Transport Model Based on Three-Dimensional Cross-Section Generation for TRIGA Core Analysis

N. Kriangchaiporn[1], K. Ivanov[1], A. Haghighat[2], and C. F. Sears[1]

[1]- *Department of Mechanical and Nuclear Engineering*
The Pennsylvania State University

[2]-*Department of Nuclear and Radiological Engineering*
University of Florida

ABSTRACT

The development of a three-dimensional (3-D) transport model for TRIGA core analysis based on the discrete ordinates (S_n) method has been conducted. The effective fine- and broad- group structures for the TRIGA cross-section libraries were selected based on CPXSD (Contributon and Point-wise Cross-Section Driven) methodology. Different 3-D pin/core configurations are used to verify and validate the selected effective group structures. Thirteen-group structure was finally selected to be used for core analysis. The results agree with continuous energy cross-section Monte Carlo calculations for eigenvalues and normalized pin power distributions, which are used as a reference in this research.

KEYWORDS: TRIGA, discrete ordinates, cross-section generation, deterministic transport, core analysis, DORT/TORT

INTRODUCTION

The current tendency in reactor physics research is to utilize the neutron transport theory based methods for simulation of real reactor core analysis problems to obtain detailed and accurate solutions. In the past, three-dimensional (3-D) transport core numerical simulations were computationally expensive and impractical. However, recent advancements in computer technology, combined with new methods and code developments make it feasible to develop neutron transport calculation schemes capable of providing accurate solutions in an efficient manner. On-going research in the framework of collaboration between the Pennsylvania State University (PSU) and University of Florida is focused on the development of an efficient 3-D transport model for TRIGA core analysis based on the discrete ordinates (S_n) method. In the previous papers [1, 2], the development of consistent multi-group cross-section generation methodology in 2-D and 3-D geometry based on the 8.5 wt% TRIGA fuel cell was presented. These studies resulted in obtaining of the following effective broad-group energy structures - a 12 group-structure in 2-D geometry vs. a 26 group-structure in 3-D geometry. This paper presents core analysis study utilizing the developed broad-group cross-section libraries, which completes the work on the development of a 3-D transport model for TRIGA core analysis.

DESCRIPTION OF THE WORK

The CPXSD (Contributon and Point-wise Cross-Section Driven) methodology [5] was used to construct fine- and broad-group structures considering two criteria: i) importance of groups and ii) pointwise cross sections of an isotope/material mixture of interest. The importance of the groups is determined using the group-dependent response flux formulation (or contributon) given by Equation (1).

$$C_g = \int_V d^3r \int_{4\pi} d\Omega \psi_g(\vec{r},\hat{\Omega})\psi_g^+(\vec{r},\hat{\Omega}) \quad (1)$$

In Equation (1), $\psi_g(\vec{r},\hat{\Omega})$ is the angular flux and $\psi_g^+(\vec{r},\hat{\Omega})$ is the adjoint ("importance") function dependent on position $\vec{r}$, direction $\hat{\Omega}$, and in group g.

The CPXSD methodology constructs group structures by refining an initial arbitrary group structure, considering the two aforementioned criteria. First, the objectives are calculated using the cross section library having the initial group structure. The importance values of all groups are calculated and the most important group is identified. Depending on the point-wise cross sections of the important isotope/mixture and/or group of isotopes/mixture, sub-groups are placed in the most important group. The number of sub-divisions in other groups are determined based on the ratio of their Cg, to the maximum Cg. Sub-divisions in other groups are performed and a new group structure is generated. The refinement process continues until a convergence criterion on the objectives is achieved.

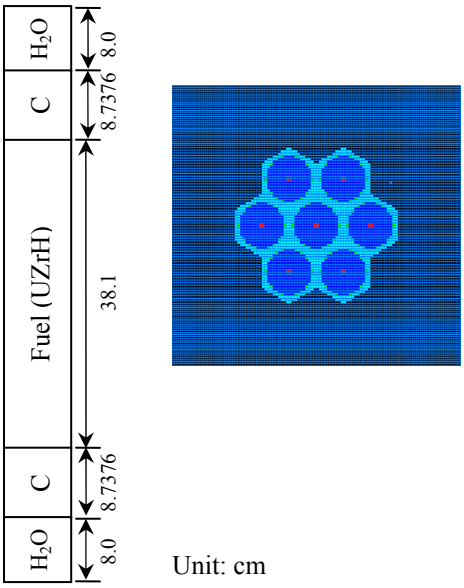
With the CPXSD methodology, we have developed the effective 280-fine- and 26-broad- group structures for the TRIGA cross-section libraries.

