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High Temperature Reactors for a proposed IAEA Coordinated Research Project on Energy Neutral Mineral Development Processes

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Abstract – *The International Atomic Energy Agency (IAEA) is promoting a new Coordinated Research Project (CRP) to elaborate on the applicability and potential of using High Temperature Reactors (HTRs) to provide process heat and/or electricity to power energy intensive mineral development processes. The CRP aims to provide a platform for cooperation between HTR-developers and mineral development processing experts. Energy intensive mineral development processes with (e.g. phosphate-, gold-, copper-, rare earth ores) or without (e.g. titanium-, aluminum ore) the possibility to recover accompanying uranium and/or thorium that could be developed and used to run the HTR for "energy neutral" processing of the primary ore shall be discussed according to the participants needs. This paper specifically focuses on the aspects that need to be addressed by HTR-designers and developers. First requirements that should be fulfilled by the HTR-designs are highlighted together with the desired outcomes of the research project.*

I. INTRODUCTION

Mineral development processes of various ores are associated with large consumption of energy to provide process heat and/or electricity. The amount of energy for processing a certain ore is to a large extent dependent on the concentration of the resource that is extracted [1]. With rising (partly exponentially) demands for mineral commodities worldwide [2] high-grade, easily extractable resources will be depleted rapidly. This trend will shift the global production to low-grade and/or currently perceived "unconventional" deposits whose extraction is presently constrained by the availability of large amounts of energy and costs.

In contrast energy- and environmental related issues (e.g. CO_2-emissions, water and land usage, waste treatment, etc.) are becoming more important in the mineral processing industry resulting in planned or already imposed legislations regarding the use of cleaner energy sources as well as increased responsibilities to beneficiate/process raw materials and recover impurities from final products [3]. Furthermore, increased political pressure to beneficiate and add value to raw materials before export, such as the recent regulation in Indonesia [4] to define minimum standards of processing and refining before minerals can be exported also incentivizes mines and industry in many countries to study new and innovative ways to do mineral processing. Uranium and thorium are present in considerable concentrations in some ores (e.g. phosphate-, gold-, copper- and rare earth ores).

The Nuclear Fuel Cycle and Materials Section (NEFW) and the Nuclear Power Technology Development Section (NPTDS) of the International Atomic Energy Agency (IAEA) is promoting the idea to use High Temperature Reactors (HTRs) to provide process heat and/or electricity for mineral development processes whilst recovering and using the accompanying uranium/thorium as nuclear reactor fuel for the HTR employed and/or other Nuclear Power Plants (NPPs) [5]. Preliminary estimates made regarding the mass- and energy balance using an exemplary phosphate fertilizer plant in North America and a High Temperature Gas-cooled Reactor (HTGR) as a representative HTR, indicate that “energy neutral” phosphate fertilizer production is technically feasible. It might also yield promising advantages as far as a smaller environmental impact is expected compared to today’s popular wet acid processing techniques [5]. However, further investigations (including experiments and detailed modeling of mass- and energy flows) will have to be conducted to establish if mineral processing using HTRs is technically and economically feasible.

A first approach in this direction is a new IAEA Coordinated Research Project (CRP): “Uranium – Thorium fuelled HTGR applications for energy neutral sustainable comprehensive extraction and mineral product development” – Code: T11006 jointly organized by NEFW and NPTDS within the framework of the IAEA [6, 7]. Fig. 1 presents an overview of the planned scope of the CRP.

In addition to phosphate ore processing with uranium recovery using HTGRs that was studied in [5], the CRP will conduct research and techno-economic feasibility studies on combinations of the following aspects: (1) the use of unconventional uranium (and thorium) resources as future nuclear reactor fuel; (2) the use of thermal processing to extract minerals and by-products in mining and mineral development processes and (3) the study of the environmental impact of these two processes. The two processes will be studied individually and combined while utilizing HTRs as the energy source and aspects such as the use/yield of resources, the amount and form of residues and the emissions are included under the environmental impact study. Due to the temperature requirements, it is expected that only HTRs (e.g. HTGRs or others as indicated in Fig. 1) will be studied as options to produce the electricity and/or process heat source. Finally, the possibility of “energy neutral” value addition in mineral development projects as well as licensing of such a coupled (conventional mineral development processing plant and HTR) will be evaluated.

II. REQUIREMENTS FOR HIGH TEMPERATURE REACTOR DESIGNS

Various studies have been performed to investigate the non-electrical applications of HTRs. These include, amongst others, district heating, water desalination and process heat applications. Whereas lower temperature steam (100-130 ˚C), typically “waste heat”, can be used for district heating and desalination, a wide range of higher temperatures (200-1600 ˚C) are required for process heat applications [8].

