Overview of IAEA Co-ordinated Research Project on Evaluation of HTGR Performance

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Abstract

The IAEA conducts Co-ordinated Research Projects (CRPs) to facilitate the exchange of technical information and the conduct of co-operative research and development among participating Member States. An ongoing CRP on Evaluation of HTGR performance is summarized along with a brief description of two recently completed CRPs of relevance to the ongoing work. The scope and schedule of the CRP are reviewed along with a very brief indication of the results established to date. The results of the CRP will be provided to interested IAEA Member States in the form of an interim and a final IAEA TECDOC.

1.0 Introduction

The IAEA facilitates collaborative efforts among Member States through the organization and conduct of Co-ordinated Research Projects (CRPs). A CRP is typically 3 to 5 years in duration involving 5 to 15 Member States. The scope and schedule of a CRP is established by IAEA staff based on expressed interest and recommendations from Member States. The participants provide a substantial majority of the resources required to conduct the CRP, organizing and performing the work and documenting the results. Typically, the IAEA contributes staff time for facilitating the CRP, support for travel to periodic Research Co-ordination Meetings (RCMs), and in some cases a small funding contribution to participants from developing countries.

The CRP on Evaluation of HTGR Performance, initiated in October 1997 and scheduled to be completed in October, 2004 includes the following scope:

- Modular HTGR reactor physics benchmark analysis

- Modular HTGR hermal hydraulic transient benchmark analysis
- Demonstration of Modular HTGR safety characteristics

Benchmark problems have been defined for comparison of analytical results with experimental data from HTR-10, HTTR, and PBMR (ASTRA critical facility) projects. In addition, a code comparison problem has been defined by the GT-MHR project. IAEA Member States participating in the CRP include China, France, Germany, Indonesia, Japan, the Netherlands, the Russian Federation, South Africa and the United States. The work of the CRP expands and complements the results of the following recently completed CRPs:

- ***CRP on Validation of Safety Related Physics Calculations for Low Enriched HTGRs*** - This CRP was formed to address core physics needs for advanced gas-cooled reactor designs. It focused primarily on development of validation data for physics methods used for core design of HTGRs fuelled with low enriched uranium. Experiments were conducted for graphite moderated LEU systems over a range of experimental parameters, such as carbon-to-uranium ratio, core height-to-diameter ratio, and simulated moisture ingress conditions, which were defined by the participating countries as validation data needs. Key measurements performed during the CRP provide validation data relevant to current advanced HTGR designs including measurements of shutdown rod worth in both the core and side reflector, effects of moisture on reactivity and shutdown rod worth, critical loadings, neutron flux distribution and reaction rate ratios. Countries participating in this CRP included China, France, Germany, Japan, the Netherlands, Poland, the Russian Federation, Switzerland, and the United States of America. Work under the CRP has been completed and a final report in the form of an IAEA TECDOC is in process.
- ***CRP on Heat Transport and Afterheat Removal for Gas-Cooled Reactors Under Accident Conditions*** - Within this CRP, the participants addressed the inherent mechanisms for removal of decay heat from GCRs under accident conditions. The objective was to establish sufficient experimental data at realistic conditions, and validated analytical tools to confirm the predicted safe thermal response of advanced gas cooled reactors during accidents. The scope included experimental and analytical investigations of heat transport by natural convection, conduction and thermal radiation within the core and reactor vessel, and afterheat removal from the reactor vessel. Code-to-code comparisons and code-to-experiment

benchmarks were performed for verification and validation of the analytical methods. Countries participating in this CRP included China, France, Germany, Japan, the Netherlands, the Russian Federation and the United States of America. Work under the CRP has been completed and a final report in the form of an IAEA TECDOC is in process.

This paper summarizes the CRP on Evaluation of HTGR Performance based on the information exchanged through the third research co-ordination meeting in March 2001.

2.0 CRP Scope

The primary activities of the CRP include the specification of experimental benchmark problems and the exchange of data necessary to conduct analyses of the problems and compare results. The scope of the CRP centres around problems identified for research reactors and power plant designs as summarized below. In each case the participant specifying the problem was responsible for providing the necessary facility data, defining the problem in detail, and compiling and comparing the analysis results. The majority of information exchanged through 2000 was related to the reactor physics benchmark problems.

