SUMMARY

The Technical Committee Meeting (TCM) on "Safety Related Design and Economic Aspects of High Temperature Gas Cooled Reactors (HTGRs)" was held from 2-4 November 1998 at Tsinghua University, Beijing, People's Republic of China. The meeting was hosted by the Institute of Nuclear Energy Technology (INET), and was convened by the IAEA on the recommendation of its International Working Group on Gas Cooled Reactors (IWGGCR). Approximately fifty participants and observers from ten countries (France, Germany, Indonesia, Japan, Netherlands, People's Republic of China, Russian Federation, South Africa, United Kingdom and the United States of America) attended the TCM. Twenty-four papers were presented with time set aside for questions and comments following each presentation. Tours of the INET research facilities and the High Temperature Reactor (HTR-10) construction site followed the meeting.

The purpose of the TCM was to provide the opportunity to review the status of design and development activities associated with safety related and economic aspects of HTGRs, and to identify pathways which may provide the opportunity for international cooperation in addressing these issues. The HTGR, as a nuclear heat source for the safe, economic and efficient production of electricity and high temperature industrial processes has, within the past few years, become a significantly increasing influence in the future of nuclear power. Nuclear test facilities with the capability of achieving core outlet temperatures to 950°C are presently under construction in the People's Republic of China and Japan. These plants will be utilized to support HTGR research and development activities, including electricity generation via the gas turbine and validation of high temperature process heat applications. Also, major development programmes focusing on the generation of electricity through the direct cycle gas turbine are in progress by ESKOM, the state electric utility of South Africa, and by a consortium of organizations from the Russian Federation, USA, France and Japan. Other national programmes focusing on research and development of the HTGR are underway including the Netherlands, where an evaluation is being completed on a heat and power co-generation plant utilizing a small direct cycle HTR; in Germany, where the primary focus is centered on basic issues of reactor safety and innovative reactor technology; in Indonesia with the evaluation of process heat applications such as coal liquefaction, hydrogen production and high temperature reforming of methane; and in the USA with the recent re-introduction of national support for the HTGR specifically directed to the burning of weapons plutonium.

The status information presented in several of the papers is as of the time of drafting. Thus other later material should be referenced for more current status information. One source of current information is the IAEA Gas Cooled Reactor Project web site at http://www.iaea.org/inis/aws/htgr/index.html, which also provides links to modular HTGR research and power reactor web sites. However, the technical information provided in the papers, which constitutes the majority of the information presented, remains valid.

The TCM was opened by Professor Z. Wu, Director of INET, and Mr. J. Luo on behalf of the IAEA. Professor Wu indicated that The People's Republic of China now has a population of approximately one and one quarter billion people. The electrical requirements necessary to support the future societal development needs for the people of this vast country are extensive.

Currently, approximately three-quarters of the energy supply in China is from coal. This has placed a burden on the environment and a high demand on the transportation infrastructure. The need for extensive nuclear power development within China is significant. Mr. Luo indicated the timeliness and importance of the TCM based on current and anticipated HTGR activities of Member States comprising the IWGGCR. He indicated that the meeting was convened as an activity of the IAEA in the application of its mission to foster the exchange of scientific and technical information regarding the peaceful use of atomic energy throughout the world. Specifically to the HTGR, he also reviewed the proposed activities within the Agency's gas cooled reactor project scheduled for 1999.

