Accurate Reactivity Feedback Calculations for TRIGA Cores

M.Badea , C.H.M.Broeders, R.Dagan, A.Travleev

Forschungszentrum Karlsruhe
Institut für Reaktorsicherheit
Postfach 3640,
D-76021 Karlsruhe
badea@irs.fzk.de

Introduction

In the TRiga Accelerator Driven Experiment TRADE [1], planned in the TRIGA RC-1 reactor of the ENEA-Casaccia Centre, it is foreseen to couple an external proton beam with a tantalum target in the central part of the core. The operating temperatures for TRADE are expected to be higher than the common ones in TRIGA reactors. Therefore, it is important to evaluate accurately the temperature dependent reactivity feedback at higher temperature (380-420K). Reactivity measurements, which were recently performed in RC-1 [2], confirmed a large increase of the negative reactivity feedback at 380-420 K. This phenomenon is not explicitly addressed in the GA technical report [3] and only averaged values are presented, which were also reconfirmed in [4]. The current study aims to clarify whether the phenomenon observed in the dedicated reactivity tests [2] is unique to the RC-1 TRIGA reactor or whether it is a matter concerning all the TRIGA fuel types. Therefore, additional experimental data gained from the Slovenian TRIGA core [5] were also analysed and compared to the calculated values.

The numerical calculations were performed using stochastic and deterministic numerical methods with accurate Doppler Effect analysis and dense temperature grid for the cross sections of hydrogen bound in zirconium hydride (ZrHx). Furthermore, the emerging bubbles, which seem to be a unique void phenomena in the RC-1 reactor, were analysed with regard to their influence on the reactivity feedbacks at the various operating temperatures.

The TRIGA fuel for the experiments and calculations

The TRIGA RC-1 reactor of the ENEA-Casaccia Centre is a 1 MW thermal power swimming pool reactor, cooled by natural convection of water in the reactor pool. The investigated fuel elements are cylinders of ternary alloy uranium-zirconium-hydride with H-to-Zr atom ratio 1.7 and 20% enriched ^{235}U. The total U is 8,5% of the mixture by weight. The fuel cladding consists of stainless steel AISI 304 of 0.05 cm thickness and 7.8 g/cm^3 density. There are two graphite cylinders of 38.11 cm length at the top and the bottom of the fuel rod.

The reactivity measurements in RC-1 were carried out with the existing core configuration [6], i.e. not with fresh fuel, but rather with burned-up fuel. The measurements at the TRIGA Mark II at Slovenia were performed with completely fresh compact and uniform core.

As the goal of this study is to reveal phenomena which concern mainly the hydrogen bound in the fuel, the calculations were performed using a two dimensional model of an infinite array in radial direction of fresh fuel elements including the axial graphite reflector below the aluminium grid plate [4]. The effect of the fission products and other build up isotopes is beyond the scope of the current study.

Cross section and scattering kernels generation method

The strong peak of the optical phonon spectrum near 0.14 eV leads to pronounced oscillations in the scattering functions and to radical changes in cross sections and in the

scattering kernel. In the LEAPR [7] module of NJOY a central force lattice dynamic model is applied to treat the unique structure of hydrogen in ZrH, where a proton is bound by a tetrahedron of zirconium atoms. The LEAPR module was used to generate thermal neutron scattering data in ENDF/B-6 format (file 7) for hydrogen and zirconium bound in ZrH. The standard temperature of the LEAPR input deck [7] was replaced by dense temperature grid with 10 K intervals. The new generated data was compared with available thermal scattering data of ENDFB-VI.2 and ENDF/B.VI.3. The zirconium data of the ENDF/B-VI.2 is biased and is not recommended, while the ENDF/B-VI.3 data shows good agreement with the new generated data by LEAPR.

