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Andrea Hasche-Berger
Uranium in the Environment
Mining Impact and Consequences

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(Editors)

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Mining Impact and Consequences

With 376 Figures and a CD-ROM

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Preface

Uranium is an element to be found ubiquitous in rock, soil, and water. Uranium concentrations in natural ground water can be more than several hundreds µg/l without impact from mining, nuclear industry, and fertilizers. Considering the WHO recommendation for drinking water of 15 µg/l (has been as low as 2 µg/l before) due to the chemical toxicity of uranium the element uranium has become an important issue in environmental research.

Besides natural enrichment of uranium in aquifers uranium mining and milling activities, further uranium processing to nuclear fuel, emissions form burning coal and oil, and the application of uranium containing phosphate fertilizers may enrich the natural uranium concentrations in soil and water by far.

In October 1995 the first international conference on Uranium Mining and Hydrogeology (UMH I) was held in Freiberg being organized by the Department of Geology at the Technical University Bergakademie Freiberg by the support of the Saxon State Ministry of Geology and Environment. Due to the large scientific interest in the topic of uranium a second conference (UMH II) took place in Freiberg in September 1998. Furthermore, in September 2002 scientists working on the topic of uranium mining and hydrogeology attended the third conference (UMH III) which was jointly held together with the International Mine Water Association (IMWA) Symposium 2002. The reviewed papers and posters of the 2002 conference have been published by Springer entitled Uranium in the aquatic environment (edited by Merkel, Planer-Friedrich and Wolkersdorfer).

The immense interest in the third conference showed the still existing high significance of international exchange and interdisciplinary discussion of scientists in the field of uranium mining and remediation issues. In consequence of this, in September 2005 the fourth consecutive conference (UMH IV) was held in Freiberg. The conference addressed scientists and engineers working in the mining and rehabilitation business. The focus of the book is on uranium mining and milling sites, mining sites with considerable amount of uranium and radionuclides as by-products e.g. phosphate production for fertilizers, abandoned mines, clean up measures, natural attenuation, monitoring measures, modeling techniques, and risk assessment studies. Furthermore the book addresses scientist interested in Uranium in groundwater in general as well as water work managers and political decisions makers.

Freiberg, September 2005

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Long-term Aspects of Uranium Mining Remediation

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Abstract. After completion of the remediation of the legacy of uranium mining and milling for most of these objects and sites a continued monitoring will be necessary and some of these objects may require maintenance.

The main remediation objects in Saxony are waste rock piles, tailings ponds/deposits and underground mines. The monitoring and maintenance needs of the individual objects differ substantially and consequently the regulatory requirements (both type and extent of monitoring) placed on the individual objects will vary following an object-/site specific approach. Among the most sensitive monitoring parameters are the qualities of seepage and ground water. Another essential parameter is the monitoring of performance and maintenance of functionality of the covers placed on the waste rock piles and tailings to control radon exhalation and contaminated seepage. Unfortunately, there is no reliable database available for the long-term performance of the remediation measures and there has been no effort yet to develop such a database. To obtain a reliable estimate of the period of time needed for the active post remedial care, it is recommended to carry out studies on natural analogues. At present, the Saxon regulatory authorities demand a monitoring and maintenance period of 25 (radiation protection) rsp. 30 years (conventional waste regulations).

Provided the remedial measures taken prove to perform well, the monitoring effort will decrease with time. Considering the fact that the remediation measures implemented were designed for a 200 to 1000 years long stabile performance it is

expected that little maintenance will be needed. However, singular cases of disruption, such as damages of cover cannot be excluded.

A most relevant issue in this respect is the funding of the long-term post remedial tasks. The owner responsible for the uranium sites and objects that were in legal possession of Wismut on June 30, 1990 is and will remain the Federal Government of Germany. For the former Wismut sites, which are legally owned by other parties, the responsibility for funding of long term monitoring and maintenance is in the hands of the actual owners.

Introduction

Long-term stewardship is the only surety for a safe and healthy environment around uranium mining residues. Effective public institutions, the long-term preservation of knowledge and the provision of funds provide the main basis for a successful long-term stewardship. The lack of one of these issues may cause a failure of the stewardship and consequently also of the safety of the environment.

An international consensus regarding the necessity of long-term stewardship can be deduced from IAEA Report (2005) and similar publications.

In the following text the main objectives regarding long-term stewardship are discussed and the current status of the discussion in Saxony is presented.

Sites and Objects

Uranium mining in Saxony took place from 1945 to 1990 by the SAG/SDAG Wismut.

