

SUMMARY

1. OVERVIEW AND PURPOSE

The Technical Committee Meeting (TCM) on “Gas Turbine Power Conversion Systems for Modular HTGRs” was held from 14-16 November 2000 in Palo Alto, California. The meeting was hosted by the Electric Power Research Institute, and was convened by the IAEA on the recommendation of its International Working Group on Gas Cooled Reactors (IWGGCR). The meeting was attended by 27 participants from 9 Member States (Argentina, China, France, Japan, the Netherlands, the Russian Federation, South Africa, the United Kingdom and the United States). In addition to presentations on relevant technology development activities in participating Member States, 16 technical papers were presented covering the areas of:

- Power conversion system design
- Power conversion system analysis
- Power conversion system component design

Following the papers, a panel discussion was held on technology issues associated with gas turbine modular HTGR power conversion systems and the potential for international collaboration to address these issues. A summary of the presentations, discussions and recommendations will be prepared for use along with the papers presented in a TECDOC on the subject. A detailed report on the meeting is available.

The purpose of this Technical Committee Meeting was to foster the international exchange of information and perspectives on gas turbine power conversion systems and components for modular HTGRs. The overall objectives were to provide

- A current overview of designs under consideration
- Information on the commercial availability or development status of key components
- Exchange of information on the issues involved and potential solutions
- Identification of further development needs for both initial deployment and longer term performance enhancement, and the potential for addressing needs through international collaboration

2. GAS TURBINE MODULAR HTGR NATIONAL DEVELOPMENT ACTIVITIES

The technology for open cycle gas turbines, applied primarily to the combustion of oil and natural gas, has advanced rapidly over recent years, driven by cost and performance competition and supported by advances in high temperature materials, fabrication techniques, engineering design tools, etc. Concurrent application of similar technological advances to heat exchangers has resulted in compact, low cost gas-to-gas units for an expanding range of applications. Advances in electronics support the development of magnetic bearings and introduce the possibility of other innovations, such as a high-speed turbo-generator with high power frequency converter. While these are proven technologies already in commercial application, they have not been combined as a system under the environmental conditions and design constraints relevant to a modular HTGR.

Modular HTGRs utilising closed cycle gas turbines for generation of electricity are a source of considerable current interest and activity among several IAEA Member States. Designs under consideration incorporate recent developments in high temperature materials, electronics, heat exchangers, gas turbine technology, etc. These features are used in conjunction with modular HTGR concepts that have been under development for two decades with an emphasis on passive safety characteristics. Proponents of these designs expect that the simplification of systems from the passive safety characteristics and the reduction in total equipment relative to a steam cycle will allow for an economically competitive nuclear power generation option in the 100 to 300 MWe net unit power rating range.

Representatives from each of the participating Member States reported on relevant national activities, as summarized below:

Argentina – Innovative reactor development efforts are focused mainly on the CAREM integral PWR, but some economic assessment work is under way regarding modular HTGRs

China – Loading of fuel in the HTR-10 test reactor was expected to begin in mid November 2000, with initial criticality planned for December. Hot commissioning testing to reach full power is expected to take about one year. Irradiation testing of fuel spheres made in China for the HTR-10 is under way in the Russian Federation, with positive initial results. An evaluation of future directions for development of the modular HTGR in China, assuming successful operation of HTR-10, is under way with consideration of both steam turbine and gas turbine cycles.

France – Most of the activity in France is associated with the European Commission 5th Framework program. The EC work currently addresses fuel technology, reactor physics and fuel cycle, and materials development. Work is in progress on recuperator design in advance of anticipated activities on power conversion system components in the 5th Framework.

Japan – The power ascension testing of the HTTR is continuing, having reached a level of about 10 MWt. Gas turbine modular HTGR feasibility studies addressing both pebble and prismatic block fuel over a core power range of 300-600 MWt are under way. The gas turbine modular HTGR is being considered in a national review of the long-term nuclear energy development program, expected to be completed in December 2000. The Japan Atomic Industrial Forum has requested that the government perform a feasibility study on commercialisation of modular HTGRs. The possibility of locating nuclear power stations in the Tokyo Bay area was raised by the Tokyo metropolitan governor. In related discussions, PBMR was raised as one of the candidates.