Additional refinements concern the hydrogen scattering tables for stochastic calculations:

a: In the THERMR module of NJOY [8] there is a standard 59 energy points set for which 59 $S(\alpha,\beta)$ tables are generated. For hydrogen in ZrH it is recommended [12] to use more energy points due to the optical phonon peak at 0.14 eV.

b: One can also increase the number of equi-probable energy points in each table from the common 20 points to 30 or more.

A recent development based on [9] allows for including $S(\alpha,\beta)$ tables for isotopes with pronounced resonances as an input for MCNP instead of the existing approximated method. In particular the absorption within the first 8 resonances of the TRIGA fuel isotope ^{238}U is biased. The Doppler Effect in the TRIGA core is 20% of the total reactivity effect at 400 K, which justifies the look at an improved model for the resonance absorption.

Calculation methods and results

The dense temperature dependent scattering tables for bound hydrogen were prepared for two types of calculations:

- Monte Carlo calculations with the continuous energy option of the MCNPX code, beta version 2.5.d [10]
- Deterministic multi-group calculations with KAPROS-E LINUX version 2.02 [13] using the TWODANT [11] code.

The data for the deterministic code were prepared in the same manner as was reported in [4].

For both deterministic and stochastic calculations new scattering data for hydrogen in ZrH were prepared, in 10 K intervals, in form of Legendre moments and scattering tables respectively.

The reactivity feedback measurements were performed by increasing the power and thereby the temperature of the fuel, and then measuring the compensation of the inserted reactivity by withdrawing a regulating rod with a known reactivity worth. Based on the measuring positions and the power shape of the core the averaged temperatures for the whole core were derived. In figure 1 the curves (A) and (B) represent the reactivity feedback per 1 K of the TRIGA cores in Cassacia and Slovenia respectively. Those results are subjected to the data concerning the form factors of both cores. The sharp slope in the reactivity curve, at about 120 C, is seen for both cores although the experiments were carried out with totally different burn-up values. Consequently, the origin of this phenomenon was concentrated mainly on the hydrogen temperature dependent cross section. As mentioned before the GA model, which predicts curve D in figure 1, cannot retrace the experimental behaviour at 400 K (127 C). Curve (C) in figure 1 represents the MCNP calculations where the cross sections of the hydrogen and zirconium bound in ZrH were accurately calculated every 10 K. Linear interpolation was performed between the calculated points to get the reactivity change per 1 degree. Using 5 degree K intervals did not improve the results. The statistical error for the depicted curve (C) is negligible (2-3 %). The energy grid was the standard one in the THERMR module of NJOY. The unique experimental phenomenon is qualitatively and quantitatively shown, in a sense that the location of the dip on the temperature scale and its magnitude are quite similar to the experimental results. Nevertheless the curve seems to be

shifted upwards in this temperature range and to some extent downwards at the lower temperature range. Those discrepancies could be connected to 3D effects which were beyond the scope of this study.

At the higher temperatures there are no experimental data available yet the results of curve (C) fluctuates around the average curve of GA. Further refinements were employed and their influence on the reactivity feedback were analysed. The $S(\alpha,\beta)$ probability tables were modified by increasing the energy point in each table from 20 to 30. No consistent trend was observed. Further the number of the tables was increased in the vicinity of the 0.14 eV optical phonon peak of the bound hydrogen. The reactivity feedback near 400 K increases considerably. In addition, the Doppler Effect was subjected to the correct $S(\alpha,\beta)$ treatment [9] for heavy isotopes with pronounced resonances, although the ^{238}U concentration is considerably small in the TRIGA fuel. The reactivity feedback values grew by about 0.3 pcm per 1 K.

Curve (E) in Figure 1 shows the calculated effect using the deterministic Sn code TWODANT. The 69 group does not seem to represent accurately the changes in the 380-420 temperature range, but elsewhere (as was shown also in [4]) the deterministic results are similar to the experimental values and to the MCNP calculations.