Exploration for uranium ore was performed more or less in the whole area of the former GDR. Nevertheless, the main focus was located in the south. Mineable deposits were found in Saxony and Thuringia. In Saxony three major sites were mined:

- Aue (Ore mountains) hydrothermal vein deposit
- Königstein createaceous sandstone deposit (uranium fixed at organic compounds)
- Gittersee Permian coal deposits (uranium enriched coal seams)

The ore was milled in Crossen, where one of the worlds biggest uranium tailings site

- Helmsdorf/Dänkritz

was constructed (ca. 50 ha, i.e. ca. 125 acre; ca. 50 million m³).

Beside these sites uranium was mined and milled also at some smaller sites in the ore mountain area in the first two decades (until 1962). Wismut produced in total 251 000 t of ore.

The residues from conventional underground mining are

- waste rock piles,
- tailings ponds,
- open mine shafts and drifts and
- contaminated mine water.

From in – situ – leach mining

- acidic solutions (sulphuric acid; pH 1.5 – 3)

remained in the pores and fissures of the host rock and in the mine shafts and drifts.

Additionally

- soil and building material

contaminations existed at former mining and milling areas.

Remediation measures

Waste rock

Waste rock piles commonly are shaped in a way to provide for surface water drainage from the tops and stability of the slope areas. Subsequently they are covered with one meter of soil. The soil properties are optimized resp. low permeability for precipitation and radon emission (Leitfaden Uranbergbausanierung 2000; Forschungsinstitut für Bergbaufolgelandschaften e.V. and G.U.B 1987; Freistaat Sachsen 1997).

Tailings

For tailings ponds a similar procedure is needed. After pumping and treating the pond water from the surface, an intermediate cover to stabilize the surface for further steps is applied.

Following this, the slopes and surface area are shaped and covered (Palme and Wittig 2003; Palme 2003a, 2003b). The minimum cover thickness is 1.5 m.

Underground mines

The stabilization of open mine shafts and drifts is subject matter of the mining authorities only.

The flooding water on he other hand has to be treated in a way to guarantee low emissions of radionuclides and heavy metals (Merkel 2002; Meyer et al. 2002). Experiences from old mines show that after a maximum of two decades following the flooding of the mine natural attenuation processes will bring the water quality to original background values.

Steps

The chronological procedure from the end of uranium mining to the long-term phase is shown in a simplified way in Fig. 1.

After remediation of the objects described above a warrantee phase of 5 years is following. During this phase the remediation measures are undergoing a practical test. The monitoring program of the remediation phase may be reduced. The plant cover is developing which has to stabilize the cover geotechnically.

In the eventually following long-term phase the base monitoring program is replacing the monitoring of the remediation phase. Maintenance, i.e. repair activities, may be needed and must be institutionally fixed and technically installed.

Remediation is the step where the highest effort and costs are needed, while the warranty phase and the long term phase are comparably inexpensive.

In the last few years many comments on the length of time needed for the long term phase were made. They showed that society cannot come away from the responsibility for the uranium mining legacy. To take this responsibility does not necessarily mean high burden.

Funding

A basic legal fact is the responsibility of the owner for the funding of long-term measures.

In the case of the Wismut legacy the federal government has to provide the financial means. It has been discussed also to entrust the State of Saxony with the ownership and consequently with the funding and with the responsibility for long term stewardship. In such a case the former owner has to provide the new owner with the respective financial means.

If ownership changes responsibility for the funding of long term measures is also changing.

The new owner has to take care for all issues associated with long term stewardship.