2.1 Reactor Physics Benchmark Problems

Four sets of reactor physics benchmark problems have been defined for the HTTR, HTR-10, the GT-MHR, and the PBMR (via the ASTRA critical facility)

2.1.1 HTTR

The following six benchmark problems were defined for the HTTR facility:

- HTTR-FC(Phase 1) – (First Criticality) The first core loading of HTTR was conducted by initially loading the reactor with graphite blocks, then replacing the graphite blocks with fuel blocks one column at a time. The outer ring of fuel was loaded first, then successive inner rings. The problem involved prediction of number of fuel columns required to achieve the first criticality, including the excess reactivity when the column resulting in criticality was fully loaded.
- HTTR-FC(Phase 2) – (First Criticality) The initial results generally underpredicted the number of fuel columns required, thus a second phase of calculations was conducted. This

involved the following adjustments to the data used in the original calculation:

1) Allowance for air in the graphite voids;

2) Revised impurity contents in the initially loaded graphite blocks;

3) Aluminum in the temporary neutron detector holders.

- HTTR-CR – (Control Rod Worth) Evaluation of the control rod insertion depths at the critical condition for the three cases listed below. All control rod insertion levels to be adjusted on the same level except three pairs of control rods in the outermost region in the side reflectors, which were assumed to be fully withdrawn.

  1) 18 columns (thin annular core);

  2) 24 columns (thick annular core);

  3) 30 columns (fully-loaded core).

- HTTR-EX – (Excess Reactivity) Determination of the excess reactivity for the three cases mentioned above, assuming moderator and fuel temperatures of 300°C and one atmospheric pressure of helium as the primary coolant condition.

- HTTR-SC – (Scram Reactivity) Scram reactivity for a 30 column core fully loaded with fresh fuel for the following two cases:

  1) All reflector CRs are inserted at the critical condition;

  2) All CRs in reflector and core are inserted at the critical condition.

- HTTR-TC – (Temperature Coefficient of Reactivity) Isothermal temperature coefficients for a fully-loaded core should be evaluated from 280 to 480°K, assuming a fixed control rod position based on critical conditions at 480°K.

The following additional benchmarks were proposed at the third RCM:

- HTTR-PCR – Calculation of control rod insertion depth at 9, 20 and 30 MWt, assuming ten days of burnup in each case to reach equilibrium levels of xenon and samarium.
- HTTR-PTC – Calculation of temperature coefficients at 9 and 20 MWt, given control rod positions at each power level and considering the buildup of xenon and samarium.

2.1.2 HTR-10

The following benchmark problems were defined for the HTR-10 Facility

- HTR-10FC – (First Criticality) Amount of loading (given in loading height, starting from the upper surface of the conus region) for the first criticality: K_{eff}=1.0 under the atmosphere of helium and core temperature of 20 °C, without any control rod being inserted.
- HTR-10TC – (Temperature Coefficient of Reactivity) Effective multiplication factor K_{eff} of full core ($5m^3$) under helium atmosphere and core temperature of 20 °C, 120 °C and 250 °C respectively, without any control rod being inserted.
- HTR-10CR – (Control Rod Worth) The following sets of conditions are defined:
    1) Reactivity worth of the ten fully inserted control rods under helium atmosphere and core temperature of 20 °C for full core;
    2) Reactivity worth of one fully inserted control rod (the other rods are in withdrawn position) under helium atmosphere and core temperature of 20 °C for full core;
    3) Reactivity worth of the ten fully inserted control rods under helium atmosphere and core temperature of 20 °C for a loading height of 126cm;
    4) Differential reactivity worth of one control rod (the other rods are in withdrawn position) under helium atmosphere and core temperature of 20 °C for a loading height of 126cm, when the lower end of the control rod is at the following axial positions: 394.2cm, 383.618cm, 334.918cm, 331.318cm, 282.618cm, 279.018cm, 230.318cm.

2.1.3 GT-MHR

The following code comparison problems are defined for the GT-MHR design with plutonium fuel:

- Cell Calculations

1) Dependence of K_{inf} for unit cell versus burnup;

2) Content of the main isotopes vs. burnup.

- Reactor Calculations

1) Isothermal reactivity coefficients versus temperature at the beginning and at the end of fuel cycle;

2) Control rod worth in the active core;

3) Control rod worth in the side reflector.

