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High Temperature Gas-cooled Reactors in a European Electricity Supply Environment; Main Outcomes of a Project in PSI

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ABSTRACT

This paper describes the main findings of a four year project focusing on the High Temperature Gas-cooled pebble bed Reactors (HTGRs) and their applicability in an European electricity supply environment. The first part briefly describes the accident phenomenology of the pebble bed HTGR and the simulation results obtained for loss of forced cooling accidents using the MELCOR severe accident code. Next, the economic aspects of the modular HTGR are discussed and the results for the capital cost of a HTR-PM-600 are presented. The final part of the paper focuses on the fuel cycle optimization of HTGRs by looking at the open and closed equilibrium cycles for the reactor, as well as the initial fuel cycle with possible thorium utilization.

1 INTRODUCTION

During the years 2015-2019, the Paul Scherrer Institute engaged in a project named "Feasibility and plausibility of innovative reactor concepts in an European electricity supply environment". In this project we looked into two nuclear reactor concepts: the High Temperature Gas-cooled Reactor (HTGR) and the Molten Salt Reactor (MSR) with the aim of studying the advanced features of these designs and assessing their applicability in the European energy markets.

In the HTGR, the reactor fuel is in the form of a small fuel kernel surrounded by a silicon carbide layers called TRISO coating. In so-called pebble bed reactors, which were the main focus of this project, coated fuel particles are encased in fuel spheres made of graphite (See Fig. 1.).

Several pebble bed HTGRs have been built and operated around the world. Two reactor prototypes were built and operated in Germany, namely the AVR and the THTR. On the basis of the experience with these reactors, the concept of a modular pebble bed reactor was developed. Recently, China has built a prototype at Tsinghua University with 10 MW thermal power (HTR-10). The construction of a 210 MWe HTR-PM prototype plant nearing completion in Weihai in Shan Dong province. After the termination of the South-African PMBR project, the Chinese projects are the only substantial activities concerning pebble bed reactors worldwide.

The now finished project involved different groups from PSI and ETH Zürich in Switzerland and the main purpose was to build-up the specific HTGR know-how in Switzerland that is necessary to provide in-depth information for decision makers and to identify research needs for the future. In this paper, we will describe some of the main findings of the project, focusing on the pebble bed HTGR reactors. The addressed topics include a qualitative study of accident phenomenology in HTGR, economic assessment and an optimization of the fuel cycle in HTGRs.

2 ACCIDENT PHENOMENOLOGY IN MODULAR PEBBLE BED REACTORS

The past TRISO fuel testing programs and safety analysis have shown that the diffusion of the fission products through the fuel coating and the failure of the TRISO particles starts to be more predominant at temperature above 1600 °C [1]. For the HTR-PM, the fuel temperature limit in the accident conditions has been set to 1620 °C [2]. This is the maximum temperature that the fuel is allowed to reach during any accident situation. Accident analyses have been performed for the De-pressurized and Pressurized Loss Of Forced Cooling (D/PLOFC) accidents and for water ingress and air ingress accidents by the HTR-PM development project [2]. All these simulations have indicated that the maximum fuel temperature always stays below the above mentioned safety limit.

In this project a simulation of Pressurized and De-pressurized loss of forced cooling accidents (PLOFC/DLOFC) in the HTR-PM were performed using the MELCOR severe accident code [3]. The model was developed by using open literature data of the plant and the accident conditions. The reactor power distribution was obtained as a part of a HTR-PM fuel cycle work, performed during the project and described in the following section. The results on the maximum fuel temperature in the MELCOR simulations were found to compare well with the previously published safety studies by Zheng et al. using THERMIX code [2] (Fig. 2).