Three different 3-D pin/core configurations were utilized to verify the developed broad-group effective group structures. The first one is a fuel pin in an infinite lattice; the second one is a mini-core model, and the third one is a realistic TRIGA core loading. In all multigroup calculations, the TORT 3-D Sn code [3] is utilized, and the MCNP5 Monte Carlo code [4] is used to determine the reference solution. The cross- section libraries for TORT and MCNP5 calculations are based on the ENDF/B-VI library.

The first model, a fuel pin, is used to study the effect of geometry (3-D vs. 2-D) on multigroup cross-section generation.

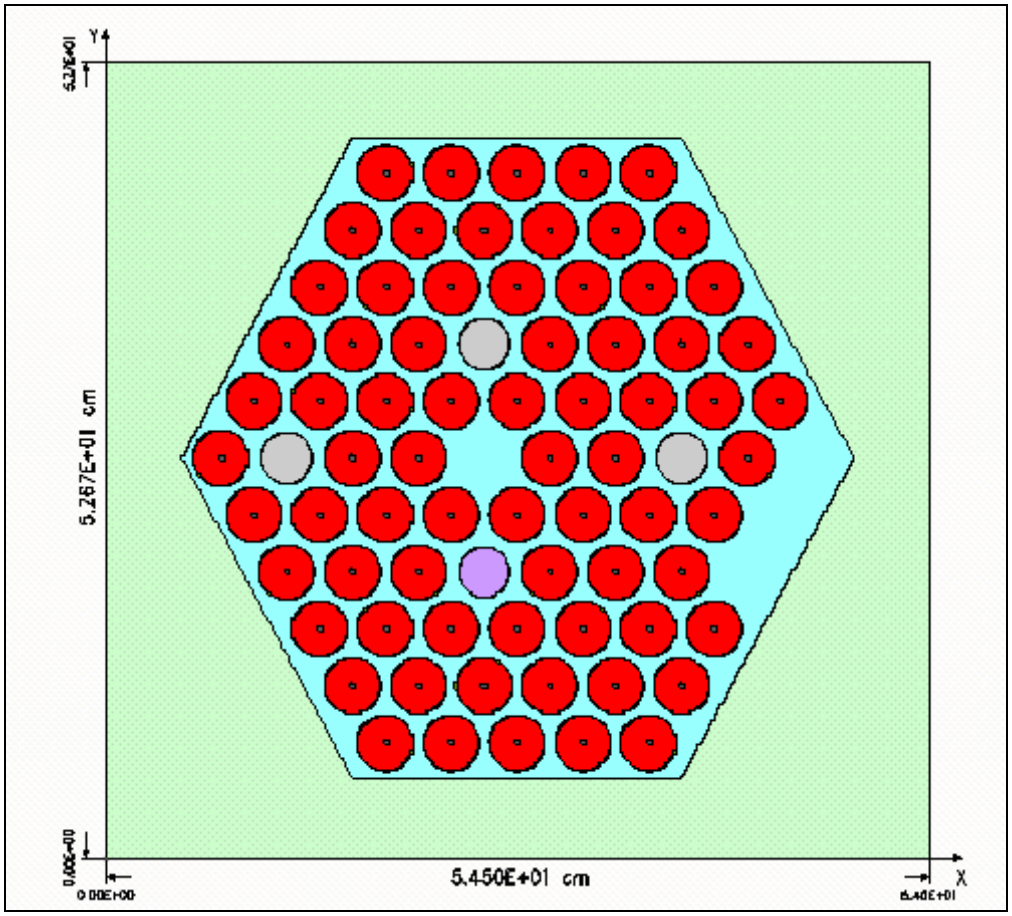
The second core model – the mini-core model consists of 7 fuel elements as shown in Fig. 1. A 1/8 mini-core sector of size 11.53x11.28x35.79 cm^3 is considered. This model was used to examine the importance of using the 26-group structure cross-section library.

