9. SUMMARY AND CONCLUSIONS

To address the need for core physics validation data for advanced gas-cooled reactor designs, the IAEA established, in 1990, a CRP on Validation of Safety Related Physics Calculations for low-enriched, gas-cooled reactors. Based on the requirements as expressed by international experts on the occasion of the IAEA Specialists Meeting on Uncertainties in Physics Calculations for Gas-cooled Reactor Cores in May 1990, a comprehensive theoretical and experimental program was established involving 11 institutions in 8 different countries. The following institutes participated in this CRP:

- Institute for Nuclear Energy Technology, Tsinghua University, Beijing, China
- Centre d'Etudes de Cadarache, St. Paul les Durance-Cedex, France
- KFA Research Center, Jülich, Germany
- Japan Atomic Energy Research Institute, Tokai-mura, Japan
- Interfaculty Reactor Institute, Delft University, Delft, the Netherlands
- Energy Research Center, Petten, the Netherlands
- Experimental Machine Building Design Bureau, Nizhny Novgorod, Russia
- Russian Research Center Kurchatov Institute, Moscow, Russia
- Paul Scherrer Institute, Villigen, Switzerland
- General Atomics, San Diego, USA
- Oak Ridge National Laboratory, Oak Ridge, USA

The main objective of the CRP was to fill the gaps in theoretical methods and data used for design and safety analyses of innovative gas-cooled nuclear reactors.

9.1. LEU-HTR PROTEUS PROGRAM

The main activities of the CRP were conducted within an international project at the PROTEUS critical experiment facility at the Paul Scherrer Institute, Villigen, Switzerland. Within this project, critical experiments were conducted for graphite moderated LEU systems to determine core reactivity, flux and power profiles, reaction-rate ratios, the worth of control rods, both in-core and reflector based, the worth of burnable poisons, kinetic parameters, and the effects of moisture ingress on these parameters. These experiments were conducted over a range of experimental parameters such as carbon-to-uranium ratio, core height-to-diameter ratio, and simulated moisture concentration in ten different HTR-PROTEUS configurations.

The HTR-PROTEUS facility can be broadly described as a graphite cylinder of 3.26 m diameter and 3.3 m height, with a central cylindrical cavity of 1.25 m diameter and ~1.7 m height. Reactor shutdown and control were achieved by means of four boron-steel shutdown rods, located symmetrically around the core and four stainless-steel control rods, all situated in the radial reflector. Four safety rods, identical to the shutdown rods, were always maintained in withdrawn positions. The core consisted of 60 mm diameter moderator (pure graphite) and fuel (containing 16.7% enriched UO_2 particles) pebbles located in either deterministic or random arrangements. Measurement devices could be introduced into the vertical channels in the radial reflector as well as in the channels of the deterministic core lattices.

9.2. BENCHMARK CALCULATIONS

Calculational benchmark problems based on some of the initially proposed configurations for the LEU-HTR critical experiments in the PROTEUS facility were prepared and distributed by PSI to the organizations in the CRP in 1990. The benchmarks consist of six graphite-reflected 16.76% enriched-uranium pebble-bed systems of three different lattice geometries and two different moderator-to-fuel pebble ratios (2:1 and 1:2). Calculated results were requested for both unit cells and for the whole reactor.

For the unit cells the following parameters were requested:

- k_{inf} (0) for B^2=0, i.e. production/absorption for B^2=0,
- the critical buckling B^2_{cr} and k_{inf} (B^2_{cr}),
- the migration area M^2,
- the spectral indices rho-28 (ρ□), delta-25 (δ□), delta-28 (δ□) and C^*.

For the whole reactor the following results were requested:

- k_{eff} for the specified dimensions and specified atomic densities,
- the critical pebble-bed core height H_{cr},
- the spectral indices at core center and core averaged,
- neutron balance in terms of absorption, production and leakage, integrated over the pebble-bed core region.

