IAEA Coordinated Research Projects on Core Physics Benchmarks for High Temperature Gas-Cooled Reactors

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Abstract – *High-temperature Gas-Cooled Reactor (HTGR) designs present special computational challenges related to their core physics characteristics, in particular neutron streaming, double heterogeneities, impurities and the random distribution of coated fuel particles in the graphite matrix. In recent years, two consecutive IAEA Coordinated Research Projects (CRP 1 and CRP 5) have focused on code-to-code and code-to-experiment comparisons of representative benchmarks run by several participating international institutes. While the PROTEUS critical HTR experiments provided the test data reference for CRP-1, the more recent CRP-5 data has been made available by the HTTR, HTR-10 and ASTRA test facilities. Other benchmark cases are being considered for the GT-MHR and PBMR core designs. This paper overviews the scope and some sample results of both coordinated research projects.*

I. INTRODUCTION

Modular High Temperature Gas-cooled Reactor (HTGR) designs are one of the reactor concepts being considered by some for future nuclear power plant deployment. Gas-cooled reactor design concepts have been evolving since the 1940's and in recent years there have been a surge of global interest in their modular variants due to their claimed features of enhanced safety and improved economics. HTGR fuel is characterized by a spherical kernel of TRISO coated particles, with a diameter in the range of 500 microns or less and featuring three levels of coating. In the block design, the coated fuel particles are bonded within a graphite matrix to form cylindrical compacts while in the PBMR design, the particles are also imbedded in a graphite matrix but in the form of spherical pebbles. The combination of coated fuel particle design, graphite moderator and helium coolant, gives the HTGR design its distinctive features of high core thermal capacity and high core outlet coolant temperatures, allowing increased efficiency in both electricity production as well as process heat applications such as hydrogen production.

In recent years, several international institutes have joined hands within the framework of two consecutive IAEA coordinated research projects (CRPs), with the objective of validating existing HTGR core calculation methods, by benchmarking them against each other and against available test data. In this respect, the PROTEUS critical facility in Switzerland, played a central role in providing critical and reaction rate data for CRP-1, while data for the more recent CRP-5 has been provided by the HTTR reactor in Japan, the HTR-10 reactor in China and the ASTRA facility in Russia. In addition, additional benchmarks are being considered for the GT-MHR and the PBMR core designs. The codes used vary from detailed Monte Carlo methods to a combination of cell transport and core diffusion models.Streaming effects, double-heterogeneities, impurities and the random distribution of coated fuel particles in the graphite matrix are some of the challenges encountered in these calculations. In the next section, we present an overview of CRP-1, while Section III covers the status of CRP-5.

II. HTR- PROTEUS BENCHMARKS[1]

CRP-1 was completed in 1997 and made use of test data provided by the HTR-PROTEUS experimental facility at the Paul Scherrer Institute in Switzerland. The HTR-PROTEUS facility consisted of a cylinder of graphite, 3304mm in height and 3262mm in diameter. A central cavity, with base 780mm above the bottom of the lower axial reflector and having a horizontal cross-section in the form of a 22 sided polygon with a flat-to-flat separation of 1250mm, contained fuel (16.7% enriched) and moderator (pure graphite) pebbles, either randomly arranged or in one of several different geometrical arrangements. Additional graphite filler pieces were used at the core-reflector boundary to support the irregular outer surface of the deterministic pebble arrangements. A removable structure in the form of a graphite cylinder of height 780mm contained within an aluminum tank formed the upper axial reflector, normally with an air gap between it and the top of the pebble bed. An aluminum "safety ring", which was designed to prevent the upper axial reflector from falling onto the pebble-bed, in the case of an accident, was located some 1764mm above the floor of the cavity.

Critical experiments were conducted for several graphite moderated core configurations of the pebble bed type, over a range of carbon-to-uranium ratios, core height-to-diameter ratios and simulated moisture concentrations. Some of the configurations had a controlled deterministic packing fraction while others were random. The tests included critical loadings, control rod worth, reaction ratio distributions and kinetic parameters. Water ingress was also simulated by use of equivalent polyethylene rods.

Calculation results obtained from 11 international institutes participating in the CRP were compared to test data. Codes used varied from diffusion to transport to full Monte Carlo methods. In general, criticality was more closely reproduced by Monte Carlo methods which better capture spatial and energy heterogeneity details. This understandably comes at the expense of increased computational cost. Calculations also show that diffusion results are improved when streaming effects are corrected for. Sample results for "U-238 capture-to-U-235 fission reaction ratios" are shown in Table 1 and show good comparison to experimental data.

III. CRP-5 BENCHMARKS[2]

CRP-5, another IAEA-sponsored research project involving 11 international institutes, was initiated as a follow-up to CRP-1. Critical data was made available to CRP-5 participants by the HTTR, HTR-10 and ASTRA facilities. Currently, additional benchmark cases are being considered for the PBMR and GT-MHR designs. Results for a first set of benchmarks have already been published, while those for a second set are still awaiting completion. In addition to core physics, the CRP has also included some thermal-hydraulic benchmarks related to HTTR decay heat removal and a South African Pebble Bed Micro Facility simulating key PBMR turbo-machinery components.