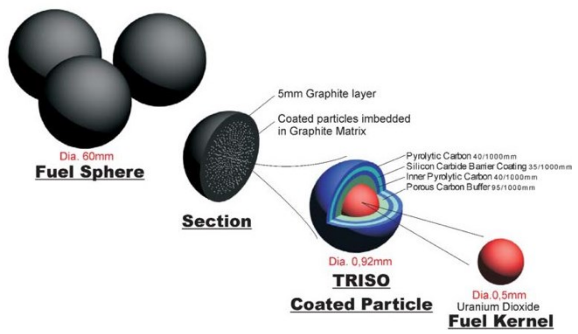

Figure 1: Schematic of a pebble bed reactor fuel. Picture from: https://nuclearstreet.com/.

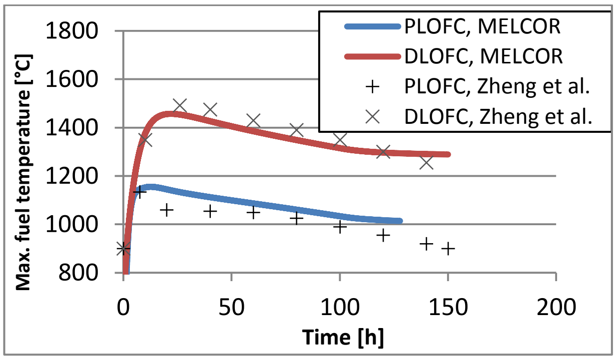

Figure 2: Comparison of maximum fuel temperatures during D/PLOFC accidents in HTR-PM [3].

3 ECONOMIC ASSESSMENT

Many of the economic challenges faced by modular HTGRs are common for other new Small Modular Reactor (SMR) designs. In addition to technical feasibility, acceptable safety risks and environmental burdens, an acceptable cost is also a necessary condition for any new reactor design. This does not mean that a new reactor must be cheaper than all current competitors, but it does mean that the cost must have an acceptable tradeoff with other performance indicators used for the decision to build. The main question for smaller, modern reactor designs is whether their increased cost due to a lack of economies of scale is adequately met by reduced costs due to design simplification and also possible economies due to series factory construction of modular reactor components, minimizing on-site costs or reduction or elimination of active safety systems. No matter the advantages of a new, first-of-a-kind technology, many, if not most, customers will prefer to wait and order a mature and proven n^{th}-of-a-kind plant design. This can especially be a problem if the SMR is to be series produced at a dedicated factory, since the decision to build or adapt the necessary facilities depends on an “order book” of purchase commitments sufficient to justify the capital investment.

Additionally, reactor licensing is a significant cost that must be born for any new reactor design. This means that there is a cost advantage to seeking regulatory approval in larger markets first, so that this fixed cost is shared across a larger potential number of sales. The main issue here is to have approval for a fixed design so that the process need not be repeated, and there is advantage in a legal venue where national design safety approval also guarantees a local construction permit. Factory-built, modular SMR’s are likely to have an advantage, as the reactor design is less likely to change than with small, site-built reactors.

Cogeneration, where part of the nuclear heat is used for a chemical process like coal gasification or liquefaction, desalination of sea water or distribution of low temperature heat for district heating can improve the economy of the HTGR plant. In a cogenerating HTGR, load following could also be performed by using more power for the process heat when the electricity production is not necessary. Additionally, hydrogen production using, for example, the sulfur iodine cycle has been envisioned for HTGR co-generation, although the hot coolant temperature in the current modular HTGR designs like the HTR-PM, is not yet high enough that the efficient H_2 production could be achieved.

In this project, the economic assessment work focused on how to estimate future capital costs for SMR designs, including the HTR-PM. The HTGR effort took cost breakdown data for the HTR-PM and estimated costs for a scale up to a 600 MWe design, with cost reductions for shared equipment in a 2x600 MWe plant, and further learning curve cost reductions, as shown in Fig. 3. The cost reductions are expressed in comparison to a reference Chinese Generation II+ CPR1000 design, using the costs of the Fuqing 1-3 reactors.