The Netherlands – A study of PBMR deployment in the Netherlands after demonstration in South Africa is being conducted for Netherlands utilities. Work is underway to study the failure of SiC coatings under mechanical loading as a part of studies on long-term waste behaviour of coated particle fuel. Additional supporting activities are being conducted for the PBMR project.

Russian Federation – Work is continuing on the preliminary design of the GT-MHR. Fuel development efforts have produced about 200 g of plutonium kernels for subsequent use in fabrication of coated particles. A test programme for components of the GT-MHR Power Conversion Unit is under development.

South Africa – The PBMR project is proceeding with the addition in recent months of BNFL and Exelon Generation Co. (formerly elements of PECO Energy and Commonwealth Edison) as partners. The detailed PBMR feasibility study is underway, an Environmental Impact Assessment (EIA) has been submitted and the review is in progress, and a Safety Analysis Report has been submitted to the National Nuclear Regulator (NNR) for review. The reviewing Government organisations have agreed to target dates for completion. Assuming a favourable outcome of the EIA, a construction license from NNR, shareholder approval and Government consent, construction activities could commence by the first half of 2002.

United Kingdom – Continued supporting technology development and operation of the Magnox and AGR reactors are producing relevant experience and data. BNFL is playing an active role as a partner in the PBMR project. Organisations in the UK also involved in the PBMR project as contractors include AEA Technologies on graphite internals, GEC Alstom on the turbo-generator, and Heatrix on the heat exchangers.

United States – Several activities on modular HTGR development are in process in the US. The US Department of Energy has an ongoing project with General Atomics and Oak Ridge National Laboratory, in collaboration with organisations in the Russian Federation, for the development of the GT-MHR concept, and several DOE Nuclear Energy Research Initiative projects are related to HTGR technology. Exelon Generation Company and BNFL/Westinghouse are active participants in the PBMR project, while a co-operative effort of MIT and INEEL is developing a plant concept based in part on the PBMR design. Also, EPRI has initiated an HTGR programme covering a range of specific issues considered important to the success of the technology.

An important aspect of modular HTGR technology development is the emerging trend toward multinational projects. For example, the GT-MHR project involves participants from France, Japan, the Russian Federation and the United States. The PBMR project involves partners and contractors from France, Germany, the Netherlands, the Russian Federation, South Africa, the United Kingdom and the United States. While this trend enhances international exchange of information within the projects, as the technology approaches deployment commercial considerations are beginning to restrict exchange of information outside the projects. This is more the case with power conversion system technology because it primarily involves adaptation of existing commercial technology. Information exchange and co-operative activities in the reactor technology area, as illustrated by activities related to the start-up and operation of the HTTR and HTR-10 test reactors, is less affected.

3. TECHNICAL PRESENTATIONS

As noted earlier, technical presentations were grouped into the subject areas of system design, system analysis, and component design. The information presented in these three areas is very briefly summarized below and copies of the papers are provided later in this report, with the exception of Argentina and the United States, which did not provide their presentation material in paper form.

3.1 Power conversion system design

Presentations on the subject were made by participants from Argentina, China, the United States, Japan and the Russian Federation:

Argentinean Approach of GT Reactor Technology – Argentina technology development is centered around the CAREM integral PWR design. An economic assessment of GT modular HTGR technology was performed to identify cost targets. Using a higher contingency factor based on Argentina's views of the uncertainty in the costs of this technology, it was concluded that a cost target of US \$30-40 million for a plant in the 200-300 MWth size range would be needed.

Study on Coupling a Gas Turbine Cycle to the HTR-10 Test Reactor – The original design of the HTR-10 included provision for replacing the steam generator, to be installed initially, with a heat exchanger for process heat or indirect cycle gas turbine testing. Design studies have been performed for both a direct and indirect gas turbine cycle in future HTR-10 operations. It is anticipated that future operations will include testing of a gas turbine, but a decision on the cycle to be used has not been taken at present.

US History of Direct Cycle Gas Turbine HTGRs – US experience included early design and prototype projects beginning with open cycle gas turbines for the ANP project in the late 50's. Closed cycle designs were developed in the 60's and a large HTGR design was developed in the late 70's. The evolution of the modular HTGR and its coupling with a gas turbine in the early 90's was reviewed, including the large number of configuration options considered in the selection of the current design configuration.

