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COMPARISON OF CODES AND NEUTRON IC DATA USED IN US AND RUSSIA FOR THE TOPAZ-II NUCLEAR SAFETY ASSESSMENT

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Abstract

Topaz-II is a heterogeneous, epithermal reactor, fueled with highly enriched uranium-dioxide, cooled with NaK, and moderated with zirconium-hydride. The reactor core contains 37 single-cell thermionic fuel elements, and is surrounded by a radial beryllium reflector that contains 12 rotatable control drums with poison segments. For the physics analysis of TOPAZ II it is necessary to use the Monte Carlo method. The United States (US) and Russia used two different Monte Carlo codes, namely MCNP and MCU-2, respectively. The work described in this paper was aimed at comparing the codes and neutronic data used in the US and Russia for verification of Topaz-II nuclear safety. For this purpose, the US and Russia developed a joint benchmark model of the Topaz-II reactor. The American and Russian teams performed independent computations for a series of variants representing potential water immersion accidents.

Our comparison of the MCNP and MCU-2 codes showed somewhat different results both for the absolute values of k_{eff} and for reactivity effects. Future calculations will be performed to obtain a detailed understanding of the reasons for such discrepancies. For these analyses it will be necessary for the US and Russian teams to exchange neutronic data on Topaz-II physics calculations.

INTRODUCTION

Previous research has shown that nuclear power systems using a thermionic converter reactor (TCR) as the power source show promise for use in space exploration missions (N. N. Ponomarev-Stepnoi 1989).

Topaz-II is a heterogeneous, epithermal reactor, fueled with highly enriched uranium-dioxide, cooled with NaK, and moderated with zirconium-hydride. The reactor core contains 37 single-cell thermionic fuel elements, and is surrounded by a radial beryllium reflector that contains 12 rotatable control drums with poison segments. Performing neutronics calculations for the Topaz-II reactor is difficult because of its (1) small dimensions, (2) complicated heterogeneous structure, (3) highly enriched fuel, (4) in-core TFEs with the electrodes made of molybdenum and tungsten, (5) zirconium-hydride moderator, (6) rotatable control drums in the side reflector, (7) complex neutron energy spectrum, (8) high neutron leakage, and (9) increase in reactivity if accidentally immersed in water.

The Monte Carlo method must be used to perform neutronics calculations for Topaz-II. The US and Russia used two different Monte Carlo codes for reactor physics calculations: the MCNP code developed at Los Alamos (Briesmeister 1986) and the MCU-2 code developed at the Kurchatove Institute, Moscow (Gomin et al. 1990). Our goal was to compare the codes and the neutronic data used in the US and Russia for computational analyses of Topaz-II reactor neutronics, including water immersion.

This paper describes briefly the results of such work. The US and Russian teams developed joint benchmark computational models of the reactor and the core cell. Using these models, comparison calculations of the reactor and core cell neutronics were performed with the MCNP and MCU-2 codes. The results obtained are somewhat different both for absolute values of k_{eff} and for reactivity effects. It seems likely that these discrepancies are primarily the result of the difference in the neutronic data used in the US and in Russia. To understand these differences it will be necessary for the US and Russian teams to exchange neutronic data on Topaz-II reactor physics calculations.

DESCRIPTION OF THE CODES AND NEUTRONIC DATA

The MCU-2 system being used in Russia for Topaz-II reactor neutronics calculations was developed at the Russian Science Center - Kurchatov Institute, Russia (Gomin et al. 1990). The code includes a program for reactor physics computations using the Monte Carlo method and libraries of nuclear data.

The MCU-2 neutronic data library includes thermal cross sections that account for chemical binding of atoms and the crystalline structure of neutron moderators, nuclide resonance parameters in the range of allowed resonances, and a 26-group system of constants.

The MCU-2 code has a modular architecture, which consists of physics, geometrical, control, and source modules. The physics module models neutron collisions in the fast, resonance, and thermal energy (thermalization) ranges. The geometrical modules model the reactor geometry. For the Topaz-II reactor model, a general purpose geometric module based on the combinatorial geometry method was used. Basic geometric forms include parallelepipeds, hexagonal prisms, cylinders, cones, spheres, planes, etc. The control and source modules allow the code to solve neutron fields and k_{eff} eigenvalue problems using iterations of the fission neutron sources. They can solve problems with prescribed distributions of neutron sources and can find asymptotical solutions for problems of lattices with neutron leakage.

