International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009)
Saratoga Springs, New York, May 3-7, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009)

TIME-DEPENDENT ANISOTROPIC DISTRIBUTED SOURCE CAPABILITY IN TRANSIENT 3-D TRANSPORT CODE TORT-TD

A. Seubert and A. Pautz
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH
Forschungsinstitute, D-85748 Garching, Germany
armin.seubert@grs.de

M. Becker and R. Dagan
Forschungszentrum Karlsruhe GmbH, Institut für Reaktorsicherheit
Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
maarten.becker@irs.fzk.de, ron.dagan@irs.fzk.de

ABSTRACT

The transient 3-D discrete ordinates transport code TORT-TD has been extended to account for time-dependent anisotropic distributed external sources. The extension aims at the simulation of the pulsed neutron source in the YALINA-Thermal subcritical assembly. Since feedback effects are not relevant in this zero-power configuration, this offers a unique opportunity to validate the time-dependent neutron kinetics of TORT-TD with experimental data. The extensions made in TORT-TD to incorporate a time-dependent anisotropic external source are described. The steady state of the YALINA-Thermal assembly and its response to an artificial square-wave source pulse sequence have been analysed with TORT-TD using pin-wise homogenised cross sections in 18 prompt energy groups with P_1 scattering order and 8 delayed neutron groups. The results demonstrate the applicability of TORT-TD to subcritical problems with a time-dependent external source.

Key Words: Neutron transport, time dependence, discrete ordinates, time-dependent source, subcritical assembly

1. THE TIME-DEPENDENT 3D DISCRETE ORDINATES TRANSPORT CODE TORT-TD WITH TIME-DEPENDENT EXTERNAL SOURCE

The time-dependent code TORT-TD solves both the steady-state and time dependent 3-D multi-group transport equation in discrete ordinates representation. It is based on the steady-state 3D transport code TORT [1, 2] from the DOORS package which has been developed at ORNL. Anisotropic scattering is treated in terms of a Legendre P_n cross section expansion where n denotes the scattering order. For treating thermal-hydraulic feedback, TORT-TD has been coupled to the thermal-hydraulic system code ATHLET [3].

TORT-TD has been extended to account for a time-dependent anisotropic distributed external source. This is accomplished by explicitly considering the quantity $q_g\left(\vec{r},\vec{\Omega},t\right)$ in the time-dependent transport equation:

$$\left[\frac{1}{v_g}\frac{\partial}{\partial t}+\hat{\vec{\Omega}}\cdot\vec{\nabla}+\sigma_g^{tot}(\vec{r})\right]\psi_g(\vec{r},\vec{\Omega},t)=q_g(\vec{r},\vec{\Omega},t)+\sum_{g'}\int_{4\pi}d\vec{\Omega}'\sigma_{gg'}(\vec{r},\vec{\Omega}'\cdot\vec{\Omega})\psi_{g'}(\vec{r},\vec{\Omega}',t)+$$
$$+\chi_g(1-\beta)\sum_{g'}\upsilon\sigma_{fg'}(\vec{r})\phi_{g'}(\vec{r},t)+\sum_l\chi_{gl}^d\lambda_l c_l(\vec{r},t).$$

$\phi_g(\vec{r},t)$ is the scalar neutron flux of energy group g, which results from the angular flux $\psi_g(\vec{r},\vec{\Omega},t)$ by integration over all solid angles or discrete ordinates. Aiming at unconditional stability, both the transport and the precursor equation

$$\frac{\partial}{\partial t}c_l(\vec{r},t)=\beta_l\sum_{g'}\upsilon\sigma_{fg'}(\vec{r})\phi_{g'}(\vec{r},t)-\lambda_l c_l(\vec{r},t)$$

are integrated using the fully implicit time discretisation scheme. Although the numerical effort is significantly higher compared to explicit schemes, this allows for large time steps Δt that are mainly limited by the discretisation error and the convergence behaviour. The precursor equation describes the delayed neutron dynamics in terms of generation and decay of the precursors, given by the distribution $c_l(\vec{r},t)$ for the delayed neutron group l. With $\sigma_g'(\vec{r}):=\sigma_g^{tot}(\vec{r})+\frac{1}{v_g\Delta t}$ and the modified fission spectrum $\chi_g':=\chi_g(1-\beta)+\sum_l\chi_{gl}^d\lambda_l\gamma_l\beta_l$, the implicitly discretised transport equation is obtained after some algebra:

