Neutron Physics Investigations for TRIGA Fuel

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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. An important objective of the project is to gain experience with the coupling of a powerful proton accelerator with a sub-critical fission reactor system at power levels with significant system feedback effects. The purpose of the current study is to evaluate the fuel temperature feedback in the unique TRIGA fuel type as preparation for further dynamic investigations. The fuel temperature effect in the TRIGA reactor causes its highly inherent safety features, see also e.g. [2]. It consists of 2 main components: the Doppler broadening of the fuel resonances and the spectral shift caused by the changes in the moderating properties of the hydrogen in the TRIGA specific zirconium hydride fuel. This behaviour of the two temperature effects in the TRIGA fuel was investigated systematically, starting with 1-dimensional unit cell calculations followed by a 2-dimensional model for an infinite array of individual fuel elements. Three dimensional full core calculations are in progress. Two codes were applied, based on different approaches: the international Monte Carlo code MCNPX [3] and the deterministic multi-group code system KAPROS [4,5], developed at FZK. The temperature dependent reactivity feedbacks and the neutron physics parameters were carefully studied and the reliability of the deterministic code could be confirmed by comparison with the MCNPX results.

Characteristics of the TRIGA Fuel

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 considered fuel elements are cylinders of ternary alloy uranium-zirconium-hydride with H-to-Zr atom ratio 1.7 and uranium enrichment 20% in ^{235}U, being 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 at the top and bottom of the fuel rod of 38.11 cm length. For this fuel two types of calculations were performed:

- One dimensional unit cell with reflective axial boundaries and “white” (reflection with cosine distribution) radial boundary. The fuel matrix is surrounded by the 0.05 cm thick cladding and additional 0.485 cm ring of water.
- Two dimensional model of an infinite array in radial direction of fuel elements including the axial graphite reflector and the aluminium grid plate.

Calculation Methods

For these investigations two alternative approximations of the neutron transport equation were applied:

- Monte Carlo calculations with the continuous energy option of the MCNPX code, beta version 2.5.d
- Deterministic multi-group calculations with KAPROS-E LINUX version 2.02.

A specific problem with deterministic codes and TRIGA fuel is the availability of data for scattering on hydrogen in zirconium hydride. Up till now KAPROS (and for example also the European code system ERANOS) did not contain data for this reaction. The very general MCNPX code contains old data on the code libraries. First exploratory investigations with MCNPX showed that the effect of thermal scattering bindings may have large impact on criticality of TRIGA reactors (≈ 3500pcm difference in a TRIGA fuel assembly).

Basic ENDFB formatted nuclear data libraries with thermal scattering data could be found on the WEB download area of LANL (t2.lanl.gov) for new cross section generation. Two versions with older[6] and updated [7] data are available. The standard code NJOY99.81 [8] has been applied for the creation of MCNPX libraries using the modules RECONR, BROADR, THERMR and ACER, producing direct useable data for MCNPX. Multi- group constants in GENDF format are produced in the same way, but with the GROUPR module instead of ACER. Unfortunately, the standard interface file MATXS, being used in KAPROS as starting file for reformatting, cannot be used for thermal scattering data output. A careful analysis showed that the program NSLINK [9] can process thermal scattering data in GENDF format to the easily accessable AMPX format [9]. Therefore it was decided to create the program RAMPX for reformatting AMPX data files to KAPROS GRUBA format. In this way the temperature dependent cross sections and the zero and the three higher properly normalized scattering moments are tabulated on GRUBA libraries. In the KAPROS system linear interpolation can be made within these tabulations. However, the accuracy of these interpolations has to be assessed carefully before application. The investigations in this paper are based on temperatures available in the prepared temperature dependent tabulations.

The unit cell calculations were performed by utilizing data with the WIMS 69 energy group structure together with the TWODANT [10] S_n transport code.

For the two dimensional fuel assembly calculation including the axial reflectors, a two step procedure was applied with the deterministic code. First the one dimensional fuel cell with fuel matrix, clad and water was homogenized in a unit cell calculation. The second step utilizes the homogenized data together with graphite and the aluminium plate on the top to calculate the criticality value which was compared to the value obtained with MCNPX. For the TWODANT calculation usually the S_8P3 order was used.

Results of Calculations for TRIGA Fuel

The results of the criticality calculations for the two fuel configurations are plotted in figure 1 (left). The both upper curves for the one-dimensional unit cell model show good agreement in the temperature dependence and a systematic difference in ΔK/K of about 1% between MCNPX and TWODANT, acceptable at this stage. The both lower curves in this figure for the two-dimensional fuel assembly model show very good agreement for both temperature dependency and reactivity level. Further detailed analysis are needed to investigate possible compensating effects. The temperature dependent reactivity data in figure 1 may be well fitted by an analytical function, based on work in ref. [11] for temperature dependent scattering:

$$K(T)=C_1-C_2/T\cdot\exp(-C_3/T)$$

The direct differentiation of this formula gives the fuel temperature coefficient dK/dT, an important parameter for dynamic simulations:

$$dK/dT=-(C_2.C_3)/T^2\cdot\exp(-C_3/T)$$

Figure 1 (right) shows for the fuel assembly model the analytical functions dK/dT with the fitted parameters from MCNPX and KARBUS calculations. The agreement is very satisfactory and the overall shape of the two results is similar as the General Atomic [11] original data which was derived with simplified analytical models.