The HTR-10 Test Module is a major project in the Chinese National High Technology Programme and is currently under construction at the INET research site northwest of Beijing. Construction of the reactor building was completed in October 1997 and initial criticality is scheduled for late 1999. The objectives to be achieved with the HTR-10 include the evaluation of the design, operation and safety aspects of the HTGR, to test and validate its co-generation capabilities including the gas turbine for generation of electricity, to support the development of nuclear process heat applications, and as an experimental and irradiation facility for HTGR related component and system evaluation. The design of the HTR-10 is significantly influenced by the passive safety features of the HTGR. The safety philosophy for this plant deviated from the traditional approach for nuclear power plants which relies on redundant and diverse active components and systems including their power supplies. This test reactor will serve to demonstrate passive safety features and will be instrumental in support of future licensing and regulatory developments for the HTGR. As the HTR-10 is a new generation of nuclear power plant, there has been extensive development efforts by INET in its components and systems. Typical of this is evaluation of the safety characteristics of the core pressure vessel which was evaluated for the case of a large rupture accident and included studies on the effects of pressure loss and associated transient stresses. INET is also involved in the development of future applications of the HTGR including the desalination of seawater through the energy source of the HTGR. In this regard, a techno-economic analysis has been developed to assess diverse desalting systems. Initial comparative analyses has shown the steam turbine-MED as the favorable choice for the dual production of potable water and electricity.

Construction of the High Temperature Engineering Test Reactor (HTTR) at the Japan Atomic Energy Research Institute's (JAERI) facilities in Oarai, Japan, is now complete. Initial fuel loading of this 40 MWt test reactor continues with first criticality achieved on 11 November 1998, with an annular core fuel configuration. Annular core physics tests will include control rod reactivity worth, scram reactivity, neutron flux distribution, excess reactivity and reactor noise analysis. Subsequent fuelling of the full core will then proceed followed by zero power physics tests including those similar to the annular core and also including tests to determine maximum reactivity insertion rate, excess reactivity, shutdown margin, nuclear power correlation and the temperature coefficient of reactivity. Rise-to-power tests will be conducted to confirm plant design, validate respective codes, demonstrate typical HTGR safety features and confirm the integrity of high temperature components.

A major safety component of the HTGR is the coated fuel particle. To initially fuel the HTTR, Japan's Nuclear Fuel Industries Ltd. established the fabrication technology and successfully produced approximately 900 kgU of coated fuel particles. Testing of this fuel resulted in the quality values of $8x10^{-5}$ for the SiC defective fraction and $2x10^{-6}$ for the bare uranium fraction. The safety evaluation of the HTTR required confirmation that there is no chance of core damage and that the barrier design against fission product release is appropriate. One requirement to assure that the maximum temperature of the reactor pressure boundary does not exceed permissible values was to demonstrate that the helium circulator will brake within ten seconds following a pressurized water cooler pipe rupture and reactor scram. Upon demonstration, the DC electrical braking system designed for the HTTR circulators allowed the pressurized water cooler temperature piping to reach 368 degrees °C, well within the accident limit of 650 °C.

The HTTR will be utilized to establish and improve on HTGR related technology, for the performance of innovative research, as a test facility for fuel and materials irradiation, and to demonstrate process heat applications such as hydrogen production. JAERI currently has under design a hydrogen production system which will utilize steam reforming of natural gas with HTTR nuclear heat of 10 MWt and a core outlet temperature of 905°C. This project is beginning with an out-of-pile test facility to simulate key components on a scale of one to thirty.

The safety attributes, high thermal efficiency, flexibility of high temperature heat applications such as electricity generation and industrial processes, and low capital and operating costs are the key attributes in seeking commercialization of the HTGR. Two specific programmes are currently under design for the generation of electricity through the use of an HTGR coupled to a closed cycle gas turbine power conversion system. These include the Gas Turbine-Modular Helium Reactor (GT-MHR) and the Pebble Bed Modular Reactor (PBMR). A consortium consisting of organizations belonging to the Russian Ministry on Atomic Energy (MINATOM) and companies from the USA (General Atomics), France (FRAMATOME) and Japan (Fuji Electric) are combining their experience and knowledge in the HTGR and the design and fabrication of components such as recuperators and turbo-compressors for development of the GT-MHR. Conceptual design has been completed on this 600 MWt/293 MWe plant which is currently under development for the destruction of weapons plutonium, but with the longer term goal of commercial deployment. The next stage of development is in preliminary design of the plant which will begin early 1999. Most of the design work on the GT-MHR is being performed within the nuclear organizations of the Russian Federation with financial and management/technical support from all members of the consortium. A recent significant development in the advancement of the GT-MHR is the authorization of financial support by the US government on a matching resource basis with MINATOM. Although the GT-MHR is initially to utilize a weapons plutonium fuel cycle which has the capability of achieving a burnup approaching 95%, the versatility and flexibility of this core will allow for the application of a wide range of diverse fuel cycles. Fuel derived from uranium, thorium and a variety of plutonium grades is under consideration for long term applications in the GT-MHR.

