sustainability

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Project Report

On the Sustainability and Progress of Energy Neutral Mineral Processing

Frederik Reitsma [1,*], Peter Woods [1], Martin Fairclough [1], Yongjin Kim [1], Harikrishnan Tulsidas [2], Luis Lopez [3], Yanhua Zheng [4], Ahmed Hussein [5], Gerd Brinkmann [6], Nils Haneklaus [7], Anand Rao Kacham [8], Tumuluri Sreenivas [8], Agus Sumaryanto [9], Kurnia Trinopiawan [9], Nahhar Al Khaledi [10], Ahmad Zahari [11], Adil El Yahyaoui [12], Jamil Ahmad [13], Rolando Reyes [14], Katarzyna Kiegiel [15], Noureddine Abbes [16], Dennis Mwalongo [17] and Eduardo D. Greaves [18]

1 International Atomic Energy Agency, VIC, P.O. Box 100, 1400 Vienna, Austria; p.woods@iaea.org (P.W.); m.fairclough@iaea.org (M.F.); yo.kim@iaea.org (Y.K.)
2 United Nations Economic Commission for Europe, Geneva 1200, Switzerland; harikrishnan.tulsidas@un.org
3 National Atomic Energy Commission (CNEA), Av. del Libertador 8250, C1429BNP CABA, Argentina; lopez@cnea.gov.ar
4 Institute of Nuclear and New Energy Technology (INET), Tsinghua University, Beijing 100084, China; zhengyh@tsinghua.edu.cn
5 Nuclear Materials Authority, El-Maadi-Kattamiya Road, P.O. Box 530, Cairo 11311, Egypt; ah_mady@yahoo.com
6 BriVa Tech Consulting, Andreas Sapper Str. 15, 91334 Hemhofen, Germany; gerd.brinkmann@gmx.de
7 Institute for Reactor Safety and Reactor Technology, RWTH Aachen University, Kackertstr. 9, 52072 Aachen, Germany; nils.haneklaus@rwth-aachen.de
8 Bhabha Atomic Research Centre, AMD Complex, Begumpet, Hyderabad 500016, India; kachamanandrao@yahoo.co.uk (A.R.K.); tsreenivas@ymail.com (T.S.)
9 National Nuclear Energy Agency (BATAN), Jalan Lebak Bulus Raya No. 9, Jakarta 12440, Indonesia; aguss@batan.go.id (A.S.); kurnia.t@batan.go.id (K.T.)
10 Radiation Protection Department, P.O. Box, Sharq Al-Qadeseyah 16087, Kuwait; khaldiy@hotmail.com
11 Malaysian Nuclear Agency, Bangi, Kajang 43000, Malaysia; khairulikram@nuclearmalaysia.gov.my
12 Centre National de l'Énergie, des Sciences et des Technique Nucléaires, B.P. 1382, Route Principale, 10001 Rabat, Morocco; adilelyahyaoui@gmail.com
13 Pakistan Atomic Energy Commission, P.O. Box 734, Peshawar 25000, Pakistan; jamilahmad333@yahoo.com
14 Philippine Nuclear Research Institute, P.O. Box 213, 1101 Quezon City, Philippines; ryreyes@pnri.dost.gov.ph
15 Institute of Nuclear Chemistry and Technology, Dorodna 16, Warsaw 00-019, Poland; k.kiegiel@ichtj.waw.pl
16 Groupe Chimique Tunisien, Direction de Recherches, Gabes 6000, Tunisia; abbes.noureddine@gct.com.tn
17 Tanzania Atomic Energy Commission, P.O. Box 743, Arusha 0206, Tanzania; dennis_mwalongo@yahoo.com
18 Universidad Simon Bolivar, P.O. Box 89000, 1080A Caracas, Venezuela; egreaves20002000@yahoo.com
* Correspondence: f.reitsma@iaea.org; Tel.: +43-1-2600-22565

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Abstract: A number of primary ores such as phosphate rock, gold-, copper- and rare earth ores contain considerable amounts of accompanying uranium and other critical materials. Energy neutral mineral processing is the extraction of unconventional uranium during primary ore processing to use it, after enrichment and fuel production, to generate greenhouse gas lean energy in a nuclear reactor. Energy neutrality is reached if the energy produced from the extracted uranium is equal to or larger than the energy required for primary ore processing, uranium extraction, -conversion, -enrichment and -fuel production. This work discusses the sustainability of energy neutral mineral processing and provides an overview of the current progress of a multinational research project on that topic conducted under the umbrella of the International Atomic Energy Agency.

Keywords: energy neutral mineral processing; unconventional uranium extraction; comprehensive extraction; high temperature reactors

1. Introduction to Energy Neutral Mineral Processing

Energy neutral mineral processing is the extraction of unconventional uranium (and/or thorium) during primary ore processing for use as raw material to produce nuclear reactor fuel [1]. Energy neutrality is reached if the extracted unconventional uranium is used to generate energy equivalent to or larger than the amount of energy required for mineral processing of the primary ore and uranium extraction, -conversion, -enrichment and -fuel production. Figure 1 illustrates the very basic idea of energy neutral mineral processing.

