CROSS-CHECKING OF THE TRANSURANUS BURN-UP MODEL FOR Gd-DOPED UO_2 WWER-1000 FUEL BASED ON RESULTS OF HELIOS CODE

M. Ieremenko, I. Ovdiienko

State Scientific and Technical Centre for Nuclear and Radiation Safety
(SSTC N&RS)
35-37, V.Stusa street, 03142 Kyiv-142, Ukraine

ml_eremenko@sstc.kiev.ua, *yn_ovdienko@sstc.kiev.ua*

1. ABSTRACT

This paper describes results of testing of the TRANSURANUS burn-up model (TUBRNP routine) for Gd-doped WWER-1000 fuel pin based on results of HELIOS code. The testing covers the analysis of different types of nuclear fuel rods from a neutronic point of view that one can encounter in the WWER-1000 reactor core. The HELIOS computations simulate the assembly geometry, and combine 4 different ^{235}U enrichment configurations with 4 different Gd_2O_3-concentrations. For each of these combinations the radial distribution of the concentrations of ^{155}Gd and ^{157}Gd compute in one Gd-doped rod. Based on these results the recommendations on using cross section of Gd in TRANSURANUS TUBRNP model were proposed.

2. KEYWORDS

TRANSURANUS, TUBRNP, HELIOS, WWER-1000, Gd-doped fuel pin.

3. INTRODUCTION

TRANSURANUS [1, 2] is a computer code for the thermal and mechanical analysis of cylindrical fuel rods in nuclear reactors. As part of the code, the TUBRNP model calculates the local concentrations of U, Pu and Nd as a function of the radial position across a fuel pellet (radial profiles). These local quantities are required for the determination of the local power density, the local burn-up, and the source term of fission products. In view of the primary importance of the relative radial power profile for the thermal and mechanical analysis of nuclear fuel, priority is given to relative rather than to absolute concentrations.

The present paper pursues our work by testing the TUBRNP model for Gd-doped WWER-1000 fuel. To this end, Gd-doped fuel rods in a WWER-1000 assembly were simulated by neutron transport calculations for different initial fuel compositions and different neutron spectra. The calculated local concentrations of ^{155}Gd, ^{157}Gd and radial power distribution were used for proposing of recommendations on using cross section of Gd in TRANSURANUS TUBRNP model.

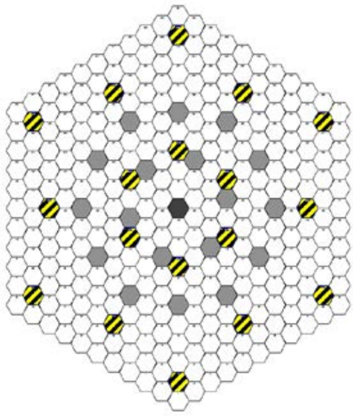
4. GOAL OF TESTING

This testing was done in framework of "Software Licensing Agreement No31796" signed by ITU, Germany and SSTC NRS, Ukraine. According this Agreement for testing following objects were chosen:

- TRANSURANUS version - v1m1j11;
- TUBRNP routine, describing the radial power profile in nuclear fuel rods of profiled bundles with Gd-doped UO2 fuel;
- FA for WWER-1000 reactors. Combine 4 different ^{235}U enrichment configurations with 4 different Gd2O3-concentrations. For each of these combinations the radial distribution of the concentrations of ^{155}Gd and ^{157}Gd compute in one Gd-doped rod.

5. INITIAL DATA FOR TESTING

All Initial data for testing were chosen according with Software Licensing Agreement, [6] and with typical operational data for WWER-1000. On Figure 1 configuration of a WWER-1000 fuel assembly is presented. This FA are different with last modification of FA with Gd-fuel pins used on Ukrainian NPPs but this differences are not significant for testing TUBRNP routine. Various of ^{235}U- and Gd- enrichments, of Gd-pins places in FA covers all modern FAs and their neutron spectrum characteristic. In Table 1÷Table 3 initial ^{235}U enrichments, contents of Gd_2O_3 and main parameters applied for simulating are presented.