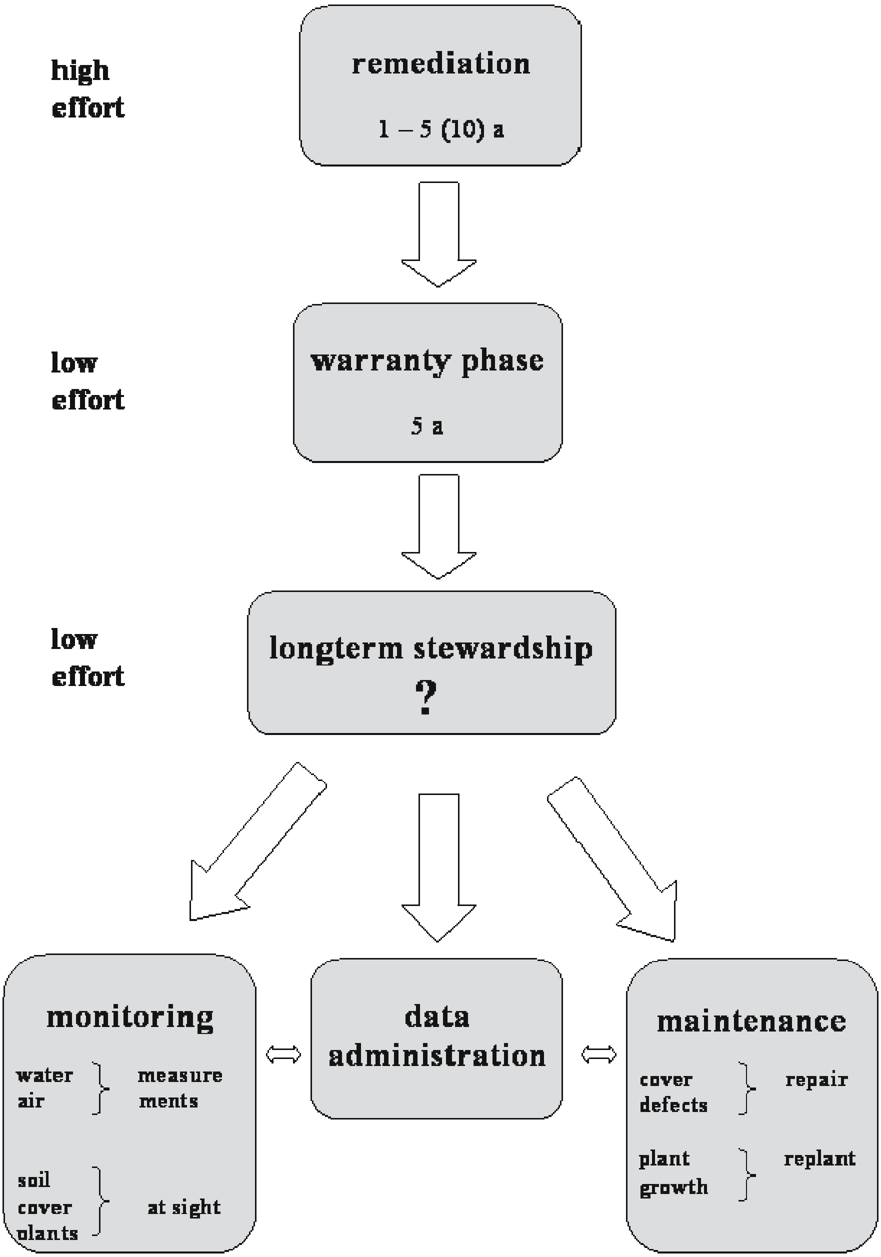

Fig. 1. Chronological procedure from the end of uranium mining to the long-term phase.

The planning of the dimensions of the financial means needed for long term measures has to take into consideration possible future interest rates. Conservative calculations should base on not more than one percent. This is the result of considerations on the development of the interest rates between the year 1950 and the year 2000 in the USA.

Knowledge

To ensure that information is kept over generations two main factors have to be taken into account:

- Willingness of the communities to take over responsibility for information transfer.
  The main issue is to make information about the restricted use of the objects long term stable. The communities are those concerned by the restricted use of objects situated on the community area. They are making decisions on the future use of their municipal land. To feel responsible for the remediated objects is prerequisite for the functioning of their long-term stability. For this reason permanent contact and exchange with the communities from the beginning of remediation is needed. The discussions already during the remediation process are a helpful base for the acceptance of the remediated objects. The objects must become harmonically and aesthetic fitting components of the natural scenery. On such a base the communities will take care and make wise use of their objects and make sure money for remediation measures is well spent.

Fig. 2. Surface water runoff facility at waste rock pile 366 in Schlema.

- Optimized information/data management
  Generally two types of data have to be managed: Object data (properties of objects) and monitoring data (field and lab measurements, visual inspection results). Monitoring data are representing the “living” part of the data store while the object data are representing the “dead” part. Monitoring data are the base of all future technical decisions about e.g. ongoing water treatment, need of cover repair, need of monitoring frequencies or change of use restrictions.
  The data bank systems for the monitoring data should contain tools to evaluate the data (developments, statistics etc.) and to represent the state of the information (graphs, outlines etc.). There should be tools to connect the monitoring data with the object data and to export informations for the public to fulfil the conditions of the environmental information law. The German Environmental Information Law of February 2005 was made on the base of the European Directive on Public Access to Environmental Information (2003/4/EC).

In Saxony the data bank KANARAS (cataster for natural radioactivity in Saxony) is in construction. It is consisting of

- Wismut data bank (Wismut sites, produced by Wismut ltd)
- A.LAS.KA (radiological data of old sites, federal)
- FbU (radiological and geographical data of old sites, federal prod.)
- DURAS (radiological analyses of saxon state lab UBG)

There are no experiences at all on the long-term safety of digital data. On the other hand the longevity of paper written information was prooved in many cases. Under these circumstances there is still a need to keep as much paper documents as possible.

Additionally there will be a need for long-term conservation of some important object informations in the Saxonian state archive. The legal and material conditions for this step are not yet compiled.

Institutional Control

Institutional control in the long-term stewardship phase will – as in the remediation phase - be an issue for different state authorities.