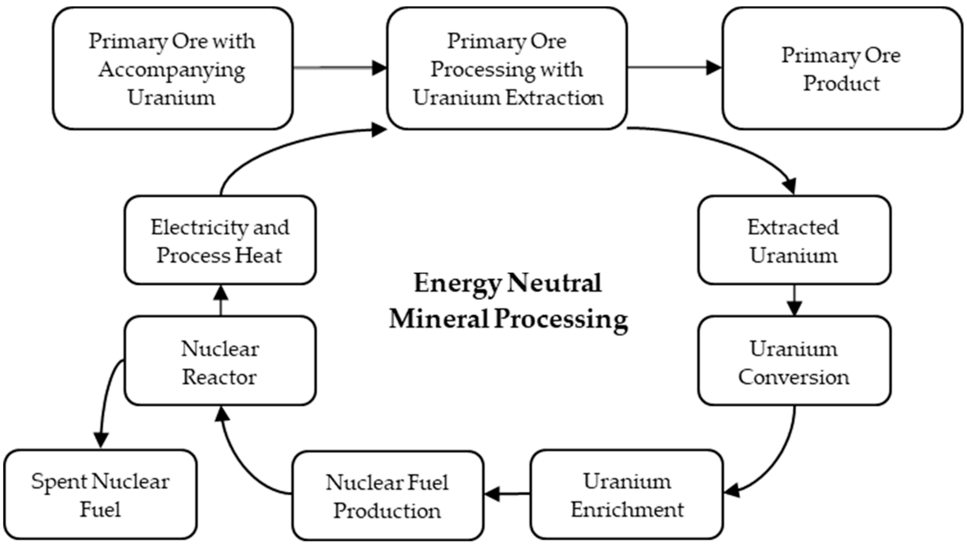


Figure 1. Brief overview of energy neutral mineral processing.

Extracted uranium, usually shipped as uranium ore concentrate (UOC), can be sent for uranium conversion/enrichment and later nuclear fuel production at a nuclear fuel manufacturer in the same way traditional uranium mines handle their product. Poly-metallic mines such as the Olympic Dam mine in Australia (copper, uranium, silver and gold mine) are already in operation today [2]. The efficiency of energy neutral mineral processing may further be enhanced if the energy source is deployed in the vicinity of the processing plant and even more so if used to directly supply process heat for energy intensive mineral ore development and/or supporting energy intensive operations such as water desalination [3–6]. Spent nuclear fuel from the energy source can be safely stored [7] or reprocessed.

2. Motivation Behind Energy Neutral Mineral Processing

Today between 8% and 10% of the world total energy consumption is dedicated to the extraction of materials that the society demands [8]. This number does not take into account metallurgical processes, transport and other mining-related activities. Ore grades worldwide are depleting rapidly while the demand for mineral commodities is constantly rising [9–13]. Processing lower grade mineral resources constitutes a general trend that is associated with often exponentially increasing energy requirements [14–17] and larger amounts of mine tailings. Environmental concerns such as greenhouse gas emissions, water and land usage, waste treatment, etc. are becoming more important in the mineral processing industry today [18–20] leading to planned or already imposed legislations regarding the use of cleaner energy sources, as well as increased responsibilities to beneficiate/process mine tailings or waste materials. The majority of mineral processing operations today are powered by burning fossil fuels. In addition to renewable energy sources nuclear power may be a viable option to provide the large amounts of electricity and process heat required for present and future mineral processing operations with a drastically reduced environmental footprint.

Available resources and raw materials, as well as demanded products made from these, will determine the mineral development processes that have to be used for ore development. The required mineral processes will determine the energy demand that will have to be covered by an available energy source. The energy source will have certain resource requirements that may partly or, in the case of energy neutral mineral processing, entirely be covered by unconventional resources from byproduct extraction. The described interdependency is illustrated in Figure 2. While thermal nuclear power plants presently use uranium fuel (and in the future possibly thorium fuel), present day renewable energy sources require relevant amounts of rare earth elements (REE) for their production [21–27]. These REEs may also be (at least partly) provided as a byproduct from primary ore processing.

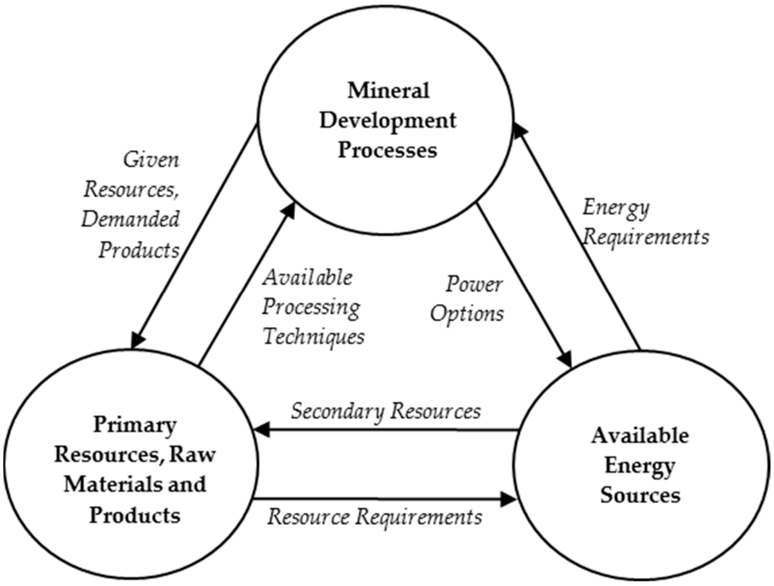


Figure 2. Interdependence of available primary resources, raw materials and demanded products (**bottom left**), required mineral development processes (**top**) and available energy sources (**bottom right**).