The principal conclusions resulting from the comparison of the benchmark calculations obtained from the different institutes may be summarized as follows:

- The k_{inf} and k_{eff} values agree much better with each other than the spectral indices.
- The important spectral index C^* (ratio of captures in ^{238}U to fissions in ^{235}U) is generally well predicted.
- Larger discrepancies were observed for the δ□ (ratio of fissions in ^{238}U to fissions in ^{235}U) and the δ□ (ratio of epithermal-to-thermal ^{235}U fissions) spectral indices. However, only about 0.2% of all fissions occur in ^{238}U which means that the impact of δ□ variations on the reported k_{inf} and k_{eff} values is negligible. Furthermore, the percentage of fission in ^{235}U occurring above 0.625 eV is about 10% in the under-moderated LEUPRO-1 benchmark and about 6% in the better moderated LEUPRO-2 benchmark, which means that the impact of δ□ variations on the reported k_{inf} and k_{eff} values is not very large either.
- The k_{inf} results from the unit cell calculations agree better with each other (have a smaller relative standard deviation) than the whole reactor results k_{eff}. One of the reasons for the larger spread in the whole reactor k_{eff} results is the presence of neutron streaming corrections in the KFA, ORNL and ECN (MCNP) results which systematically lower the whole reactor k_{eff} values. The streaming corrections to the whole reactor k_{eff} values are of the same magnitude as the relative standard deviations of the k_{eff} values.

The PROTEUS-LEU-HTR benchmark results show the general capability of the contributing institutions to deal with such problems with respect to theoretical modeling as well as computational tools and data bases. The remaining safety related uncertainties were identified within the CRP to be mainly due to non-sufficient descriptions of neutron streaming effects. The comparison against the experimental results later has shown similar tendencies

A "VHTRC Temperature Coefficient Benchmark Problem" was also calculated with specifications made on the basis of assembly heating experiments in the pin-in-block type critical assembly, VHTRC, in which the core is loaded with low enriched uranium coated particle type fuel. This benchmark problem was used for the validation of the evaluated nuclear data for low enriched uranium-graphite systems, the calculation of effective multiplication factor and the calculation of temperature coefficient in a low temperature range.

The following general conclusions were extracted:

- The values of the most important parameter, k_{eff} for the whole reactor, showed good agreement between all institutes at all temperatures. They also agreed with the experimental values typically to within 1%, with all of the calculated values being higher than the experimental ones.
- As for the temperature coefficient of reactivity, all the calculated values of average (integral) temperature coefficient between room temperature and 200°C agreed with the experimental value to within 13%. However, the calculated differential temperature coefficients showed varying degrees of temperature dependence in the analyzed temperature range.
- The values of several cell parameters calculated by some institutes did not agree very well with those from other institutes. Agreement in the values of the infinite multiplication factor, k_{inf}, is much better than that for the spectral indices as already pointed out in the HTR-PROTEUS benchmark results.

The VHTRC benchmark was very valuable to the CRP, as it gave the possibility to test the models on temperature effects. Although the range covered was restricted to a relative small band at the low temperature end for novel gas-cooled reactors the results indicate an error margin for temperature coefficients of about 20%, which was accepted by the CRP participants as being sufficient with respect to licensing and safety aspects.

9.3. PROTEUS EXPERIMENTAL PROCEDURES

The measurements carried out on the HTR-PROTEUS facility can be described under five headings:

- Critical loadings
- Reactivity
- Reaction rates
- Kinetic parameters
- Absorption cross-section of the reactor graphite

9.3.1. Critical Loadings

The "approach-to-critical" for each configuration was accompanied by the usual *inverse counts versus core loading* plot with an extrapolation to 1/counts = 0 being made after each pebble loading step to give the predicted critical loading. The count rates were measured using neutron detectors situated in the radial reflector. Although the HTR-PROTEUS system is a reasonably clean one, some correction to the critical state must be made for excess reactivity due to effects such as control rod/autorod insertion at critical, reactor instrumentation in the system, etc. To this end, the individual, differential control-rod worths were measured in every configuration and the magnitude of all other effects estimated by means of the compensation technique using these calibrated rods. For reasons of time, these component worths were only measured in selected cores and the values for all other intermediate configurations inferred from the differences between control rod bank worths.