$$\left[\vec{\Omega}\cdot\vec{\nabla}+\sigma_g'(\vec{r})\right]\psi_g^{\tau+1}(\vec{r},\vec{\Omega})=\sum_{g'}\int_{4\pi}d\vec{\Omega}'\sigma_{gg'}(\vec{r},\vec{\Omega}'\cdot\vec{\Omega})\psi_{g'}^{\tau+1}(\vec{r},\vec{\Omega}')+\chi_g'\sum_{g'}\upsilon\sigma_{fg'}(\vec{r})\Phi_{g'}^{\tau+1}(\vec{r})+q_g'(\vec{r},\vec{\Omega}) \quad (1)$$

The equation of a single time step equals a steady-state fixed-source transport problem with the “fixed-source” term

$$q_g'(\vec{r},\vec{\Omega}):=q_g^{\tau+1}(\vec{r},\vec{\Omega})+\frac{1}{v_g\Delta t}\psi_g^{\tau}(\vec{r},\vec{\Omega})+\frac{1}{\Delta t}\sum_l\chi_{gl}^d\lambda_l\gamma_l c_l^{\tau}(\vec{r}). \quad (2)$$

Therein, the time-dependent distributed source is represented by the quantity $q_g^{\tau+1}(\vec{r},\vec{\Omega})$. A spherical harmonics expansion of $q_g^{\tau+1}(\vec{r},\vec{\Omega})$ similar to the angular fluxes is used to represent source anisotropy. In TORT-TD, the time dependence of the source is given by sampling the source at arbitrary time points that need not agree with the calculation time steps; source values between sampling points are obtained by linear interpolation.

According to (1) and (2), the solution of a transient problem consists of the solution of a sequence of fixed-source problems with the “fixed-source” term depending on the solution of the preceding time step. With the advantage of extrapolating the fluxes to the next time step using the space-angle resolved inverse reactor periods $\omega_g(\vec{r},\vec{\Omega})$, computing time can be saved. The extrapolation is applied individually for each mesh and energy group.

2. APPLICATION TO YALINA-THERMAL ASSEMBLY

The YALINA-Thermal subcritical assembly [4] consists of a uranium dioxide fuel rod array with 10% enrichment embedded in a polyethylene moderator and surrounded by a graphite reflector in radial direction (Fig. 1, left). It operates at $k_{eff} < 0.98$ under all conditions for safe operation and is driven by external neutron sources, either a ^{252}Cf neutron source or a deuteron accelerator with deuterium or tritium target for producing neutrons. As indicated in Fig. 1 (left), the neutron producing target is located at the assembly center. The calculations presented in this paper refer to the configuration with 280 EK-10 fuel rods.

