Safe closure of uranium mill tailings ponds - on basis of long-term stability-proofs linked with an extensive environmental monitoring

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Foreword

Deposition of ore mill tailings in in-pond tailings storages exists in different parts of the world and in different climate zones. Tailings ponds are built, in particular for gold, copper, zinc, lead and uranium mill tailings and so on, with huge dimensions. It is the mostly used method of the world to deposit mill tailings. Especially the closure of uranium mill tailings ponds is a very great challenge for environmental geotechnics. The methods for closure of the mill tailings ponds are depending on the special way on the one hand of the climate zone and on the other hand of the static and dynamic load.

This paper is founded on the extensive experiences of safe closure of uranium mill tailings ponds which are used in Germany and other countries with comparable climate and in-pond tailings storage conditions. The site-specific used method is called "Dry in-situ closure method with partial technical dewatering". That is a site-specific multiple-functional-layer cover system (multi barriers).

Fig.1 Gold mill tailings pond, WA (Goldfields)/Kalgoorly/hot arid climate zone/ left: free pond water infiltrated and evaporated; right: tailings pond with pond water lamella, photos by M. Lersow, 2005

0 A short look on the history

After the second world war Germany was divided in 4 parts. In the part which was dominated by the Soviet Union an enormously mining and milling industry was started to produce uranium. The SDAG Wismut, the Soviet German stakeholder company, the biggest Uranium enterprise of the world was founded, see figure 2. The GDR was the third biggest uranium producer of the world. From

Fig.2 Left and middle: abandoned tailings ponds site "Culmitzsch" impoundment and discharge point; right: remediation progress tailings ponds site "Trünzig" 2002, (M. Lersow, 2006)

1946 to 1990 approximately 230,000 tons of uranium were produced with 180 million cubic meters of mill tailings. The Tailings Storage Facilities (TSF) included an area of approximately 600 hectares, see table 1. The uranium mining in Saxony and Thuringia took place in a densely populated area of a unique cultural landscape of Europe. After the reunification of Germany the German society had to reclaim all these legacies. The total costs be summing up to 6.5 billion Euros. That includes also the 6 main mill tailings ponds, see table 1.

TAILINGS IMPOUNDMENT	Culmitzsch A	Culmitzsch B	Trünzig A	Trünzig B	Helmsdorf	Dänkritz I
Tailings surface area (ha)	159	76	67	48	205	19
Tailings volume (Mio m^3)	61	24	11	6	45	5
Solid mass (Mio t)	64	27	13	6	49	7
max. tailings thickness (m)	72	63	30	28	48	23
U_{nat} in solids (t)	4,800	2,200	1,500	700	5,000	1,000
Ra-226 in solids (10^{14} Bq)	7.9	2.4	1.3	0.5	5.5	0.4
U_{nat} in pore water (mg/l)	0.3 … 3.9	1.0 … 16.5	1 … 19	1 … 20	2 … 30	10 … 85
Ra-226 in pore water (mBq/l)	… 5,000	… 2,300	… 630	n.a.	500 … 2,000	n.a.

Tab.1 Main uranium mill tailings impoundments of SDAG Wismut, (M. Lersow & P. Schmidt, 2006)

1 Legal requirements and hazards

1.1 Legal requirements

Mill tailings storages belong to the configuration of many mining and milling enterprises. Both, the construction as well as the closure are subject of the permission and controlling of the mining authorities, of the water authorities and of the radiation protection authorities, world-wide.

Legal requirements

- Mining Act
  - elimination of any considerable residual risk on site, especially securing geomechanical stability and
  - preparation of mining areas for re-utilisation after mine closure, incompliance with regional land use concepts
- Water Resources Act and Soil Protection Act
  - long-term protection of ground and surface waters and soil from contamination
- Atomic Act and subsidiary regulations (e.g. Radiation Protection Ordinance)
  - Justification and optimisation of any measures
  - Compliance with dose limits to workers and public
    - Individual dose to public < 1 mSv/a, see table 3, action level and goal of remediation
      * Safekeeping of radioactive material
      * Minimization of radon exhalation, avoidance of propagation of dust born radioactivity
      * Minimization of percolation of precipitation water through tailings, protection of aquifers
      * Restricted land reuse

1.2 Main hazards of mill tailings ponds

First it was important to classify the main dangers, which run off from the tailings ponds and which risks are important for the long-term stability proof of the tailings ponds.

The following main hazards are based on the uranium mill tailings storages:

- Dam failure (loss of mechanically and hydro-mechanically stability),
- Contamination of the groundwater,
- Dust blowing (arsenic, radium) and
- Radioactivity from gamma-radiation and also radon exhalation, see figure 3

2 Closure plan and remediation works

2.1 Closure plan

Integrated planning of design, of construction, of operation and of closure enclose the minimization of the environmental impacts. The minimizing of

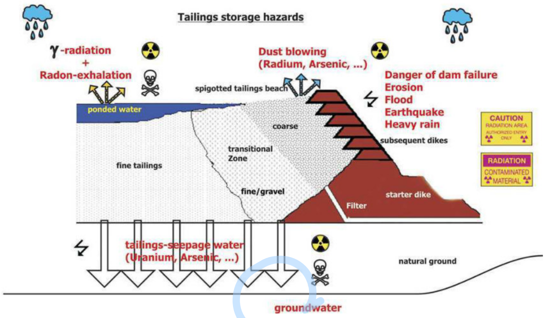


Fig.3 Construction of tailings impoundment and main hazards source: M. Lersow/www.ecm-ing.com

risk as well as effective monitoring programs for the tailings storage facilities and today are standard in many countries. In guidelines (framework for tailings storage management) the set of rules is given to the design, construction, operation, closure and the accompanying monitoring as well as long-term monitoring. Such experiences did not exist at the start of the closure of the Wismut-tailings ponds in Germany. Apart from the guidelines of the ICOLD [international Commission on Large Dams], only international experiences with the closure of tailings ponds could be used at the start of the closure works of the Wismut-tailings ponds with priority.

The closure plan is not static or finished with the start of the closure works. It follows the progress of closure works and must be adapted occasionally if it is necessary. The closure plan for the Wismut-tailings ponds has been developed continually and has been adapted to the in-situ conditions gradually.