The impact of voids within the coolant was checked by using deterministic codes. Additional calculations were done with the MCNP code near 400 K. Figure 2 shows the results of the TWODANT code. The four curves represent 0%, 2%, 5% and 8% reduction in the water density surrounding the fuel pin. In all curves the trend of the enhanced negative reactivity feedback is increased, yet the effect is quantitatively small due to the group structure of the deterministic calculation. The reduced density moderates to some extent the negative reactivity as a consequence of the hardened neutron spectrum. However, the overall core reactivity behaviour is seen to be indifferent to moderate density changes. This result was also reconfirmed by selected MCNP calculations in the 380-410 K temperature range. The negative reactivity growth was similar to curve (C) in figure 1 , but starting at lower negative reactivity level at 380 K.

Conclusion

The main reason for the unique temperature reactivity feedback around 400 K was shown to be directly connected to the bound hydrogen cross section. Nevertheless, 3D calculations are needed to evaluate the existing deviations of the MCNP unit cell results in comparison with the experimental results. From the other model improvements, it seems that the most important one is the generation of specific probability tables. A recent extensive work done by Mattes [12] with its new $S(\alpha,\beta)$ tables set for bound hydrogen in ZrH would probably affect, to some extent, the current results. Furthermore the improvement in the Doppler Effect treatment has a non-negligible influence on the reactivity feedback. A more complicated task is to assess the burn-up level and the effect of the fission products. This should be done parallel to improvements of the deterministic solution schemes.

References

[1] The Working Group on TRADE (TRIGA Accelerator Driven Experiment) – TRADE Final Feasibility Report, March 2002.

[2] R. Rosa , RC1 Casaccia. Activities performed on the 6-7 weeks of 2004. Reported on the TRADE official Web Site – “In pile Experiments” section. February 2004. Data evaluated by M. Schikorr FZK (private communication).

[3] General Atomics, TECNICAL FOUNDATIONS OF TRIGA , GA-471 (1958).

[4] Badea M. Broeders C.H.M, .Dagan R., Travleev A,. Neutron Physics Investigations for TRIGA Fuel, Jahrestagung Kerntechnik Düsseldorf, 2004

[5] I. Mele , M. Ravnik, A. Trkov. TRIGA MARK II Benchmark Experiment, Part I: Steady State Operation, Nuclear Technologies p. 37 Vol 105 , Jan 1994. . Data evaluated by M. Schikorr FZK (private communication)

[6] Philibert H., Rosa R. Imel G. Search for the Reference SCO Sub-critical Configuration (K=0.995) for the TRADE program. CEA/DEN/CAD/DER/SPE/DIR DO. 263 1.9.04.
[7] R.E.MacFarlane. New Thermal Neutron Scattering Files for ENDF/B-VI Release 2 , LA-12639-MS, March 1994,
[8] MacFarlane, R.E., Muir, D.W., The NJOY Nulcear Data Processing System, Version 91 (LA-12740-M), 1994.
[9] Rothenstein W. Proof of the Formula for the ideal gas scattering Kernel for Nuclides with Strongly energy dependent scattering cross sections. ANE pp. 9-23 vol. 31, 2004.
[10] J.S.Hendricks, G.W.McKinney, L.S.Waters et.al. MCNPX-VERSION 2.5.d (LA-UR-03-5916), 2003
[11] Ray E. Alcouffe, Randal S. Bake, Forrest W. Brinkley, Duane R. Marr, and R.Douglas O'Dell, USER'S Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport (version 3.0).
[12] Trkov A. Current projects of the IAEA-NDS, JEFF/EFF Meeting , PARIS Nov. 2004.
[13] C.H.M.Broeders, R.Dagan, V.Sanchez, A. Travleev, „KAPROS-E: Modular Program System for Nuclear Reactor Analysis, Status and Results of Selected Applications", Jahrestagung Kerntechnik Düsseldorf, 2004