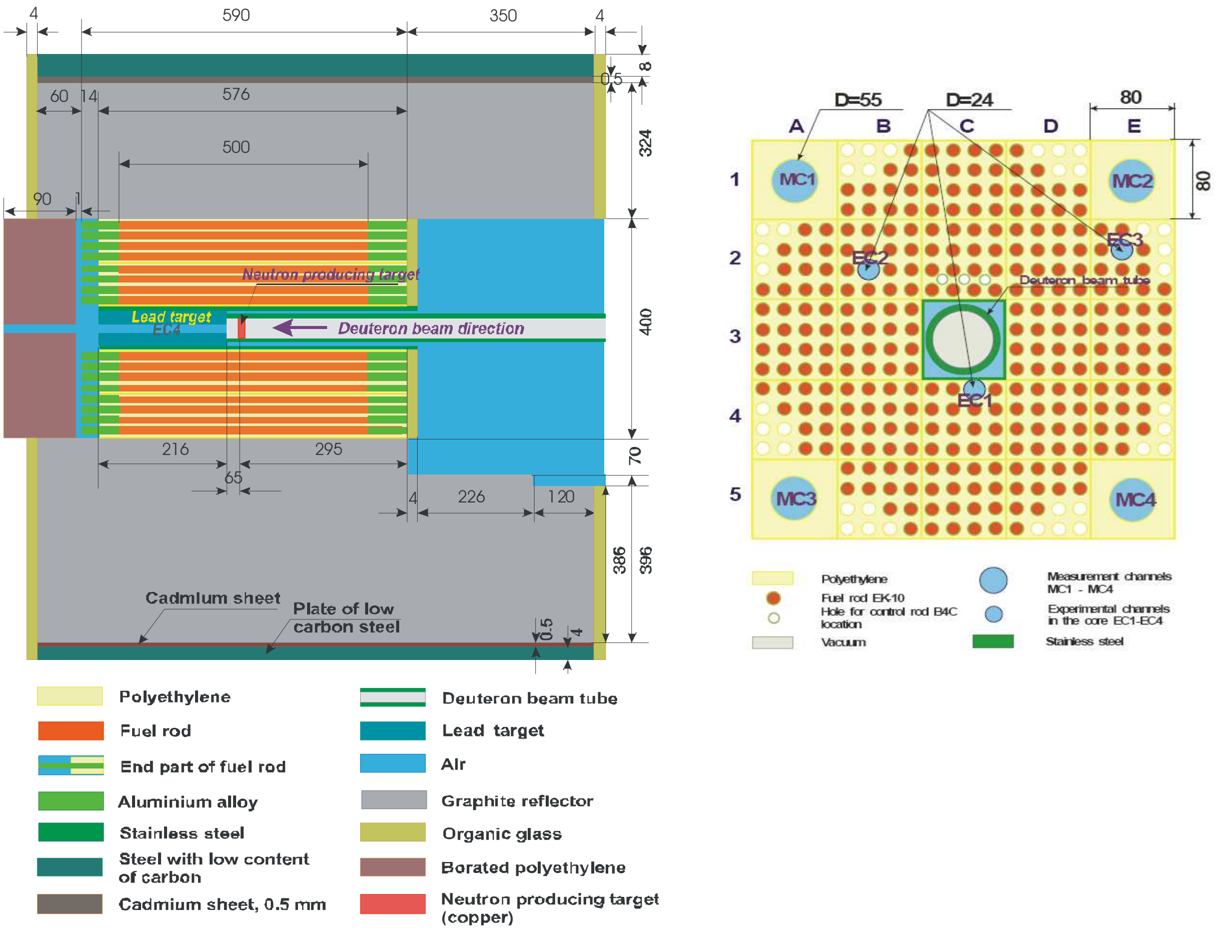

Figure 1. Axial (left) and radial (right) cross section of the YALINA-Thermal assembly with 280 EK-10 fuel rods.

2.1. Extension of TORT-TD geometric capability and meshing of the YALINA geometry

In addition to the implementation of the time-dependent external source, the geometric capabilities of TORT-TD have been extended in order to account in detail for the rather complex geometry of the system. This in particular applies to the representation of circular shapes in a Cartesian coordinate system, like the central deuteron beam tube or the measurement channels shown in Fig. 1 (right). In TORT-TD, the system geometry is defined in terms of an array of rectangular fuel assemblies which, in turn, are represented by arrays of pin cells. Each pin cell can be treated either as a homogeneous unit or spatially resolved: In the first case, the pin cell can be subdivided into an arbitrary number of meshes; in the second case, the circular shape of, e.g., a fuel rod or the central deuteron beam tube is approximated by a staircase function that preserves the original cross sectional area. (In this respect, benefit has been gained from previous applications of DORT and TORT to the C5G7 benchmark series [5, 6].) Several radial zones can be considered. Each radial zone as well as the remaining “background” (the space of the pin cell that is not occupied by the rod) can be assigned a parameterised cross section library and/or a time-dependent external source specification.

