

Chapter 9

CHALLENGES TO COMMERCIALIZATION OF THE GAS TURBINE HTGR PLANT

The gas turbine HTGR represents an advanced nuclear power concept that has not been demonstrated with an actual plant. The GT-MHR and PBMR are both in the development phase with detailed design yet to be completed. Successful design, construction and demonstration of these plants is expected to provide the electric utility industry with a highly efficient, relatively low cost, safe and environmentally clean method of producing electricity. However, achieving successful deployment of this plant type will require careful development of the systems and components comprising the design, many of which are either new to the nuclear power industry, involve recent technological advancements, and/or consist of component applications operating in environments and configurations never before demonstrated.

The design organizations readily acknowledge that these plants will require extensive development in order to achieve final commercialization. This is particularly evident with the power conversion system components, where physical size, orientation and operating environment challenge the existing experience base. In this regard, the developing organizations of the PBMR and GT-MHR conceptual plants have subjected their designs to multiple independent international technical and economic reviews resulting in the strong, nearly unanimous, consensus that these designs are viable with no technological “show-stoppers”.

The following challenges are based on the editor’s judgment primarily with focus on the PBMR and GT-MHR closed cycle gas turbine plants because of their advanced stage of development. Due to the basic design of this concept, these challenges all tie directly to the primary coolant system and can be categorized as either “reactor plant” or “power conversion system”.

9.1. REACTOR PLANT

9.1.1. PBMR reactor design

The intent of the PBMR designer is to use the German HTR-MODUL (by Siemens/Interatom) and HTR-100 (by ABB/HRB) concepts coupled with the experiences gained from the operation of the pebble bed AVR and THTR-300 plants as the development basis of the PBMR. However, the final design of the PBMR may include significant differences from these two German reactors that will require code validation(s) and additional development and testing prior to licensing. An example of the difference in core design includes the use of non-fuelled graphite pebbles in the center of the core resulting in an annular configuration. This use of unfueled graphite pebbles in the center of the core will essentially cause the flux profile to expand outward thereby allowing for flux flattening at high power and to provide for better core control capability. This will represent a significant change in the basic core physics characteristics of the PBMR.

Also, acceptance by the South African nuclear regulatory agency, the National Nuclear Regulator (NNR), of the reactor design and its specific HTGR related safety attributes without the need for added requirements and their attendant increase in plant costs represents a risk to commercialization of the PBMR.

The significance to achieving deployment due to this challenge is the reactor performance for both normal and accident operating conditions and associated core physics characteristics for the PBMR will have to be well understood prior to receipt of the final operating license. Any significant deviation from the German design(s) will require modeling and code validation prior to licensing. Although much of the German background can be incorporated into the PBMR, any change in core design represents an additional R&D requirement with an attendant risk for plant licensing. However, if core performance is found to significantly infringe on the safe operational envelope of reactor performance, the consequences could be substantial to future commercialization.

ESKOM has interfaced with the NNR in the development of the PBMR for the past three years. The NNR is currently evaluating the design and supporting documentation relative to their regulatory standards. At issue for the license to construct the first unit is whether the CNS will: a.) Accept and incorporate into the South African nuclear regulatory base the results of the German licensing authority relative to the pebble bed design, or b.) Require further validation which could include additional research, computer modeling, and testing which will most probably be the case for any deviation from the basic German reactor design, and c.) Accept ESKOM's intent to secure the final operating license by "licensing by test" of the first unit.

Acceptance of the PBMR design will require the NNR to determine that the design safety attributes specific to the HTGR meet (or exceed) the overall safety criteria for nuclear power in South Africa. This will include such attributes as very low core power density, use of the TRISO coated fuel particle, an inert single phase (gas) primary coolant and a reactor structure, principally of graphite, with slow heat up characteristics under accident conditions. However, in balance is whether these attributes will provide the equivalent safety dictated by existing regulations such as the need for an overall pressure containment, and allow for a reduced emergency planning zone and a significantly reduced number of safety class systems and components. If ESKOM is unable to provide the supporting justification(s) to the satisfaction of the NNR, the significance could be anywhere from minor to great depending on what additional requirements might be imposed on the PBMR design. This includes the risk of the PBMR becoming cost prohibitive.