But the framework for these authorities will be different. While during remediation an active constructive development of the best resp. optimized measures was needed, in the long-term phase the institutions play a relatively passive observative role.

For radiation protection institutions Radon behavior is the radiologically most important factor. Therefor they will - as well as ground- and surface water authorities - be interested in the visual control of the covers and the monitoring data for the water path. The quality development of seepage water will be an issue for many decades. As long as active water treatment will be needed, good technical performance of the treatment plants has to be guaranteed and it has to be taken care that the residues of the treatment are minimized and deposed in a radiologically safe way.

Secondarily radiation protection authritics will controll plant growth by vision. This item will be the main issue for the forestry authorities.

Cover and slope stability will be monitored under the responsibility of the mining authority. Anyway also the water and radiation protection authorities have the duty to take care for the protective function of the covers. From the radiation protection point of view an opening in the cover may work as a chimney for radon and is defintely a case for immidiate repair activities.

Further on all institution for public concerns must be provided after remediation with updated maps of the remediation areas. They have to take care that restrictions for use are kept when the communities are planning new projects.

Maintenance

All remediation measures are planned and performed in a way to minimize future activities.

Nevertheless it may be the case that mending of covers or other subjects is needed. E.g. after storms uprooting of trees may happen and covers of waste rock piles or tailings ponds may be perforated or – in the worst case - completely destroyed.

Surface water runoff facilities like the one shown in the Fig. 2., may be other important subjects of maintenance especially in the first years of long-term stewardship. Experience has already shown, that leavefall in autumn may fill the facilities. As a consequence mixtures of leaves and earth may create blockades for the runoff (Ohlendorf 2004).

Consequences and work to be done

The Saxon state agency of environment and geology as the responsible licensing authority has developed a task schedule for all open questions regarding long-term stewardship. It contains the following issues:

- Financial arrangements of the federal government
- Longterm responsibility for the stewardship /Change of ownership
- Long-term stewardship measures
- Documentation and data management
- Authorities – controlling
- Communities – Bearer of information and project planners

For the tasks which are in the responsibility of the State of Saxony a time schedule was made.

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Returning the WISMUT Legacy to Productive Use

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…- Cela est bien dit, répondit Candide, mais il faut cultiver notre jardin »
Voltaire, Candide

Abstract. The prime goal of the Wismut environmental remediation (ER) project follows from the legal requirement to abate health risks, mitigate existing environmental damages and prevent future hazards.

The extent of remedial measures is derived by investigation of the object-specific remediation feasibility rather than by application of uniform standards. The ER workflow, unlike common civil engineering projects that are a linear succession of tasks, is an iterative process. Within the ER workflow, Conceptual Site Models (CSM) guide the optimization of designs and investigations while both operational works and environmental base line are monitored. The acquired data are collected and analyzed on a corporate wide level to provide decision-making support for senior management.

In the present, advanced stage of the Wismut remediation the reutilization of the reclaimed areas and objects is receiving an increased attention. There are no legal restrictions on utilization of areas, which received a complete clean up. Utilization of areas, waste rock piles and tailings ponds reclaimed for restricted use allows only settlement of industry and trades or forestation, however, exemptions are possible if the responsibility for long term monitoring and maintenance are satisfactorily ensured. A mutually beneficial integration of reclamation plans with the communal/regional development has been successfully practiced in two former

mining towns, the first leading to rebirth of the health spa in Schlema and the second helping the preparation of the Federal Garden and Landscape Exhibition in 2007 (BUGA 2007) hosted by the towns of Ronneburg and Gera.

Background

Between 1945 and reunification of Germany (1989) more than 231 000 t of U_3O_8 have been produced in Saxony and Thuringia, East Germany. The mining and milling sites are in Fig. 1.

The mining and milling operations affected an area of approximately 100 km^2 and left behind probably the “worst” uranium-mining legacy in the world. The inventory and range of liabilities left behind at the time of production closure in December 1990 was as follows:

Operations areas (37 km^2), five (5) large underground mines, an open pit mine (84 M m^3), waste rock dumps (311 M m^3) and tailings (160 M m^3). The specific activity of the waste rock is 0.5 to 1 Bq/g and of the tailings up to 10 Bq/g.

To proceed with the Environmental Remediation (ER) of this legacy, a special “Wismut Act” has been passed in the Federal Parliament, December 1991. Based on this Act the Federal Government committed DM 13 billion (€ 6.6 billion) to the ER Program (the sum was later revised to € 6.2 billion) and for purposes of reclamation the national corporation Wismut GmbH was established.

