case within the WISMUT rehabilitation project in Saxony and Thuringia, as both the regional setting and past mining methodsprecluded conventional approaches to mine rehabilitation and what's more, the appropriate lines of action still had to be identified.

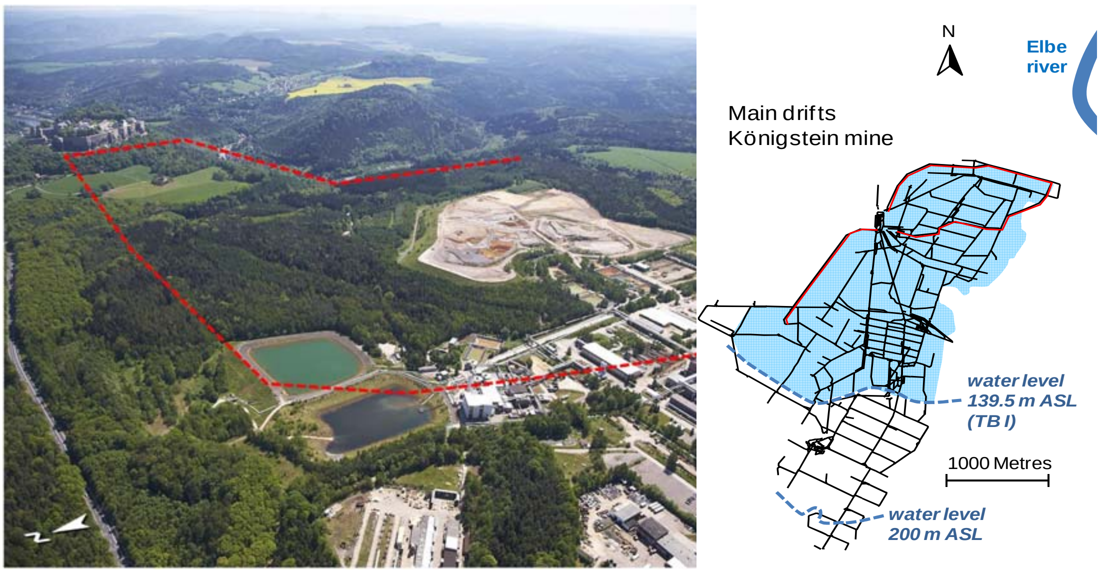

***Fig. 1** Left: View of the Königstein mine site/Germany (Background: Elbe river and National Park); Right: schematic map of main drifts with flooded sector (blue) and control drifts (red)*

The ore body is located in the 4th sandstone aquifer, the deepest of four hydraulically isolated aquifers in a Cretaceous basin. The 3rd aquifer is an important water reservoir for the Dresden region and is environmentally very sensitive. The uranium was extracted from the 4th sandstone aquifer initially using conventional mining methods, but later an underground block leaching method using sulphuric acid supplanted conventional mining. Development of the mine site extended over a surface area of ca. 6.5 km^2 and comprised 4 main levels (fig. 1).

Mining and the associated acidification processes but more particularly leach mining using sulphuric acid have fundamentally altered geochemical conditions within the developed section of the fourth aquifer. Pre-remediation investigations documented elevated levels of sulphuric acid, dissolved metals, and uranium.

Results

Rehabilitation of the former Königstein uranium mine was carried out by way of flooding. Flooding of mine sector I (TB I) was initiated in January 2001 when the flood water table was at a level of ca. 24 m ASL and was terminated in January 2013 upon rising to the target water level of ca. 139.5 m ASL, were discharge of contaminated flooding water into surroundings is been ensured. This brought a complex remediation project involving orderly closeout to a successful conclusion.

Due to the specific site conditions and to permit requirements, preparations for flooding took several years to complete and included a number of large-scale flooding experiments. As a result of these preliminary studies, the concept of controlled mine flooding was devised (Jenk 2001). This concept, in essence, consists in a stepwise flooding of the mine and providing protection for the nearby aquifers. For that purpose, the mine was equipped with a specific underground water catchment system (control drifts (fig. 1, red lines), pumping wells) to ensure the controlled withdrawal of flooding water. Basically, control of flood water rise was based on the reduction and scheduled shutdownof pumping capacities inherited from mining as well as on the caption of outflowing contaminated flooding water by means of the control drift system. Pumped to the surface, the flooding water is treated prior to discharge into the Elbe River.

The entire flooding process was followed by comprehensive and partly automated monitoring of the atmospheric and hydraulic exposure pathways as well as of a range of geomechanical topics. In addition to conventional equipment for flooding and groundwater monitoring, a number of technological innovations were put into practice to obtain representative water samples from the aquifers. Among those innovations was a mobile pump-based sampler unit for groundwater sampling down to a depth of 300 m.