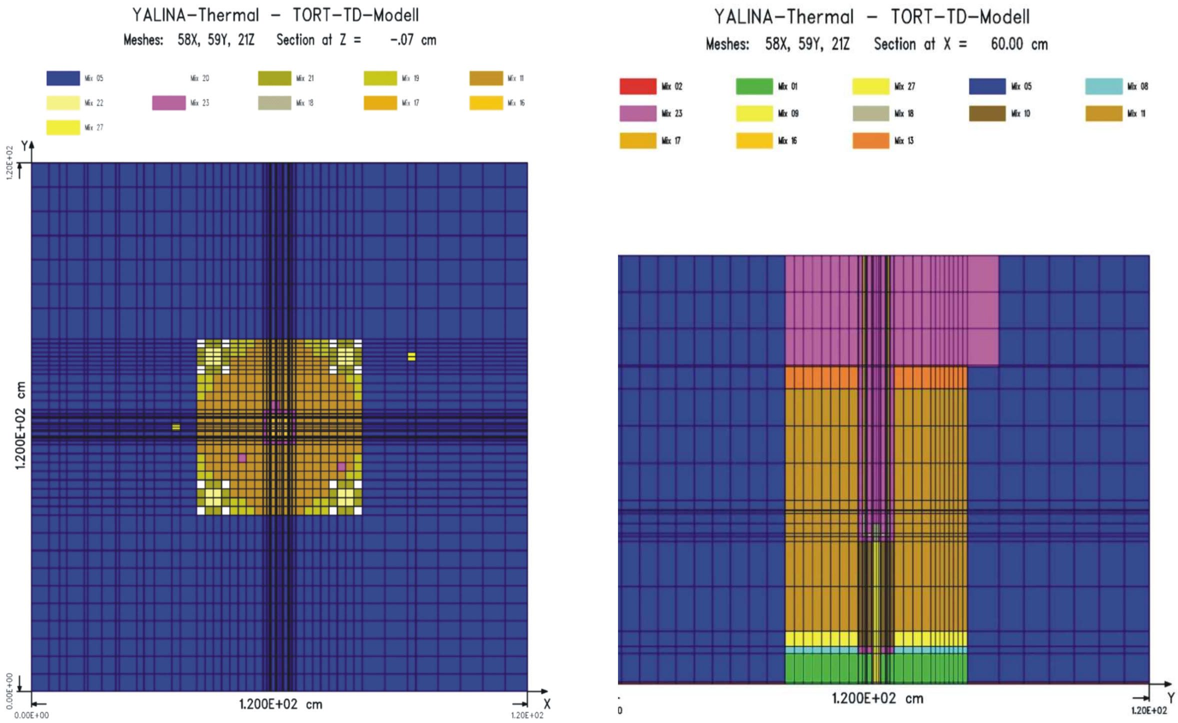

Figure 2: Radial (left) and axial (right) cross section of the YALINA-Thermal meshing used in TORT-TD.

2.2. TORT-TD calculation of the YALINA-Thermal steady state and its response to a source pulse

The steady state of the YALINA-Thermal assembly with 280 EK-10 fuel rods has been analysed using pin-wise homogenised nuclear cross sections for each fuel pin cell. Nuclear cross sections in 18 prompt energy groups with P_1 scattering order and 8 delayed neutron groups have been prepared by Forschungszentrum Karlsruhe using the KAPROS code system [7]. The reported TORT-TD results are obtained with S_8 level-symmetric quadrature. The meshing is based on 58×59 nodes in radial direction and 21 axial nodes, resulting in a total number of 71862 meshes. The circular shapes of the individual radial zones of the central beam tube are represented by squares with their cross sectional areas being conserved. Radial and axial cross sections of the meshing and the material distributions are shown in Fig. 2. The resulting multiplication factor $k_{eff} = 0.96111$ compares well with the value $k_{eff} = 0.96080$ reported in [8].

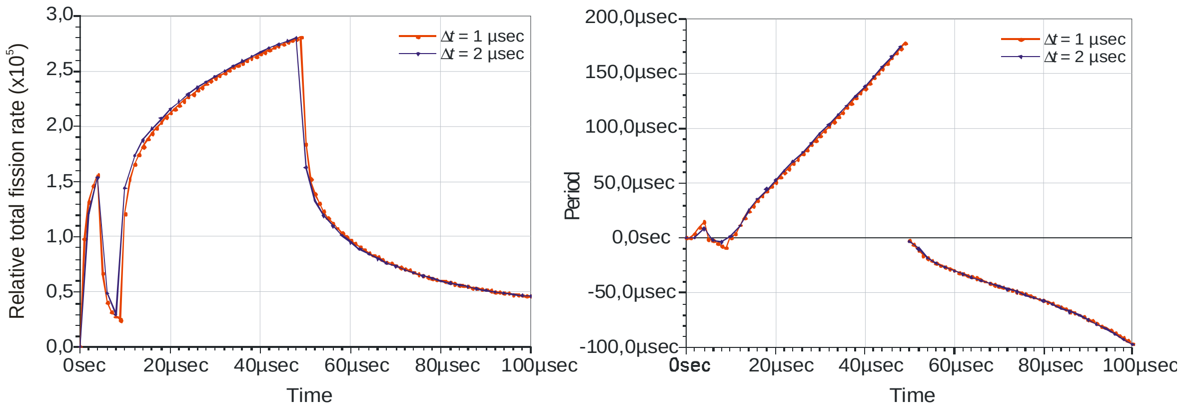

Figure 3. TORT-TD calculation of the YALINA-Thermal response to two square-wave pulses with 5 µsec and 40 µsec duration, separated by 5 µsec, for two different time step sizes (Δt = 1 µsec and Δt = 2 µsec). The left panel shows the overall fission rate (normalised to the initial state), the right panel the reactor period.