Initially there was no sufficient and proven uranium mine closure experience available in Germany and, in order to commence work without delay, extensive use has been made of the experience available internationally. Cooperation was sought with the US Department of Energy’s UMTRA Project and the relevant institutions and companies in Canada. Yearly international topical workshops were

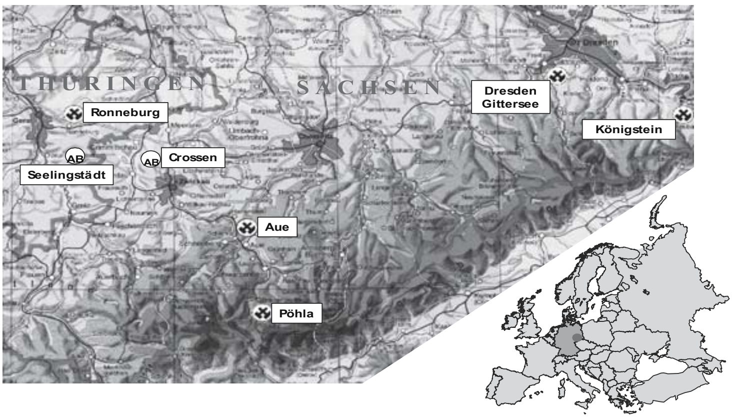

Fig. 1. Mining and milling sites of Wismut.

organized at Wismut to foster know how acquisition and identify suitable technologies to be adopted; Regular meetings of the Uranium Mine Remediation and Exchange Group, UMREG served as a platform for international peer review of the envisaged concepts, methodologies and regulatory approaches.

Objectives and scope of the Wismut Remediation Program follow from the legal requirements of the "Federal Mining Law" (*BbergG*) stipulating the owner's obligation to abate public hazards and mitigate damages caused by mining as well as prevent future hazards after mine closure, "Ordinance for provision of radiation protection for waste rock dumps and industrial settlement ponds and for use of materials deposited therein" (*HaldAO*) regulating the radioactive aspects of remediation and "Water Resources Management Act" protecting surface and ground water from contamination.

The paper views the reclamation of the Wismut legacy as an opportunity to return the affected land, mining and milling waste sites to productive use, thus enhancing the revitalization of the former mining areas in Saxony and Thuringia.

Reclamation Management Framework

The remediation process

Prior to commencement of remedial measures, the pre-existing status of the area deemed to have been affected by mining/milling activities (approximately 100 km^2) was appraised in an initial gamma radiation survey in 1990. The initial characterization survey showed that approximately 85 % of the "affected" area had near background levels of radiation and could be released for unrestricted use.

Following initial survey, the reclamation focused on five mining sites (Ronneburg, Aue/Schlema, Poehla, Koenigstein, Gittersee) and two mill sites (Seelingstadt and Crossen). Conceptual remedial designs and closure plans were developed for each site, often concurrently with preparation of detailed designs and plans. The basic remediation goal (*s. s.*) follows from legal requirements of the Federal Mining Law, Radiation Protection Ordinance and Water Resources Management Act. Compliance with legal requirements can be achieved by straightforward technical measures such as, (a) excavation and relocation of contaminated materials, (b) reshaping of the affected areas, waste rock piles and tailings deposits to stabile landforms having slopes resisting erosion and providing good surface runoff, (c) covering of contaminated areas and objects to contain the health and environmental hazards and support vegetation, and (d) treatment of seepages and discharges.

At the present stage of the Wismut project, the implementation of the remedial measures is done in 14 projects coordinated from 3 Site Management Units (Ronneburg, Aue and Königstein). Strategic direction, feedback, optimization and specialists support is provided from the Head Office in Chemnitz.

Remedial work at Wismut begins with preparation of an object-specific Environmental Impact Assessment (EIA) specifying the type and extent of physical measures to be taken. Although the preparation of EIA sometimes necessitates the acquisition of additional data and performance of investigations, it has the advantage of a transparent and traceable justification of the extent of remediation. The object-/ site-specific EIA approach has been selected over the use of prescriptive environmental limits because the EIA directly relates the extent of remediation to the actual level of risk presented by the contaminated area or object. Thanks to this approach a better remediation economics has been achieved than by use of a prescriptive generic “one solution fits all remedial problems” approach, which in most cases leads to over-engineering and consequently to excessive costs.

The radiological impact is measured by the effective individual dose, calculated for realistic release and uptake scenarios. If the calculated dose in excess of the background level exceeds the 1 mSv per year –a limit recommended by the International Commission for Radiation Protection, ICRP- the required remedial measure is specified such to achieve compliance with the 1 mSv per year criterion. Along with the radiological impact assessment, the regulated limits for conventional contamination are observed as well (e.g., As is a commonly occurring contaminant, which may take precedence over radiological impact). Following impact assessment, the feasibility of remedial design options is evaluated based on cost/benefit analysis.