Figure 1: The configuration of mini-core



The third model for TRIGA core loading 2 was developed with parametric studies on quadrature order, scattering order, and mesh size. It consists of 72 8.5% wt. fuel elements with 4 control rods. Fig. 2 shows the cross sectional view of the core arrangement. A 1/2 core sector was modeled in this study. The overall size of the 3-D model is 54.50x52.67x35.79 cm^3. The fuel elements were modeled explicitly specifying the detailed structure of the rod to eliminate any homogenization effects. The problem is that 26 groups are still computationally expensive for a whole 3-D core calculation. A "coarse" group structure has been selected from the 26 broad-group structure in order to make these calculations feasible. The 13-coarse group structure was developed from the 26-group structure by combining the groups that has less importance. The obtained 13-coarse group structure library was verified on the fuel pin model by comparisons with the 26-broad group structure results [6].

Figure 2: The TRIGA core loading 2



RESULTS

The results of 3-D calculations for the Penn State TRIGA core are analyzed below.

A. Fuel Pin calculations

A fuel pin was simulated using the code TORT with an S_8 Square Legendre-Chebyshev quadrature order and P_1 scattering order. First, the 26-group structure was utilized for both 2-D and 3-D cross-section generation procedures in order to study the effect of using 2-D vs. 3-D flux distribution in energy-group collapsing procedure. The comparative analysis indicated a very small deviation in k_{eff} (about 20 pcm) and maximum reaction rate deviation of 14% (for the absorption rate in fast energy range of graphite). Then the results of 12-group calculations (obtained in 2-D cross-section generation process) was compared to those of 26-group calculations (obtained in the 3-D cross-section generation process). The deviation in k_{eff} is about 700 pcm. However, the 3-D 26-group structure cross-section library produces much better agreement with the reference MCNP model.

B. Mini-core model

The study was performed with S_8- Square Legendre Chebyshev (*SLC)* quadrature set with P_1 and P_3 scattering order. The flux convergence was set to $1x10^{-4}$ and the eigenvalue convergence was set to $1x10^{-6}$. The reference solution was obtained by MCNP5 with 3000 number of histories per cycle, 1000 number of skipped cycles and 4000 number of active cycles. The standard deviation is within 1% for reaction rates. Table 1 gives the eigenvalues calculated by MCNP5 and TORT for P_1 and P_3 cases.

Table1: The k_{eff} calculated from TORT and MCNP

	k_{eff}	Deviation From MCNP In pcm of Δk
MCNP	0.50469 $\pm 0.00060(3\sigma)$	-
TORT,S_8P_1	0.49943	-526
TORT,S_8P_3	0.50556	87

Results indicate that scattering order has a pronounced effect on the eigenvalue. The P_3 case agrees with MCNP5 better than the P_1 case. Tables 2 and 3 show the percentage deviations of reaction rates between TORT and MCNP for P_1 and P_3 cases, respectively.

Table 2: Percentage deviation of reaction rates between TORT-P_1 and MCNP

Reaction Type	Zr	Fuel	Clad_fuel	Water_fuel	Graphite	Clad_gra	Water_gra	Reflector
Abs_Fast	-1.52	-3.44	-3.14	-4.96	-3.72	-3.34	-0.28	7.22
Abs_Epi	-1.76	-1.76	-7.33	-3.46	-0.32	-11.60	-0.34	-0.39
Abs_Thermal	0.52	-0.91	-3.26	-3.31	-0.54	-0.83	-1.16	-1.20
Abs_Total	-0.31	-1.03	-3.35	-3.35	-0.89	-0.94	-1.15	-1.15
Nu-Fis_Fast	-	-4.32	-	-	-	-	-	-
Nu-Fis_Epi	-	-4.46	-	-	-	-	-	-
Nu-Fis_Thermal	-	-0.78	-	-	-	-	-	-
Nu-Fis_Total	-	-0.97	-	-	-	-	-	-
Tot_Fast	-1.51	-3.15	-2.06	-1.39	1.50	-5.72	1.71	2.72
Tot_Epi	-0.09	-3.59	-4.54	-3.06	0.18	-5.33	0.47	0.13
Tot_Thermal	-2.03	-1.46	-2.53	-3.18	-1.13	0.34	-0.81	-0.84
Tot_Total	-1.23	-2.36	-3.07	-2.97	-0.43	-1.30	-0.54	-0.62

