EXTRACTION OF HAZARDOUS CONSTITUENTS FROM TAILINGS RESULTING FROM PROCESSING OF HIGH-GRADE URANIUM ORE*

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Abstract. Conventional production of uranium across the world creates millions of tonnes of tailings annually, which are typically placed in above-ground tailings impoundments. However, particularly tailings resulting from leaching of high-grade uranium ores have the potential to cause serious environmental impacts. In spite of significant improvements which have been made in recent years to operational and short-term safety of those tailings impoundments, their provision of reliable long-term safety is still not satisfying. By advancement of the processing technology for uranium ore a solution is achieved to comprehensively eliminate risks which can derive from those tailings. Removal of radionuclides other than uranium as well as toxic metals can be achieved, if also these are intentionally extracted. The overall objective is to prevent the generation of future uranium production legacies with associated high follow-up costs.

1. Background

The surficial disposal of tailings in engineered impoundments has been considered to be generally a reasonable solution. By relatively moderate effort a disposal opportunity has been provided, which apparently has been meeting operational requirements.

Conventional above-ground tailings impoundments, however, can also comprise disadvantages. If properly engineered, such facilities are able to cope with challenges like dam failure or seepage generation during operation and in the short-term (e.g. up to some centuries). However, it is potentially a fundamental disadvantage of conventional tailings impoundments that long-term safety and integrity, which from a radiological point of view can be necessary up to several tens of thousands of years, may be provided insufficiently.

Provided that maintenance and monitoring measures are ensured, conventional tailings impoundments can provide integrity maximum for a timespan of up to 1000 years [1]. Their integrity duration can be even much shorter in case of high georisks (like earthquakes, floods etc.). Furthermore, in many countries institutional control is assumed to be reliable not longer than 300 years [2].

Consequently, the disposal of tailings resulting from conventional processing e.g. of high-grade uranium ore in above-ground tailings impoundments appears to be a temporary rather than a true long-term solution to their containment.

2. Justification

Of particular concern for the long-term safety of applicable tailings impoundments is that long-living daughter nuclides of uranium are conventionally disposed of with tailings. The contained radioactivity

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is predominantly caused by radium (mainly Ra-226) and its daughter nuclides like radon (Rn-222) as well as by thorium (mainly Th-230\textsuperscript{2}). Approximately 85 % of the original activity remains in conventional tailings [3]. Almost 65 % of the original Ra-226 mass will still remain even after the maximum envisaged lifetime of tailings impoundments (1000 years, as mentioned).

Typically the low-level activity tailings resulting from uranium production fulfil criteria for classification as Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) waste. Moreover, conventional tailings resulting from processing uranium ore yet with a grade > 0.3% need to be classified as long-lived radioactive waste \textsuperscript{3}. To cope with this significant content of long-living radionuclides the IAEA recommends at first consideration of underground disposal of tailings, whilst acknowledging that “the use of engineered surface impoundments may be the only viable option and should be [also] considered” [5].

Above-ground disposal of tailings has been in use mainly due to the huge volumes of tailings involved [6]. The historical acceptance of above-ground tailings disposal does not mean that the usual approach is recommendable, just that it is understandable. Whereas long-lived radioactive waste generated in nuclear energy generation (even long-lived radioactive waste of much lower activity than e.g. spent nuclear fuel) is generally intended to be disposed of in underground repositories, a similar approach so far becomes not apparent in uranium mining, raising the impression that different safety levels may be applied. However, tailings exist in much greater quantities and whilst the measures to manage them properly are different to those involved in nuclear energy waste, the same objective of acceptable risk should be applied.

The radiological long-term safe disposal of eligible tailings would be enhanced if both radium and thorium were to be extracted and removed. The extraction of non-radioactive hazardous constituents such as the so-called heavy metals and other toxic elements would also enhance the safe disposal of tailings. Hazardous constituents contained in tailings could spread out into the environment should tailings impoundments lose integrity. To prevent this in the long-term, ongoing maintenance of conventional tailings impoundments can become necessary to maintain their integrity with time. However, such approach may not be cost-effective, because of potentially large and on-going follow-up costs.

Therefore, advanced processing appears to be justified in following cases:

- In cases of high georisks of tailings impoundment failure due to earthquakes, floods and other natural causes;
- Where tailings are poorly stored in densely populated areas;
- Where higher grades of the uranium ore are involved; and
- Where there are high concentrations of non-radioactive toxic elements.