ESKOM, the state utility of South Africa, has completed a detailed technical and economic evaluation of the PBMR as a power generation source for future additions on their electrical grid. ESKOM's determination is that the PBMR represents the nuclear option of choice, as well as a viable and attractive investment opportunity for commercialization. The conceptual design of this plant is now largely complete and it features a pebble bed HTGR of 265 MWt coupled to a power conversion system utilizing the closed cycle gas turbine for an electric output of 117 MWe per module. The projected advantages of the PBMR as a power source for the South African electrical system include the capability for distributed generation, particularly along the coast, short construction time, small unit size with excellent load following characteristics, low environmental impact and economic projections of being competitive with power generation using coal. Commercially, the PBMR is seen to be a viable and attractive investment opportunity in that there is adequate technology within South African industry with a limited anti-nuclear movement and a non-prescriptive nuclear licensing environment, a cost structure for power generation that imposes a strong cost cap, and the backing of a very large utility with credibility and a good public image.

Both the PBMR and the GT-MHR are anticipating plant capital and operating costs significantly below those being experienced by nuclear power plants recently placed in operation or currently under construction. Upon commercialization, the PBMR is projecting a current capital cost of less than US$1,000 per installed kW with an operating cost of < 1.5cents/kWh based on 6% discount and a 40 year plant life. The GT-MHR projects a capital cost of US$928 million (<US$900 per kW installed) with a generation cost of 1.76 cents/kWh for a uranium fuelled four module commercial plant. The economic evaluations of these two plants were derived independently from each other and result from the simplicity of plant design, modularized construction and the high plant efficiency achievable with the closed cycle gas turbine.

The unique safety characteristics of the HTGR, with its slow response to accident conditions and ability to rely on passive rather then active safety systems, is a significant area of continued development by virtually all Member States of the IWGGCR. A major reason for this includes the capability to significantly reduce plant complexity and corresponding cost without a reduction in safety to the public or environment. In this regard, Mitsubishi Heavy Industries is investigating possible changes in the safety and code class to allow expansion in the use of non-nuclear grade equipment in the plant. JAERI also continues to evaluate the safety characteristics of advanced HTGRs including the development of a code to model reactor dynamics and heat removal from the surface of the reactor pressure vessel for the 400 MWt severe accident free HTR (SFHTR). It has been analytically determined that no reactor melt will occur, even under the worst case design basis accident. Future plans are to perform the safety demonstration test in the HTTR as validation of this code.

The South African nuclear regulatory authority is currently in the first stage of safety review of the PBMR. The licensing approach envisioned for this plant would include a design basis which respects prevailing international norms and practices and a quantitive risk assessment in accordance with the fundamental safety standards of the South African Council for Nuclear Safety (CNS). As this is a new advanced nuclear power plant, it will be necessary to establish general design criteria and design rules in order to assure that the PBMR complies with CNS's currently established risk criteria, and that, as a minimum, the same degree of protection is afforded to the public, operator and environment as that required for the current generation of nuclear plants, including societal trends with regard to levels of safety.

Development activities incorporating the gas turbine are also underway in the Netherlands and Japan. The Nuclear Research and Consultancy Group is developing a conceptual design of an HTGR for combined generation of heat and power for industry. The Advanced

Atomic Co-generator for Industrial Applications (ACACIA) plant incorporates a 40 MWt pebble bed HTGR for the production of 14 MW of electricity and 17 tons of steam (10 bars, 220 degrees) per hour. Transient analysis development work in support of this plant is continuing and includes the calculational coupling between the (Panthermix) high temperature reactor code and the (Relap5) thermal hydraulics code for the energy conversion system. Evaluation of this coupling has resulted in a more realistic simulation of the entire plant system.