Besides currently deployed mineral processes that will require increasing amounts of energy to process lower grade ores, certain lower grade resources may have to be developed using alternative processing techniques. At the moment, for instance, most (>90%) phosphate rock is processed using the wet phosphoric acid (WPA) process. The WPA process cannot develop lower grade phosphate rock. Pre-concentration of phosphate rock that ranges from simple scrubbing and screening to more advanced techniques such as flotation and calcination [28–31] is required to separate impurities prior to subsequent WPA processing. In addition to more advanced pre-concentration techniques, energy intensive thermal phosphate rock processing that can process lower grade ores may have to be used. Phosphate rock is mined for its phosphorus component that is vital to global food security. The availability of higher grade phosphate rock resources that can be processed using the WPA process is part of an active scientific discussion [32–36].

Nuclear power does not directly emit greenhouse gas emissions. Greenhouse gas emissions are, however, emitted indirectly as a result of uranium mining/milling and -enrichment as well as plant construction, -operation and -decommissioning. Besides greenhouse gas emissions uranium mining and milling operations generate radiotoxic mine tailings that can pose harm to the environment [37–39].

Uranium mining/milling already accounts for a considerable share of the environmental impact of nuclear power that may further increase with decreasing uranium ore grades [40,41]. In the long term this environmental impact of nuclear energy may be reduced if fast breeder reactors are deployed [42]. In the short term this environmental impact of nuclear power can partly be reduced if uranium is extracted as a byproduct from another primary ore. Again, phosphate rock is used as an example to illustrate the environmental impact of uranium byproduct extraction vs. traditional uranium mining and milling. Uranium byproduct extraction from merchant grade phosphoric acid, an intermediate product during WPA processing, has been practiced on an industrial scale in the past [43–46] and is at the edge of being profitable again today [47–49]. Phosphate rocks contain considerable amounts of accompanying uranium in quantity and concentration [50–54]. Figure 3 briefly compares uranium mining and milling (top) to uranium extraction from wet phosphoric acid (bottom). Extracted UOC is further transported to a facility for fuel conversion and subsequent uranium enrichment. Enriched uranium is used for nuclear reactor fuel production. It is anticipated that uranium ore is only mined for its uranium content so that the full environmental impact (red box Figure 3) needs to be taken into account. Since phosphate rock is mined, crushed/ground and digested for its phosphorus content anyway only the environmental impact for additional byproduct uranium extraction (green box Figure 3) has to be considered in a direct comparison.

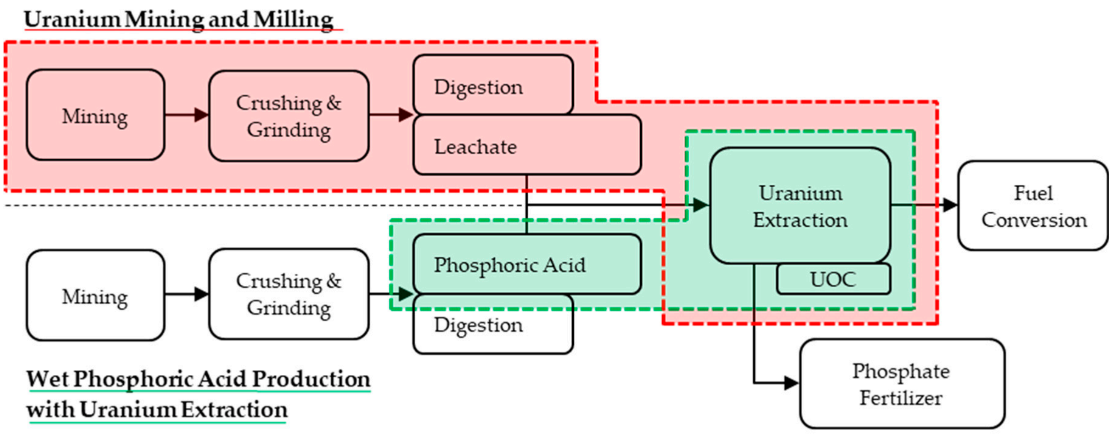


Figure 3. Traditional uranium mining (**top**) in comparison with uranium extraction from wet phosphoric acid (WPA) (**bottom**).