In the case of HTGRs the potential to participate in the larger energy market (not only electricity) has

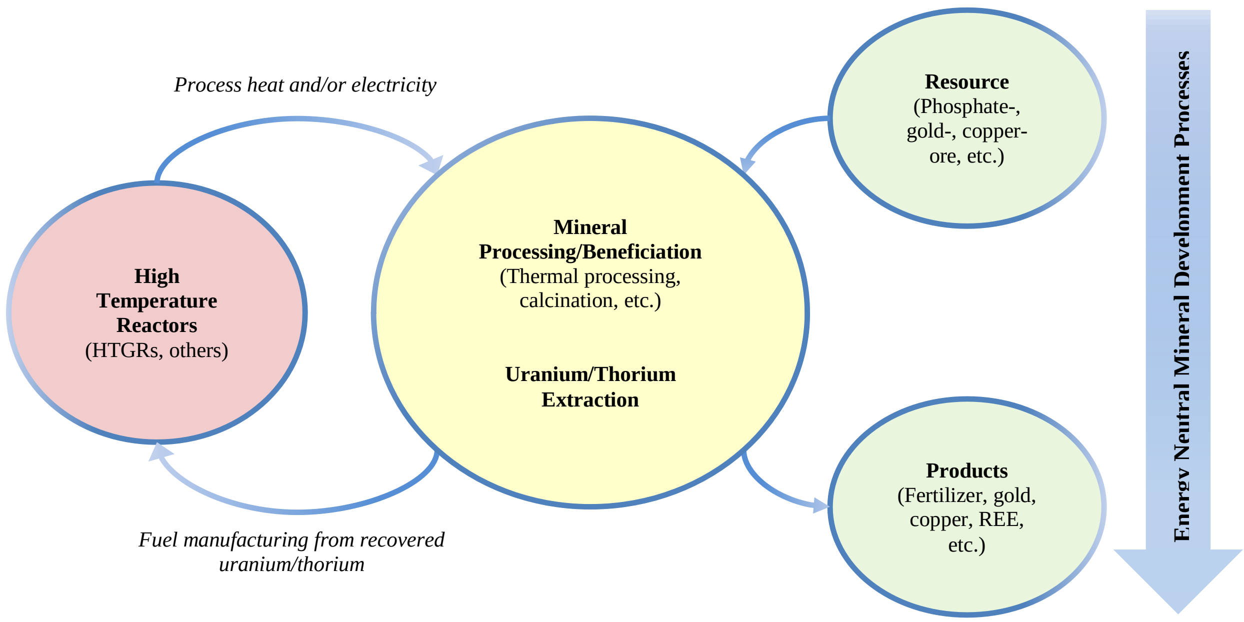

Fig. 1: Scope of the coordinated research project

been recognized for a long time with concept designs like the German PR-500 [9] made in 1973 for steam-reforming, etc. Many other projects, like the experimental HTTR (High Temperature Engineering Test Reactor) in Japan, support hydrogen production research [9]. Other recent studies on the potential of process heat and/or co-generation have been performed within the European Union (EUROPAIRS) [10] and the USA (NGNP project) [11] and it is also pursued in other member states.

The scope of past- and present research concerning process heat applications using HTRs focused and focusses to a large extend on various industrial heat/steam applications (e.g. hydrogen production, coal gasification, etc.). The CRP presented here aims to investigate whether mineral development processes could be added to the list of process heat applications that can be performed satisfactorily using a HTR as the power source.

Developers of different HTR-designs are encouraged to participate in the CRP. The IAEA aims to provide a platform where mineral development process experts and HTR-developers may connect and discuss mutual interests. Although first estimates were performed using an HTGR [5] the IAEA in accordance with its statute [12] supports a technology-neutral (i.e. independent of reactor technology) approach that will consider different HTR-technologies and different HTR-designs. Since the idea is to use reactors for co-generation (electricity and process heat source) many reactor technologies that do not reach the required reactor outlet temperatures (see II.A.) are not considered.

Core designers and developers of both fast- and thermal HTRs are welcome to apply for participation in the CRP.

The main objective of the CRP is to study whether or not certain mineral processes can be driven by suitable HTR-designs. A first summary of requirements on HTR-designs is listed below in no particular order. The determination of the detailed end-user requirements to be met by the proposed HTR-designs is one of the major objectives of the CRP and cannot be totally foreseen at this point of time. However, the first requirements given below provide guidance on expected requirements relevant to the CRP.