The MCU-2 code and neutronic data have been benchmarked against experiments on critical assemblies.

The MCNP code was developed at Los Alamos National Laboratory (Briesmeister 1984) to solve particle (gamma quanta, electrons, and neutrons) transport equations using the Monte Carlo method. A combinatorial geometry method is used to model neutron trajectories of any complex geometry. MCNP use nuclear data based on the ENDF/B V library of evaluated neutronic data (Kinsy 1979), The basic ENDF data of this library are transformed into MCNP cross section libraries using NJOY-type codes. In the neutron energy range of thermalization, the scattering cross sections are described in the form of laws that account for the chemical binding and crystalline structure of moderating materials.

MCNP has been benchmarked against analytical calculations performed for critical assemblies, and a successful prediction of calculated results has been demonstrated (Wagner et al. 1992).

COMPUTATIONAL MODEL OF THE CORE CELL AND THE TOPAZ-II REACTOR

A joint benchmark model of the Topaz-II reactor was developed to compare the MCNP and MCU-2 codes and neutronic data being used in the US and Russia for Topaz II physics analyses. The basis for the computation model, which was designated as MODEL1, was the Topaz-II experimental prototype V-71. The neutronic parameters of this prototype were extensively studied experimentally. The experimental results serve as a basis to judge the accuracy of the calculated results.

The computer model comprised a 60° sector of the reactor, symmetric about the reactor midplane. Additional zones were provided outside of the side- and end-beryllium reflectors to allow simulation of accidental reactor water immersion. The internal core cavities that could fill with water if the reactor was accidentally flooded were modeled in detail. When water was not present, the reactor internal cavities and outside its surroundings were modeled by aluminum of very low density. Adequately modeled rotatable control drums were located in the side beryllium reflector. We included only the primary material components, and neglected impurities in view of their small influence on reactor reactivity.

The calculational model of the Topaz-II reactor core cell was assumed to have a form of a right hexagonal prism with a height of 485 mm and a distance across flats of 37 mm. Mirror reflection boundary conditions were assigned to the side faces of the cell and vacuum conditions to the top and bottom surfaces. The cell model takes into complete account the fuel, gaps, emitter, collector, steel tubes, coolant, end reflectors, and moderator.

RESULTS OF MCU-2 AND MCNP CALCULATIONS OF THE REACTOR AND THE CORE CELL PHYSICS PARAMETERS

Reactor physics calculations were performed with MODEL1 for 5 cases, which differed in the control drum position, the presence of the beryllium side reflector, and the presence of water around the reactor and in its cavities. Calculated values of k_{eff}, obtained with MCNP and MCU-2 are shown in Table 1.

Table 1 shows that for all of the above variants, the absolute value of k_{eff} obtained with MCU-2 exceeds that obtained with MCNP on an average of about 1%. It should be noted that the value of the reactivity margin experimentally obtained for the V-71 unit without water and with the drums turned out gives the value of k_{eff} = 1.014, which is very close to the mean k_{eff} calculated by MCNP and MCU-2 ($k_{eff} = \sim 1.016$). We therefore made a preliminary conclusion that the true value of k_{eff} lies between the MCNP and MCU-2 calculated values.

In addition to k_{eff} absolute values, we have also calculated several reactivity effects. Table 2 shows the calculated values of reactivity effects and also shows the control drum worth for a dry reactor, and for a water flooded and immersed reactor. Table 3 shows the reactivity effects of flooding and immersing a reactor with the side beryllium reflector in place, and control drums turned in and out. The MCNP- and MCU-2-calculated reactivity effects are shown to be somewhat different although the difference is not fundamental.

TABLE 1. The k_{eff} Results of MODEL1 Calculations.

No.	Water	Control Drum Position	MCNP (US) k_{eff}	MCU-2 (Russian) k_{eff}
1	No	Turned out	1.0099± 0.0008	1.0226± 0.0015
2	No	Turned in	0.9510±0.0010	0.9620±0.0015
3	Yes	Turned out	1.0739±0.0009	1.0858±0.0015
4	Yes	Turned in	1.0258±0.0008	1.0308±0.0015
5	Yes	Side reflector off	1.0118±0.0008	1.0161±0.0015

TABLE 2. Control Drums Worth (ΔK).