2.1 Selection of the site specific closure method for uranium mill tailing ponds

Based on a Conceptual Site Model (CSM) the site specific remedial solution for closure of Wismut-uranium mill tailings ponds could be selected: "The dry in-situ closure method with partial technical dewatering." This had been the main selection reasons:

- Site-specific remedial solution, sustainable in the long term
- Is the preferred remediation under the Central European conditions (comparable e.g. with great parts of the USA and to Northern Canadian)
- Identified by probabilistic long-term cost and risk assessment.

Advantages:

- Low environmental impacts during the remediation
- Lowest residual risk in post remediation period

2.2 Objectives of Closure and Remediation of Tailings Ponds

Long-term stabilisation of tailings impoundments

- Proof of dam stability

Reduction of

- external radiation, • radon exhalation,
- percolation of precipitation water

Avoidance of

- propagation of dust-born radioactivity;
- oxygen diffusion in cases if acidification proneness

- **Safekeeping** of radioactive and toxic material
- **Protection** of aquifers and receiving streams
- Restricted land re-use

2.3 The site specific remedial works

2.3.1 The sites specific works for safe closure of uranium mill tailings

In the 1990s, world class environmental restoration technologies, mainly developed in the US and Canada, were studied to arrive at site-specific remedial options for achieving safe storage and long-term stabilisation of the tailings ponds. As a result, dry in-situ stabilisation with partial dewatering of the tailings was identified as the most appropriate option. This option involves the following steps, see figures 4 and 5:

a) **Remove** and treatment of the **supernatant water** and pore water; a higher stability of surface in sections of fine grain tailings will be developed by drainage;

(b) **Placement** of an **interim cover** on the tailings surface to provide the consolidation load and create a stable working platform;

(c) Reshaping of dams with respect to dam stability in the long term

(d) **Construction of a stable surface** contour providing suitable run off conditions for the surface water (profiling);

(e) **Capping** of the (profiled) surface with a **final soil cover,** Capping with a soil cover designed to limit external radiation, radon exhalation and limit infiltration into the tailings body.

(f) **Re-vegetation** of the surface (landscape). The surface of the cover is re-planted to control erosion and to blend in with the surrounding landscape.

(g) **Collecting, treatment** and discharge of **seepage**, and **long-term monitoring**

The cover is designed to minimize both radon exhalation and the infiltration of precipitation. It is a multiple-layer system placed into phases. During the first phase, an interim cover is put in place that consists of geosynthetics such as geocomposite drains or geogrids on which typically waste rock material will be placed. The additional load of the material accelerates the desired partial tailings dewatering. The effect is enhanced by the installation of vertical drains (wicks) which are typically driven down into the tailings to a depth of 5 metres. During the second phase, at the end of essential consolidation (settlement) processes, the final cover will be placed using barren soil and a re-cultivation layer as topsoil with heavy earth moving equipment.

An essential prerequisite for the safe storage of the tailings ponds is removal of the supernatant water. The contaminants in this water as well as in the pore water released during dewatering must be extracted from the waters and immobilized. This is done in sophisticated water treatment plants in a way to meet discharge limits and to enable the release of the treated water into receiving superficial waters. The residues of the water treatment are disposed in prepared areas of the tailings beaches and finally covered by soil, see figure 5.

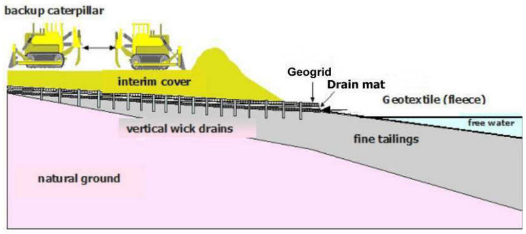


Fig.4 Put in place of different geosynthetics and interim cover as working platform, insert of wick drains, source: M. Lersow/www.ecm-ing.com

A special situation requiring modification of the rehabilitation technology can be seen at tailings pond sites with difficult geo-technical conditions on the ground in the central areas of the supernatant water lakes, the fine-grained slurries had to be stabilised before water removal. For this purpose, from a floating barge material (sand, gravel, fine-grained waste rocks) was tipped out on the weak slurries ("sub-aquatic tipping").

Despite of the difficult geo-technical conditions at the sites, a big progress was received in rehabilitation of the Wismut tailings ponds. From most of the ponds, supernatant water has been removed and the so-called interim cover has been established. In some of the areas the final contour of dams is prepared and placement of the final cover is in operation. To guarantee long-term stability of the final cover, mainly natural material is placed on the concepts for landscaping and after-use of the tailing facilities were agreed with regulatory agencies, communities and other stakeholders. The reclaimed areas are to be integrated into nature conservancy schemes. The design will be that of a nature-oriented landscape comprising green spaces and water bodies. Reclamation is aimed at walking away schemes demanding minimum care and maintenance. Finally, the environs of the reclaimed tailings facilities are to be afforested.

The profiling of contour, the landscape design and the final capping needed a best practice of material management. The height of costs for closure works is considerably influenced by both availability and as well as characteristics of material. If possible waste rock is used. Finally the requirements to the material are determined by the necessity of limitation of the mobility of acid mine water and of the mobility of the radioactive nuclides, by re-vegetation and maintenance of closure construction. Especially the requirements to the material are determined by long-lived radioactive nuclides and decay products and their quantity and their location in the tailings-body.

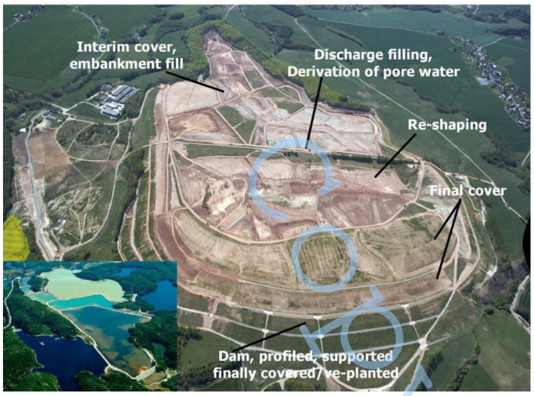
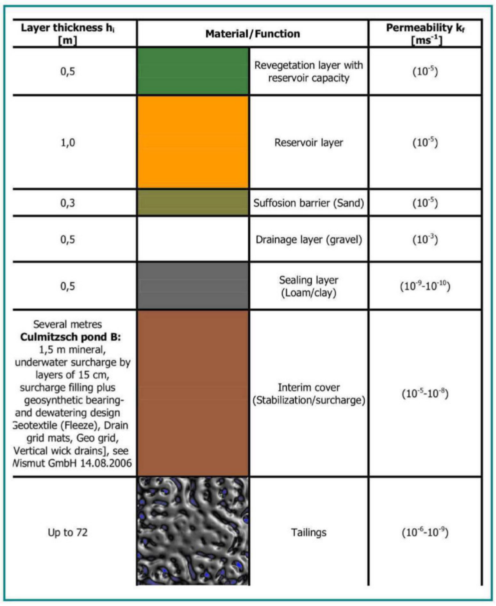