II.A. Power Requirements

HTRs considered in the CRP shall be used to supply process heat and/or electricity for mineral development processes. In a first step the power demand (including load variations) of different mineral development processes that shall be considered in the CRP will be assessed. This assessment will include the amount of electricity and/or process heat (including steam) that is required for certain mineral development processes. In case of process heat applications the type of carrier as well as its technical characteristics (e.g. average and maximum -temperature, -pressure, -flow rate) will be determined. In addition, the costs for the carrier will be measured to support economic studies whether or not certain heat applications are economically feasible.

Since heat- and electricity shall be available for mineral processing, the HTR-designs should consider cogeneration (combined heat and electricity production) with a minimal reactor outlet temperature set at 600 ˚C (for now). This lower-temperature limit might not be sufficient to completely power all mineral development processes but can in any case reduce the overall amount of energy needed from other power sources [13]. The specific temperature requirements for selected mineral development processes will be part of the outcome of the CRP. The given temperature minimum is based on previous studies [14] that have given a similar lower-limit temperature for a variety of industrial processes.

HTRs will most likely be considered as a multipurpose reactor or “hybrid HTR system” [15] covering most or even all energy demands of a mineral processing plant. Fig. 2 illustrates an HTR (HTGR, 2 loop design) for multipurpose energy production.

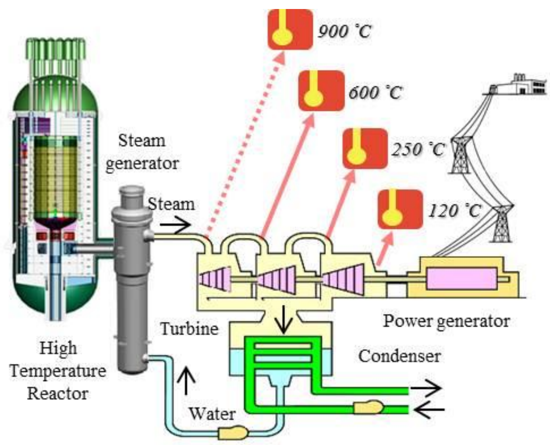

Fig. 2: Illustration of the expected cogeneration capabilities of HTRs

Multipurpose reactors might be favorable for mineral development processing since processing plants are often operated far from the electricity grid and other supporting infrastructure. Energy may therefore also be needed for other processes supporting mineral processing such as water desalination. Due to environmental concerns or other reasons (e.g. water scarcity) plant-operators are often through legislation required to provide the processing plants water needs independently and not from naturally occurring reservoirs or public water supply [16].

The multipurpose energy production assumes that the HTR-system must be able to switch between process heat and electricity production according to the needs of the processing plant. Therefore, the extend, frequency and feedback effects of dynamic switching between process heat production for different applications and electricity generation should be incorporated as design requirements by the HTR-developers.

Further power requirements that are to be assessed as part of the CRP are related to the availability and reliability of power. Mineral development processes such as phosphate rock processing usually operate "24 hours per day, 365 days per year" [17]. In addition, these processes are sensitive to discontinuation in power supply as even short interruptions can cause considerable production losses. This aspect, and plant locations that may be far from the established electricity grid, may lead to requirements of grid-independent power backup to support a large number of mineral processes. Using a HTR as power supply should not introduce additional risks to the mineral development plant operators. Therefore, HTR-developers should consider providing solutions for redundant power- and heat supply. Both nuclear (e.g. additional reactor modules) and/or conventional (e.g. fossil fuel-fired boilers) solutions can be investigated as for instance done in [18] towards their technical and economic feasibility as part of the CRP. Specific requirements for the availability of process heat may also place specific requirements on the size and number of HTRs to allow for maintenance and refueling.

II.B. Fuel Requirements

The CRP aims to examine the recovery of uranium and thorium during mineral development processes so that it can be further processed and used as nuclear reactor fuel. The recovered uranium/thorium shall be considered as supply from so-called unconventional resources and therefore further reduce the environmental impact and extend the lifetime of the nuclear reactor fleet. It may be used in commercial power reactors (light water reactors or others) and/or the HTRs used for the mineral development processing to enable "energy neutral" mineral development processing. Accordingly HTR-designs presented in the CRP should, if applicable, consider both uranium and thorium as viable raw materials for their nuclear reactor fuel. During "energy neutral" mineral development processing HTR-fuel will most likely be enriched and manufactured at established enrichment- and fuel manufacturing plants [5]. Therefore, HTR-fuel manufacturing with the focus on basic resource requirements and high level fuel cycle studies will be the only part of HTR-fuel manufacturing of relevance to the CRP.