The modelling of the actual time-dependent source term is currently underway. As a first test of the extensions made in TORT-TD to account for time-dependent external sources, the response to a sequence of two square-wave pulses with 5 µsec and 40 µsec duration, separated by 5 µsec, has been analysed. Although this source is in a certain sense artificial, the pulse durations are close to actual YALINA-Thermal conditions. The resulting fission rate history (normalised to the initial state) is displayed in Fig. 3 (left) together with the reactor period (right) which is time dependent and discontinuous at $t = 50$ µsec. The calculation has been done using two different time step sizes, $\Delta t = 1$ µsec and $\Delta t = 2$ µsec. It shows a rapid increase at the beginning of the pulse and a decrease that is governed by the delayed neutron dynamics. This behavior is physically plausible as judged from validation calculations [9].

3. CONCLUSIONS

This paper describes the implementation of a time-dependent distributed external source in TORT-TD by explicitly considering the external source in the “fixed-source” term of the implicitly time-discretised transport equation. Anisotropy of the external source is represented by a spherical harmonics series expansion similar to the angular fluxes. The YALINA-Thermal subcritical assembly serves as a test case. In a first step, the steady state with 280 fuel rods has been analysed with TORT-TD and nuclear cross sections in 18 energy groups and P_1 scattering order generated by the KAPROS code system. Good agreement is achieved concerning the multiplication factor. In the second step, the response of the system to an artificial time-dependent source consisting of two square-wave pulses has been calculated. The result is physically plausible and qualitatively comparable to validation calculations. It demonstrates the time-dependent external source capability of TORT-TD.

ACKNOWLEDGEMENT

This work was supported by the German Federal Ministry of Economics and Technology. The authors acknowledge the support from IAEA Coordinated Research Projects on Analytical and Experimental Benchmark Analysis on Accelerator Driven Systems and Low Enriched Uranium Fuel Utilization in Accelerator Driven Sub-Critical Assembly Systems.

REFERENCES

1. W. A. Rhoades, R. L. Childs, “The TORT Three-dimensional Discrete Ordinates Neutron/Photon Transport Code“, (ORNL-6268), Nucl. Sci. Eng. 107 (1991) 397
2. W. A. Rhoades, D. B. Simpson, “The TORT Three-dimensional Discrete Ordinates Neutron/Photon Transport Code (TORT Version 3)“, ORNL/TM-13221 (1997)
3. A. Seubert, K. Velkov, S. Langenbuch, “The time-dependent 3D discrete ordinates code TORT-TD with thermal-hydraulic feedback by ATHLET models”, International Conference on the Physics of Reactors, Interlaken, Switzerland, September 14-19, 2008
4. V. Bournos et al., “YALINA-Thermal Benchmark Specifications for the IAEA Coordinated Research Projects on Analytical and Experimental Benchmark Analysis on Accelerator Driven Systems and Low Enriched Uranium Fuel Utilization in Accelerator Driven Sub-Critical Assembly Systems”, IAEA (2007)
5. A. Pautz, “Results on the OECD/NEA C5G7-MOX benchmark obtained with the discrete ordinates code DORT”, Prog. Nucl. Energy **45**, No. 2-4 (2004) 153
6. A. Seubert, W. Zwermann, S. Langenbuch, „Solution of the C5G7 3-D extension benchmark by the S_N code TORT“, Prog. Nucl. Energy **48**, No. 5 (2006) 432
7. C. H. M. Broeders et al., “KAPROS-E: Modular Program System for Nuclear Reactor Analysis, Status and Results of Selected Applications,” Jahrestagung Kerntechnik, Düsseldorf (2004)
8. H. Kiyavitskaya, “YALINA Subcritical Facility to investigate neutronics of ADS: Yalina-Thermal Benchmark, Yalina-Booster Benchmark”, IAEA Technical Meeting, Rome, Italy, 12-16 November (2007)

9. C.-M. Persson, “Reactivity Determination and Monte Carlo Simulation of the Subcritical Reactor Experiment – Yalina”, M.Sc. thesis, Royal Institute of Technology, Stockholm (2005)