Fig.5 “Trünzig”-site, different parts of cover design, small photo: water covered tailings pond, Rio AlgomQuirke site/Elliot Lake/ Ontario/ Canada; source: BHP Billiton, 1999 and M. Lersow/Wismut GmbH May 2007



Layer thickness h_i [m]	Material/Function		Permeability k_f [ms^{-1}]
0,5	🟩	Revegetation layer with reservoir capacity	(10^{-5})
1,0	🟧	Reservoir layer	(10^{-5})
0,3	🟨	Suffosion barrier (Sand)	(10^{-5})
0,5	⬜	Drainage layer (gravel)	(10^{-3})
0,5	⬛	Sealing layer (Loam/clay)	(10^{-9}-10^{-10})
Several metres **Culmitzsch pond B:** 1,5 m mineral, underwater surcharge by layers of 15 cm, surcharge filling plus geosynthetic bearing- and dewatering design Geotextile (Fleeze), Drain grid mats, Geo grid, Vertical wick drains], see Wismut GmbH 14.08.2006	🟫	Interim cover (Stabilization/surcharge)	(10^{-5}-10^{-8})
Up to 72	▨	Tailings	(10^{-6}-10^{-9})

Fig.6 Cross section of multiple layers for dry in-situ cover, source: Wismut GmbH/ www.ecm-ing.com

2.3.2 Use of geosynthetics in multiple layer cover designs

2.3.2.1 Placement of the interim cover

The tailings surface is not stable after removal of supernatant water. With the installation of geosynthetics consisting of needle-punched nonwoven geotextiles, geocomposite drains, geogrids and synthetic vertical wick drains, a platform is now existing on which the mineral interim cover can be placed. Placement of an interim cover with different geosynthetics with following functions on the one hand provides the consolidation load and on the other hand creates a stable working platform, see figure 4

Placement of the interim cover

a) trafficable tailings beaches:

Placement of 1.0 …1.5 m waste dump material

b) low trafficable fine tailings:

1. Placement of needle-punched nonwoven geotextile and geosynthetic composite drain (overlapping)
2. Placement of biaxial geogrids with short-term strength ≥ 25 kN/m in both directions and initial modulus J ≥ 1000 kN/m at 1 % elongation
3. Stitching in of vertical wick drains (triangular grid spacing: ca. 1.5 m, 5…6 m deep)
4. Placement of a permeable layer (gravel or geocomposite drain)
5. stepwise placement of waste rock material in layers ≥ 0.5 m, thickness of interim cover usually 1.5 m , (Jakubick, A.T., 2000)

2.3.2.2 Placement of geosynthetic in the a multiple-layer system

Final dry cover systems of uranium mill tailings pond are composed of multiple layers, which can be grouped into five categories (Rumer, R.R and Mitchell, J.K. , 1996). Undoubtedly, not all layers are needed for all types of covers. The design criteria are based on a number of site-specific factors including:

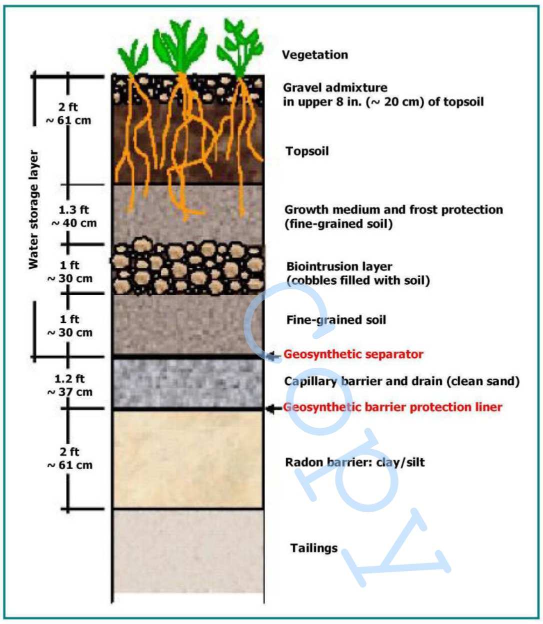


Fig.7 Following cover design for the UMTRA Monticello containment structure, Utah, [IAEA-TECDOC-1403, August 2004]

- Climatic conditions of the site
- Geomechanical/ geochemical properties and environmental risks of the disposal area
- Borrow material type and availability
- Closure strategy and • Cost.

The multi-functional cover systems for uranium mill tailings ponds have to fulfill the following demands:

→ increase of stability,
→ protection against infiltration,
→ radiation protection,
→ emission protection,
→ vegetation layer for re-vegetation etc.

A multiple layers cover system has been designed for the abandoned uranium mill tailings ponds of Wismut, which could be classified as "conventional dry cover with low permeability layers", see figure 6. The cap incorporates a 0.5 m thick layer of highly compacted silty clay soil, partially amended with bentonite, having a low permeability, i.e. k_f: $<10^{-9}$ m/s, overlain by layers for protecting the radon barrier against erosion, frost, and infiltration. The capillary barrier under a thick soil 'sponge' mimics the natural soil profile, in which thick loess stores precipitation that is eventually lost through evaporation, thus maintaining unsaturated conditions in the subsoil.

A large amount of research of the design of dry covers for uranium mill tailings ponds was conducted under the US Uranium Mill Tailings Remediation Action Program (UMTRA-Program). Based on the regulations promulgated by the Environmental Protection Agency (EPA: 40 CFR 192) and the Nuclear Regulatory Commission (NRC: 10 CFR 40), the uranium tailings pile must have a cover designed to control radiological hazards for the long time of 1,000 years (long-term stabile), to the extent reasonably achievable, and in any case, for at least 200 years. It must also limit radon (^{222}Rn) releases to 20 picocuries per square meter per second 20 pCi $m^{-2}s^{-1}$ = 0.74 Bq $m^{-2}s^{-1}$ averaged over the disposal area (Robinson, P., 2004). An example of cap designed by UMTRA is shown in figure 7.