However, a precondition is that the concentration of hazardous constituents and the risk of their release causing significant harm is high enough to warrant the effort and expenditure. The extraction and removal of trace amounts of radioactive or other contaminants might be neither technically feasible nor justified.

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\textsuperscript{2} To simplify calculations it is assumed that all radium- and thorium-isotopes are generated by decay of U-238.

\textsuperscript{3} If radioactive waste comprises long-living radionuclides (i.e. radionuclides with a half-life time above that of Cs-137) in such an amount that the average \( \alpha \)-activity of long-living radionuclides is \( \geq 400 \text{ Bq/g} \), final disposal in the underground is required [2, 4]. Note that there may be countries, where this usual limit is not in force.
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Therefore, advanced processing appears particularly indicated in cases, which require increased safety measures like high-grade uranium ore\(^4\), which, if conventionally processed, result in tailings rich in radioactive daughter nuclides of uranium and pose an increased risk.

As the conventional way of above-ground tailings disposal has been appearing to be questionable, yet almost 2 decades ago the proposed (but not realized) Jabiluka uranium mine in the Northern Territory of Australia has aimed to take another approach. After dewatering and mixing generated tailings with cement to a paste optionally it was planned to dispose them of into a number of constructed silos, which had their tops about 100 m below the ground [7, 8]. Though this approach for tailings management was in a technical view quite progressive at this time, the extraction and removal of hazardous constituents proposed here can provide an even more efficient alternative than underground disposal of conventionally processed tailings.

Such attempts to stabilize tailings [9] e.g. by mixing with cement are not helpful in the end, because these measures concentrate on encountering challenges already in place in the short-term like rain water ingestion, leakage of contaminants etc. They do not reduce the overall inherent hazard of the still contaminant-bearing tailings and may not encounter long-term challenges such as the release of contaminants by erosion of tailings impoundments with time. Nonetheless, stabilization can be helpful in some cases, particularly if concentrations of contaminants in tailings are too low concentrated to be economically extracted or where risks are low.

Even natural diagenesis processes in tailings, though assumingly leading to geochemical stability [10] as well as to some degree of consolidation, are not reliably able to encounter erosion forces. If particular circumstances favour this, with time natural attenuation processes in tailings impoundments may take place [11]. These might result in hardpan formation and self-sealing of conventional tailings impoundments. However, even if they occur, it is not possible to rely on these diffusion-controlled processes to prevent formation of Acid Mine Drainage (AMD), because they may take dozens of years to develop and are often incomplete.

2.1. Radium

During leaching of uranium ore by sulphuric acid or alkaline agents just 1-5% of its original Ra-226 content becomes dissolved. Widely applied in uranium production facilities today, removal of dissolved Ra-226 from the process water is addressed by dosing of barium chloride [12, 13]. The efficiency of such treatment, however, is limited, because just liquid effluents of the conventional leaching process and certain affected water seepages are treated, not the solids from which the radium comes. In effect just the mentioned relatively small portion of dissolved radium is precipitated to meet relevant discharge requirements. Moreover, after precipitation this radium is typically again mixed with the conventional tailings, which thus contain almost all the radium of the original uranium ore.

The main portion of Ra-226, which predominantly remains in the solid fraction [14, 15] cannot be removed by BaCl\(_2\) treatment and, thus, is always disposed of with the tailings. By disposal of this remaining portion of radium (and where applicable the precipitated radium from water treatment, see above) in the course of tailings disposal, fundamental long-term risks originate. These could be prevented if the whole Ra-226 content originally present in uranium ore first becomes mobilized using an appropriate extracting agent. Subsequently, radium removal can be performed comprehensively, for disposal separately to tailings.

Having a half-life of 1602 years Ra-226 has to be considered as the most critical radionuclide in tailings from conventional uranium ore processing. Decay of Ra-226 produces short-living daughter nuclides like radon (Rn-222). Radon gas and other daughter nuclides cannot be generated anymore, if

\(^4\) The term “high-grade uranium ore” appears, however, to be not exactly defined. AREVA already defines ores with a uranium content > 0.10% to be of high-grade (note: world average grade of mined uranium ore is about 0.2 %), though Canada has deposits with a uranium content of up to 20%.
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Ra-226 is removed (Fig. 1). The parent nuclides of Ra-226 are of much lower radiological significance here, because they have either much shorter or much longer half-lives\textsuperscript{5}.