Selection of JAERI's HTGR-GT Concept – A feasibility study for a gas turbine modular HTGR design has been underway at JAERI since 1996. The study has included both pebble bed and prismatic block concepts and established temperatures and power levels considered optimum for each option. Designs have been developed for a 400MWt/182MWe pebble bed and a 600MWt/284MWe prismatic block plant. Power conversion system layout options have included configurations equivalent to the PBMR and GT-MHR designs as well as a JAERI version with horizontal turbomachinery. Evaluation of the designs is continuing, with a final selection expected in the near future

Features of Adapting Gas Turbine Cycles and Heat Exchangers for HTGRs – OKBM optimisation studies for the GT-MHR Power Conversion Unit have been conducted to determine design layout and operating conditions. A reactor inlet temperature of 490°C, limited by reactor vessel material considerations, resulted in an optimum reactor outlet temperature of 850°C. Other parameters studied included reactor pressure, PCU pressure ratio, intermediate conditions and component configuration. A single shaft turbomachine was selected to provide protection against overspeed on a loss of electrical load.

The necessity of achieving competitive economics and balancing of projected cost and technological risk were common themes of the papers. As noted in the US paper, gas turbines have been considered for nuclear power generation for over 40 years, with a major increase in interest and activity in the past decade. Considerable variation in power conversion system

layouts (e.g., single vs. multiple shaft, vertical vs horizontal orientations) remains in the designs currently under development.

3.2 Power conversion system analysis

Presentations on the subject were made by participants from the Netherlands and South Africa:

Dynamics of a Small Direct Cycle Pebble Bed HTR – The ACACIA 40MWt cogeneration design was analyzed for safety related transients. Loss of coolant and loss of flow events were analyzed along with other events. A long-term low load transient without limits on reactor vessel exit temperatures resulted in the highest fuel temperatures due to reactivity insertions from xenon decay.

Dynamic Modelling of a Cogenerating Nuclear Gas Turbine Plant – A dynamic model of the ACACIA 40MWt cogeneration design was developed to study response to operational transients for various design options. The model structure and simplifying assumptions were described along with analytic results. The system response for various ratios of heat and electrical output were studied to identify effects of design options and control system parameters. The closed loop responses showed that good set-point tracking for the electricity production and good disturbance-rejection for the recuperator temperature can be achieved.

PBMR Dynamic/Transient Operation and Performance Prediction – The theory behind the off design and transient modelling of the PBMR design, development of a computer simulation model, and the selection of the PBMR control scheme was described. Areas addressed in the performance review included material selection, modular design, testing and commissioning, prediction of plant performance and controllability, and control system design. Two primary control schemes studied were heat source bypass and inventory control, with the selection of inventory control for efficient changes at moderate speed, and heat source bypass for high-speed changes with short duration.

The papers demonstrated that the analytical capability to perform transient analysis of the power conversion system for safety, equipment protection, and control purposes is well developed. However, because of the complexity of dynamic component behaviour and interactions among components, empirical data on full-scale components and systems is necessary to accurately predict performance with high confidence.

3.3 Power conversion system component design

Presentations on the subject were made by participants from Japan, the Netherlands, France, the United Kingdom and the United States:

Study of Fission Product Release, Plate-out and Maintenance in Helium Turbomachinery – The generation, release, transport and deposition of ^{137}Cs and $^{110\text{m}}\text{Ag}$ was studied for a 600 MWt prismatic design and a 300 MWt pebble bed design. Fission product distribution calculations were based on available empirical data adjusted for the temperature and heat transfer conditions of the designs studied. The local activities were used to estimate allowable time for maintenance of the turbine rotor. The results were considered to have high uncertainties, but times were reported as 11 minutes for the prismatic block and 5.5

hours for the pebble bed. It was concluded that measures to reduce the dose levels for both cases is desired, and a ceramic coating on the turbine blades was identified as the leading candidate.