Flooding of the mine took place in several stages in order to ensure required underground stabilisation efforts to proceed. In the flooding scenario per se, not only the mine voids volume, but also the readily fillable pore volume is an operative issue. As a consequence of the length of the flooding process, slowly-replenishable pore volumes also gradually filled up.

Table 1 *Available fill volume predicted at begin of flooding versus influx volume identified upon reaching final flood water level*

	Pre-flooding estimate		End-of-flooding balance
	Readily fillable volume (m³)	Total fillable volume (m³)	Total filling (m³)
Mine voids	2,386,000	2,386,000	2,386,000
Pore volume (c_1s_{qu}, c_1c_{wl}, backfill)	4,103,660	6,945,800	4,500,000
Total volume	6,489,660	9,331,800	6,986,000

When the flooding water table reached the maximum permitted level at the end of January, 2013, the total fill volume has been identified amounting to a total of ca. 7 million m³ of water. This figure, minus the mine voids volume considered to be fully flooded, meant that ca.

4.5 million m³ pore porosity were replenished, which is some 10 % above the pore volume rated as readily fillable but significantly smaller than the total fillable volume. In this way, predictions have been confirmed by the observed filling volume.

Particular importance was attached to the description of how a heavily contaminated flood water body would evolve. For that purpose, a model concept capable of describing aquifer recharge behaviour in the mine environment as well as hydraulic and hydrochemical conditions within the flood water body was developed at an early project stage in order to establish credible predictions of the flooding scenario(Metschies 2011). Tailor-made and adapted model tools were used to predict the flooding process. Flooding water quality predictions had been proven true in all their major aspects by the actual flooding process.

As expected, the evolution of flooding water quality had been characterised by highly elevated acid and contaminant levels (pH ~ 2, uranium ~ 260 mg/L) during the early stages of flooding. In the further course of flooding, contaminant levels diminished as a consequence of dilution with groundwater and chemical processes. Initially elevated local differences began to fade away. Even though the flooding water table has risen to its target level, the water remains acidic(pH ~3) and contains uranium and heavy metals in a concentration range of some mg/L (fig. 2 and 3).

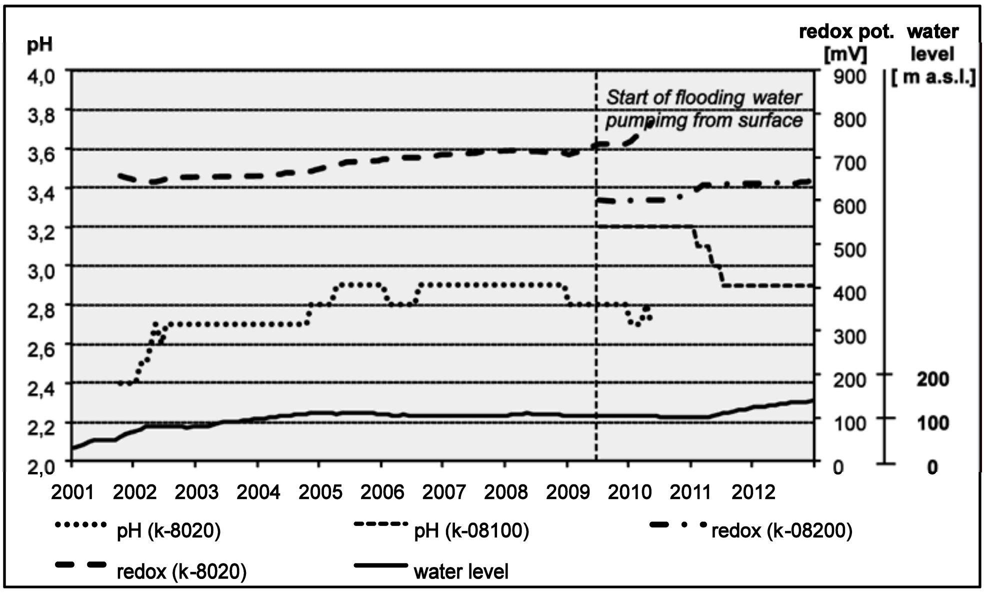

Fig. 2 *Mine water level, pH and redox potential of flooding water over 12 years*

During the flooding of TBI, approx. 35 million m³ of water were pumped to the surface as a flood control measure by which a significant amount of acid and dissolved contaminants was removed from the void subject to flooding and taken to safe disposal. Within that 12-year-period, approx. 900 t of uranium, approx. 45,000 t of sulphate, approx. 9,000 t of iron, and approx. 500 t of zinc were removed from underground for proper disposal. This corresponds approximately to half of the estimated total mobile potential. In this way, the mining-induced impact to the 4th aquifer was significantly mitigated and a partial cleanup of the contaminant source (underground mine) achieved.