Unlike in regular civil engineering projects, the implementation of the remedial measures is an iterative process rather than a linear succession of tasks, Fig. 2 (WISMUT 1995).

Although most of the delays in the remedial workflow occur due to the feedback loop created by the regulatory process, sometimes they are caused by inadequate knowledge, need of additional data and investigations. This is particularly the case for contaminants sources collocated at the same site. For optimization of the engineering solution and additional data requirements as well as prioritization of the additional remedial investigations and measures in such cases the use of a Conceptual Site Model (CSM) proved to be very helpful (Jakubick, Kahnt, 2002).

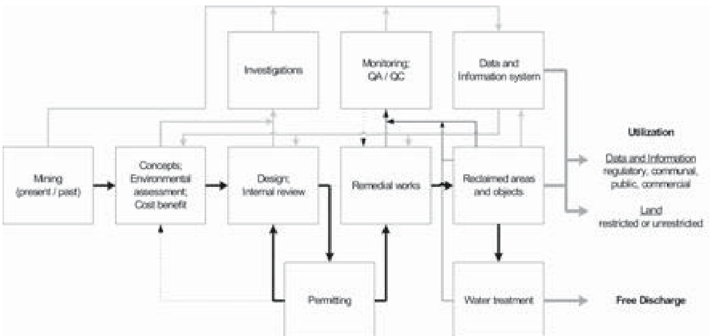

Fig. 2. Remediation process flow, products of remediation and subsequent utilization.

Data Management

The reclamation workflow is managed by an SAP based interactive, process oriented system equipped with applications and tools sufficiently flexible to adjust to the changes occurring in course of the reclamation progress.

For data and information management an interactive, object oriented system has been created that makes the heterogeneous databases accessible on a corporate wide basis, while leaving maintenance and updating responsibilities at the data source level. The typical data/information content of the database comprises documents, photographs, object-related data, monitoring data, measurements and digital maps, geo-referenced aerial survey photographs.

Data transfer is realized through a web-based access to the “source” databanks with subsequent placement of the requested data in an object related (holding) databank on a central ORACLE server (Fig. 3). This allows fast overviews, rapid applications, specific data quires to answer multifaceted questions that require overlaying of different types of data and information. Tasks, using locator and intersection functions for geometry-based data (polygons of objects, locations of measurement points), handled otherwise by GIS can be easily accomplished using the capabilities of the databank. Users access to a continuously updated GIS supported information system is provided at all times and the only requirement on the user side is an internet explorer and fast internet access (DSL). Data safety is secured by applying very stringent conditions to the inter-/intranet access.

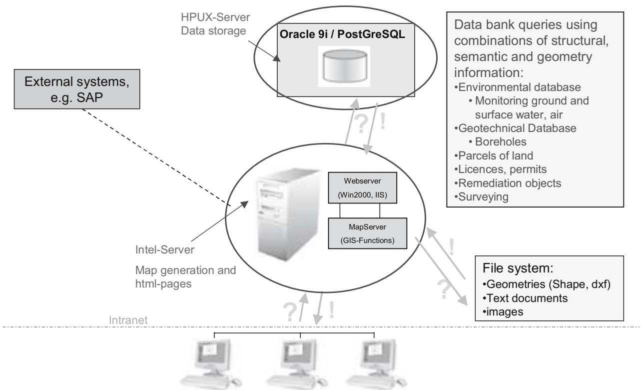

Fig. 3. Technical Data and Information management system used to integrate detached heterogeneous databases.

Implementation of Remedial Measures

Contaminated areas

The reclamation goal for contaminated areas is (whenever feasible) to maximize the number and size of areas reclaimed for unrestricted use, which usually requires a complete area clean up.

Waste rock

Reclamation of waste rock piles is by reshaping/stabilization and covering *in situ* or by relocation to a central pile or into the open pit mine.

At Ronneburg, the waste rock piles located near the surface mine were relocated into the open pit thus resolving both the remediation of the waste rock piles and the stabilization of the open pit. The backfilling procedure follows the strategy of placing the waste rock with the highest acid generating potential (i.e. with high pyrite content) on the bottom of the pit into a zone below the groundwater level anticipated after flooding of the underground and surface mines, thus preventing oxidation of the acid generating minerals and development of acidic seepage (Jakubick, Gatzweiler, Mager, Robertson, 1997). Waste rock containing an overabundance of alkaline minerals is placed in the upper part (zone) of the pit, Fig. 4.

Following the described procedure, approximately 40,000 m^3 of waste rock per day are relocated into the pit.