In the case of phosphate rock, uranium extraction may be particularly desirable as radiotoxic uranium which is not extracted primarily (80–90%) transfers to the final fertilizer product [55] which is brought out onto agricultural soils [56,57]. Guidelines of the International Atomic Energy Agency (IAEA) for unconventional uranium extraction are in place and if applied correctly ensure that unconventional byproduct uranium extraction does not result in an additional risk regarding nuclear proliferation [58].

3. Mineral Processes Currently Considered

A number of ores show relevant amounts of accompanying uranium and could therefore be considered for energy neutral mineral processing. In the IAEA coordinated research project discussed here [59,60] more than a dozen different countries are participating and studying a variety of ores, determining the content of uranium and thorium, and testing different extraction processes. In Table 1 some detail is provided such as the list of IAEA member states presently participating in the study, the ores or other material forms being studied and some of the techniques and equipment used to study the ores and to evaluate its composition and uranium content. The list does not include all possible ores with potential for unconventional uranium extraction and is by no means complete but aims to indicate where the initial work in this project was undertaken. In the sub-sections below some of these ores and processes are further discussed.

Table 1. Details of the research project participation and areas of study.

Countries Participating	Ores and Other Forms Considered in the Study	Techniques and Equipment Used
Argentina, China, Egypt, Germany, India, Indonesia, Kuwait, Malaysia, Mexico, Morocco, Philippines, Poland, Tanzania, Tunisia, Venezuela	Carbonates, Columbite-Tantalite, Copper Tailings, Ilmenite, Monazite, Oil Sludge, Phosphate Rock, Phosphogypsum, Phosphoric Acid, Red Mud (Cerro Impacto Laterite), Tin Slag, Xenotime	Alpha Spectroscopy, Atomic Absorption, Electronic Microscope, Field Emission Scanning Electron Microscope, Gamma Spectroscopy, Gas Chromatography, Inductive Coupled Plasma—Optical Emission Spectroscopy, Inductive Coupled Plasma—Mass Spectroscopy, Ion Chromatography, Petrological Microscope, Pyrometallurgy Reduction, Nuclear Activation Analysis, X-ray Fluorescence

3.1. Phosphate Rock

Phosphate rock is mined for its phosphorous content used for fertilizer production. Phosphate rock contains considerable amounts of uranium and REEs [52,61]. Phosphate rock can be developed using the wet-acid or the thermal route. At the moment, most (>90%) phosphate rock is processed using the wet-acid route (WPA process) while back in the 1950s, phosphate rock was developed to equal quantities using the wet-acid and thermal route in the U.S., the largest phosphate rock producer at that time. Uranium extraction from WPA is a well-known process and was practiced on an industrial scale in the 1980s–1990s until it became unprofitable due to decreasing uranium prices. With the chance of increasing uranium prices, uranium extraction from WPA is once again a very active field of research and new molecules and improved extraction techniques are being developed that may rival traditional open-pit and underground uranium mining as well as in situ leach operations in the near future. During WPA production nuclear process heat from a high temperature reactor (HTR) may best be used for energy intensive calcination prior to the digestion process [62] or providing energy for thermal phosphate rock processing [63–65]. At present, approximately 10% of all phosphate rock processed using the wet-acid route is calcined to drive off undesired impurities, notably carbonates and organic matter. Figure 4 illustrates the very basic flow sheet of wet-acid phosphate rock processing with calcination and uranium extraction currently investigated as part of the research project.

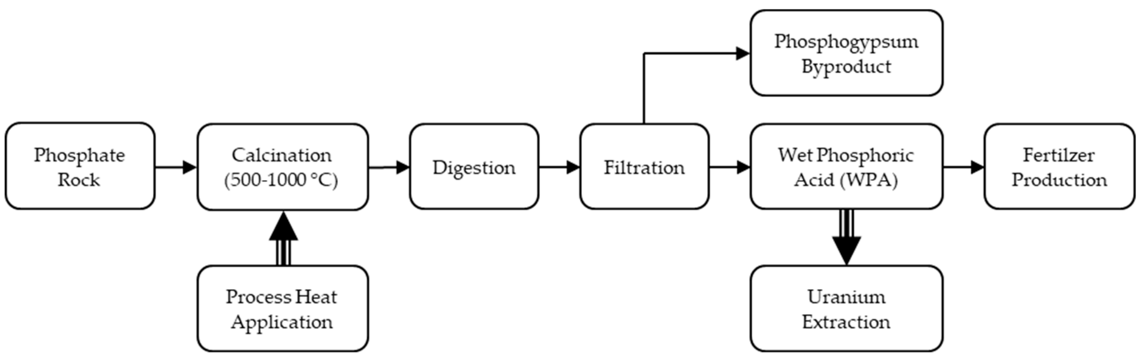


Figure 4. Uranium extraction during wet-phosphoric acid (WPA) production with calcination using process heat.

If calcination is used as a means of beneficiating phosphate rock prior to the digestion process, a cleaner ("light-green") WPA is produced. Based on lab-scale experiments it is believed that uranium extraction from "light-green" WPA is considerably cheaper than uranium extraction from "merchant-grade" WPA produced using flotation as a means of beneficiation. However, this does not consider the costs for energy intensive phosphate rock calcination.