Due to the flooding of the mine and of the control drifts, the depression cone at the mine's northern and western edges (4^{th} aquifer) began to recede as predicted. Sitting on top of the mine and also depleted due to mining activities, the third aquifer groundwater table is recharging at a slow rate. This gets us closer to hydraulic conditions which prevailed prior to mine development. Mine flooding had no impact on hydrochemical conditions in the 3rd aquifer. Hydrochemical impacts to the 4th aquifer were confined to a small area on the edges of the mined area.

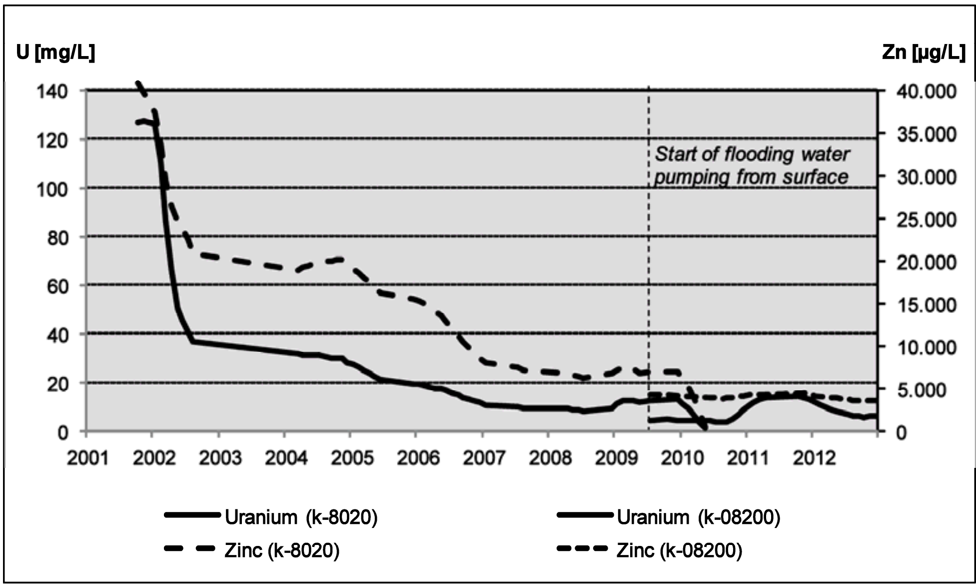

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Fig. 3 *Uranium and Radium-226 levels in flooding water over 12 years*

Environmental monitoring of the atmospheric pathway was carried out at 8 cast-up locations (mine shafts and ventilation boreholes) to determine air volumes, radon and dust-borne radon decay products. 37 immission measurements in the near-ground air were performed at yet another set of 37 measurement locations. Underground occupational surveillance involved measurements of radioactive and non-radioactive components at 4 stationary and 10 mobile measurement points in connection with ambient dose measurements at working places as well as personal dosimetry. All concerning this matter boundary limits have been kept.

Geomechanical surveillance demonstrated that ground subsidence was minimal (maximum settlement 52 mm). Subsidence slopes derived from measurement data are within detection limit (< 1 mm/m). Ground movements, on the whole, were marginal and have faded away. There is no risk of surface subsidence whatsoever.

In order to optimise the further flooding strategy basic approaches for in-situ water treatment have been investigated over the flooding period. To raise and the pH and to immobilize radio nuclides and heavy metals in the mine water body a field-scale experiment was carried 2010/2011. Using surface boreholes alkaline solutions were injected into the flooded mine and a decreasing of concentrations of uranium and heavy metals could be observed in the flooding water over months. (Jenk 2014).

Outlook

Since flooding of TB I reached the target level of ca. 139.5 m ASL in January, 2013, while maintaining an elevated water throughput (rinsing of the flooding water body) the flooding water table is kept and maintained at this level. The further rise of the flooding water table to the natural overflow level of approx. 200 m ASL as outlined in the mine closure plan and for which a permit application was submitted in 2011 has not yet received regulatory approval.

Continued flooding water pumping via pumping wells is imperative to prevent the rise of the water table in the mine beyond the level of 140m ASL owing to the natural inflow of groundwater. Further continuation of the flooding process notwithstanding, rehabilitation of the site’s surface structures and of areas no longer used for mining or water treatment purposes shall be continued.

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