A. <u>HTTR BENCHMARKS</u>

The HTTR reactor is a 30 MW high temperature gas-cooled test reactor, operated by the OARAI Japan Atomic Energy Agency labs. The core consists of prismatic hexagonal blocks 580mm in height and 360 mm in width across the flats. Heterogeneous enrichment and burnable poisons are used to optimize power distribution. Heat removal is provided by a dual system, including a helium to helium heat exchanger as well as a steam generator. A top helium core outlet temperature of 950 ºC has been demonstrated.

A total of six benchmark problems were defined for the HTTR facility as follows:

1. Initial criticality (Pre-Test)

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, followed by successively inner rings. The benchmark entails prediction of the number of fuel columns required to achieve the first criticality.

2. Initial criticality (Post-Test)

The initial results generally under predicted 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:

- Allowance for air in the graphite voids;
- Revised impurity contents in the initially loaded graphite blocks;
- Accounting for aluminum in the temporary neutron detector holders.

3. Control rod worth

The benchmark entails evaluation of critical control rod positions for the following loading configurations:

- 18 columns (thin annular core);
- 24 columns (thick annular core);
- 30 columns (fully-loaded core).

4. Excess Reactivity

The benchmark entails determination of the excess reactivity for the three cases mentioned above, assuming moderator and fuel temperatures of 300ºC and atmospheric pressure of helium as the primary coolant condition.

5. Scram Reactivity

The benchmark entails determination of the scram reactivity for a 30-column core fully loaded with fresh fuel, for the following two cases:

- All reflector control rods are inserted at the critical condition;
- All reflector and core control rods are inserted at the critical condition.

6. Temperature Coefficient of Reactivity

Isothermal temperature coefficients for a fully-loaded core are to be evaluated from 280 to 480ºK.

Sample results obtained by some participating institutes for the initial criticality test are listed in Table 2 and discrepancies in the critical number of assemblies show variations from one up to three assemblies.

B. HTR-10 BENCHMARKS

HTR-10 is a 10 MW high temperature gas cooled test reactor operated by the INET Institute of Tsinghua University in China. The core is a pebble bed design currently using a steam cycle for core heat removal. Plans however exist for introducing helium-to-helium cooling and a gas turbine design. The following HTR-10 benchmark problems were defined for CRP-5:

1. First Criticality

The benchmark entails prediction of the loading height, starting from the upper surface of the cone region, for the first criticality under helium at atmospheric conditions and a core temperature of 20 °C, with all control rods out.

2. Temperature Coefficient of Reactivity

The benchmark entails calculating the core temperature coefficients of reactivity at 20 °C, 120 °C and 250 °C.

3. Control Rod Worth

Integral multi-rod worth as well as single rod differential worth are to be calculated for different core configurations.

4. Control Rod Withdrawal Without Scram

The transient is initiated at 3 MW by withdrawing a control rod at operational speed, introducing ~5 mk of reactivity in 128 s. The protection system is disabled to avoid control rod scram. Nine seconds into the transient, primary helium circulation is stopped and the primary system is isolated from the secondary side. The evolution of the transient power response is to be determined.

5. Loss of Primary Flow without Scram

The transient is initiated at 3 MW by stopping primary helium circulation, with the protection system disabled to avoid control rod scram. The evolution of the transient power response is to be determined.

Sample results obtained by some participating institutes for the HTR-10 initial criticality test are listed in Table 3 and also show variations in critical height prediction. Errors in dummy sphere densities, boron impurities and ambient temperature may have been partly responsible for the observed discrepancies.

C. OTHER BENCHMARKS

Other HTGR core physics benchmarks being considered within the scope of CRP-5 address the GT-MHR, a Russian Plutonium-fuelled block design concept as well as the South African PBMR design and related critical tests performed at the Russian critical facility ASTRA. Results of these benchmarks are awaiting completion.

IV. CONCLUDING REMARKS

Core physics benchmarks defined within the scope of the two IAEA CRPs, CRP-1 and CRP-5 have been overviewed. The benchmarks provided a useful framework for assessing HTGR core calculation uncertainties related to challenges posed by streaming effects, double-heterogeneities, impurities and the random distribution of coated fuel particles in the graphite matrix. Useful data has been provided by all participating institutes, in the form of test data, calculation data or in some cases both.

Table 1: HTR-PROTEUS U-28 Captures/U-25 Fissions : Calculations vs. test data

Core	5	7	8	9
Test data	.187	.096	.152	.096
MICRO X	.192	.098	.156	.098
VSOP	.181	.100		
INAS	.189	.096		
MCNP	.187			

Table 2: HTTR initial criticality test: Pre-test critical number of fuel assemblies predicted by calculations vs. test data

Institute	Diffusion	Monte Carlo
JAEA	17	18
CEA	18	17
FZG	16	
BATAN	18	
OKBM	16	
RRC-KI		17
Experiment	19	

Table 3: HTR-10 initial criticality test: Critical bed height in centimeters predicted by pre-test Calculations vs. test data

Institute	Diffusion	Monte Carlo
INET	126	126
FZG	127	
NRG	125	
HCU-Turkey	119	130
JAEA	113	
ORNL		128
Experiment	123	

REFERENCES

[1] IAEA-TECDOC 1249," Critical Experiments and Reactor Physics Calculations for Low-Enriched High Temperature Gas Cooled Reactors (2001)

[2] IAEA-TECDOC 1382," Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis related to initial testing of the HTTR and the HTR-10 (2003)