2.2. Thorium

Differing amounts of thorium become dissolved by conventional leaching of uranium ore with $\text{H}_2\text{SO}_4$ (between 30-90 %, while under alkaline conditions thorium appears to be much more insoluble and mainly remains in the tailings [14]). After separation of uranium from the leaching solution dissolved thorium nowadays is precipitated in order to meet discharge requirements by adjusting the pH (usually with lime milk). As with radium the precipitates rich in thorium are finally mixed with the resulting tailings. In the end conventional tailings contain almost all thorium originally present in the uranium ore.

Though a large step forward is taken by the proposed radium removal, it is advisable to extract and remove thorium as well, as it was shown radium and thorium together are responsible for over 90 % of the effective dose rate besides tailings impoundments. Otherwise decay of Th-230 leads to regeneration of its daughter nuclide Ra-226 and after 10,000 years about 10% Ra-226 would be generated again, compared to the original Ra-226 content.

Looking at the evolution of the effective dose (Fig. 1) it is obvious that the necessary level of safety, which can be ensured by the removal of radium and thorium, could only be achieved by integrity of conventional tailing impoundments of more than ~20,000 years.

\textbf{FIG. 1.} Modelled reduction of the effective dose rate directly besides a tailings impoundment in case of no removal, removal just of radium and removal both of radium and thorium (inhalation pathway). Calculations are based on [16].

2.3. Non-radioactive hazardous constituents

Conventional uranium ore tailings can contain - in addition to radioactive daughter nuclides - differing amounts of non-radioactive constituents (e.g. arsenic and the so-called heavy metals). By conventional water treatment these non-radioactive constituents are usually co-extracted from the process solution. Subsequently, the precipitates are then co-disposed of together with the actual tailings. However, in

\textsuperscript{5} It should be noted that certain radionuclides can additionally pose a chemotoxic hazard.
the course of extraction of radium and of thorium from uranium tailings these non-radioactive constituents can be mobilized and removed as well.

3. Technological opportunities

Generally, by another leaching chemistry - instead of or in addition (subsequently) to sulphuric acid or alkaline agents - extraction of the hazardous constituents present in uranium ore can be achieved.

Various extraction agents for uranium processing were tested in the past. As leaching of uranium ore by sulphuric acid or alkaline agents provides generally the highest operational efficiency and cost effectiveness, these latter technologies became widely applied.

In addition, uranium production today is expected to meet the highest environmental standards. It has to be managed in an environmentally safe and long-term reliable manner.

3.1. Operational uranium milling

In addition to efficient uranium extraction (typically about 85-95% of the original ore content can be won today), the objective of advanced processing is also the efficient extraction of hazardous constituents.

The hazardous constituents can become available for removal by continuing the processing of uranium ore also to extraction from uranium tailings. In effect, such processed tailings would be virtually harmless and their disposal in above-ground tailings impoundments will not give reason for concern. To achieve this two general approaches appear feasible.

3.1.1. Extracting constituents in one step

By use of a non-specific agent such as HCl [14] all constituents of interest can be extracted in one step (historical attempts made use of HNO₃ [17] and other agents). However, if tailings are aggressively leached in such a way, many constituents could come into solution (e.g. iron, aluminium and other common mineral constituents as well as major ions like calcium, magnesium and others). Thus, the extraction might need to be more specifically targeted.

By use of specific (selective) ion exchange resins precipitation and capture of harmful constituents from the “pregnant” leaching solution could be achieved. At an existing uranium extraction plant, an almost complete replacement of existing (conventional) processing lines could be required to extract all constituents at once. Therefore, this solution would be more applicable for new, purpose-built uranium production plants.

3.1.2. Stepwise extraction (complementing existing processing lines)

Stepwise extraction of tailings after uranium extraction and before disposal appears to be preferable in most cases. This could be realised by integrating a new module between existing components that is immediately after conventional solid-liquid separation, which separates the pregnant leaching solution from the remaining tailings. The advanced processing module receives the conventional tailings as input for further treatment.

By stepwise dosing of reagents with different (specific) extraction capacity in adequate extraction reactors the different hazardous constituents become dissolved sequentially. If a general aggressive leach is not conducted, the leaching of each targeted element can be optimized. A possible technical solution is outlined in Fig. 2.
FIG. 2. Simplified process flow diagram of a technical solution for advanced uranium ore processing (extraction / removal steps shown just for radium and for toxic metals).

The liquid phase or phases, which then contains specific hazardous constituent(s) in dissolved form, is separated from the solid (tailings) phase by means of a solid-liquid separation (e.g. by a filter press). Subsequently, the dissolved hazardous constituent(s) in the liquid phase separated in this way is (are) precipitated by dosing of another capable reagent in a precipitation reactor and finally filtered for removal.