The inserted geosynthetics - geosynthetic separator and geosynthetic barrier protection liner - has the following functions in the multiple layer cover system, demonstrable (IAEA 2004):

- Geosynthetic separator protects the capillary barrier (drain) against suffusion safely. It is in fact a suffusion barrier.
- Geosynthetic barrier protection liner protects the radon barrier against drying out. Different settlements are the result of drying out and in consequence of developing tears in the barrier, which thereby lose partially their radon barrier properties.

As two-dimensional products with a low mass per unit area and a low volume, geosynthetics can be easily integrated into the geotechnical construction works. A good integration of geosynthetics into the geotechnical constructions of closure works can support its long-term stability. But the site-specific factors decide, whether geosynthetics could be used successfully into the design of dry covers for uranium mill tailings ponds or not. The UMTRA-Programs and others programs, in particular which were promoted by IAEA, have been very helpful and important in these questions. It can be shown that the functionality and also the long-term safety of such multiple layer cover systems, which in such a way inserted geosynthetics, are higher than without geosynthetics. So we can reduce the costs for remediation and maintenance of uranium mill tailings ponds if multiple layer cover systems are used with geosynthetics in place.

2.3.2.3 Geosynthetic for floors of uranium mill tailings ponds and for upstream starter dam

From the past, the lessons have been learned and guidelines or frameworks for design, construction, operation and closure of mill tailings ponds have been designed on this basis. The closure plan is now an integrated part of each mill tailings ponds design. Floor sealings become integrated in mill tailings ponds designs today. In this way an active groundwater protection can be constructed which is designed for a lifetime up to 1,000 years. Enormous costs will be economized with the integration of closure planning in the design of tailings ponds in relation to the total lifetime. Geomembranes (HDPE) or geosynthetic clay liners (composite) are often important parts of site-specific floor sealing design. It is important to determine that the designer of the tailings storage facility has to define which characteristics the geosynthetics have to own for best functionality of the floor sealing, because only then the producer of geosynthetics can offer the geotechnical design elements accordingly.

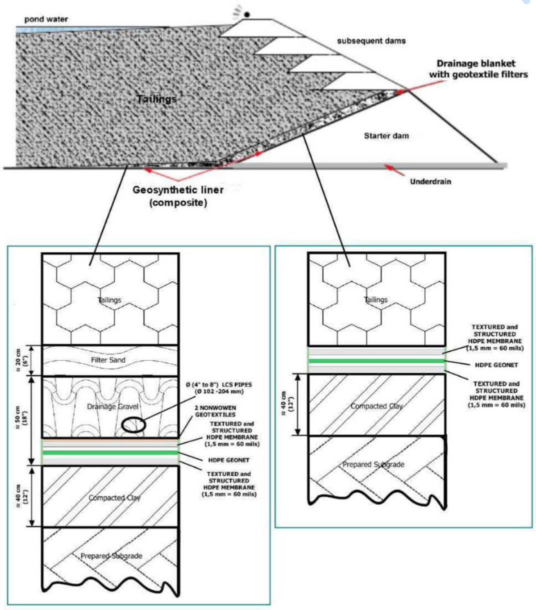


Fig.8 above: principle design of basis and starter dam sealing and drainage system; below left: following application example for floor; below right: following application for starter dam of uranium mill tailings ponds, (Uranium One USA, 2009)

The Canadian-based enterprise Uranium One Inc. (Uranium One USA, 2009) has presented a best available technology (BAT) design and regulatory requirements for a proposed tailings storage facility to manage tailings for a uranium mill in an arid region of the western United States. The general design of the tailings storage facility consists of a single 12 ha cell with capacity for 4 to 8 years of storage, depending on ore production rates. Tailings are proposed to be placed into the pond (cell) using conventional slurry discharge methods. Figure 8 shows the design for the floor of a tailings pond (cell) and a tailings dam (starter) and the placement of geosynthetics, which follow this example.

2.3.3 Re-vegetation of the surface

Re-vegetation is an essential part of rehabilitation process. A vegetation cover on mill tailings can be effective in controlling surface erosion, providing the necessary surface stability to prevent wind-blow of tailings particles, reducing infiltration by interception of rainfall and improving aesthetics (Ritcey, G.M., 1989). The vegetation layer design is the most important thing for a successful re-vegetation. It is demonstrated that the use of regional specific plants for re-vegetation safes the success. The experience by many examples show that using of regional not specific plants has endangered the success of some remediation projects, (P. Waggitt, 2008). In Germany exists the guideline DVWK 204 (1984). This guideline describes the effects of plants for the stability of dikes and is a good example. But with the selection of the plants however their roots depth has to be considered that radon permeabilities can not develop and so that the radon exhalation can rise to not allowed values.

It is important for the closure plan to integrate a re-vegetation plan, because a regionally specific re-vegetation has increased the long-term stability of the remediation facility enormously.

On the hand of above quoted effects of re-planted areas can be shown that the long-term stability of rehabilitated mill tailings ponds with multiple layer cover design increase enormously. The following long-term stability increasing effects by vegetation can be demonstrated:

→ Increase of the shear strength by water abstraction (by increasing of tension)

→ Increase of the shear strength by the reinforced effect of the plant roots

→ The cover will be given an tensile strength by the reinforced effect of the plant roots, (Tobias, 1991, 2003).

The reinforcing effect of the plants is however difficult to quantify for the long-term stability of the cover design.

Steeper slopes can be designed and constructed with geogrid veneer reinforcement.