9.1.2. GT-MHR reactor design

The GT-MHR includes significant changes in core and internal component design from the existing experience base of reactors utilizing prismatic fuel elements. These changes, coupled with the need for acceptance by the Russian licensing authorities (GAN) of the specific safety attributes inherent in the HTGR without added requirements being imposed on the design, represent significant challenges to the sponsors. Examples of changes anticipated for the GT-MHR core include:

- The GT-MHR is an annular core with the central region consisting of unfueled graphite elements. This is believed to represent first-of-a-kind core geometry.
- Basic operating characteristics of the GT-MHR reactor such as power level, core temperatures, response to accident conditions, etc. represent core physics characteristics which are different from the established experience base.
- Active core height of the GT-MHR will be ten fuel elements, whereas past experience was six elements high (at Ft. St. Vrain).
- The refueling scheme includes shuffling of fuel elements to different core locations for burn-up purposes.

- The control rod drive mechanism and the reserve shutdown actuation mechanism are a new design without a proven experience base.

Acceptance of the GT-MHR design will require GAN to determine that the design safety attributes specific to the HTGR meet (or exceed) the overall safety criteria for nuclear plants in the Russian Federation. This will include evaluation of such attributes as the very low core power density, use of the TRISO coated fuel particle, an inert single phase (gas) primary coolant and a reactor structure, principally of graphite, with slow heat up characteristics under accident conditions. However, in balance is whether these attributes will provide the equivalent safety of existing regulations and allow for regulatory changes such as a reduced emergency planning zone and a reduced number of safety class systems and components. If the sponsors are unable to provide the supporting justification(s) to the satisfaction of the licensing authorities, the significance could be anywhere from minor to high depending on what additional requirements would be imposed on the GT-MHR design. This includes the risk that the GT-MHR could become cost prohibitive. It should be noted that the present design calls for an external, pressure tight containment for the plutonium burning plant. Whether this will also be the case for the commercial GT-MHR has, as yet, not been decided.

Regarding changes, the core and associated component design deviations from the existing experience base will have to be proven analytically prior to acceptance for initial licensing. The GT-MHR core configuration represents physics issues that can only be completely validated when full power is achieved (and then when being tested under accident conditions). If significant issues become evident when modeling the reactor, further research, including testing and validation will be necessary prior to licensing. Similarly, if significant deviation occurs from predicted core response during initial plant testing, the end result could be a substantial issue in attaining competitive deployment.

Technical failures in core reactivity control mechanism design would require additional re-design prior to licensing which would place an economic burden on deployment of the plant. Similarly, shuffling of elements during refueling, if not properly accounted for in the design, would extend the plant outage causing an unanticipated economic burden.

9.1.3. Primary coolant environment and fuel development

The radiological makeup of the PBMR and GT-MHR primary coolant will influence the materials utilized on major components such as the vessel(s) and turbo-compressor blading, and also be a dictating force in the development of tools for component maintenance to assure personnel exposures ALARA.

The GT-MHR and PBMR represents the first application of its kind for many of the primary system components. Past gas cooled reactor plant experience with a helium primary system environment represents a limited base of knowledge. Other system parameters such as helium temperature and chemical contamination, in conjunction with the radiological environment, may compound the challenge placed on the primary system components.

With regard to the fuel, an extensive TRISO particle operational experience base has been established principally in the reactors of FSV, AVR and the THTR-300. This, coupled with numerous irradiation tests of UO₂ TRISO capsules in the USA, Germany, the Russian Federation and Japan, have provided consistently high performance results for application to the GT-MHR and PBMR. Note, an exception to this high performance was with the HRB-21

capsule in the USA, which exhibited high failure of the silicon carbide (SiC) coating due to unanticipated stresses placed on the coating by the addition of other, (now considered) unnecessary coatings.

This base of experience has given the PBMR and GT-MHR designers confidence that the coated fuel in their respective plants will perform to the required standard of quality and that the fuel is not viewed as a significant challenge. However, the operation of the PBMR and GT-MHR will include high fuel burn-up at high temperatures for extended periods of time. It is a known condition that the silver isotope, Ag-110m, is released from the TRISO particle at high temperatures. The amount and level of influence this isotope has on the metallurgical and maintenance considerations for the PCS components over the long period of plant operation has not yet been fully determined [9-1]. Also, if operation is allowed to exceed a fuel temperature of 1250°C. over an extended period of time, SiC coating thickness deterioration will occur due to palladium attack [9-2]. Also, although the commercial GT-MHR is to utilize low enriched uranium as the fissionable fuel, the initial deployment of this plant is for the burning of weapons plutonium in the Russian Federation. As such, an extensive plutonium fuel particle development program is required for the first (non-commercial) GT-MHR plants.