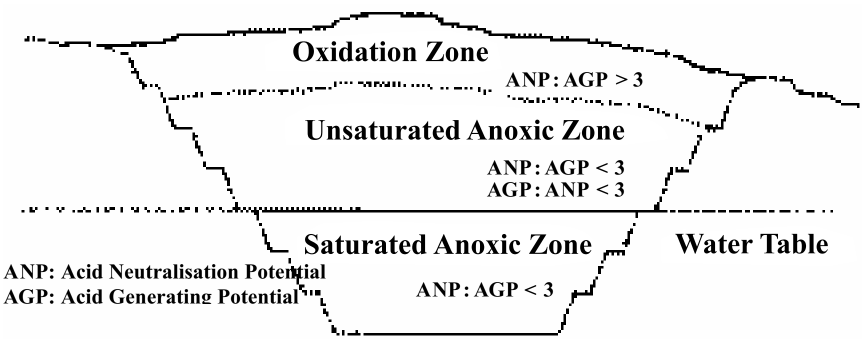

Fig. 4. Backfilling strategy of the open pit mine at Ronneburg. Acid generating waste rock is placed in the saturated anoxic zone, neutral waste rock in the unsaturated anoxic zone and alkaline waste rock into the oxidation zone.

Tailings ponds

The objectives of remediation are stabilization of the tailings mass, provision of erosion stability and prevention of environmental contamination (WISMUT 1999). The tailings ponds at Wismut are reclaimed as "dry landforms". The "dry" reclamation strategy was justified by using a probabilistic risk assessment under consideration of the remedial costs, health and environmental benefits as well as socio-economic factors with the aim to develop a site-specific remedial solution sustainable in the long term.

The results of the risk analysis for the Helmsdorf tailings pond are presented in Fig. 5 in terms of cumulative probability of equivalent costs (sum of reclamation costs and environmental benefits -including costs of post reclamation maintenance and repairs) over the lifetime of the reclaimed tailings object. The comparison of the "dry" and water capped remedial solutions in Fig. 5 shows a better performances for the dry reclamation above 65 % of cumulative probability, i.e. in the long term, when less probable events of severe consequence (such as dam failure) enter consideration (Roberds, Voss, Jakubick, Kunze, Pelz, 1996). In the short and mid term (up to a cumulative probability level of approximately 65 %), the remedial solution using a water cap (similar to the solution implemented at Elliot Lake) promises a better economic performance. Whether decision-making should consider low probability, high consequence events or not depends on the socio-economic factors relevant for the site. In case of the Helmsdorf site, the seismic zoning of the area and the fact that the main tailings dam is located only 150 m upstream from the community of Oberrothenbach made it necessary to include the possibility of an earthquake in the analysis and consider consequences of a dam failure. The obvious result was the preference of a dry remediation, which precludes any liquefaction of tailings.
On a more general level, Fig. 5 demonstrates that ultimately, beyond cost/benefit

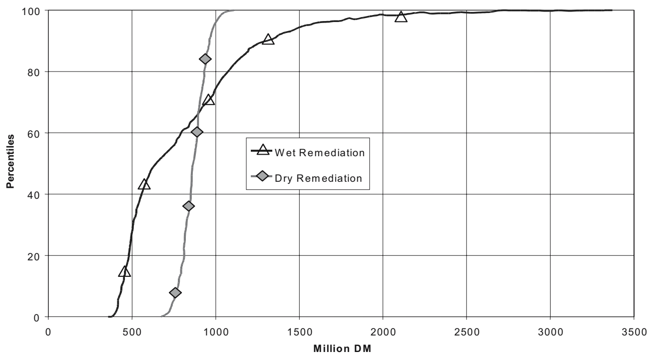

Fig. 5. Equivalent Costs (remedial costs minus environmental gains) for the Wet and Dry Tailings Reclamation Options for the Helmsdorf tailings pond.

considerations, decision-making in reclamation is controlled by stakeholder's related socio-economic factors.

An overview of the most common technologies, used (worldwide) for stabilization of tailings and limits of their applicability are summarized in Fig. 6 (Jakubick, McKenna, Robertson, 2003). The suitable ranges of application of a particular technology depend primarily on the state of consolidation of the tailings, which is expressed in Fig. 6 in terms of the *in situ* shear strength of the tailings/slimes.

Final Covering

All landforms created out of reclaimed tailings deposits, waste rock piles (remediated *in situ* or relocated into the open pit) receive a final cover designed to reduce radiation, radon exhalation, and limit infiltration and support vegetation of the surface. An exhaustive overview and international comparison of various cover types has been presented at UMREG 2002 (Hagen, Jakubick, Lush, Metzler, 2003).