No.	Reactor State	MCNP (US)	MCU-2 (Russian)
1	Dry	0.0589 ± 0.0012	0.0606 ± 0.0021
2	Flooded and surrounded by water	0.0481 ± 0.0012	0.05501 ± 0.0021

TABLE 3. Effect of Water Flooding and Immersing the Reactor with the Side Reflector (Be) in place (ΔK).

No.	Reactor State	MCNP (USA)	MCU-2 (Russian)
1	Drums turned out	0.0640 ± 0.0012	0.0632 ± 0.0021
2	Drums turned in	0.0750 ± 0.0012	0.0688 ± 0.0021

In order to understand the reasons for the discrepancies between the MCNP and MCU-2 calculated results, a comparison was made of nuclear reaction rates over the reactor volume for the following reactor states using MODEL1: (1) dry reactor, drums turned out; (2) water immersed and flooded reactor, drums turned out; (3) dry reactor, drums turned in; and (4) water immersed and flooded reactor, drums turned in. As an example, the results of the comparison for the dry reactor with the drums turned out are shown in Table 4.

The comparison of reaction rates indicate that the difference between the k_{eff} values obtained with MCNP and MCU-2 primarily are the result of the difference in the neutronic data used in the calculations.

Table 5 shows the results of the comparison calculations performed for the Topaz-II reactor core cell. The MCU-2 calculated k_{eff} value slightly exceeds the value obtained with MCNP, which is in agreement with the earlier results of the total reactor calculations. The results again indicate that the reason for the discrepancy is related to the difference between neutronic data, making it necessary to perform MCNP and MCU-2 calculations with the exchange of neutronic data between US and Russia.

TABLE 4. Integral Balance and Rates of Fundamental Nuclear Reactions Over the Reactor Volume for a Dry Reactor with the Drums Turned Out.

Parameter	**Computational Program**		$\frac{MCNP - MCU\text{-}2}{MCU\text{-}2}$ %
	MCNP	**MCU-2**	
G-^{235}U		1.02259	
G-^{238}U		0.00124	
Neutron Multiplication in (n, 2n) reactions	0.024043	0.0241	-0.2
Neutron leakage	0.29512	0.28587	3.2
F-^{235}U	0.40912	0.41636	-1.7
C	0.31872	0.32196	-1.0
C-^{235}U	0.11177	0.11219	-0.4
C - H (ZrH$_x$)	0.025038	0.03075	-18.6
C - H (ZrH$_x$)	0.017993	0.01853	-2.9
C - ^{10}B	0.061866	0.05867	5.4
C - Mo	0.054447	0.05510	-1.1
C - Fe	0.014974	0.01715	-12.7

Designations used in Table 4:
G Fission neutrons generation rate
F Fission rate
C Radiation capture rate
An element (isotope) symbol following F or C means that the number of reactions is shown for this element (isotope).

TABLE 5. The Calculated Values k_{eff} for theTopaz-II Reactor Core Cell .

Reactor State	k_{eff}		$\frac{\text{MCNP - MCU-2}}{\text{MCU-2}}$
	MCNP	MCU-2	%
Without water	1.4326 ± 0.0008	1.447 ± 0.001	-1.0
With water	1.4528 ± 0.0007	1.459 ± 0.001	-0.4

CONCLUSION

A comparison study was made between the codes and neutronic data used in the US and Russia for reactor neutronics calculations and nuclear safety assessment of the Topaz-II thermionic SNPS. For this purpose, joint calculational computer models of the Topaz-II reactor and the core cell were developed, and independent MCNP and MCU-2 calculations were performed for variants of these models. These variants included differences in the presence of water in the reactor and core cell cavities, differences in water outside the reactor, and differences in the position of the side reflector control drums.

Some discrepancies were revealed between the calculated values of k_{eff} and reactivity effects, which are most likely the result of a difference between the neutronic data used in MCNP and MCU-2. Future joint research between the US and Russia will provide a more careful analysis of the reasons for such disagreement. These analyses will require the US and Russia to exchange neutronic data used in the MCNP and MCU-2 physics calculations of the Topaz-II reactor.

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