-Gd-doped WWER-1000 fuel pin

Figure 1 - Configuration of a WWER-1000 fuel assembly [6]

Table 1 - Initial ^{235}U enrichments for WWER-1000 fuel rods

$^{235}U/^{tot}U$, (wt.%)		
Gd-doped rods	Periphery rods	Remaining rods
2.4	2.4	3.0
3.3	4.0	4.0
3.6	3.6	4.0
3.6	4.4	4.95

Table 2 - Initial contents of Gd_2O_3 for WWER-1000 fuel rods

Gd_2O_3/Fuel, (wt.%)
5.0
6.0
8.0
9.0

Table 3 - Main parameters applied for simulating the WWER-1000 fuel rods

Pellet inner radius (mm)	0.75
Pellet outer radius (mm)	3.785
Cladding inner radius (mm)	3.860
Cladding outer radius (mm)	4.55
Pin pitch (mm)	12.75
Mean fuel temperature (°C)	732
Mean moderator temperature (°C)	305
Moderator density (g/cm^3)	0.72
Boron concentration (g/kg H_2O)	3.0

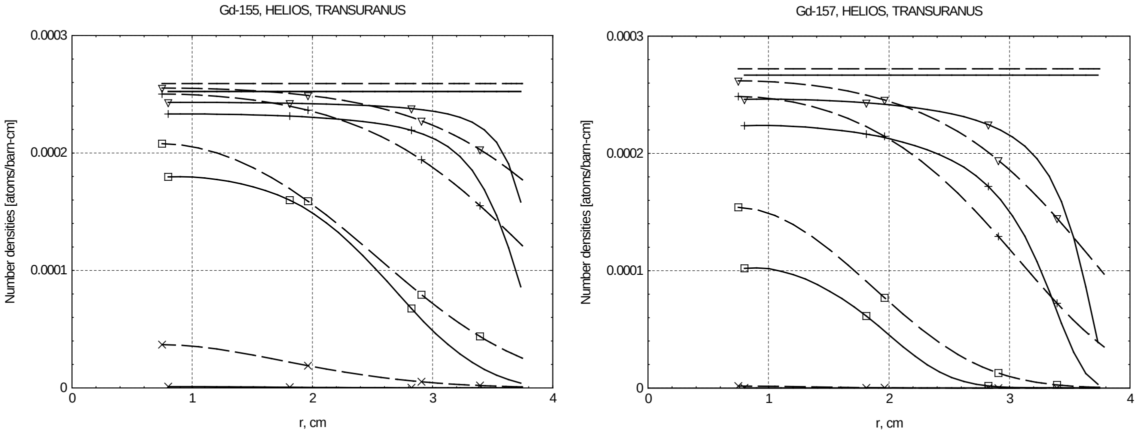
6. HELIOS MODEL

A HELIOS code [3] for detailed neutronic transport as well as depletion calculations was used. FA was presented as 1/6 part of whole assembly with mirror boundary conditions.

Gd-doped rods in HELIOS model was divided on 30 rings. Visualisation of HELIOS FA model are presented at conference in PowerPoint version of this paper.

7. RESULT OF STANDARD VERSION OF TRANSURANUS CODE

On Figure 2 concentration of ^{155}Gd, ^{157}Gd calculated by HELIOS & TRANSURANUS codes at different burnup points is presented. On Figure 3 radial power distribution calculated by HELIOS & TRANSURANUS codes at different burnup points is presented. As it is possible to see from figures, there are differences between results of two codes in the radial profile of power and of gadolinium concentration. The reason of difference and a proposal on optimisation of code TRANSURANUS are presented in following chapters of paper.



^{155}Gd ^{157}Gd

Figure 2 - Concentration of ^{155}Gd, ^{157}Gd. HELIOS (solid line) & TRANSURANUS (dashed line), Burnup=0, 0.4, 0.8, 3.1, 10 MW*d/kgU

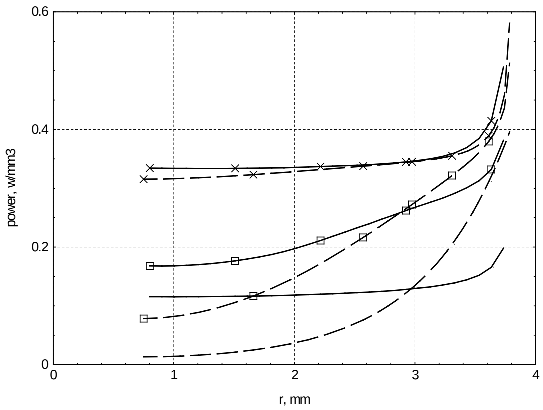


Figure 3 - Radial power distribution. HELIOS (solid line) & TRANSURANUS (dashed line), Burnup=0, 3.1, 10 MW*d/kgU