2.1.4 PBMR/ASTRA

The PBMR benchmarks are defined with respect to the ASTRA critical facility, which is being used to provide reactor physics data for the PBMR design.

- Core Height for Criticality - The requirement for this task is to determine the height at which the ASTRA facility will achieve criticality, assuming that no control rods or shutdown rods are inserted.

- Control Rod Worth - This task involves the determination of the worth of control rods with the pebble bed raised to a height of H_{pb}=268.9 cm

  1) The Worth of Control Rods Depending on their Position in the Side Reflector - This task requires the determination of the control rod worth for 6 distances from the core boundary to the axis of the control rod.

  2) Interference of a System of Control Rods - Control rods worth are to be determined for single control rods as well as for combinations of 2 and 3 rods. For these combinations it is necessary to determine the worth as well as the interference coefficient.

- Control Rod Differential Reactivity - This task requires the evaluation of the differential reactivity of the CR5 and MR1 control rods as a function of depth of insertion.
- Investigation of Critical Parameters with Varying Height - For this task it is required to determine the change in reactivity due to an increase in the height of the ASTRA critical assembly pebble bed.

2.2 *Thermal Hydraulics Benchmark Problems*

Thermal hydraulics problems have been defined for the HTTR facility as follows:

- HTTR-VC – (Vessel Cooling) - Participants should predict heat removal by the Vessel Cooling System (VCS) and temperature profile on the surface of the VCS side panel at 9 and 30 MW power operation. The analytical results will be compared with measured heat removal and temperature profile. Conditions for this benchmark problem such as power distribution, mass flow rate of coolant, reactor inlet temperature, etc. are given by JAERI.
- HTTR-LP – (Loss of Off-Site Electric Power) – This benchmark problem requires evaluation of the transient response of the HTTR to a loss of off-site electric power from initial steady state operation at 20 and 30 MWt. During normal operation, called parallel loaded operation, the intermediate heat exchanger, and the primary and secondary pressurized water coolers are operated simultaneously, removing heat from the primary system in parallel. The following problems are defined:

  1) HTTR-LP(15MW) - Analytical simulation of the transient behaviour of the reactor and plant during a loss of off-site electric power from normal operation at 15 MW thermal power
  2) HTTR-LP(30MW) - Analytical simulation of the transient behaviour of the reactor and plant during a loss of off-site electric power from normal operation at 30 MW thermal power

  In both simulation cases, the items to be estimated on a time dependent basis are as follows; (1) hot plenum block temperature, (2) reactor inlet coolant temperature, (3) reactor outlet coolant temperature, (4) primary coolant pressure, (5) reactor power, (6) heat removal of the auxiliary heat exchanger. Estimation duration is for 10hr from the beginning of the loss of off-site electric power.

During the third RCM, JAERI proposed the following additional thermal hydraulic benchmark problems for consideration by the CSIs:

- HTTR-CFR – (Core Flow Reduction) – Shutdown of 2 of the 3 helium circulators from single loaded steady state operation at 850°C and various power levels, with control rods kept withdrawn.
- HTTR-RI – (Reactivity Insertion) – Withdrawal of the central control rod pair for various distances from single loaded operation at various power levels.

2.3 *Demonstration of HTGR Safety Characteristics*

Participants in the CRP will review the definition, conduct, and data gathering plans for safety demonstration tests to be conducted with the HTTR and HTR-10 facilities. Representatives from each facility will provide information on planned tests for review by the CRP. Specific aspects of some of the tests may be identified as benchmark problems for the CRP (e.g., HTTR-LP).

3.0 CRP Schedule

The CRP schedule is centred around the RCMs, which serve as forums to present and discuss information benchmark problems, including problem definition as well as experimental and analytical results. Sufficient contractual agreements with participating Member States were in place by October 1997 to initiate the CRP, with a five-year duration ending in October 2002. In 2000, the International Working Group on Gas Cooled Reactors recommended that the CRP be extended two additional years. This recommendation was reviewed and approved by the IAEA, resulting in extension of the CRP to October 2004. The results of the first three RCMs are briefly summarized below, with benchmark problems referenced in the discussions defined in the previous section.