3 Long-term stability proofs

3.1 Context between safeties of single elements and safeties of total systems

You can take out from the description above that we have to distinguish between safeties of single systems (e.g. cover) and safeties of total system (uranium mill tailings pond remediation project). This results from the multiple functionality of cover. If the cover loses e.g. its radiation protection function [**radiological risks (air path, water path, pathway of minerals)**], the function of construction will be disturbed in all. The radiation protection function can be described with the radon exhalation rate. While for this in the USA (EPA) the limit value has been prescribed 20 pCi $m^{-2}s^{-1}$ = 0.74 Bq $m^{-2}s^{-1}$, the radiation exposure with ≤ 0.3 µSv/h has been filtered out as limit value in Germany, see table 3.

for a dictated period the functionality of the cover with all part functions has to be proved now. The suggestion, the proof of a period of 1,000 years to carry out was developed out of the UMTRA-programs. The explanation for this are on the one hand the long-lived alpha emitters (^{238}U, ^{234}U, ^{232}Th, ^{230}Th, ^{226}Ra and other) and on the other hand the radioactive nuclides of inventory of the tailings ponds of hazardous contaminants, which are the main producers for ^{222}Rn. This are in particular the isotopes ^{226}Ra and ^{230}Th (can be ignored) of ^{238}U decay chain, see table 1. The isotope ^{222}Rn is a decay product with a half-life of 3.8 days. ^{222}Rn is an alpha emitter and decays among other in the solid isotopes of polonium, bismuth and lead. In case of inhalation of radon in the lungs, the solid isotopes adsorb there. Therefore the legal rules for exhalation limit values are also very strict. For "Trünzig"-site, pond A, the share of radioactive nuclides in inventory was determined with 1.3*10^{14}Bq = 130 TBq. The half-life of isotope ^{226}Ra amounts to 1,602 years, see table 1. A amount ^{226}Ra run off the radioactive inventory also by the seepage water. In "Trünzig"-site, pond A, was found out 630 mBq/l in pore water, see table 1. The seepage water is gathered and supplied to a water treatment plant. They are treated there and released in a receiving water. It can be shown that after 1,000 years the radioactivity of the main radon emitters will have been approx. halved in inventory of the uranium mill tailings pond (decay, drainage - radioactive nuclide run off, immobilization) and therefore the main reason of radon exhalation. In this description the immobilized effect of a secondary mineralization of tailings was not calculated. But the secondary mineralization of tailings is verifiable across a period of 1,000 years also under conditions of a cover, which means that the identified radioactivity is essentially smaller than above described.

Figures 6 and 7 do show multi-functional cover designs, which are stable for 1,000 years against radiological hazards. This has been supervised under site specific conditions with a great number of tests and will be supervised and controlled with inserted long-term monitoring further. Radon permeability in the cover of the tailings body or in weakness zones will be provoked by erosion processes. Therefore the safeties against internal and external erosion are also proofs of radiation protection function of cover. Simultaneous weakness zones could be also the reason, which develop on account of internal and/or external erosion-processes, that the reducing of the dam stability is so evident, that failure becomes very probable.

Because of lack of room here, site-specific chemical or hydrological models [**environmental risks (contamination of groundwater)**] can not be presented here, though it is very important to know in which direction the contaminant plume runs off and with which contamination content. This is also important for the assessment of main environmental hazards of rehabilitated site and of its surrounding.

3.1 Long-term stability proofs

3.1.1 General procedure

The long term stability proof of closure building includes the following single proofs:

- Long term stability proof of tailings dam
- Long term stability of multiple-functional-layer cover system
- Protection of groundwater and recipient water (run off protection).

It is necessary, that between the proofs of long term stability (prediction) and the long term monitoring of geotechnical environment building exist a strong linking, so that the authorized safety level of geotechnical environment building for the service life will be sufficiently checked and guaranteed.

General procedure:

- The selection of material law must conform with the executed soil- and rock-mechanical experiments and with the parameters which were measured.
- Beside proof (verification) of a selected model (among other the kind of discretization, the comparison with possible existing analytical approximations) the question is enormously important how can the material parameters be transferred on practical tasks of engineering applications, which were measured in laboratory. The last aspects have a special meaning at time-dependent processes (creeping, consolidation). At such calculations an important interaction exist between the geometrical discretization and the value of selected time-steps.
- The sufficient complexity of material equations in dependence on relevant questions is an essential condition for a realistic modelling.
- Different definitions of stability are possible in principle. And so the specifically numerical realizations of calculation of safety are to assess site-specific.
- For the numerical modelling of linked hydraulically-mechanical problems, that is considering of pouring groundwater (also confined water), whether using of FEM is sensible, should be proved.

The geotechnical categories are described according to the German standard DIN 1054 „Geotechnical proofs“. In this way an allocation will be carried out according to the geotechnical categories; in particular: loads, characteristic loads, design of loads and characteristic resistances of ground, design values of resistances according to the geotechnical proofs which are described in the guideline.

In general the procedure can be described as follows:

- Selection of calculation procedures and determining procedures for the parameters of state,
- Selection of long-term monitoring, procedures and interpretations of readings,
- Parameters of state (resistances) and the loads, which are used by the stability safety proofs, will be ascertained at the time $\mathbf{t_0}$. A first prediction of the time-depend behaviour of the parameters of state is contained in it. On this basis the long-term stability safety $\mathbf{S(t_0)}$ will be calculated.
- Improved prediction $\mathbf{S(t_1)}$ of the long-term behaviour at the time $\mathbf{t_1}$.

3.2.2 Concept, which has been realized at Wismut GmbH

Long-term stability proof for uranium mill tailings storages and parts of them in accordance with German standards DIN 19700 part 10 + part 15; DIN 4084; ICOLD-Bulletins and other special guidelines (radiation protection) which have to be considered in single case; include the following single proofs:

- ▶ Statical long-term stability proof (BISHOP, JANBU, proof for 1.000 a)
- ▶ Dynamical long-term stability proof on Operating Basis Earthquake (OBE, proof for 500 a)
- ▶ Dynamical long-term stability proof on Maximum Credible Earthquake (MCE, proof for 10,000 a)
- ▶ Hydraulically safety
  - Hydraulically failure
  - Safety against internal erosion

(erosion channel)

- Long-term stability against external erosion (flute)

3.2.3 Geotechnical stability calculations

In principal different definitions of geotechnical stability can be applied. Therefore one has to evaluate the specific numeric modelling with respect to the respective definition of geotechnical safety. In principal different definitions of geotechnical stability can be applied. Therefore one has to evaluate the specific numeric modelling with respect to the respective definition of geotechnical safety. In numerical analysis procedures geotechnical stability is usually described as (Eq.1). A common failure criterion, typically used in soil mechanics, is the flow criterion according to Mohr-Coulomb, (Eq.2). A dilatancy function is used to implement soil behaviour of dilatancy and contractancy.