9.3.2. Reactivity

The reactivity worth of control absorbers in the core and reflector of configurations with a range of moderation properties was a very important aspect of the HTR-PROTEUS experimental program. The choice of the reactivity measurement techniques was based on the following criteria:

- the method must be compatible with small, highly reflected thermal systems
- the method must be applicable to deeply subcritical cores
- there must be as little dependence upon calculation as possible
- the accuracy of the method should be greater than the current physics methods for LEU HTRs
- the methods chosen should be complimentary techniques, which are, as far as possible, subject to different systematic errors or uncertainties
- the economics of the method should be justifiable.

It was decided, on the grounds of applicability, complimentarity and required effort, that the Pulsed Neutron Source (PNS) and Inverse Kinetics (IK) techniques would be the main reactivity measurement techniques applied to HTR-PROTEUS.

With the PNS technique, the reactivity of a subcritical system is obtained from its response to a regularly pulsed neutron source. Several different theories were developed to analyze such response, but they all fall into one of two broad categories: “inhour” or “area-ratio”. The basis of the inhour analysis of PNS measurements is to isolate the prompt neutron decay from the delayed neutron decays and to use this along with a knowledge of the generation time to derive a value of the reactivity. The disadvantage is that the value of the reactivity is directly dependent upon the generation time, which can be reduced to a dependence upon the variation of the generation time with the reactivity change, the value of which is expected to be less sensitive to the calculational approach chosen. With the area-ratio method the reactivity is proportional to the ratio of the prompt to delayed areas. Unfortunately due to “kinetic distortion” the value of the reactivity is spatially dependent and has to be corrected. The magnitude of this effect can amount to many tens of percent depending on the position of the detector in the reactor. Correction factors can be obtained by taking the calculated ratio of the kinetic to static fluxes at the position where the measurements are made. Experiments carried out at HTR-PROTEUS clearly showed that the use of epithermal neutron detectors reduces significantly the spatial dependence of the measurements.

With the IK technique, the reactivity is derived via the analysis of the system response following a reactivity perturbation to a critical system, for example the insertion of an absorber rod from an initially critical state. However, the dropping of an absorber into the system not only causes a reduction in reactivity and a consequent decay in the space-integrated neutron density, but also a disturbance in the local neutron density distribution and its energy distribution. Any neutron detector placed within or close to the system will therefore experience both global and local effects. Calculated spatial correction factors are hence necessary to take into account the local perturbation of the neutron density. Some IK measurements were also carried out at HTR-PROTEUS with epithermal neutron detectors and the results were found to be significantly less dependent upon spatial correction calculation.

Reactivity measurements were carried out in all of the 10 different core combinations of HTR-PROTEUS using the PNS and IK techniques. In Cores 5, 7, 9 and 10 epithermal neutron detectors were used for PNS measurements and in Cores 9 and 10 the epithermal detectors were also used for IK measurements. The results showed that, in almost all of the cases, there is a good agreement between the different methods used to measure the reactivity, with discrepancies smaller than 5% for reactivities up to 16$.

9.3.3. Reaction Rates

Alongside critical loadings and reactivity worths, the third main theme of the HTR-PROTEUS experiments was the investigation of the individual neutron-balance components, including fission and capture rates and leakage/reflector effects, in particular the measurement of the capture rate in ^{238}U (C8), in doubly heterogeneous fuels. In this context, novel techniques were developed involving the use of the fuel particles themselves as activation foils thus avoiding the need for self-shielding correction factors. Some of the apparatus used for the reaction rate measurements are listed below:

- miniature fission chambers to measure relative reaction-rate traverses in the axial channels between the pebbles
- Uranium/Aluminum foils to measure the fission rates in ^{235}U (F5) and metallic, depleted-uranium foils to measure fission and capture rates in ^{238}U (F8 and C8)
- Special “foils” consisting of fuel matrix material
- demountable fission chambers with absolutely calibrated deposits used as a reference source in the determination of absolute fission rates