II.C. Site Requirements

Mineral processing plants have limitations regarding the location of their plant that are mainly determined by the feedstock of raw materials and transportation of the final product to the customer. Some mineral processing plants, especially those processing low-grade feed material, are found close to remote mining locations. Therefore, these plants have their own grid-independent energy supply. HTR-designs presented in the CRP should be able to operate independently from an electricity grid without compromising safe operation. In addition to energy supply, accessibility of large amounts of water for cooling of the HTR in potential locations desirable for mineral development processing plants will be assessed. Most mineral development processing plants are located close to waterways (rivers, seas, etc.) to allow transportation of their products [17] or the raw materials used for processing [19]. However, exceptions are found were large ore processing plants are located in arid regions far away from waterways that (e.g. Olympic Dam, South Australia [20]). The presence of water bodies nearby could provide large amounts of cooling water for a reactor

Some mineral processing plants receive their raw materials from deposits that are far away from their location (e.g. Redwater phosphate rock processing plant in Canada receiving phosphate rock from North Africa [19]) so that they can be operated independently from mining operations. Other mineral processing plants are located close to the mining site (e.g. Olympic Dam, South Australia [20]). In order to better understand how the mineral development plant and the HTR(s) at one location may function economically the potential lifetime of both plants will be determined and used as input for the techno-economic studies.

Furthermore, it should be noted that remote mineral processing locations might not be easily accessible so that transporting large reactor plant equipment might be challenging for these sites.

II.D. Safety Requirements

HTRs coupled to sensitive mineral processing plants such as phosphate fertilizer plants with integrated ammonia (derived from hydrogen) production (so called "mixed fertilizer plants" [21]) might raise safety concerns. The CRP will elaborate on possible mutual influences regarding safety between relevant mineral development processing plants and the employed HTR. This first evaluation will build on previous assessments (e.g. [22, 23]) that for instance discussed different coupling options resulting in different distances between the HTR and the commercial plant. These first safety consideration will be carried out to consider possible challenges for licensing such a coupled (conventional mineral development processing plant and HTR) plant.

Furthermore, it shall be ensured that safety is addressed in all stages of operation considering grid-independent energy supply, limited availability of large amounts of cooling water, etc.

II.E. Product Requirements other than Power

In addition to the power requirements listed before certain mineral development processes may have certain requirements associated with for instance the quality of their final product that might need further attention from HTR-developers. The amount of radionuclides in a final product can be a first example for an additional requirement other than power.

Tritium and other radionuclides build up in the coolant loops of a nuclear reactor as a result of the performed nuclear chain reaction [24, 25]. Their occurrence and possible legal limits in the final product will be discussed between HTR-developers and mineral development processing experts.

III. DESIRED OUTCOME OF THE COORDINATED RESEARCH PROJECT

Generally the CRP aims to investigate in detail whether (“energy neutral”) mineral processing using HTRs is technically and economically feasible. To do so IAEA will facilitate technical interaction between mineral development processing experts and HTR-developers and coordinate their joint research efforts. Specific case studies where both groups can study the same integrated system are encouraged. The case studies will take place under the umbrella of the IAEA CRP. They should take all mentioned requirements into account and may model the specific mass- and energy flow between the regarded coupled systems to present side specific examples where HTRs might or might not be a feasible power option.

By the end of the four year project the studies will be published in an IAEA technical document. The document will provide information and guidance to IAEA member states interested in the technology and may illustrate technical- and economical-possibilities as well as limits of using HTRs for (“energy neutral”) mineral development processing.

Furthermore, additional investigations that are not necessarily related to the specific case studies are also welcomed in the CRP.

It is assumed member states may contribute to selected areas of the CRP research scope due to non-availability of expertise in all the technical areas. This is to be expected in a multi-disciplinary CRP where different expertise, typically not to be found in one organization, is required.

Licensing such a coupled plant (conventional mineral development processing plant and HTR) which may also be useful for other HTR-heat applications

Investigations regarding innovative processing techniques that are presently not considered for economical or other reasons (e.g. limited availability of power at certain remote locations) but might become feasible if a HTR is employed (e.g. thermal processing of low-grade phosphate rock [26])

Investigations regarding innovative processing techniques concerning tailings/waste that is associated with the present and/or future processing techniques and could find new usage as a raw material for different applications (e.g. sulfuric acid production from phosphogypsum, which being an exothermic process can provide backup heat to the system).

Findings of the additional investigations may be recognized in the IAEA technical document of the CRP or elsewhere.

V. CONCLUSIONS

This paper specifically addresses the research to be performed by HTR-designers and -developers in the upcoming IAEA-CRP on “energy neutral” mineral development processes. A first set of requirements for HTR-designs that will be further developed within the CRP as well as the desired outcomes of the CRP are presented and briefly explained. Although requirements for HTR-designs are based on the end-user needs that will be finalized as part of the CRP this paper may provide guidance and a first overview about the planned scope of the new project on mineral development processing. The paper is intended to encourage HTR-designers and -developers to apply for participation in the CRP.

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