$$St = \frac{\text{available shear strength}}{\text{max. shear stress at critical failure}}; \quad St = \frac{\tan \varphi_k}{\tan \varphi_{ult}} = \frac{c_k}{c_{ult}} \qquad \text{Eq. (1)}$$

$$F(\underline{T}_h) = \min\{\frac{\sigma_{max} + \sigma_{min}}{2} \sin\varphi + c \cdot \cos\varphi - \frac{\sigma_{max} - \sigma_{min}}{2}; \sigma_{min}\} = 0 \qquad \text{Eq. (2)}$$

$$F(\underline{T}_h) = 0 \wedge \min\{\sigma_1; \sigma_2; \sigma_3\}; \quad \sigma_{max} = \max\{\sigma_1; \sigma_2; \sigma_3\};$$

$$\sigma_{min} = \max\{\sigma_1; \sigma_2; \sigma_3\} \qquad \text{Eq. (2a)}$$

Φ – angel of the internal friction, **c** – cohesion;
σ_i – main stresses

If tension forces do exist, a **tension-cut-off criterion** is added.

3.2.4 Material parameters, parameter of state

The parameters of state **S_i**, (Eq.3), with which the soil-mechanical state of foundation is described, are defined with the following functional relationship, see (Backhaus G., 1983):

$$S_i = S\,(x, y, z, t, \chi, \theta) \qquad \text{Eq. (3)}$$

x, y, z – place co-ordinates ; **t** - time ;
χ - parameter of state; **θ** - correlation coefficient

The behaviour of material of loose rocks under different loads can be described by a function of different influential quantities, see (Eq. 4).

$$F(\dot{\varepsilon}, \varepsilon, \sigma, T, S) = 0; \qquad \text{Eq. (4)}$$

F(...) - functional relationship of quantities;
ε - deformation; **$\dot{\varepsilon}$** - velocity of deformation
σ - stress; **T** - absolute temperature;
S - parameter of state.

For the parameters of states S_i, determined on the place with the co-ordinates x,y,z, the following functional connection can be found, see (Eq. 5).

$$S_i = f(w, e_0, \sigma`_1, t) \qquad \text{Eq. (5)}$$

w - water content; **e_0** - parental void ratio (no-tension); **$\sigma`_1$** - effective main stress

Two kinds of non-linear behaviours should be noticed basically during modelling with FEM of soil- and rock-mechanical tasks:

- geometrically non-linear behaviour (at large deformations) and
- physically non-linear behaviour (provoked by the properties of material).

This concept of long-term stability for closure of tailings ponds considered only geometrically linear behaviour (small deformations). Therefore the principle of linear superposition can be used. The

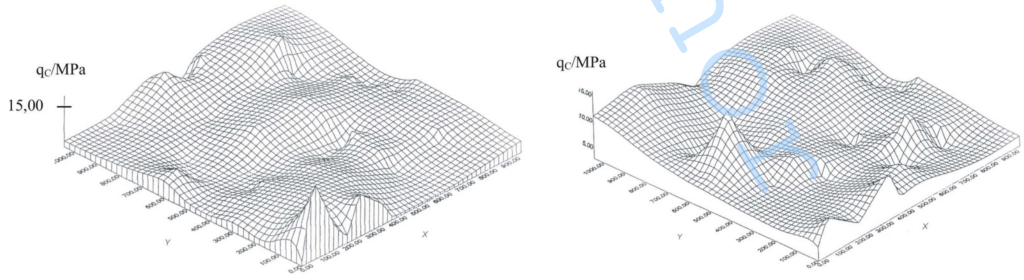


Fig.9 3-D Visualisation of cone pressure q_C of regression analysis in different depths, (M. Lersow, 2003)

single measured parts of settlements could be summarized in this case, see (Eq. 6):

$$s_g = s_e + s_l + s_{gw} \qquad \textbf{Eq. (6)}$$

s_g - total settlement;
s_e - settlement under own weight of tailings body
s_l - settlement under loads of tailings body
s_{gw} - part of settlement by dewatering (rising of groundwater) of tailings body

CPT-No	2-13	24	24a	2-6	2-9	29a	31a	35
a/MN/m²	- 1.01129	2.17634	- 7.87406	0.223683	3.43668	- 0.959411	2.21298	-2.70202
b/MN/m³	0.265345	0.161439	0.590386	0.244968	0.175812	0.213584	0.122971	0.230851
Correlation coefficients	0.955095	0.689819	0.849254	0.885242	0.949680	0.932856	0.765281	0.706560

Tab.2 Regression and correlation coefficients of CPTs, waste disposal site “Gröbers” near to the City of Leipzig, extract (M. Lersow, 2003)

On closer viewing of physical non-linear behaviour of soil- and rock-mechanical tasks it is essential to expect inhomogeneous and anisotropic material. The parameters of state will be determined with help of theirs statistical behaviour and correlation coefficients. The existed anomalies could be detected with geophysical methods. Table 2 shows an extract of results of CPTs on an waste disposal site and their evaluation which are the basis of figure 9.

4 Long-term and post remedial monitoring

4.1 Environmental monitoring, part of the closure of mill tailings ponds

The mission of the environmental monitoring is to measure which impact the various liabilities have on the environment as well as to examine which impact the remedial action itself has on soil, air and water. Here, a distinction is made between the baseline monitoring and the operational rehabilitation monitoring.

Goals:

- Surveillance of the environmental impact of objects, residues, contaminated areas, etc.
- Surveillance of the environmental impact of remedial measures
- Proof of successful implementation of the remediation

Baseline monitoring, see figure 10, involves those measurements which are independent on remedial actions, which use a network of fixed monitoring locations and which are performed according to defined methods and in compliance with legal requirements. Apart from that, releases and discharges from the sites are also measured. The baseline monitoring functions as a long-term monitoring network for the surveillance of the post-remedial situation to document remedial performance.

Operational remediation monitoring involves complex measurements and investigations before the remediation in order to identify the best-suitable options for remediation, but also an environmental surveillance during remediation activities. This kind of monitoring is characterized by its operation for a limited period of time. It also involves the monitoring of the remediation workers radiation exposure.

The huge amount of collected data does require an efficient data management and an austere quality control. This involves also the testing and certification of instruments, methods including sampling techniques, as well as approval of the source data. Special-purpose computer programmes compile and check on-site the data measured and provided from he laboratories. Quality-controlled data are then stored in a central environmental database (e.g. Oracle-based). In addition to the remediation and environmental data the database also contains climate dates and data provided by engineering contractors and consultants.