8. PROPOSAL FOR OPTIMISATION OF TUBRNP ROUTINE

According to [1] in order to determine neutron flux distribution $\Phi(r)$, thermal flux diffusion theory can be applied as follows:

$$\nabla^2\Phi - \kappa^2\Phi = 0 \qquad (1)$$

The inverse diffusion length:

$$\kappa = \sqrt{\frac{\Sigma_{a,tot}}{D}} \tag{2}$$

is derived from the macroscopic absorption cross sections:

$$\Sigma_{a,tot} \approx \sum_k \sigma_{a,th,k} \mathrm{N}_k \tag{3}$$

The resulting solutions of the differential equation are based on the modified Bessel functions (of the first and the second order type) and the flux profile function of inverse diffusion length κ (2):

$$\Phi(r) = f(\kappa) \tag{4}$$

and κ is function of microscopic absorption of gadolinium

$$\kappa = f(\sigma_a) = f(\sigma_a^{155,157}) \tag{5}$$

Concentration of gadolinium is defining by following equations:

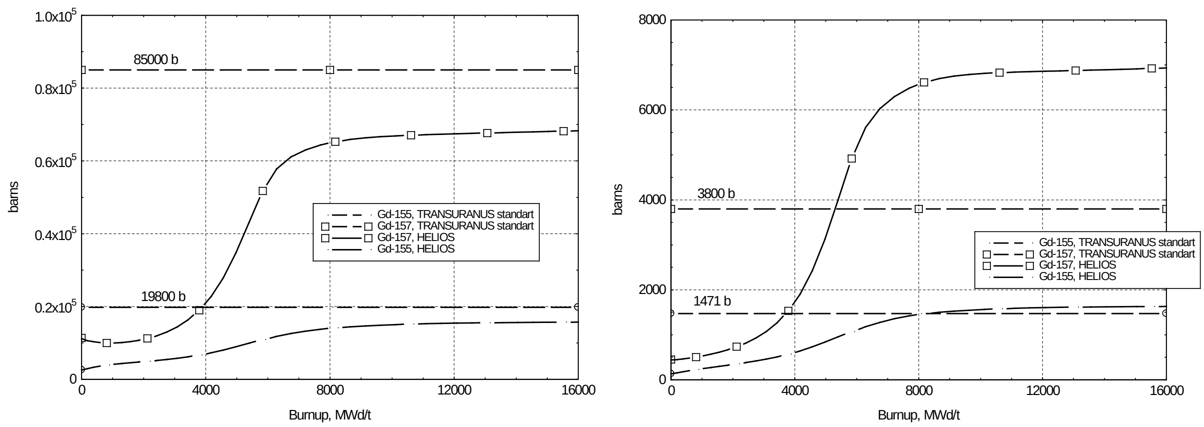
$$N_{155}(bu_{n+1}, r) = N_{155}(bu_n, r) e^{-\sigma_a^{155} A_{dbu}}\ ,\ N_{157}(bu_{n+1}, r) = N_{157}(bu_n, r) e^{-\sigma_a^{157} A_{dbu}} \tag{6}$$

For calculation of neutron flux (power) distribution Φ(r) and concentration of gadolinium isotops 155 and 157 the constant value of microscopic cross sections are used:

$\Phi(\mathrm{r})\ldots\ \sigma_{a,therm}^{157} = 85000\ \mathrm{b}$, $\sigma_{a,therm}^{155} = 19800\ \mathrm{b}$