Table 3: Percentage deviation of reaction rates between TORT-P_3 and MCNP

Reaction Type	Zr	Fuel	Clad_fuel	Water_fuel	Graphite	Clad_gra	Water_gra	Reflector
Abs_Fast	0.88	-1.49	-1.65	-3.62	-4.43	-3.91	-0.95	5.43
Abs_Epi	0.22	-0.07	-5.73	-1.80	-0.41	-11.63	-0.34	-1.20
Abs_Thermal	1.81	0.29	-2.09	-2.20	-0.69	-0.97	-1.33	-1.45
Abs_Total	1.29	0.22	-2.17	-2.22	-1.11	-1.09	-1.32	-1.42
Nu-Fis_Fast	-	-2.56	-	-	-	-	-	-
Nu-Fis_Epi	-	-2.83	-	-	-	-	-	-
Nu-Fis_Thermal	-	0.41	-	-	-	-	-	-
Nu-Fis_Total	-	0.25	-	-	-	-	-	-
Tot_Fast	0.88	-1.01	-0.38	0.05	0.82	-6.30	1.10	0.27
Tot_Epi	1.95	-1.75	-2.86	-1.43	0.08	-5.40	0.36	-1.00
Tot_Thermal	-0.73	-0.26	-1.30	-2.03	-1.26	0.21	-0.97	-1.11
Tot_Total	0.79	-0.81	-1.63	-1.68	-0.65	-1.46	-0.71	-1.05

Again, it is evident that using P_3 scattering order improves the accuracy of the 3-D multigroup calculations as compared to the MCNP predictions.