In addition to using HTRs to provide process heat for phosphate rock calcination concentrated solar power (CSP) is considered for this purpose in the research project. CSP has already been considered for calcination of limestone and solar calcination experiments were successfully conducted by Flamant et al. [66,67], Licht et al. [68], Meier et al. [69–72], as well as Salman and Kraishi [73]. Conveniently, the largest phosphate rock reserves are found in Northern Africa and the Middle East [74,75] where solar radiation is good to excellent. It was found that in the future phosphate rock calcination with both CSP and HTR may become economically competitive [76]. In addition to phosphate rock this research project is actively looking into processing byproduct phosphogypsum [77]. The WPA process generates some 5 tons of phosphogypsum per ton of phosphoric acid produced [55,78]. Phosphogypsum contains naturally occurring ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K [79] and is presently stored indefinitely at most locations because of the resulting weak radioactivity.

3.2. Rare Earth Element Ore

REE ores are usually leached using sulfuric-, hydrochloric- or nitric acid. Most minerals containing REEs are either phosphates (monazite and xenotime) or fluoro-carbonates (bastnaesite). To increase the solubility, low-temperature (<300 °C) or high-temperature (>300 °C) acid roasting is used prior to water leaching. The general acid roasting process for bastnaesite and monazite is provided in Figure 5 [80–82]. Uranium, thorium and REEs can be extracted from the leachate after several additional treatments [83,84].

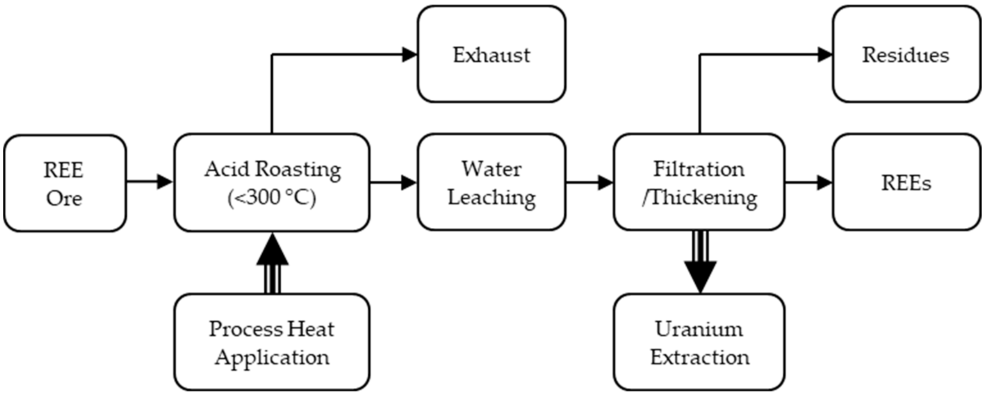


Figure 5. General high-temperature roasting and leaching process for bastnaesite and monazite.

HTRs and CSP are foreseen as greenhouse gas lean energy sources to provide process heat and/or electricity for acid roasting. If relevant uranium concentrations are found in the ore, uranium may be extracted as part of the process.

Other, rather unconventional, REE ores are laterites that result from the leaching and weathering of certain rock formations leading to the concentration of elements and resulting in interesting deposits that may contain thorium, REE and other valuable metals. Such is the case of the Cerro Impacto mineral deposit in Venezuela [85–87] that is investigated as part of this research project. It was found that the material is amenable to sulfuric acid leaching followed by solvent extraction for the recovery of niobium thorium and REE [88]. The process does however lead to highly contaminating acid effluents incompatible with the deep forest environment of its location. The use of a high temperature pyrometallurgical reduction process [89] has shown promise for a less contaminant procedure on a lab scale. With appropriate reductant and high temperature conditions, achieved with HTR process heat and electricity, reduction to a metallic phase containing the iron, niobium, vanadium and nickel may be feasible.

3.3. Copper Ore

Copper is one of the four most used metals in society and demand is expected to further increase [16]. Two main routes of primary copper production: pyrometallurgical and hydrometallurgical can be differentiated. The pyrometallurgical route accounts for some 80% of the world's primary copper production. Copper sulphide mineral deposits that can show relevant quantities of byproduct uranium are processed using the pyromtellurgical route. Byproduct uranium was economically successfully recovered at the Parabola mine in South Africa [90] and is economically successfully mined at the Olympic Dam mine in Australia [2,91]. Figure 6 provides a brief overview of pyrometallurgical copper production with uranium recovery. Furthermore, uranium can be recovered from copper mine tailings as for instance discussed by Chmielewski et al. [92].