Failure to understand the isotopic makeup, method of deposition on equipment and associated radiological dose levels for the PBMR and GT-MHR primary system(s) could result in increased failure of equipment, additional plant downtime and larger than anticipated personnel exposures. As an example, the turbo-machines are expected to operate up to seven years without the need for repair/replacement. Seriously misjudging the radiological effects on the machine components could pose a significant problem both for plant availability and risk of substantial equipment failure.

Not knowing the extent of Ag-110m release as well as continuous high temperature operation and possible neutron streaming may significantly increase the maintenance considerations on the PCS components and cause deterioration in the life of the first stage turbine blades. Ag-110m is expected to deposit on the cooler surfaces of the PCS components thereby increasing the need for tooling/shielding when maintaining this equipment. However, the significance for competitive deployment due to this deposition of silver is not expected to be a substantial limitation to the commercial viability of the PBMR or GT-MHR.

Also, these reactors have not, as yet, been validated to assure the requirement that core locations do not exist where fuel is subjected to long term operation in excess of 1250°C. Due to the established experience base and previously validated HTGR codes and models, this is not expected to be a significant challenge to commercialization.

9.2. POWER CONVERSION SYSTEM

9.2.1. Turbine, compressor and generator development

The commercial producers of large turbines, compressors and generators that have provided input to the PBMR and GT-MHR designers are in general agreement that the technological development required for these machines does not represent substantial risk of failure. However, these will be the first application for the utilization of magnetic bearings on machines of this size in a vertical configuration, with high temperature, ultra-dry radiologically contaminated helium as the working fluid. Developmental issues that challenge the designers include:

- Understanding and optimizing the rotor-dynamic characteristics of the machine(s)
- Determination of materials which will operate in the above mentioned helium environment for the extended lifetime of 6 years between overhauls and 60 000 hours without component failure
- Development of magnetic bearings and associated catcher bearings for the intended rotor size, weight, orientation and operating environment⁸
- Application of seals for reliable performance in the required helium environment and in conditions where substantial thermal movement exists on the sealing surfaces
- Generator insulation and stator support designs to prevent migration of the stator windings as a result of insulation deformation coupled with electromagnetically induced vibration in a vertical position
- Stator insulation and exciter diode design to prevent “pop coming” in the event the generator pressure vessel sustains a rapid depressurization following sustained full pressure operation
- Accessibility for maintenance and to assure safe and efficient operational performance.

Economical development of the rotating equipment will be a significant factor in achieving competitive commercialization of the PBMR and GT-MHR plants. Although these machines share many design similarities, the GT-MHR unit incorporates a single rotating shaft including an exciter, electrical generator, turbine, high pressure compressor and low pressure compressor; whereas the PBMR utilizes three rotating machines including a high pressure turbine-compressor, a low pressure turbine-compressor, and a turbine-generator.

A key to the HTGR closed cycle gas turbine plant, with its attendant high efficiency (through the use of the Brayton Cycle) and projected low capital and operating costs, rests with being able to develop this rotating machinery. If this is unattainable, either because of unsolvable technical issues, unanticipated substantial safety and regulatory concerns and/or unexpected developmental or operational costs which result in lack of competitiveness, the future deployment of this advanced nuclear power plant will be at risk and probably will not occur.

9.2.2. Magnetic bearing development

Incorporation of magnetic bearings and their associated catcher bearings on the rotating machines of the GT-MHR and PBMR will represent a significant departure from the established experience base. The areas of departure include: a.) bearing size; the axial (thrust) and radial bearings of these machines are the largest application ever undertaken for magnetic bearings; b.) operational environment of these bearings; particularly with regard to helium with elevated temperature and pressure, ultra dry, but chemically and radiologically contaminated conditions, has not been previously experienced; c.) orientation; all PBMR and GT-MHR rotating machines will have a vertical shaft orientation, which, to my knowledge, represents a first-of-a-kind condition for machines of this size, weight and speed.