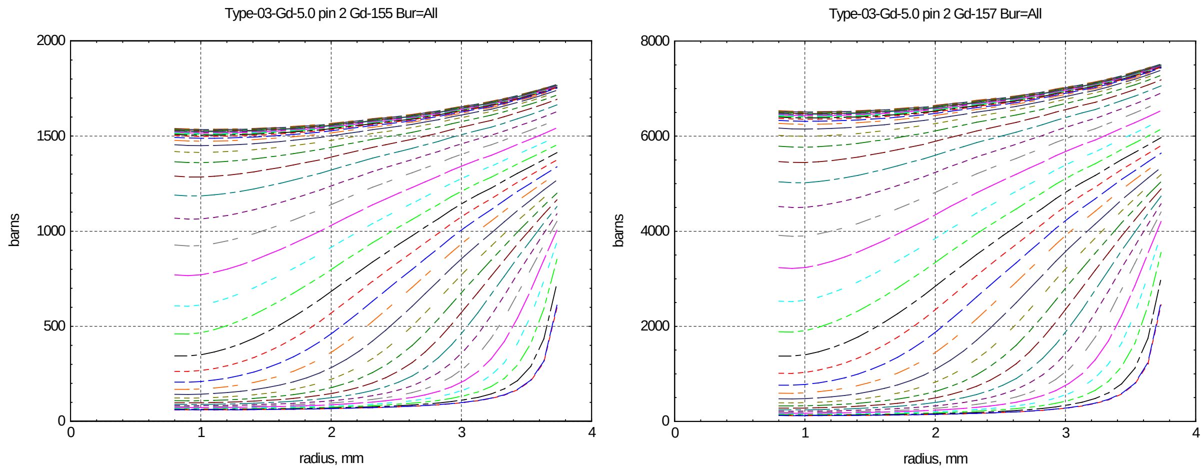
$\mathrm{N}_{155,157}(\mathrm{r})\ldots\ \sigma_a^{157} = 3800\ \mathrm{b}$, $\sigma_a^{155} = 1471\ \mathrm{b}$.

But absorption microscopic cross sections of gadolinium isotopes 155 and 157 has a strong dependence form burnup (Figure 4) and radial positions (Figure 5).



$\sigma_{a,therm}^{155,157}$ $\sigma_a^{155,157}$

Figure 4 - Microscopic cross sections σ_a and $\sigma_{a,therm}$ of gadolinium isotops at burnup



σ_a^{155} σ_a^{157}

Figure 5 - Microscopic cross sections σ_a of gadolinium isotops at radius. Botom line – burnup =0, top line – burnup>10 MW*d/kgU

For the account of this factor to replace constant values of gadolinium cross sections by dependences on burning and radius was offered:

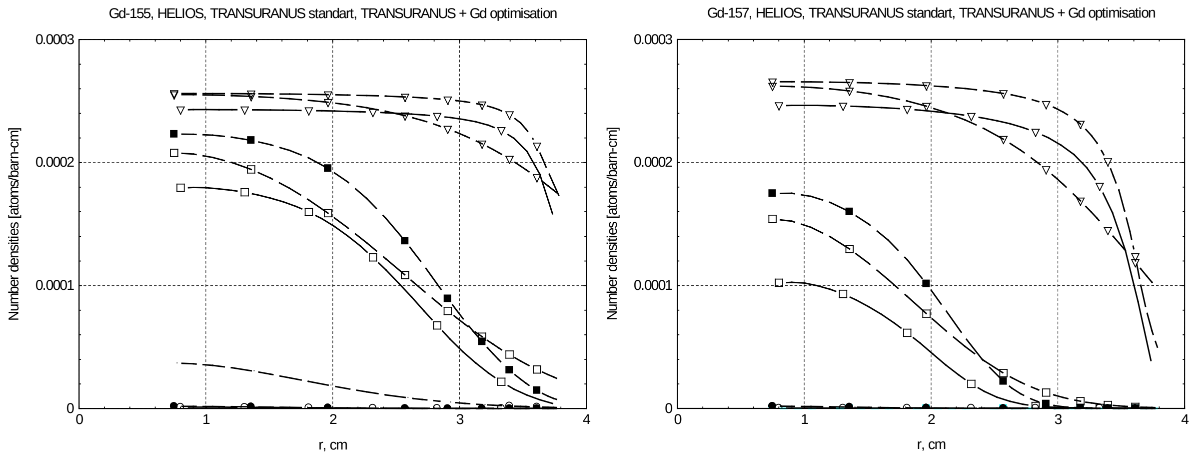
$$\Phi(\mathrm{r}),\ \sigma_{a,therm}^{155,157} = const \rightarrow \sigma_{a,therm}^{155,157} = f(bur)$$

$$N_{155,157}(\mathrm{r}),\ \sigma_a^{155,157} = const \rightarrow \sigma_a^{155,157} = f(bur,r)$$

For this activity the gadolinium cross-sections in tables format was used. This tables of gadolinium cross-section were calculated by HELIOS code.