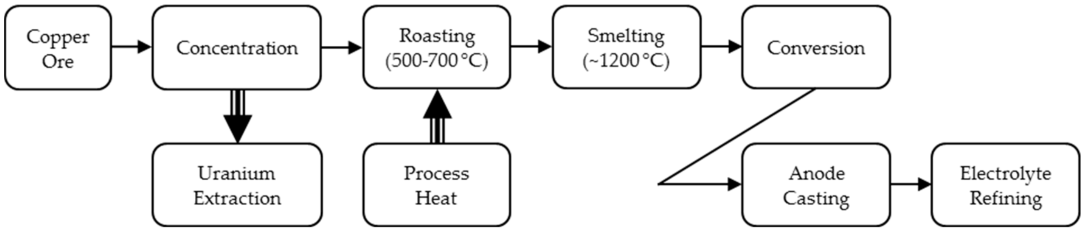


Figure 6. Pyrometallurgical copper ore processing with uranium recovery.

Copper production, especially pyrometallurgical copper production, is an energy intensive process [93,94]. HTRs do not reach the high temperatures required to deliver process heat for the smelting step. They may, however, be used to provide process heat for the roasting of the copper concentrate. In addition, HTRs could provide electricity for the production of pure copper and distilled water (through desalination of seawater [95]) of which plenty is used during the whole ore development process [96,97]. In addition to HTRs, CSP may again be a viable alternative in areas with high solar irradiation. This may be the case for Chile, the largest copper producing country in the world [98].

3.4. Tin Slag

The smelting process in tin production generates slag which contains radioactive elements such as uranium and thorium. Therefore tin slag often has to be categorized as technologically enhanced naturally occurring radioactive material (TENORM). Valuable elements such as REEs, niobium-tantalum, zirconium and titanium are contained in tin slag. The radioactive elements should be removed prior to extraction of those valuable elements. Some studies of tin slag characterization show the existence of an amorphous silica structure and resulting poor performance in direct leaching [99,100]. Pre-treatment of tin slag is required to increase the effectiveness of acid leaching. The silica structure can be broken by reaction with sodium hydroxide at high temperature (alkali fusion). As a result, silica is converted into a water-soluble form that can be dissolved in a subsequent water leaching step. In the next stage, direct leaching using sulfuric acid can dissolve uranium and thorium, while REEs stay in the solid phase [101]. Figure 7 provides a brief overview of the tin slag processing with uranium and thorium extraction that is presently investigated as part of the research project.

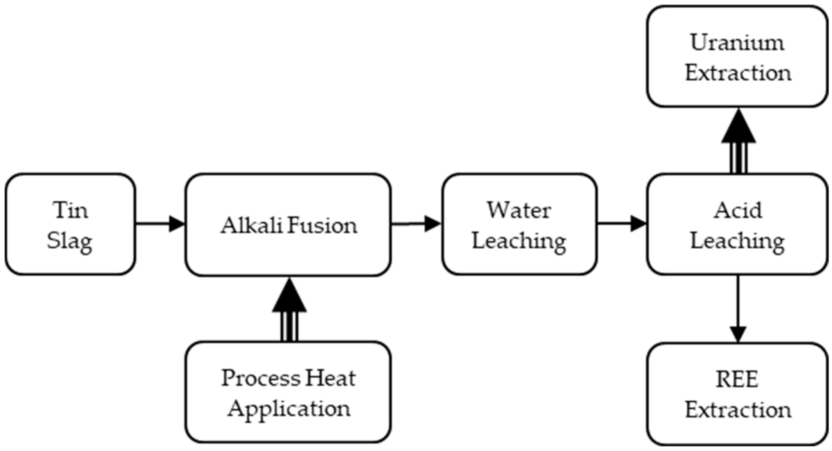
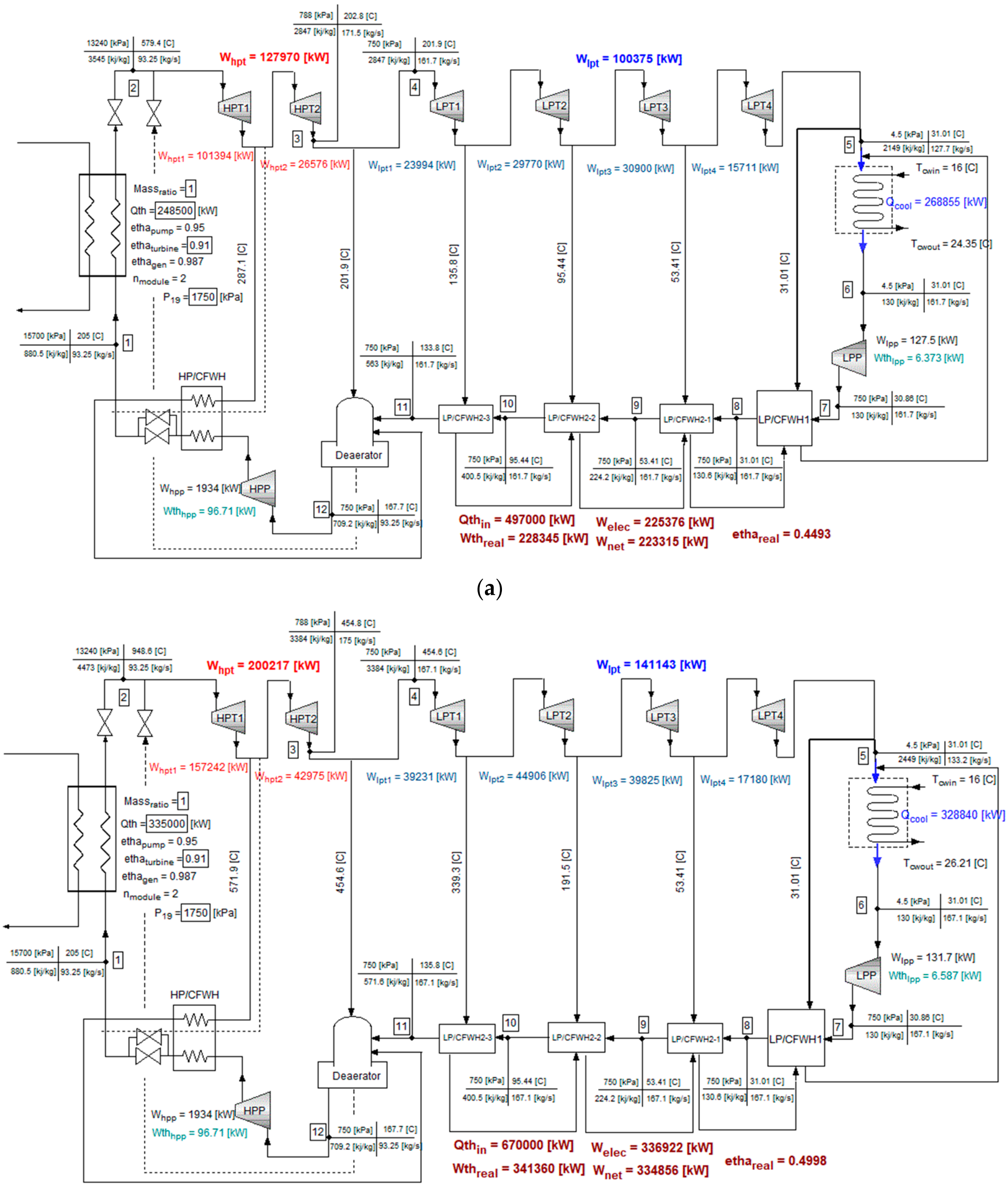