With regard to the effort for handling and disposal of extracted radium two general options for separation are given. The choice between these would need to balance financial and technical effort.
3.1.3. Precipitation of the extracted radium by dosing of BaCl₂

Since much sulphate is still present from previous leaching of the uranium ore by H₂SO₄, the extracted radium can be precipitated as a Ba(Ra)SO₄-sludge. Though the activity of this sludge would be presumably not very high (i.e. not very demanding), in the end its relatively large volume might lead to higher total disposal costs.

3.1.4. Precipitation of the extracted radium by membrane technology

By deploying membrane technology the extracted radium can be precipitated in a more concentrated form (as well as, potentially, allowing even lower concentrations of radium to be extracted). In comparison to the sludge of the above option this concentrate would be of higher activity (requiring higher radiation protection effort), but due to lower volume might lead to lower total disposal costs. A similar decision as with radium needs to be made on precipitation of dissolved thorium – regardless of how it became dissolved (if by the conventional extraction of uranium ore or by the proposed extraction of tailings). As mentioned above dissolved thorium is precipitated by pH adjustment in the course of process water treatment today. In order to prevent the conventional disposal of thorium together with the tailings, those precipitates need to be collected separately also for disposal as long-living radioactive waste. However, presumably other dissolved species like so-called heavy metals co-precipitate together with thorium leading to an increased volume of waste of comparatively low activity. Alternatively, dissolved thorium can be precipitated e.g. by using specific sorbents or also by membrane technology, which enable to separate in a more concentrated form.

In further sequences the remaining solid tailings are again treated by other extraction reagents for dissolution of further specific hazardous constituents, as required. The composition of the tailings to be processed as well as the selectivity needed dictate type and number of sequential extraction steps.

Compared to conventional processing (only two main fractions – yellow cake and tailings) by advanced processing uranium ore is split in up to five fractions:

1. Uranium (won as yellow cake by the original process);
2. Radium (contained in long-living radioactive waste to be forwarded to responsible authorities for underground disposal);
3. Thorium (long-living radioactive waste to be forwarded to responsible authorities for underground disposal, or storage for possible future re-use as a nuclear fuel);
4. Non-radiologic hazardous constituents (conventional waste to be disposed of e.g. in hazardous waste landfills); and
5. Processed tailings (now virtually harmless, thus disposable in landfill/simplified tailings disposal facilities).

In order to increase the efficiency of the indicated disposal ways it is essential to achieve a high degree of separation between the different constituents as well as to increase the purity of resulting fractions.

Many countries need to make arrangements for underground disposal of radioactive waste anyway. No doubt that handling and disposal of radium and thorium as long-living radioactive waste will be demanding (e.g. occupational radiation protection, pressure build-up in waste containers due to generation of Rn-222 by decay of Ra-226 etc.). Radium and thorium are both α-emitters and can be high-level- (radium) or low-/intermediate-level waste (thorium), respectively. However, managing these waste types is feasible, including specific radiation protection needs, and the volumes are small compared to those of tailings.
By variation of process details generally every realization needs to contribute to specific conditions of each uranium deposit. Even if a particular technology works well for one type of tailings, there is no guarantee that it will work in the same way elsewhere due to site-specific particularities like chemical/mineralogical composition, grain size etc. Also there might be the necessity to adjust process details even during treatment, because the tailings specifics resulting from the same deposit might change with time.

3.2. Remediation of legacy tailings impoundments

For reprocessing of legacy tailings in the course of remediation, similar technology as for operational uranium milling (section 3.1) could be suitable, provided that the content of hazardous constituents is high enough to enable and justify this. However, to treat legacy tailings, these need to be brought in a workable condition first, e.g. by re-mining.

The reprocessing of existing tailings, which would lead to removal of hazardous constituents, in fact finalizes final remediation. Virtually no radionuclides or other toxic metals are available anymore in tailings treated in this way.

Similar to operational usage, also reprocessed legacy tailings are split in up to five fractions:

1. Radium (long-living radioactive waste);
2. Thorium (long-living radioactive waste);
3. Non-radioactive harmful constituents;
4. Reprocessed tailings, now virtually harmless; and
5. Optionally – this would require an additional extraction step – uranium might still be extractable (depending on former processing efficiency).