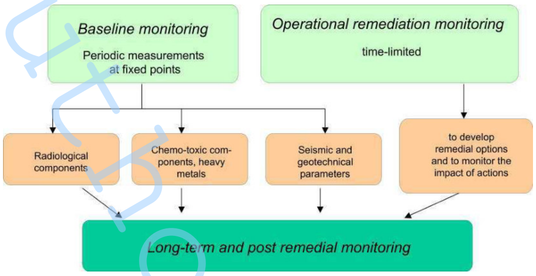


Fig.10 Environmental Monitoring

Long-term and remedial monitoring

The fixed points which have been defined during the baseline monitoring provide the basis for the measuring net of long-term monitoring. It will be added by addition of measuring points on places where a higher failure likelihood or an anomaly behaviour, e.g. of the tailings dam exists.
With advancing remediation progress:

a) Proof of successful performance of the remediation

The proof of a successful performance of the remediation in compliance with the remediation targets becomes an important monitoring task. A very illustrative way to demonstrate the successful site clearance is to compare gamma dose rates before and after the remedial activities. More complex remedial actions and objects of remediation require sophisticated and complex investigations to give evidence that the remedial targets were fulfilled (radon exhalation measurements on covered tailings ponds and groundwater investigations in deep wells around tailings ponds), (M. Lersow & P. Schmidt, 2006). This shall mean that a proof for radioactive nuclides in the receiving waters is an important part of environmental monitoring that non hazards will be run off by rehabilitated tailings ponds for human and environment in the prescribed period, see table 3.

<table>
<tr><td colspan="9">Recommendations of the German Radiation Protection Commission concerning the safeguard, use or release of contaminated materials, buildings, areas or dumps regarding use of contaminated (SSK 92); extract
(Secondary levels derived from the primary 1 mSv/a reference level)</td></tr>
<tr><td colspan="5">Unrestricted use of contaminated areas, buildings and mine dumps:
- 0,2 Bq/g for the dominating radio-nuclide of the U-238 decay chain
- 300 nSv/h (0,3 µSv/h) Ambient dose equivalence rate
<u>Restricted land-use (forestry, grassland):</u>
- 0,2 -1 Bq/g for the dominating nuclide; above that site specific assessment</td><td colspan="4"><u>Drinking water :</u>
0,5 mSv/a effective dose via the water pathway in general
Drinking water:
- U_{nat}: 0,3 mg/l (7 Bq/l total)
- ^{226}Ra: 0,7 Bq/l; (^{228}Ra 0,7 Bq/l)
- ^{210}Pb: 0,7 Bq/l; ^{210}Po: 0,7 Bq/l
- application of sum formula ($\Sigma q_i < 1$)</td></tr>
<tr><td colspan="9">Typical WISMUT doses - Exposure of the local population: water pathway
(Receiving water “Lerchenbach”, locally contaminated by the “Trünzig”-site)</td></tr>
<tr><td colspan="9">Nuclide vector (results of measurements, concentration in [Bq/l])</td></tr>
<tr><td>^{238}U</td><td>^{234}U</td><td>^{230}Th</td><td>^{226}Ra</td><td>^{210}Pb</td><td>^{210}Po</td><td>^{235}U</td><td>^{231}Pa</td><td>^{227}Ac</td></tr>
<tr><td>5,2</td><td>6,1</td><td>0,17</td><td>0,02</td><td>0,025</td><td>0,024</td><td>0,24</td><td>0,015</td><td>0,015</td></tr>
</table>

Tab.3: Environmental demands and radiation protection targets in accordance to German Radiation Protection Commission, (SSK 92) for Uranium mining areas of Saxony and Thuringia/Wismut GmbH

b) Parameters of state

The parameters of state which were inserted in the long-term safety have to be controlled and have to be ascertained again on reason of the time-dependent behaviour of the parameters of state. Now a new forecast on the long-term behaviour with the safety level $S(t_1)$ could be calculated (at time t_1). If the safety level goes up, the monitoring volume will be decreased, if the safety level goes down, the long-term monitoring will have to become adapted and perhaps to become extended, see (Eq. 5a). $\mathbf{S_1= f\,(w, e_0, \sigma`_1, t_1)}$ **Eq. (5a)**

c) Special safety measures

It is necessary to take special measures for early identification of developing zones of weakness, sliding surfaces or sliding surface systems etc intailings dams, in particular near housing estates, agricultural and animal production. So special measures could be taken in time for the prevention of a disaster, e.g. for the prevention of a dam failure. Also in regions with high seismic activity or heavy rain periods and storm water measures for a early warning system with priority should be taken. The working group “Tailings” of the German Geotechnical Society gives these tasks priority ,in particular those which are connected with a suitable definition of long-term safety. Several stimulations do exist already. These have to be developed further which are then summarized up to a total solution. One possibility is the use of Polymere

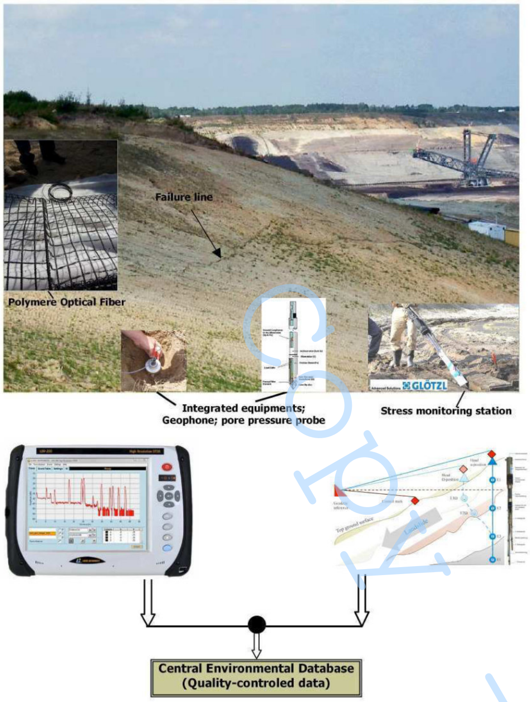


Fig.11: Principle of a "site-specific geotechnical-monitoring-equipment and central environmental database, also as a failure early warning system"/Belchatov-lignite mine site/ Poland, 2009,(Glötzl, R., 2009) © all rights by R. Glötzl/M. Lersow