Figure 7. Tin slag processing with uranium and thorium recovery.

4. Modeling of the Coupled System

As part of the research project modeling of the coupled system consisting of HTRs and mineral processing plants is performed at IAEA. For now, hypothetical high temperature gas-cooled reactor (HTGR) steam cycle models are considered. These models can be extended to include intermediate heat exchangers (for higher temperature applications). Furthermore, simplified models can be used if only low temperature (waste heat recovery) is required. Details on the energy and heat requirements for mineral processing (temperatures, transport medium, availability, etc.) are derived for the different ores and processes. The HTGR models are designed based on the HTR-PM (high-temperature gas-cooled reactor pebble-bed module) demonstation plant that is presently constructed in China [102]. Since the thermal input required for mineral processing differs for each ore, the properties and systems are amended constantly. Currently, the model focuses on the Rankine cycle. Figure 8 shows two cases: the first case (top) is for 580 °C steam right after passing through the steam generator and the second case (bottom) is for 950 °C. One bleed stream from the high pressure turbine, three bleed streams from the low pressure turbine and one bleed stream from the deaerator between the high pressure turbine and low pressure turbine are considered. For each bleed stream a closed feed water heater is implemented. Besides, one more closed feed water heater is included for waste steam. The temperature of the cooling water of the condenser is designed to be 16 °C. The energy provided by the pumps is designed to be added at static pressure depending on efficiency while the rest is added at enthalpy value. The whole calculation is performed assuming that there are no heat and pressure losses. Due to this assumption, the thermal efficiency is slightly overestimated.

The models determine the total electrical output of the reactor as a result of non-electrical, high temperature heat applications for mineral processing. The models are used to evaluate the technical feasibility of coupling HTGRs to different mineral processing applications.



(**a**)

(**b**)

Figure 8. Hypothetical high temperature gas-cooled reactor (HTGR) models for the research project. (**a**) 580 °C steam cycle model; (**b**) 950 °C high-temperature model.

5. Identified Challenges

Small modular reactors, nuclear reactors with power levels less than or equal to 300 MWe, receive increased attention from numerous countries around the world. These small reactors are believed to fill a gap in the energy market as they may be constructed in a short time, can work on less developed energy grids and do not require the considerable upfront capital costs associated with currently operated large NPPs (nuclear power plants) that make purchasing them economically challenging for most countries [103–116]. Small modular reactors caused a similar euphoria in the 1960s and again in the 1980s that did not materialize due to the smaller reactors overall less favorable economic performance when compared to large (>1000 MWe) nuclear power plants (NPPs) [117,118] or other energy generating technology. Present-day small modular reactor developers need to prove that their product can be built, operated and decommissioned economically in today's energy market to be accepted.