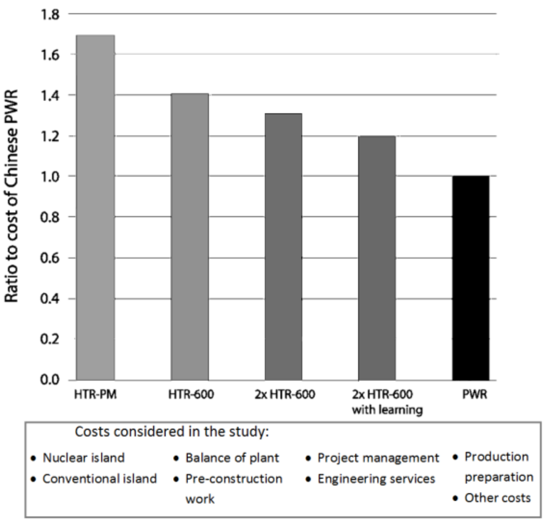

Figure 3: Estimated modular HTGR capital cost reductions.

4 OPTIMIZATION OF THE FUEL CYCLE FOR HTGR

The HTGR fuel cycle is predominantly based on Low Enriched Uranium (LEU). Nonetheless, practically all designs use higher enrichment than the LWR, ranging from 8% to 14%. The natural resource utilization in HTGRs with LEU fuel is around 0.5% and it is comparable or slightly below the values for LWR. Since the specific fuel density in HTGRs is low, the spent fuel volume is large. Several studies report the use of LWR Pu with or without the presence of a fertile material. Another option for the fuel cycle is the use of thorium which in the past was usually combined with Highly Enriched Uranium (HEU). This is no longer allowed for proliferation reasons.

In this project, the fuel cycle optimization consisted of modeling the closed and open equilibrium as well as an assessment of an initial fresh core containing thorium. In the equilibrium closed fuel simulations results from a broader study were used [4], which compared 16 different reactor designs. The major conclusion from this study was that graphite is not a suitable moderator for the ^{238}U-^{239}Pu cycle. The specific moderation feature of graphite (many scatterings with slow energy reduction) leads to higher actinides buildup. This characteristic also influences the LEU based open cycle and to a certain extent it reduces the maximal achievable burnup. The equilibrium results for the ^{232}Th-^{233}U closed cycle are much more promising. The higher actinides buildup is slightly higher than in other moderated reactors. However, this is mainly caused by the increased ^{233}Pa capture rate, which is proportional to the very high specific power. The power itself is a consequence of the very low specific actinides density in the core. The major conclusion of this part of the study is that HTGRs cannot be operated in a closed fuel cycle with purely fertile feed. At the same time, the ^{232}Th-^{233}U closed cycle equilibrium is close to criticality and Th utilization in some mixed cycles may have potential.

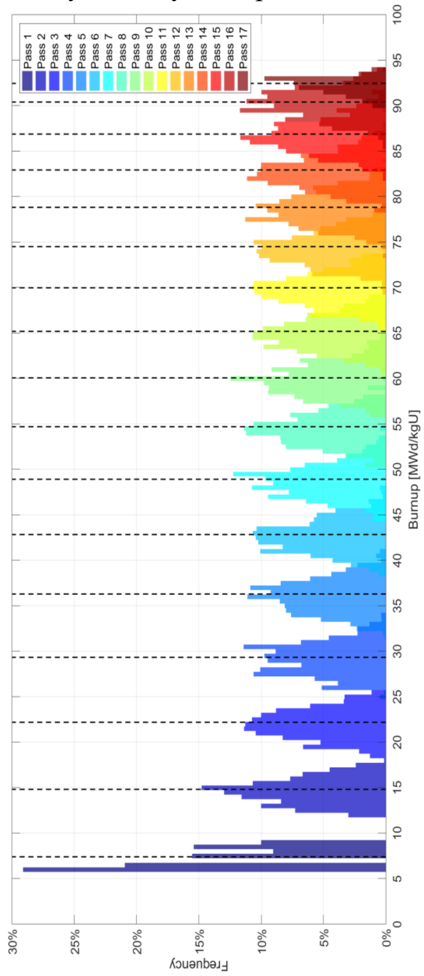

Figure 4: Statistical burnup distribution for each pass through the HTR-PM reactor with 16 passes fuel cycle.