9.3.4. Kinetic Parameter

As the methods chosen to measure reactivity effects in HTR-PROTEUS are based upon kinetics techniques, which themselves rely upon accurate estimates of the generation time (Λ) and the effective delayed neutron fraction (β_{eff}) a measurement of these two parameters was an important accompaniment to the main measurement program. Unfortunately, no practical technique is available for the direct measurement of Λ and, although the measurement of β_{eff} in isolation is in principle possible, the techniques necessary are somewhat involved if a reasonable accuracy is required. One alternative is to measure the prompt neutron decay constant at critical α_0^c and to convert this to the ratio (β_{eff}/Λ) via a calculated correction factor. Due to difficulty in isolating α_0^c from the delayed background in PNS measurements in graphite systems close to critical, it is common to measure α_0 at several different states of subcriticality and to extrapolate a fit to the measured points to $\rho=0$. The different subcritical states were achieved by inserting the control rods, having calibrated these earlier using the stable period technique. It has been seen that great care should be taken for the extrapolation to critical. A linear fit to the measured points generally overestimates α_0^c by typically 5%, and thus a fit having the form of the inhour equation should be used.

9.3.5. Absorption Cross-Section of the Reactor Graphite

One of the common features of the HTR-PROTEUS configurations was a large reflector importance and a subsequently high sensitivity to the presence of poisons in the reflector graphite. The accurate determination of this parameter was therefore vital for code validation via measurements in PROTEUS. The effective absorption of graphite was measured in several ways:

- chemical analysis, which yields elemental concentrations in small samples which must be converted to absorption via tabulated cross sections
- reactor-based measurement, which give a direct measurement of the effective absorption cross-section of small samples via comparison with standard absorbers
- decay-constant measurement, which give a direct indication of the global effective absorption in a system.

9.4. COMPARISON OF MEASUREMENTS WITH CALCULATIONS

The measurements carried out at the HTR-PROTEUS facility were compared to calculational results obtained from the different institutes participating in the CRP.

The comparisons were made for the following experimental results:

- critical balances
- reaction rate ratios and distributions
- control rod worths
- water ingress effects
- reactivity of small samples
- kinetic parameter

The principal conclusions resulting from the comparison of the calculations with experiments are reported below.

It has been seen that a good agreement with measurements is achieved in the calculation of the critical balances when the correction for streaming is correctly taken into account for both diffusion and transport theory codes. The calculated k_{eff} is then usually within 1% compared to the experiment. However, the use of an isotropic streaming correction, i.e. neglecting the non-isotropy, especially for the point-on-point loading, overestimates the multiplication factor by up to 2.5% in Core 7. On the other hand when the streaming correction is totally ignored discrepancies of more than 4% can be observed. Monte Carlo calculations performed with the KENO and MCNP codes also showed good agreement when all the pebbles are modeled explicitly, with less than 0.5% of discrepancy with the experimental values in Cores 5, 7, 9 and 10.

Direct calculations with diffusion theory were seen to overpredict the worth of the fine control rods in Cores 5 and 7 by ~21%, whereas the worth in Cores 9 and 10 was underestimated by ~12%. However, using the method of ‘equivalent cross-sections’ in combination with a standard diffusion calculation, excellent agreement with the experiment was obtained. Monte Carlo calculations were seen to agree within the statistical errors with the measured worths, except for Core 10, in which the worth was overestimated by 28%. Although in licensing procedures an agreement within 10% is required, the discrepancies found are not expected to have consequences for the HTR design. Recall that the fine control rods are only used for fine control of the reactor. Shutdown of the reactor is assured by means of the safety and shutdown rods. Hence, the worth of the fine control rods is not a safety issue.

The calculations of the shutdown rod worth generally showed better agreement than the fine control rods. Transport theory calculations performed with TWODANT and DORT agree within 10% in almost all the shutdown rod combinations in Core 5, 7, 9 and 10. Excellent agreements were obtained with the Monte Carlo codes MCNP and KENO with less than 5% discrepancies compared to the measured shutdown rod worths.

The variation of the reactivity with water ingress has been investigated experimentally employing PNS techniques in Core 10. Measurement results were compared with transport calculations using TWODANT and with Monte Carlo calculations using MCNP. It has been found that the TWODANT calculations slightly overestimate the Δk_{eff} effect of water-ingress simulating polyethylene rods by about 4 ± 2%. As regards the MCNP calculations, the Δk_{eff} effect is predicted well within the experimental error of ~2%. This result has to be considered as very satisfying. The theoretical description of the water-ingress reactivity effect was one of the main issues of the CRP, because of its utmost safety relevance. The demonstration of the high accuracy in theoretically determining these reactivity effects is one of the major successes of the CRP.