If small modular reactors are going to be built on a large scale, safe operation of these reactors is paramount. Most small modular reactors have technical features that make them different from currently deployed large (>1000 MWe) commercial light water reactors. Licensing small modular light water reactors with new features, such as passive cooling, is challenging and in most countries associated with increased costs for the licensing procedure and uncertainties regarding the outcome of the licensing process [119,120]. NuScale's present attempts to license their small modular reactor design in the U.S. may be a good example of this [121,122]. Licensing small modular reactors that are not only different in power level but show fundamental differences to currently deployed light water reactors such as a different coolant or moderator creates additional uncertainties for the licensor and thus increase the risk of the applicant to provide additional information, that results in increased costs for the overall licensing procedure [123–128]. Ramana et al. [129] provide an overview of the present status of licensing small modular reactors globally. Discussed are countries that already have a nuclear infrastructure in place and operate or operated commercial light water NPPs. Countries that cannot profit from this experience need to gain it so that the licensing process is further prolonged. Challenges associated with building an infrastructure to license small modular reactors are for instance discussed for Jordan [130].

In the case of energy neutral mineral processing, though it may be realized, HTGRs could be the first choice over other emerging HTR technology [131–133], such as the compact high temperature reactor (CHTR) [134,135], fluoride salt-cooled, high-temperature reactor (FHR) [136–139], gas-cooled fast reactor (GFR) [140–142], lead-cooled fast reactor (LFR) [143–145], molten salt reactor (MSR) [146] and others that may deliver process heat at temperatures higher than or equal to 600 °C. Five countries: Great Britain, the U.S., Germany, Japan and China have experience with operating and thus licensing HTGRs. An overview of past HTGR plants and projects is provided in Figure 9. The Republic of South Africa is included since considerable knowledge was gained as part of the PBMR (Pebble Bed Modular Reactor) project. However, the project did not result in actually building and operating an HTGR.

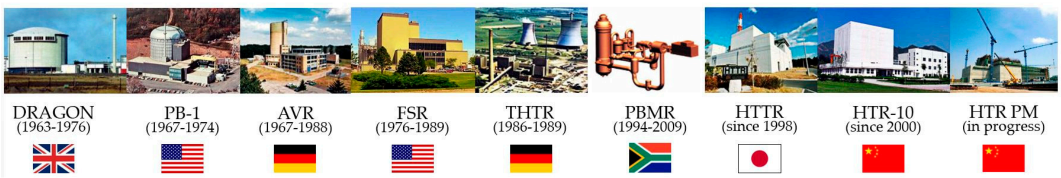


Figure 9. Past and present high temperature gas-cooled reactor (HTGR) plants/projects by country.

The UK operated the first HTGR research reactor called DRAGON from 1963 to 1976 [147]. The UK heavily relied on gas-cooled commercial reactors (other than HTGRs) in the past so that licensing HTGR plants may be less of a stretch for the UK licensing body than it could be in other countries that primarily relied on light water reactor technology. The U.S. and Germany are the only countries that operated research- (PB-1 and AVR) as well as prototype (FSR and THTR) HTGRs with China soon to join this group once the prototype HTR-PM has been constructed and is operational. Besides the HTR PM prototype reactor currently under construction in Shandong Province [102], China plans to build additional commercial HTGRs in the near future [148]. From a regulatory point of view, licensing a prototype reactor is somewhat different to licensing a research reactor. Research reactors are operated at research institutions or areas controlled by the military and are therefore (in most cases) easier to license than larger prototype reactors built primarily for power production. Besides, research reactors are usually much smaller and show greatly increased safety margins since economics are less of an issue and they are not built for power production [149,150].

Licensing HTGRs for process heat application is yet another challenge as the interconnection with the process heat receiving chemical plant needs to be taken into account. This may be particularly challenging in the case of hydrogen production [151–154]. The first experience on this was gained in Germany with the THTR that did not provide process heat but was erected in an industrial complex to learn about potential challenges for future HTGR process heat licensing procedures.

Countries that did not operate HTGRs in the past but operate large nuclear plants (Mexico, Brazil, South Africa, Russia, and India) may profit from this knowledge. Ideas for turnkey modular reactors, where maintenance, fuel supply and disposal is taken care of by the vendor/operator may also be an option in the future given the modular nature of past and present HTGRs. This may allow the deployment of HTGRs in newcomer countries that could profit from energy neutral mineral processing in the very far future.

6. Conclusions

Decreasing ore grades that result in much larger energy requirements for processing these ores as well as increasing public awareness regarding the way this energy is produced creates global interest in energy neutral mineral processing as a more sustainable way to power mineral development. At present, more than a dozen member states of the International Atomic Energy Agency (IAEA) investigate forms of energy neutral mineral processing. This work aims to provide a brief overview of the latest developments of these investigations. At present, the most prominently investigated ores are phosphate rock, rare earth element (REE) ores, copper ore and tin slag. High temperature gas-cooled reactors (HTGRs) such as the HTR-PM currently constructed in China and concentrated solar power (CSP) plants such as the Gemasolar plant operating in Spain are foreseen as greenhouse gas lean energy sources. Besides technical challenges, regulatory burdens have been identified as the largest challenge for energy neutral mineral processing.

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