Fission Product Transport in the Primary System of a Pebble Bed High Temperature Reactor – Fission product transport and deposition in the ACACIA 40 MWt pebble bed reactor with a combined heat and power configuration was investigated. Four radionuclides were identified for investigation based on their volatility and radiotoxicity: ^{137}Cs , ^{90}Sr , $^{110\text{m}}\text{Ag}$, and ^{131}I . Fission product release and distribution in the primary system was calculated as a function of time for normal operation, and for a core heatup incident with damaged fuel.

Compact Heat Exchanger Technologies for HTR Recuperator Applications – Industrial compact heat exchanger technologies for possible application in the recuperator of a helium gas turbine cycle were investigated. Design categories reviewed included plate, spiral, plate and shell, plate-fin, microchannel, matrix, and flat tube and fin heat exchangers. All of the options identified were assessed for their range of operating parameters relative to the conditions for a recuperator in a modular HTGR closed cycle gas turbine circuit. Diffusion bonded microchannel heat exchangers were identified as the most promising concept for this application.

High Temperature Alloys for the HTGR Gas Turbine: Required Properties and Development Needs – Potential high temperature alloys were reviewed for application in the turbine blades and disks of a gas turbine modular HTGR. Turbine materials development for HTGR application was reviewed along with advances in materials for open cycle gas turbines, with consideration of failure modes due to thermal and environmental effects in modular HTGR applications. Nickel based superalloys are being considered for both blades and disks in the current GT-MHR design. Future materials development, and mechanical testing and life modelling requirements were also addressed.

Nuclear Graphite for High Temperature Reactors – Graphite components for cores and reactor internals of both prismatic and pebble bed reactors were reviewed in terms of design conditions and issues. Graphite component manufacturing processes and feed materials were also reviewed along with effects on product microstructure and material properties. Issues and important parameters for reliable service were identified and a proposed specification for HTR graphite was provided.

Auxiliary Bearing Design Considerations for Gas Cooled Reactors – Options for auxiliary bearings to serve as backup to the magnetic bearings employed in the gas turbine modular HTGR designs were reviewed. Existing design configurations along with design considerations and the experience base were addressed for both radial and axial bearings. While the radial auxiliary bearing technology appears well in hand, the heavy loads and vertical orientation of most gas turbine modular HTGR designs present challenges for the axial bearings.

Transportation and deposition of fission products in the form of particulate accumulation or vapour condensation is important from the standpoint of system and component maintenance. Although considerable testing has been done, relatively large uncertainties remain for a given

plant concept due to system geometry, operating conditions, and surface and material property variations. Options for mitigation include in-line filters and component surface coatings. Many varieties of compact heat exchangers are in commercial service, with a limited subset having the capability to meet modular HTGR service conditions, but needing further product development for this application. Considerations of low long term creep to maximize service intervals, avoidance of blade cooling to simplify design, and the modular HTGR chemical environment present challenges for turbine component design utilizing existing open cycle turbine technology. Temperature and fluence history are the primary factors driving the design of graphite components, with uncertainties in service life warranting design for replacement wherever practical. Advances in electronics and rapidly expanding operating experience indicate that magnetic bearing technology is generally well in hand, but considerable uncertainties remain in the design of backup mechanical bearings, particularly thrust bearings, to deal with failure of a magnetic bearing.

4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were identified as a result of the discussions at the meeting:

1. International review and collaboration is of interest for China and Japan in the planning and conduct of their test programs:
 - Both the HTTR and HTR-10 reactor projects are exploring scale model testing of a gas turbine, with the HTTR project considering a 7 MWt gas heated loop, and HTR-10 a direct or indirect cycle connected to the reactor.
 - The HTR-10 is considering a series of safety demonstration tests to be conducted following completion of the power ascension testing phase.
2. The IAEA Co-ordinated Research Project on Evaluation of HTGR Performance was noted as a possible vehicle for discussion of HTTR and HTR-10 plans.
3. Increasing restrictions on availability of technical information as the technology comes closer to commercial application were noted. The potential commercial advantages of restricting availability of information must be weighed against the added risk due to reduced information exchange and design review inputs. The general consensus was that in several areas of power conversion system design and technology development the uncertainties are sufficient that the benefits of information exchange are likely to outweigh the benefits of commercial advantage to the developers.