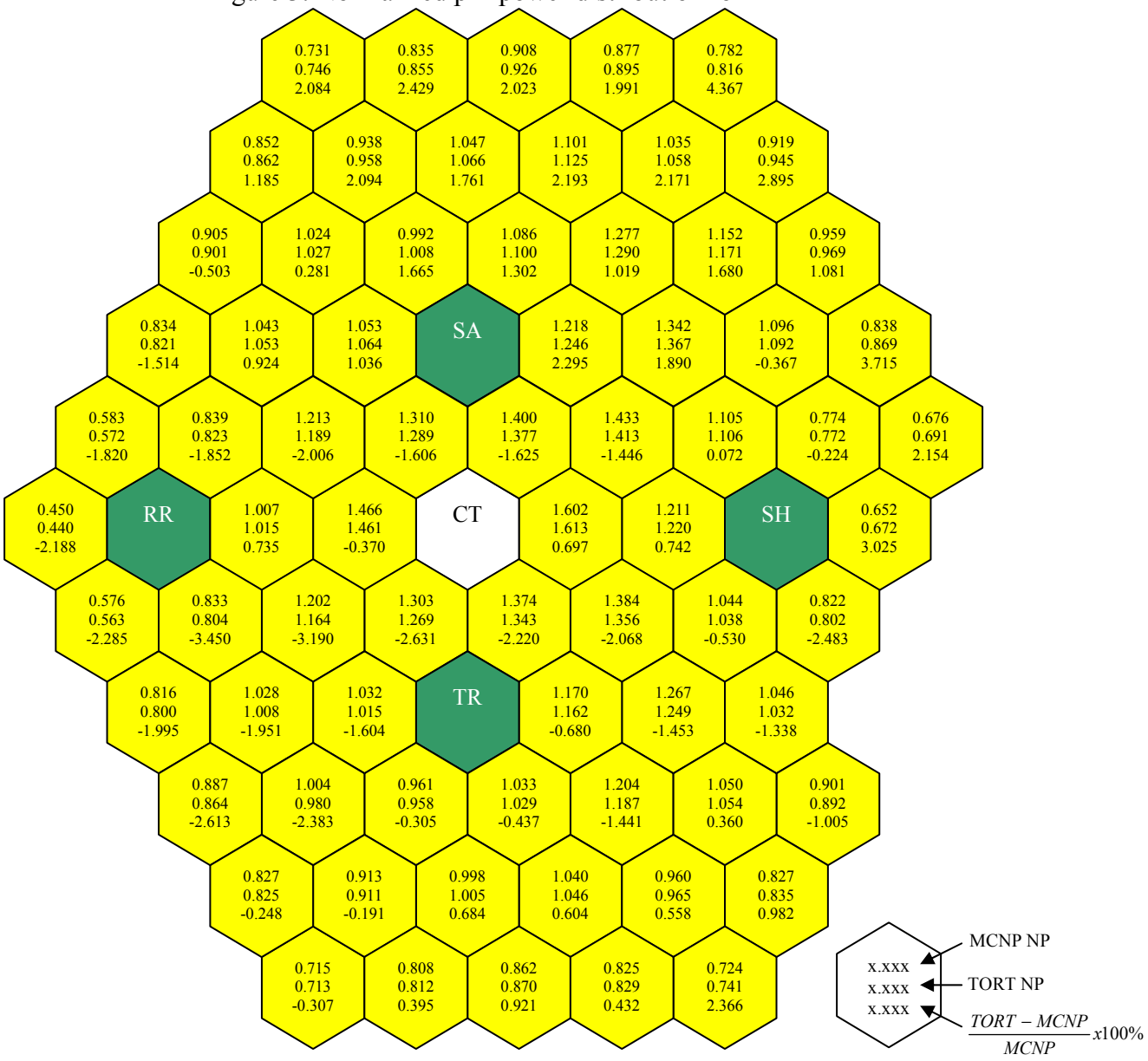
C. TRIGA core loading 2 model

The calculation of core loading 2 was performed for two cases - with and without control rods. The 13-coarse group cross section library was used with S_8 Square Legendre Chebyshev (*SLC)* quadrature set and P_1 scattering order. The flux convergence was set to $5x10^{-4}$ and the eigenvalue was set to $1x10^{-5}$. Comparison of the k_{eff} indicates that TORT overestimates the k_{eff} by 9 pcm (as illustrated in Table 4) for the case with all control rods in (ARI). The relative differences of the normalized power vary in the range of ~-3% to +4% as shown in Figure 3.

Table 4: The k_{eff} calculated from TORT and MCNP for all control rods in

	k_{eff}	Deviation From MCNP In pcm of Δk
MCNP	0.90609 $\pm 0.00060(3\sigma)$	-
TORT,S_8P_1	0.90618	9