The reactivity effect of small absorbing and moderating samples has been measured and calculated in Cores 5, 7, 9 and 10. It has been seen that the calculations performed using diffusion perturbation theory, overestimate the effect of the boron and copper samples by about 17% in all core configurations. On the other hand the effect of the gadolinium sample is significantly underestimated, which is probably due to an error in the specification of the gadolinium sample composition. The overestimation of the moderating samples is seen to increase significantly with the amount of moderation in the core. It varies from about 21% in Core 5, 32% in Core 9 to 208% in Core 10. It is believed that the relatively large error in Core 10 could be the result of an error in the treatment of the neutron streaming and/or in the moderation of fast neutrons.

The effects of small H_2O and CH_2 samples were investigated in Cores 5, 7 and 9, in order to experimentally assess the properties of polyethylene when used as a substitute for water in the HTR-PROTEUS experiments. The calculated absolute reactivity worths per mole obtained with TWODANT for the central Core 5 CH_2 and H_2O samples agree reasonably well with the experimental values (C/E ~1.08) and the calculated CH_2/H_2O reactivity per mole ratio of 0,992 ± 0.020 agrees well with the experimental value of 1.002 ± 0.022. On the other hand, the calculated absolute reactivity worths per mole for the Core 5 CH_2 and H_2O samples located in the layers 1 & 2 strongly disagree with the experimental values (C/E ~0.38) even though the calculated CH_2/H_2O reactivity per mole ratio of 1.044 ± 0.140 agrees well with the experimental value of 1.041 ± 0.053. The calculational results for that sample location are not very reliable because they are the results of the difference of two nearly equal numbers and because there is a much larger gradient in the thermal neutron flux and fission rate near the lower axial reflector in Core 5 than in the other two cores. In Core 7, the calculated absolute reactivity worths per mole for the CH_2 and H_2O samples agree reasonably well with the experimental values ($0.89 < C/E < 1.07$). The calculated reactivity worths per mole for the Core 7 CH_2 samples range from 0.998 ± 0.03 to 1.002 ± 0.03 times the reactivity worths of H_2O samples of the same size in the same location. This is in opposition to the experimental results, which consistently give three to four percent higher reactivity per mole for the CH_2 samples than for the H_2O sample. Calculations were repeated with the non-stoichiometric $CH_{2.034}$ giving C/E values for the $CH_{2.034}/H_2O$ reactivity per mole ratios very close to unity. In Core 9, the calculated absolute reactivity worths per mole for the CH_2 and H_2O samples are considerably larger than the experimental values ($1.3 < C/E < 1.5$). The calculated reactivity worth per mole for the CH_2 sample is 0.945 ± 0.069 times the reactivity worth per mole of a H_2O sample which gives a C/E value for the CH_2/H_2O reactivity per mole ratio of 1.16 ± 0.13. With the non-stoichiometric $CH_{2.034}$ a better agreement is obtained with the experimental value with a C/E of 1.07 ± 0.12.

The kinetic parameter β_{eff}/Λ obtained from PERT-V/TWODANT calculations show good agreement with the measurements, with less than 3% average discrepancy when the streaming correction is applied. If the streaming is ignored when calculating the fluxes with TWODANT, discrepancies of more 6% and 12% are obtained in Cores 9 and 10 respectively.

In total the experiments performed in the CRP produced a great amount of valuable results to be used in validation procedures of theoretical models and data bases. Together with the broad benchmark and evaluation program running parallel to the experiments a deeper insight into the safety relevant neutron physics of graphite moderated gas-cooled reactors has been obtained. The CRP has demonstrated the high quality of experimental techniques and of computational tools. Moreover it has gathered international experienced scientists around the world to define the state of the art, to identify the still existing validation deficiencies and to prescribe a way to improve the knowledge in safety related questions of gas-cooled nuclear reactors.