However, re-opening of legacy tailings impoundments for reprocessing of those tailings needs to be decided after very serious consideration. Under the precondition of technical feasibility (e.g. increased concentration of extractable hazardous constituents) it could be justified just, if otherwise an unacceptable risk persists. Given that, a good opportunity for reprocessing might be provided, if also other criteria suggest re-opening and relocation of tailings impoundments.

4. Overall advantages

Basically the advantages deriving from advanced processing originate from:

• Extraction and removal of hazardous constituents lead to virtually harmless tailings; and

• Isolation and concentration of hazardous constituents lead to an enormous volume reduction of radioactive / hazardous waste to be managed.

The concentration and isolation of hazardous constituents would transform tailings into a safely manageable form. The proposed advanced processing is advantageous (a) for states as well as (b) for the uranium production industry.

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6 By the mentioned BaCl₂ process together with other agents removal of radium from drainage/seepage of existing tailings impoundments is sometimes applied in the course of remediation [18]. By contrast, advanced processing does not risk actively treating long-lasting symptoms, because it already prevents from their occurrence by a preceding one-time process. Thus, it is effective much earlier.

7 For each indicated way of disposal, see above.
a. States benefit from reducing the environmental impact leading to dramatically decreased follow-up costs:

- As hazardous constituents become removed regular institutional control appears to be dispensable: even in the case of any loss of integrity of engineered tailings impoundments in the short-term or in the long-term, from a radiological point of view there is no risk of contaminant spreading (as for other removed hazardous constituents, as applicable);
- Reduced or no need for repeated and expensive maintenance of tailings impoundments in the future.

b. The private economy (uranium production industry) can benefit from advanced processing of uranium ore in the following way:

- No on-going exhalation of radon;
- Reduced or no according liability (compensation claims due to accidental tailings spreading, health risks etc.);
- Overall reduced operational management effort as well as less reclamation effort for due to their substantially reduced hazardousness of tailings;
- Tailings, which result from advanced processing, do not need to be stored in such complex constructed facilities as conventionally: therefore, reduced construction effort of tailings disposal facilities is possible.
- Less need for maintenance and monitoring of closed tailings disposal facilities due to less hazardous inventory and reduced risk; and
- Whilst advanced processing cannot prevent from accidental spreading of tailings, but should it occur, it can substantially mitigate the environmental consequences;

Moreover, with regard to the mentioned advantages, which are achieved by advanced processing of uranium ore the uranium produced by this technology:

- Might be preferred by the state (regulators); and
- Might be better accepted by the public.

The uranium deposit Kuriskova in Slovakia, which has been investigated for possible mining, could be an example for this is. Only when this mining project is approved by a local referendum would the Slovak regulator intend to issue the necessary licence [19]. Interestingly, the Canadian province Québec, following the provinces Nova Scotia and British Columbia, has decided to issue presently no permits for uranium mining, what has led to the closure of Strateco Resource’s promising Matoush prospect [20]. Recently, the government of Québec stated “how is it possible to assert that [conventional tailings disposal] technology will prove to be reliable in the longer term …?” [21]. We expect that by application of the proposed advanced processing technology it will be better possible to convince possibly concerned state and public and thus, to get licenced as well as to achieve final acceptance (“social licence”) of uranium production.

\[\text{In very selected cases, where respective objections to the potential impact persist, even advanced processing of tailings resulting from low-grade uranium ore might be considerable, though its cost-benefit ratio should be closely examined as it could, potentially, put the economic viability of a project into question. Similarly, where uranium is a by-product, a similar scenario may exist.}\]
Moreover, the advantages of advanced processing might provide companies with the potential to increase in the longer term the market demand for innovatively won uranium. Thus, to apply advanced processing could once even turn into a competitive advantage.

5. Economic implications

Estimates show that caring for sustainable safety already during the lifetime of operations in the end can become about five times cheaper than later remediation (e.g. [22]). Anyhow, it is evident that this would require initial investment into e.g. new components to complement existing processing lines or significant amounts of reagents.

To be confirmed by a cost-benefit-analysis we expect that possible higher initial costs are overall compensated by the above listed advantages. However, a sound cost-benefit analysis, which alone enables to determine a cost/throughput ratio, needs to take site-specific conditions into account, e.g. uranium ore composition and grade as well as local disposal costs. General aspects ruling the economics, which have to be considered here, are listed in Table 1.

Table 1. General aspects, which need to be considered in a site-specific cost-benefit analysis.