3.1 *First Research Co-ordination Meeting*

The first RCM was initially scheduled to be held in Japan in March 1998, but administrative difficulties required rescheduling, and the meeting was held in Vienna in August 1998. CRP participants at the time of the first RCM included representatives from China, Germany, Indonesia, Japan, the Netherlands, the Russian Federation and the United States. Information exchanged in advance of the RCM allowed for presentation and discussion of results on the HTTR-FC, HTTR-CR and HTTR-EX benchmarks. Also, initial discussions were held regarding the definition of the HTTR-SC, HTTR-TC, HTR-10 SC, HTR-10 TC and HTR-10 CR benchmark problems. Participants gave indications of intent regarding participation in the active benchmarks, and the date and location of the second RCM were tentatively agreed.

3.2 *Second Research Co-ordination Meeting*

The second RCM was hosted by the Institute of Nuclear Energy Technology of Tsinghua University in Beijing, China in October 1999,. Participants included representatives of the Member States attending the first RCM plus representatives from South Africa and France. Discussions were held regarding HTTR-FC, HTTR-CR and HTTR-EX, including calculational results completed after the first RCM and consideration of data from the HTTR initial criticality, which had been achieved in November 1998. Results were also presented and discussed for HTTR-SC, HTTR-TC, HTR-10 SC, HTR-10 TC and HTR-10 CR benchmarks. Additional benchmarks tentatively defined included HTTR-FC(Phase 2), HTTR-VC, HTTR-LP, GT-MHR code comparisons, and PBMR/ASTRA benchmarks. Initial indications of intent to participate in the additional benchmark problems were provided by the meeting participants, and the third RCM was tentatively scheduled for March 2001 in Oarai, Japan.

3.3 Third Research Co-ordination Meeting

The third RCM was hosted by the Japan Atomic Energy Research Institute in Oarai, Japan in March 2001. Participants included representatives of all nine Member States active in the CRP. Results were presented and discussed for the benchmarks HTTR-FC, HTTR-CR, HTTR-EX, HTTR-SC and HTTR-TC, including additional data obtained since the second RCM, as well as for HTR-10 FC and HTR-10 CR. The PBMR benchmarks were reviewed along with those of the GT-MHR project, and PBMR burnup calculations and approach to equilibrium core were presented. Thermal hydraulic benchmark problems HTTR-VC and HTTR-LP were discussed, including review available relevant HTTR data from the power ascension programme Japan proposed two reactor physics benchmarks (HTTR-PCR and HTTR-PTC) and two thermal hydraulics benchmarks (HTTR-CFR and HTTR-RI) for consideration by the CSIs. Safety demonstration test plans for the HTTR and HTR-10 facilities were also briefly presented and discussed. The fourth RCM was tentatively scheduled for October 2002 in Vienna.