Failure, due to a significant (uncorrectable) technical flaw, of the magnetic bearings and/or associated catcher bearings to meet their intended function would result in the GT-MHR and PBMR not attaining commercial status. There is no realistic bearing alternate (except, possibly, a hybrid arrangement for the generator thrust bearing which could

⁸ Due to the individual difficulty of challenge and high significance, the areas of magnetic/catcher bearing development and seal design are included in this report as stand-alone technical challenges.

incorporate a conventional bearing system). Within the primary coolant environment, oil or water lubricated bearings are not seen as an acceptable alternate.

A situation could arise where the bearings fail due to a technical flaw that is correctable. This may not represent a fatal situation, depending on the cost associated with redesign, replacement and other changes in the PCS such as possible vessel and/or heat exchanger reconfiguration mandated by the modified bearing arrangement.

9.2.3. Helium seal development

Helium seals will be utilized to prevent leakage and bypass flow between components of the PCS. These seals will be required to operate in an ultra-dry (non-lubricating), high temperature, high pressure, radiologically contaminated helium environment, with the added requirement to be able to grow and move with temperature changes of the PCS components.

Long term operation of these seals and the thermal expansion between PCS components and associated supporting structures represent design requirements and configurations for which no experience base exists.

Failure of the seals to remain leak tight throughout the duty cycles expected for the PCS could result in a situation where the GT-MHR or PBMR are not able to attain commercial status (most severe situation), or result in a situation as minimal as a minor reduction in overall cycle efficiency due to helium bypass leakage slightly in excess of design.

Helium is a difficult gas to contain. Bypass leakage of helium has a direct influence on overall cycle efficiency, and, therefore, reflects on the ability of the plant to achieve competitive deployment.

9.2.4. Recuperator, precooler and intercooler

The recuperator required for both the GT-MHR and the commercial PBMR will represent the largest application of its type ever built. The GT-MHR utilizes the prime surface variant of the plate-fin design. The PBMR will include a standard plate-fin type recuperator. Although the overall recuperator will consist of individual, repetitive modules, its design, size and environmental operating requirements have yet to be proven in an existing application. Similarly, the precooler and intercoolers, although of a generally standard design will require development and qualification testing to assure their successful performance prior to coupling to a nuclear heat source.

Examples of areas of development and testing for these heat exchangers include: a) assuring that the 95% effectiveness criteria for the recuperator is attained, and; b) the ability to test, locate and repair (minor) leakage paths in all heat exchangers without the requirement for removal of the unit.

The inability to attain the required recuperator effectiveness will directly affect overall system efficiency resulting in loss of generation and attendant economic penalties.

Throughout the life of the recuperator, precooler and intercooler heat exchangers there will be the necessity to test the unit(s) for component degradation and to locate and repair minor leaks without the need to remove or replace the unit. Without this capability, the task of

replacing a heat exchanger is quite significant, requiring entrance into the PCS vessel and subsequent removal of major PCS components in order to access the faulty unit.

9.2.5. Overall PCS performance

The GT-MHR and PBMR represent the first application(s) of a closed cycle gas turbine PCS coupled to a nuclear power source. Further, the primary system conditions for these plants will achieve higher operating temperatures than past HTGRs. No past experience base exists which can be applied to fully assure the technical and economic performance expected by these plants.

Anticipating and understanding the performance characteristics to assure that the components making up the primary coolant system will collectively operate as an integrated, functionally sound system will be the most significant overall factor in achieving commercial deployment.

Many other challenges described in this report focus on individual components in the PBMR and GT-MHR. This challenge represents the need to provide assurance that the collective integration of all of the PCS components function as a single operating entity in the manner required by the designers, license authorities and vendors. The magnitude of this challenge is considered as high.

Final validation will be required of the first unit in a stringent testing program [9-1].

REFERENCES TO CHAPTER 9

- [9-1] ELECTRIC POWER RESEARCH INSTITUTE, Helium Gas Turbine Reactor Technical Challenges: A Characterization for Use in Focusing R&D Resources, EPRI Doc. No. TP-114690, Palo Alto, CA (2000).
- [9-2] INTERNATIONAL ATOMIC ENERGY AGENCY, Fuel Performance and Fission Product Behaviour in Gas Cooled Reactors, IAEA-TECDOC-978, Vienna (1997).