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<th>Advanced Processing</th>
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<td>- Conventional processing line</td>
<td>- Integrated advanced processing module</td>
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<td>- Present operational costs</td>
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<td>Disposal(^{10})</td>
<td>Present costs</td>
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<td>- Reduced construction effort for tailings disposal facilities</td>
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<td>- Reduced management effort etc.</td>
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<td>Additional costs for conditioning and disposal of extracted hazardous constituents (e.g. US $~25-50,000/m³ waste(^{11}))</td>
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<td>Maintenance</td>
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<td>Lower costs due to in-complex tailings disposal facility</td>
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<td>Monitoring</td>
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<td>Reclamation</td>
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\(^{9}\) Note that the costs for a customized advanced processing module depend from site-specific conditions.

\(^{10}\) If re-use of the extracted hazardous constituents would be possible (e.g. use of radium for medical purposes, use of thorium as nuclear fuel etc.), the total costs for advanced processing of tailings could become significantly lower as disposal costs could be minimized and extracted constituents might be sold.

\(^{11}\) Rough estimation, depends from site-specific conditions; by advanced processing of 1 Mt of tailings resulting from processing ore of 2 (20) % U over 6 (60) kg Ra and over 300 (3000) kg Th can be extracted and will have to be disposed of separately; disposal costs for extracted non-radioactive constituents are assumed to be lower (although their volume might be higher).
6. Limitations

For broad realization of the proposed advanced processing of uranium ore, where indicated it is essential to become adopted by:

- Respective regulatory requirements; as well as
- Creation of a relevant certification system.

With regard to the mentioned advantages it appears worth to establish advanced processing as a future standard in conventional uranium mining, where indicated. Necessary for broad realization of advanced processing according regulatory requirements on the national level as well as legally binding agreements (“safeguards”) on the international level, i.e. between countries producing uranium and countries having a demand for uranium, would need to come into force.

Moreover, based on correspondingly updated internationally accepted standards (e.g. IAEA Safety Standards) a certification system would need to be created for verifying implementation of advanced processing. Expert missions like those of the IAEA UPSAT tool [23] or alternative, independent audits could confirm compliance with these requirements.

7. Discussion and conclusions

Even though they were thought to offer lasting solutions, the disposal of conventional uranium tailings in above-ground tailings impoundments appears to not always be a final, walk-away solution. Such ways of disposal might prove, with time, to just delay environmental impacts rather than avoid them. If high-grade uranium ore is processed, the same necessary level of safety, which can be ensured by the proposed removal of radium and thorium, could only be achieved by integrity of conventional tailing impoundments of more than ~20,000 years.

Currently approximately half of the world uranium production today derives from conventional uranium mining and processing. Although comprising other challenges uranium production by in-situ leaching (ISL) appears to be more environmentally safe, because ISL mining avoids large surficial accumulation of tailings. On the other hand ISL mining is limited to certain specific conditions. Therefore, it can be expected that conventional mining of uranium will continue to be of significance.

There is perhaps a growing trend of putting tailings and the worst of waste rock back underground, but this is not viable or enforced everywhere, and is itself expensive. It does, however, give an established technique against which the cost of treating tailings to make them more benign can be compared. On the contrary, not all uranium milling sites have access to a pre-existing pit where tailings can be disposed of. The costs of creating a purpose-build underground disposal pit or creating additional voids at an underground mine would be considerable.

Though also factors like regulatory / public acceptance and the related market demand for innovatively produced uranium may eminently influence an economic assessment of advanced processing, it is not possible to take these easily into account financially.
Consequently, only by the development, testing and implementation of innovative technologies like advanced processing, where indicated, may it be possible to decrease the environmental footprint of uranium mining and to achieve safety also in the long-term for sites with above-ground disposal.

The financial implications of advanced processing of uranium ore can comprise both cost-increasing and cost-decreasing points, which need to be balanced. However, it can be expected that more up-front investment, rather than long-term repeated maintenance, is likely to be preferable over the lifecycle for states as well as for operators.

8. Outlook onto specific development

To develop site-specific technology for the proposed advanced processing of uranium ore the following steps should be taken:

1. Advanced conceptual study including cost-benefit analysis;
2. Laboratory experiments to determine process details, followed by;
3. Transfer of the laboratory scale into pilot scale; and
4. Adoption of the proposed approach by relevant regulations / implementation of respective certification.

While in the first step (advanced conceptual study) light has to be put on the full range of variety, in the second and third step the laboratory and pilot scale experiments have to address in each case the specifics of the examined tailings.

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This paper builds on an earlier, more general study [24].

REFERENCES

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