9. RESULT OF OPTIMISED VERSION OF TRANSURANUS CODE

Results of calculation with use of optimised version TRANSURANUS are presented on Figure 6 and Figure 7 below. As it is possible to see from figures the distribution of gadolinium concentration and of power on pellet radius became closer to the results of code HELIOS. A difference of absolute value of gadolinium concentration is connected to differences with initial concentration of gadolinium for fresh fuel which directly define in HELIOS model and are calculated by TRANSURANUS from densities, enrichments etc.



^{155}Gd ^{157}Gd

Figure 6 - Concentration of ^{155}Gd, ^{157}Gd. HELIOS (solid line) & TRANSURANUS (dashed line). Standard version of TRANSURANUS with empty marker, TRANSURANUS with Gd-optimisations with filled marker. Burnup=0.4, 3.1, 10 MW*d/kgU

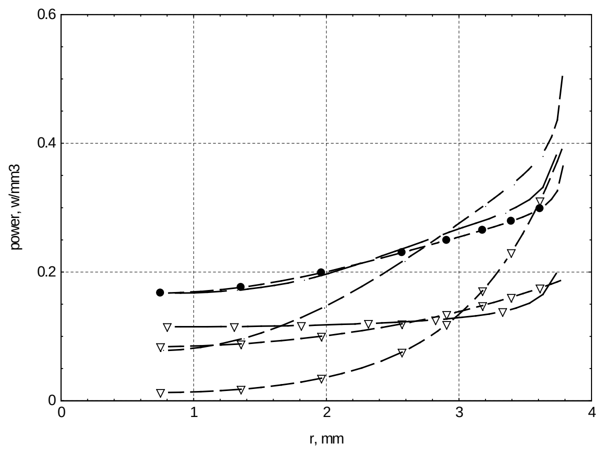


Figure 7 - Radial power distribution. HELIOS (solid line) & TRANSURANUS (dashed line). Standard version of TRANSURANUS with empty marker, TRANSURANUS with Gd-optimisations with filled marker. Burnup=0, 3.1 MW*d/kgU

10. CONCLUSION

- Using gadolinium cross-sections in view of function of burnup and radius make TRANSURANUS results (Gd and power distribution) close to HELIOS.
- Gadolinium cross-sections can be present as approximation formula, direct table values and so on.
- Sets of gadolinium cross-sections can be calculated by spectral code.

11. LIST OF NOMENCLATURE

FA .... Fuel Assembly
FP .... Fuel Pin
ITU..................... Institute of Transuranium Elements
NPP .... Nuclear Power Plant
SSTC NRS .... State Scientific and Technical Centre for Nuclear and Radiation Safety
TVS .... Fuel Assembly
WWER............... Soviet Design of Pressurized Water Reactor.

12. REFERENCE

1. *TRANSURANUS HANDBOOK*. Document Number Version 1 Modification 1 Year 2011 ('V1M1J11') January 2011. EC Join Research Centre Institute for Transuranium Elements.
2. K. Lassmann, *TRANSURANUS: a fuel rod analysis code ready for use*, J. Nucl. Mater. 188 (1992) 295.
3. J.J.Cassel et al. *HELIOS: Geometric Capabilities of a New Fuel-Assembly Program.* Topical Meeting on Advances in Mathematics, Computations and Reactor Physics. Pittsburg, Pennsylvania, April 28 – May 2 1991,Vol.2, pp 10.2.1 1-13.
4. U.Grundmann, U.Rohde, S. Mittag, S.Kliem *DYN3D Version 3.2Code for calculation of transient in Light Water Reactors (LWR) with Hexagonal or Quadratic Fuel Elements. Description of Models and Methods.* Report FZR-434, Rossendorf (2005).
5. A. Schubert, T. Safaryan, S. Bznuni, P. Van Uffelen, J. van de Laar, *Extension of the TRANSURANUS burn-up model for Gd-doped* UO_2 *fuel in WWER reactors.* WWER Fuel Performance Meeting, 8th Int. Conf. WWER Fuel Performance, Modelling and Experimental Support, Burgas, Bulgaria, 26 September – 4 October 2009.
6. *Characteristics and use of urania-gadolinia fuels*, IAEA-TECDOC-844, November 1995, p.73