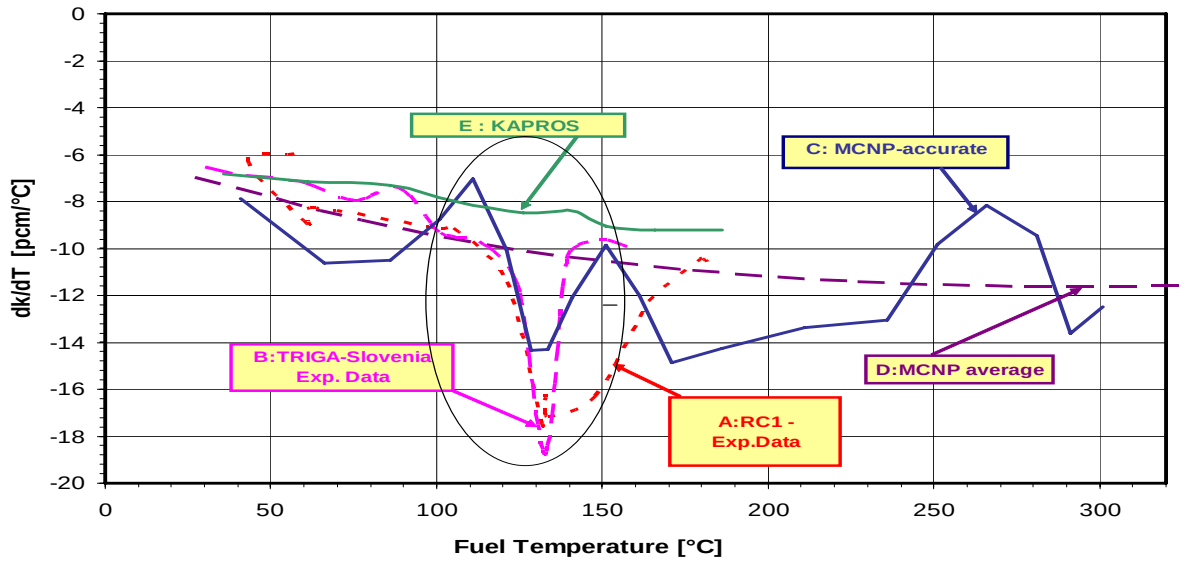

Figure 1: Comparison of experimental and computational results for the reactivity feedback of TRIGA core and TRIGA fuel pin respectively.

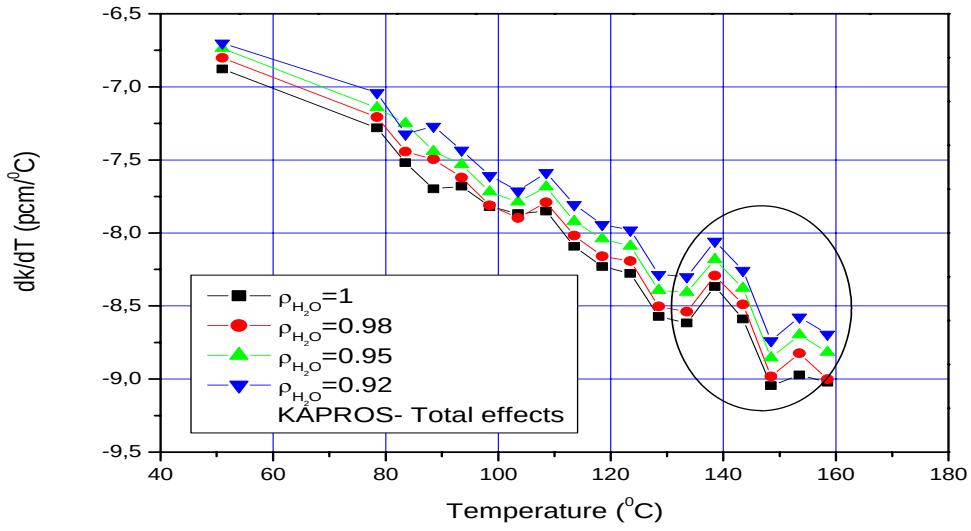

Figure 2: Total reactivity feedback effect of TRIGA fuel pin as function of void level in the water coolant.