Optical Fiber (POF), (Glötzl, R., 2009), in connection with a stress monitoring station, (Glötzl, R., 2002), see figure 11.

d) Comparison with repository for radioactive waste with negligible heat generation

A comparison with repository for radioactive waste with negligible heat generation from peaceful use of nuclear energy is possible, because the inventory of both, of the uranium mill tailings in-pond storages and of this kind of repository, are comparable. At the cut off date 01.01.1980 the total radioactivity of the inventory of approx. 126,000 barrels, which was deposited in the underground mine site Asse II (Lower Saxony State), amounted to 0.211 MCi = 7,807 TBq. At the cut off date 01.01.1980 an amount of 5.515 g of radioactive isotopes ^{226}Ra was determined, (U. Gerstmann, 2002). This corresponds to a radioactivity of 0.202806 TBq. At the cut off date 01.01.2003 it still amounted to 0.200786 TBq.

Some parameters of radioactivity of abandoned Wismut-tailings ponds are listed in table 4. It specifies the share of radioactive isotope ^{226}Ra and of U_{nat} (contains the nuclides: ^{238}U = 99.2836%, ^{235}U = 0.711%, ^{234}U = 0.0054%) in solid tailings and also the total radioactivity of the single tailings pond.

Of course we have to notice that the radioactive nuclide vector between tailings ponds and repository for radioactive waste with negligible heat generation is different, but also the difference in mobility of radioactive nuclides. The mobility of radioactive nuclides of the inventory of tailings ponds is much more higher than in the repository for radioactive waste with negligible heat generation. The proof, that engineers and scientists developed and constructed safe site-specific closure technologies for uranium mill tailings ponds worldwide, should give courage in future for design and construction of repositories of radioactive waste.

A few solutions shown herein could be used also for open pit slopes, dams of water buildings, hillsides etc. That gives an outlook in general and closes this paper finally.

TAILINGS IMPOUNDMENT	Culmitzsch A	Culmitzsch B	Trünzig A	Trünzig B	Helmsdorf	Dänkritz I
Ra-226 in solids (TBq)	790	240	130	50	550	40
U_{nat} in solids (t)	4,800	2,200	1,500	700	5,000	1,000
U-234 (Bq/mg U_{nat})	≈ 12.35 (half-life, $T_{1/2}$= 2.455*10^{5}a)					
U-235 (Bq/mg U_{nat})	≈ 0.57 (half-life, $T_{1/2}$= 7.038*10^{8}a)					
U-238 (Bq/mg U_{nat})	≈ 12.43 (half-life, $T_{1/2}$= 4.468*10^{9}a)					
U_{nat} in solids (TBq)	122	56	38	18	127	25
∑ (TBq)	912	296	168	68	677	65

Tab. 4: Radioactivity of tailings-ponds-inventory of Wismut remediation project (radioactivity in pore water ignored)

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Safe closure of uranium mill tailings ponds - on basis of long-term stability-proofs linked with an extensive environmental monitoring

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Chairman of working group "Tailings" of German Geotechnical Society

References/Inserts

The text, which was printed in the proceedings of the conference, does not correspond to the keynote lecture completely. The text, which was been made available here, but is authorized by the author. It has to be therefore attention be addressed on two conversions here: Total radioactivity 0.211 MCi = 7,807 TBq and radon exhalation rate 20 pCi m^{-2} s^{-1} = 0.74 Bq m^{-2} s^{-1}.

In the table bottom the radioactive nuclide vector of the inventory of the Asse II is presents on different cut off dates. It is so possible to show clearly, that the long-lived radioactive nuclides doing only keep a share of the total radioactivity of (TR) A«1,000 TBq.

1980;	**TR = 7,806,025 GBq = 7,806.025 TBq**			**2003;**	**TR = 2,700,000 GBq = 2,700.000 TBq**		
Isotop	**Half-life $T_{1/2}$ in a**	**Part on the TR in %**	**Part on the TR in TBq**	**Isotop**	**Half-life $T_{1/2}$ in a**	**Part on the TR in %**	**Part on the TR in TBq**
Co-60	5.26	30.94	2,415.18410	**Co-60**	5.26	4.20	113.40
Ni-63	100.00	10.27	801.67876	**Ni-63**	100.00	24.53	662.31
Sr-90	28.78	6.60	515.19765	**Sr-90**	28.78	10.60	286.20
Cs-137	30.17	11.01	859.44335	**Cs-137**	30.17	18.17	490.59
Pu-241	14.35	38.73	3,023.27340	**Pu-241**	14.35	35.68	963.36
Others	???	2.45	191.24761	**Others**	???	6.82	184.14
Σ	**22.12 (without others)**	**100.00**	**7,806.02487**	**Σ**	**35.78 (without others)**	**100.00**	**2,700.000**

Note to the above table: The inventory of Asse II consists by definition mainly off short-lived ($T_{1/2} \leq 30$ a) or a little longer-lived radioactive isotopes. In case if the decay curve will be set as basis of calculation, the fictional half-life of the total inventory can be determined at the cut off date 2003-01-01 with $T_{1/2}$= 15,02 a. "Others" are essentially long-lived radioactive isotopes (Th-232, Σ (U-235, -236, -238), Pu-239, Ra-226 etc.). If one as the cut off date 1980-01-01 as basis will set, then in the above table is the nuclide-vector of 1980 the initial-vector. The share of long-lived radioactive isotopes of the total radioactivity on 1980-01-01 was so A_{ges}< 191.24761 TBq « 1,000 TBq. This radioactivity has to be stored safely for a long time with very small long-term failure likelihood of the repository and its surrounding barriers. The fact of restricted mobility of radioactive isotopes and the potential at Rn-222 emissions off the radioactive inventory become not discusses here.

For more please see keynote lecture of M. Lersow or www.ecm-ing.com

Table under using of the source: http://www.endlager-asse.de/DE/2_WasIst/A_In6Schritten/_node.html

The author wishes the readers of this paper many suggestions, joy of trip of discovery and of course, critical response as evidence that the contribution has produced the desired effect. It is certainly interesting for the reader of this review also a paper of the author off the Geotechnics 4/10 with comparable topic to read . This is here available in German as a download at [1] .

Michael Lersow

Breitenbrunn on 2010-12-23

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