For steep waste rock pile slopes (1: 2 to 1: 2.5), Wismut experience shows that using cover designs resembling soil profiles indigenous to the area and avoiding any unnecessary interlayering that could act as a sliding plane provides usually the most stabile cover design. The relatively simple, 1 m thick, two-layer cover system (Fig. 7) used for the waste rock piles in the Ore Mountains (Erzgebirge) showed an excellent performance during the period of extreme rainstorms and inundations in August 2002. The weather event brought a multiple of the hundred years precipitation to the region and was rated as the highest rainfall expected in thousand years. Wherever the cover had been completed and the vegetation estab-

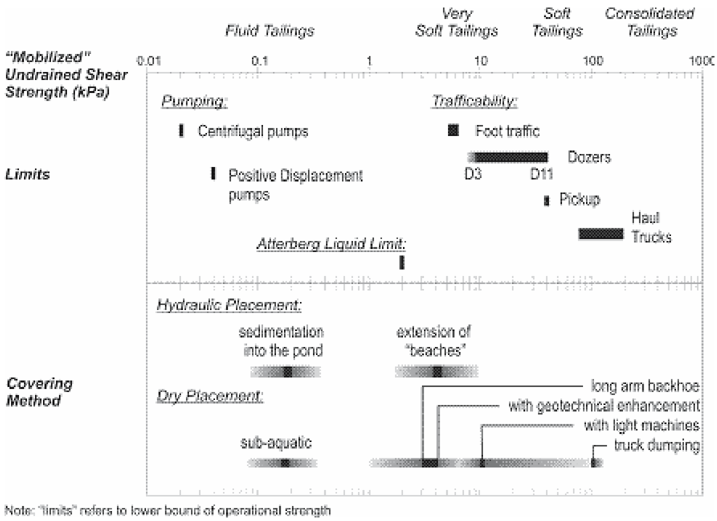

Fig. 6. Limits and ranges of safe trafficability of the tailings surface and feasibility of various tailings stabilization technologies in dependences to the *in situ* shear strength of the tailings.

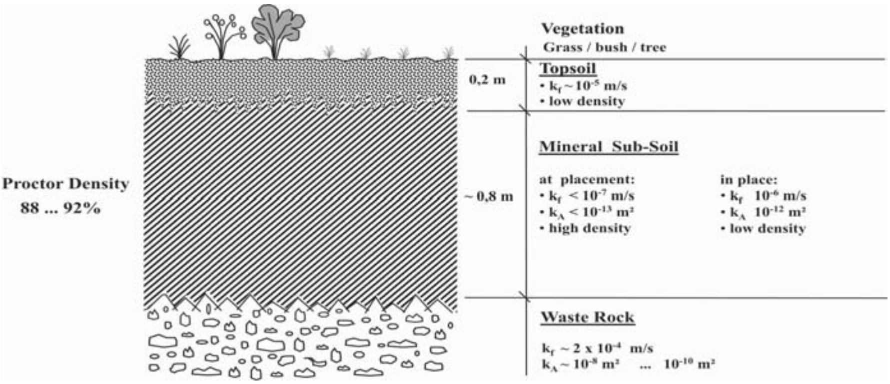

Fig. 7. A two-layer cover system emulating natural soils used at Schlema.

lished, no damage to the cover occurred. Based on the evaluation of the state of the cover after this unexpected natural test it could be concluded that the long term resilience and functionality of the described cover has been effectively proven.

One of the key performance objectives of final covers placed on uranium mining waste rock and mill tailings are, beyond physical protection of the contained contamination, radon attenuation. A novel type of assessment of long-term radon attenuation of covers has been demonstrated at Wismut (IAF Radioökologie GmbH, 2002). The method is based on measuring traces of lead (Pb-210) in the remediated object and in the cover placed on the object.

The lead traces Pb (z) are estimated as the depth-dependent differences of the specific activities of Pb-210 and Ra-226 in a cover layer:

$$Pb\,(z) = A_{Pb\text{-}210}(z) - A_{Ra\text{-}226}(z)$$

The method is primarily suitable for testing of covers older than 30 years and is based on growth of Pb-210
($t_{1/2}$ = 22 a) from Rn-222 ($t_{1/2}$ = 3,8 d), a daughter product of Ra-226 ($t_{1/2}$ = 1590 a), which is usually the main contaminant in uranium tailings.

In covers providing adequate sealing, most of the radon decays into Pb-210 after a penetration depth of 1 to 5 cm. The lead traces show discernibly positive values and the sum of the specific activities of the lead traces below and above the cover-object interface is positive.

In inadequate covers, the positive lead traces above the cover-object interface are weak (little accumulation of Pb-210) and the lead traces in the tailings or waste rock are strongly negative due to weak attenuation of radon transported toward the cover. The sum of the specific activities below and above the interface is negative.

Fig. 8 shows the performance of an inadequate tailings cover constructed more than 30 years ago. The thickness of the cover is 50 cm and consists of a single layer of mineral soil (mostly sand). The lead traces measured are clearly negative, evidencing that a 50 cm cover layer of the sandy material used is insufficient to provide adequate radon attenuation.