The two basic phenomena, Doppler effect and thermal upwards scattering, have been investigated in more detail by separating the effects. Figure 2 (left) shows the ratio of the Doppler component D(T) to the total effect D(T) plus thermal scattering effect S(T), as a function of the fuel temperature. Here we may observe significant differences at low temperatures. Further analysis showed that for the Doppler effect the differences between the MCNPX and KARBUS results are constant around 0.1%, independent of the temperature as shown in figure 2 (right). This can explain the asymptotic convergence of the both methods for higher temperatures because the influence of the constant offset becomes smaller. It gives an indication that the treatment of geometrical effects in the multi group cross section processing should be analyzed and first additional studies show indeed that changing the Bell factor treatment leads to effects of the same order of magnitude of the 0.1%. However, the dominating effect is the upwards scattering and the behaviour of the hydrogen in zirconium hydride in TRIGA fuel after irradiation or possible other time dependent processes should be assessed carefully for the anticipated neutron physics experiments foreseen in TRADE.

Conclusions

The comparison between MCNPX and KAPROS system for estimating the TRIGA fuel characteristics within the TRADE project shows an overall good agreement which confirms the confidence for future dynamical deterministic code applications. For the temperature dependency of the very important fuel temperature coefficient dK/dT a fit to an analytically function, based on information in the old original documentation of the TRIGA manufacturer General Atomics, is derived. In order to localize the impact of each of the main contributors to the inherent safety features, additional studies were performed. The importance of the thermal upwards scattering was confirmed and assessment of the influence of the actual hydrogen content in the zirconium hydride is recommended. Differences in the Doppler effect seem to be attributed to the geometrical modelling of the resonance cross section treatment in MCNPX versus KARBUS. An extensive study on the impact of the main ^{238}U resonances is now in progress.

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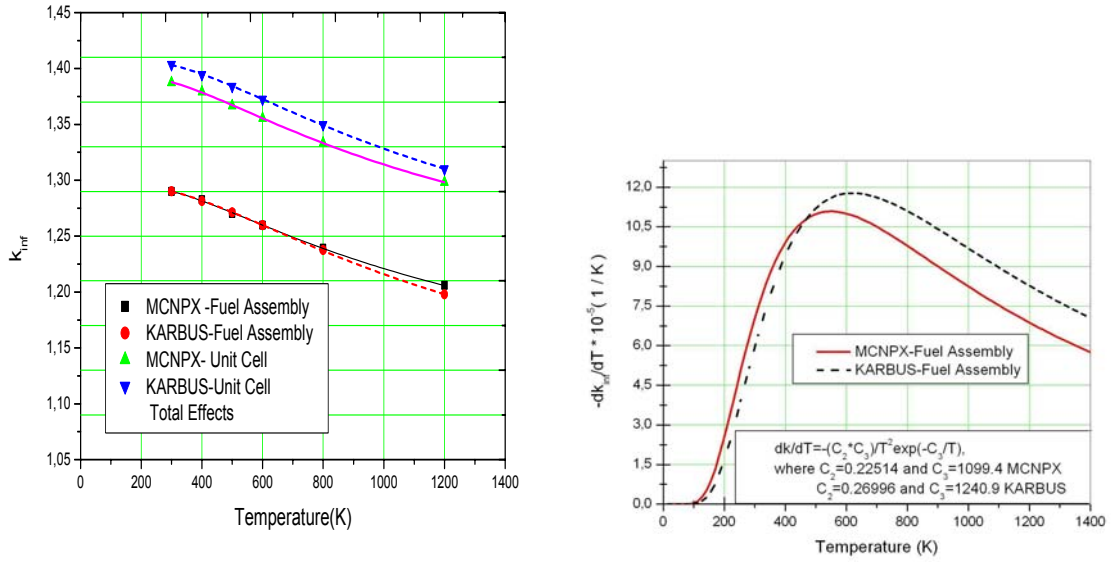

Figure 1: Comparison of MCNPX and TWODANT results for reactivity K (left) and dK/dT (right) for two TRIGA fuel models

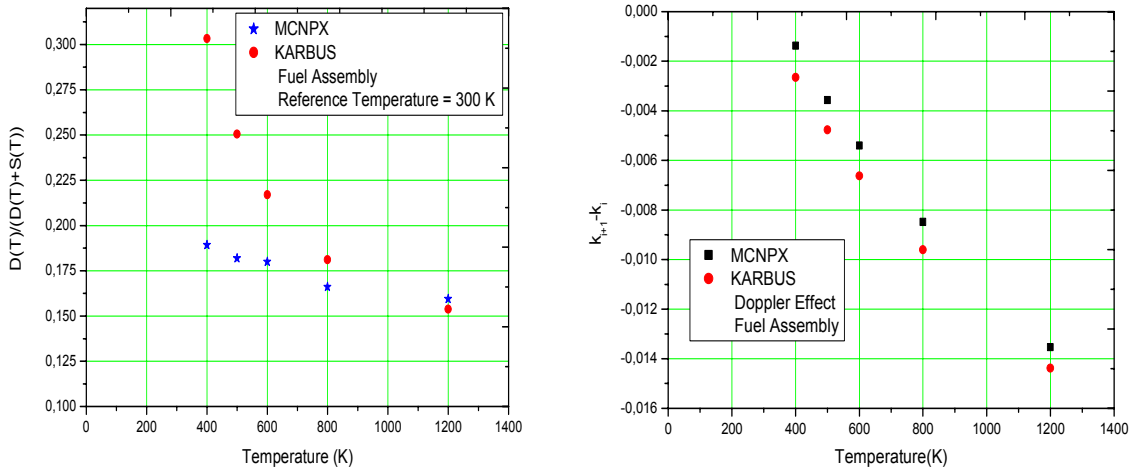

Figure 2: Comparison of MCNPX and KARBUS results for ratio of Doppler to total Doppler plus scattering effect (left) and for absolute Doppler effects (right) in TRIGA fuel assembly.