Figure 3: Normalized pin-power distribution for ARI

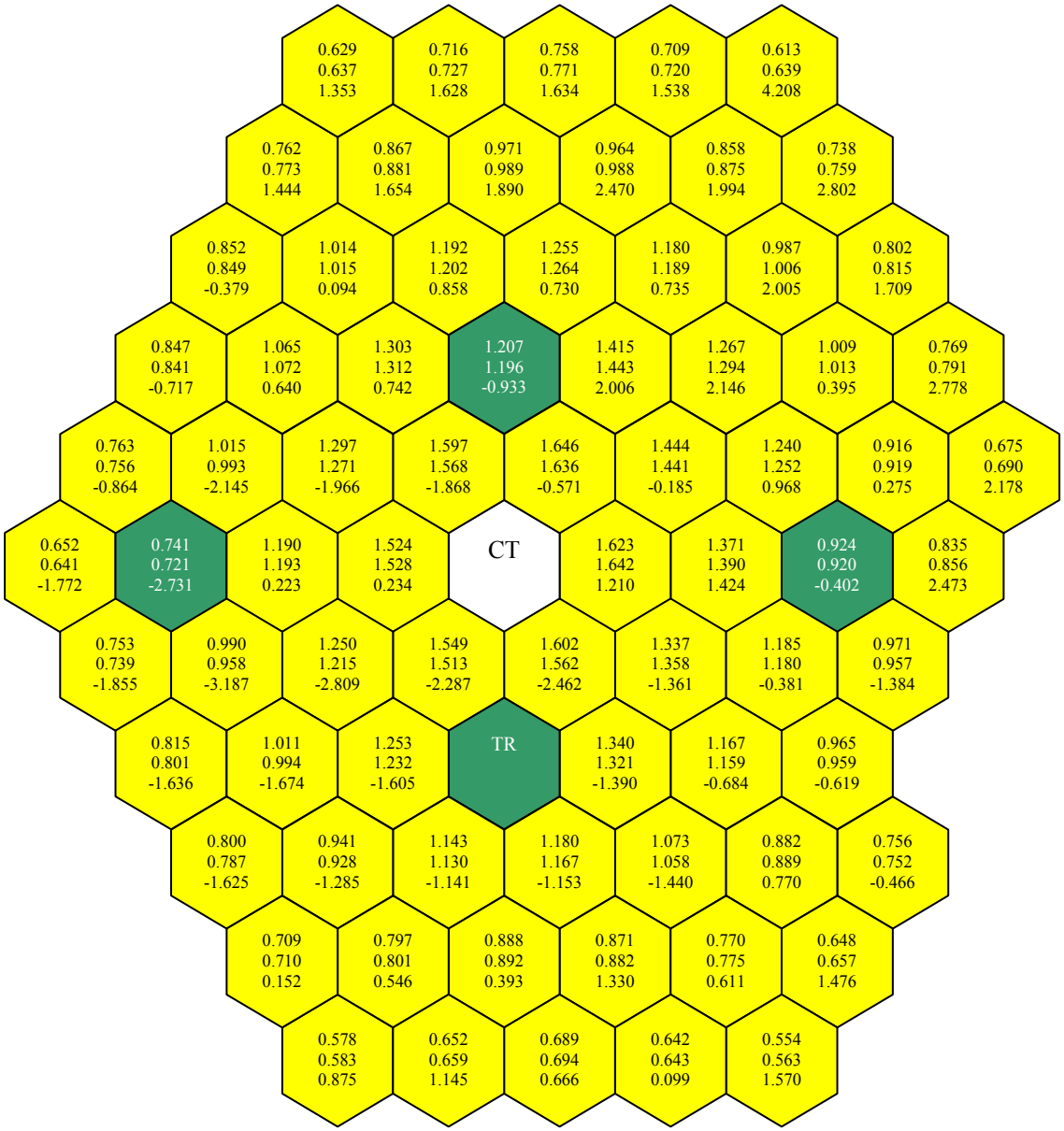


For the all control rods out (ARO) case, the comparison of the k_{eff} indicates that TORT overestimates the k_{eff} by 91 pcm (as given in Table 5). The relative differences of the normalized power vary in the range of ~-3% to +3% as shown in Figure 4. The maximum differences occur at the core periphery where the power is low.

Table 5: The k_{eff} calculated from TORT and MCNP for all control rods withdrawn

	k_{eff}	Deviation From MCNP In pcm of Δk
MCNP	1.01926 $\pm 0.00057(3\sigma)$	-
TORT,S_8P_1	1.02017	91

Figure 4: Normalized pin-power distribution for ARO



CONCLUSIONS

The effect of 2-D vs. 3-D cross-section generation was estimated using the TRIGA 3-D pin cell in an infinite lattice. The comparative analysis of the 3-D unit fuel cell using the cross sections collapsed with 2-D 12-group structure and with 3-D 26-group structure indicates the significant effect of the group structure. The 3-D 26-broad group cross section library was verified using the mini-core model. The 13 coarse-group library is obtained for whole core calculation. In comparing, the eigenvalue and normalized pin power distribution of TRIGA core loading 2 both with and without control rods, the results show good agreement even for the coarse-group structure without any spatial homogenization.

REFERENCES

1. N. Kriangchaiporn, K. Ivanov, A. Haghighat, and C. F. Sears, "Multi-Group Cross-Section Generation for TRIGA Core Analysis", TANSAO 89, pp. 608-610, 2003.
2. N. Kriangchaiporn, K. Ivanov,A. Haghighat, and C. F. Sears, "Three-Dimensional Cross-Section Generation for TRIGA Core Analysis", TANSAO 93, pp. 619-621, 2005.
3. DOORS 3.2: One, Two- and Three-Dimensional Discrete Ordinates Neutron/Photon Transport Code System, Oak Ridge National Laboratory, Oak Ridge, Tennessee, October 1995.
4. MCNP5—A General Monte Carlo N-Particle Transport Code, Version 5, Los Alamos National Laboratory, April 24, 2003.
5. F. Arzu Alpan, and A. Haghighat "Development of the CPXSD Methodology for Generation of Fine-Group Libraries for Shielding Calculations", Nuclear Science and Engineering, 149, 51-64 (2005).
6. N. Kriangchaiporn, "Transport Model based on 3-D Cross-Section Generation for TRIGA Core Analysis", Ph.D. Thesis, The Pennsylvania State University, 2006.