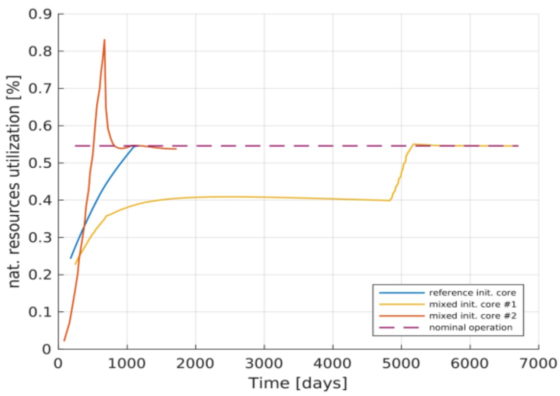

Figure 5: Natural resources utilization during reference transition scenario and during two Th pebbles based scenarios.

In the second part of the fuel cycle study, the equilibrium open cycle was simulated using a dedicated MPB burnup script [5]. The study also analyzed the reactor physics specifically for the HTGR and identified that the pebbles act as a pseudo-liquid which tends to homogenize the average fuel properties in the core. With an increase in the number of pebbles passing through the core the maximum and minimum burnups converge (see Fig 4). The simulation also confirmed that activity of ^{137}Cs can be used for burnup detection with acceptable accuracy.

Finally, the use of Th as a burnable poison for the transition cycle from initial fresh core loading to the equilibrium open cycle was assessed. The option seems to be neutronically feasible; nonetheless, economic analysis should be done to assess its added value. Two major scenarios have been evaluated and compared with the reference initial cycle for HTR-PM: 1) late Th-pebble discharge and 2) early Th-pebble discharge. In both cases the final resource utilization is the same as in the reference cycle (Fig. 5). In both cases slightly more than half of the initial core loading was Th pebbles. In the late discharge case, the Th pebbles stayed in the core for up to 14 years and reached burnup of 20 % FIMA [6].

5 CONCLUSIONS

In this paper, we have presented several findings from the PSI study focusing on HTGR "feasibility and plausibility" in European electricity supply environment. The main safety advantage of the HTGR arise from the TRISO fuel concept which is able to keep most of the activity inside the fuel, even under accident conditions, as long as burnup and the temperature in the reactor core stays within design limitations. According to various simulation studies, the fuel temperature can be limited below the safety limit in case of accidents like LOFC, air- or water ingresses by inherent heat removal mechanisms. On the other hand, inherent safety features preventing core damage due to an unprotected loss-of-flow in the reactor core does not cover the full scope of all potential accident scenarios. Without a thorough look into the design details of a modern modular HTGR, it is not possible to assess whether the above mentioned scenarios are the most severe conceivable ones.

An economic assessment of the construction costs of the HTR-PM technology was conducted within the project. For a power plant consisting of 6 reactors connected to one turbine, which is one of the target configurations of the current R&D, and under the assumption of typical learning curves characterizing expected cost reductions during the transition to serial construction, conclusion is that the capital costs are about 10 to 20 % higher than for a current reference Chinese LWR plant. This is in an acceptable range if such a plant has compensating tradeoffs such as easier siting, reduced risk, increased sustainability, better public acceptance, better dispatch flexibility, a better size match with the local market, or opportunities for cogeneration.

The general conclusion of the fuel cycle optimization study is that the HTGR is well designed to utilize LEU with efficiency comparable to the LWR. However, the spent fuel volume is much higher. With an increasing number of passes through the core the system tends to self-compensate and the average and maximal burnup converge. The LWR Pu burning option is neutronically possible, but not feasible when reprocessing is not allowed. Th based pebbles can be utilized, especially during the initial cycle. Their addition to the equilibrium open cycle will cause a reduction of the maximal achievable burnup for the LEU pebbles and its advantages and disadvantages should be carefully evaluated.

ACKNOWLEDGEMENTS

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