3.4 *Remaining Activities*

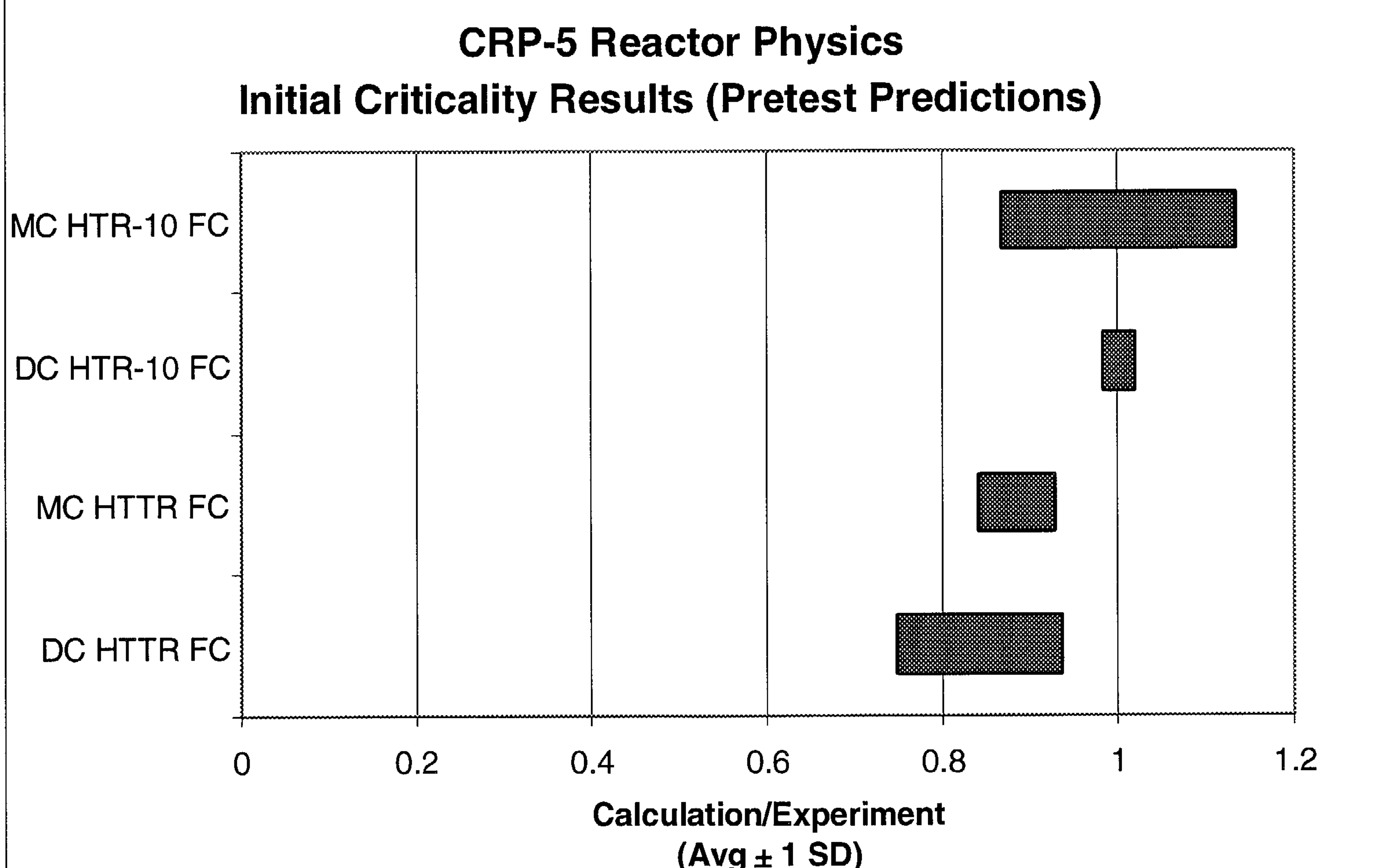
At the third RCM it was agreed that the HTTR and HTR-10 reactor physics benchmarks and the HTTR thermal hydraulics benchmarks that were complete or nearing completion would be documented in an initial TECDOC to be available in draft form in advance of the next RCM. Ongoing activities are expected to focus mainly on the thermal hydraulic benchmarks, including additional problems that may be defined in conjunction with safety demonstration testing planned at HTTR and HTR-10.

4.0 Overview of Interim Results and Conclusions

The results of the CRP will be documented in detail in two IAEA TECDOCs, following extensive review among the participating Member States. The following observations are noted:

- The experimental data being produced at HTTR, HTR-10, and the PBMR/ASTRA facility present an important opportunity to assess the accuracy of available codes and methods for predicting reactor physics and thermal hydraulic behaviour of modular HTGRs.
- The international exchange of information on computer codes, models and assumptions provides an opportunity to enhance the accuracy and efficiency of methods used by the participating Member States.
- The increasing interest and activity in the development of modular HTGR technology increases the value and importance of the work of this CRP. In particular, the experimental data may be of considerable value for code validation by organizations not participating in the CRP.
- Much of the benefit of the CRP occurs among the participating Member States as the work is performed and information is exchanged. However, timely and effective documentation of the results in an IAEA TECDOC is essential to obtain broader value and lasting benefits to all Member States.
- A combined summary of the results for first criticality of HTR-10 and HTTR is shown by the figure on the following page (DC – Diffusion Calculations, MC – Monte Carlo). As seen, there was a considerable spread in the results in three of the four problems. While these

smaller reactors (and in the case of the HTTR first criticality a very thin annular core) may present more of a challenge than larger systems due to the high leakage, the need for and value of the work being conducted by the CRP is underscored by the results.



MC – Monte Carlo Results
DC – Diffusion Calculation Results