JAERI continues investigation of new designs for incorporation of the closed cycle gas turbine with an HTGR. The preliminary design of a 600 MWt plant utilizing the monolithic fuel compact, control rod sheaths of carbon/carbon composite material and development of a plate-fin recuperator model were carried out in 1997. Currently, design work on the smaller, 300 MWt direct cycle plant is in process. This plant includes an annular core pebble bed reactor and the incorporation of thermal insulation internal to the reactor pressure vessel to achieve a plant efficiency of approximately 50%. Investigation into improvements in advanced HTGRs are also being carried out within Japanese industry and educational organizations. Fuji Electric Co. and Tokai University have completed experiments to determine the fundamental operating characteristics for use of a heat pipe decay heat removal system. It was determined that by adopting the use of a variable conductance heat pipe, it is possible to have a fully passive decay heat removal design which would minimize heat loss during normal operation and achieve lower reactor vessel temperatures during accidents.

The National Atomic Energy Agency of Indonesia is in the process of developing nuclear design codes for fuel management and safety analysis of HTGRs. These codes include the simulation of flow of pebble fuel for the once-through-then-out HTGR core as well as multi-pass pebble bed fuelling schemes. Two codes have also been developed to investigate safety and accidents in a pebble-bed HTGR. These include simulation of core reactivity accidents and plant depressurization. Simulation of the severest accident, i.e., depressurization resulted in a fuel temperature of 1600°C in the upper core after approximately 10 hours, and approximately 1800°C at 23.5 hours, assuming no corrective actions are taken.

Graphite is a key component in all HTGR cores, both as a structural member and as a moderator. The design life of these reactors is governed by the ageing of the graphite core primarily because of fast neutron damage. Due to the polycrystalline nature of nuclear graphites, the life of a graphite component in a nuclear reactor can be related to the radiation-induced damage to the individual crystals. Nuclear graphites typically shrink with age and then a "turnaround" occurs resulting in swelling. The safety implications of these changes are very important and AEA Technology and the University of Manchester have developed a two-phase finite element model of a single graphite crystal to investigate this behaviour.

Analysis of international R&D trends and the development of associated strategies to achieve commercialization of the HTGR are of primary focus of the Research Association of HTGR Plant (RAHP). This organization represents the private and industrial sector of Japan for HTGR development and is currently investigating the fuel cycle aspects and the international programmes of small modular HTGRs. RAHP has shown considerable support for the Agency's GCR programme, particularly the R&D related activities and is currently helping in the development of international HTGR data telecommunications.

Coordination of international R&D activities, including the dissemination and archiving of information and data related to existing and past HTGR development work has been of primary importance to the IWGGCR. The sustainability and advancement of nuclear energy has been supported by the European nuclear industry through its "Michelangelo Initiative" and the "Safety-related Innovative Nuclear Reactor Technology Elements-R&D" funded by the European Commission. The western European countries of the IWGGCR have formed a partnership (European Concerted Action on Innovative HTR) for the coordinated development of the HTGR which will make maximum use of available technology. Advancements in electronic communication such as use of the internet and world wide web are also being utilized, with the HTGR now having its own "Homepage", as noted earlier. Collectively, these activities have helped form the basis for a pending new Coordinated Research Programme (CRP) on Conservation and Application of HTGR Technology, which is focused on HTGR related R&D and the conservation and application of HTGR technology.

This TCM provided a forum for participants from research organizations and industry of IWGGCR Member States to share the results of their individual programmes in the advancement of the HTGR as a future nuclear energy source for both the generation of electricity and as a high temperature process heat source for industrial applications such as the production of hydrogen. The major focus of this TCM was on the safety related design and economic aspects of the HTGR, and included research developments and a review of the major technological considerations necessary for the commercialization of the HTGR.