HELIOS Calculations in Developing New Fuel Management Plan for the PSBR

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ABSTRACT

The Penn State University Department of Nuclear Engineering is currently upgrading their fuel management code analysis system for their TRIGA nuclear reactor. The current system uses LEOPARD for cross section generation and MCRAC for whole core optimization. The objective with the new plan is to use the newer, more advance codes HELIOS and ADMARC-H. Cross sections with depletion steps up to 45,000 MWD/MTU have been calculated for the single TRIGA fuel cells for both types of fuel used. Detailed comparison with the LEOPARD reference results show good comparison. A simple MCNP model has also been developed where the k_{∞} values show a difference of less than 0.5% from the HELIOS results. Comparisons between LEOPARD and HELIOS generated cross sections in whole cold initial core configurations using MCRAC agree within 1% for k_{eff} and within 6% for normalized power. There are several advantages in the ADMARC-H code that supports its use over MCRAC, and it is currently being modified for application in TRIGA analysis. Because of the advanced methods and techniques of the newer codes, more accurate and comprehensive analysis of the reactor will become possible.

INTRODUCTION

The Penn State Breazeale Reactor (PSBR) is a Mark-III TRIGA (Training, Research, Isotope production, General Atomics) light water, pool type nuclear reactor. It was installed in 1965 replacing the previous MTR type core. The PSBR is licensed to operate at a maximum steady state thermal power of 1 MW and is capable of being pulsed to 2000 MW. The fuel is a homogeneous mixture of 20% enriched uranium and zirconium hydride (U-$ZrH_{1.6}$). The PSBR uses two types of fuel rods, 8.5wt% and 12wt% with the 12wt% elements located in the center of the core. There are a total of 89 elements in the core, with one of them (I16) instrumented. Three movable control rods with fuel followers are used for reactivity insertion. Three (shim, regulating and safety) are motor driven, and one (transient) is driven by a pneumatic-seruo motor drive but can also be air actuated for use in the pulse mode. The transient rod has a hollow aluminum cylinder as a follower.

TRIGA reactors are used for research throughout the world, and are preferred for their operational flexibility and their inherent safety characteristics. The most significant safety feature is the large prompt negative temperature coefficient that can be attributed to the nature of the Zr-H mixture in the fuel. Zr-H has a crystalline structure that exhibits excited energy states with increasing temperature. Because the Zr-H is mixed homogenously with the U, its temperature rises with the fuel temperature. The excited Zr-H crystal transfers energy to the thermal neutrons up-scattering them into faster spectrum that is less likely to cause fission and more neutrons escape from the fuel element. The water temperature does not increase during a pulse; hence the water absorbs more neutrons. In large temperature transients, the water acts more as a poison than a moderator.

The PSBR is a unique TRIGA reactor because of its safety characteristics and its mobility. The top and lower grid plates that secure the fuel rods have a triangular pitch such that the core shape is hexagonal array consisting of five rings surrounding a central water thimble. The unit cell for the PSBR is also hexagonal. The PSBR is situated on a bridge that can be moved in the X, Y, and θ directions. This is useful in several of the current projects in progress at the facility.

The PSBR facility has been using a core design system originally published in 1972 by W.F. Naughton in a PhD dissertation.[1] A TRIGA core management model (TRICOM) was developed, validated, verified, and applied for performing core optimization reload analysis based on using the LEOPARD and EXTERMINATOR2 computer codes. In 1979 an improved version of EXTERMINATOR2 called MCRAC was developed by H.Y. Huang and adopted to the core management model.[2] In 1995 Y. Kim developed a Monte Carlo method of modeling and analysis.[3] There have also been several computational efforts performed to determine relative burnups for the individual fuel elements.

GENERAL STATEMENT OF THE PROBLEM

The system developed by Naughton in 1972 is old and outdated. The code is restricted to analyzing core with quarter core symmetry and the calculated results must always be normalized to experimental data. In fact this code system is used to extrapolate experimental data for quarter core symmetry. The convergence of the core configurations to non-symmetrical patterns has, after more than 25 years, established a real need for a new fuel management plan for the PSBR.

This effort has been focused on the possibility to replace the LEOPARD/MCRAC core system with the modern HELIOS/ADMARC-H system. The first objective is to model the PSBR single hexagonal pin cell and generate the cross sections as a function of burnup and temperature using the HELIOS code. Then code to code comparisons are made in with the previous results taken from LEOPARD, as well as with single pin results obtained with MCNP. The new cross section library is linked to ADMARC-H and comparisons are made with previous MCRAC results. Finally, comparisons are being performed with experimental and Monte Carlo results for whole core simulations. This paper will describe the justification for this strategy, and introduce the most current development with results from HELIOS cross section generation.

METHODOLOGY

HELIOS is the new cross section code used in this project that is compared with previously obtained LEOPARD results. HELIOS is a multi-group two-dimensional neutron and gamma transport lattice depletion code.[4] The code was first released in 1993, and is currently in its fourth version. Geometrically, HELIOS can model any two-dimensional system.

HELIOS solves the transport equation by subdividing the system into spatial elements. Internally these elements are treated by first flight probabilities while they are coupled with interfacial currents. The Current Coupling Collision Probabilities (CCCP) method is used without homogenization such that the calculations are performed within the energy groups of the cross section library. Several angular discretizations of the coupling currents between spatial elements are possible, including exact coupling of all the elements by collision probabilities.

Resonance capture is determined by expressing group fluxes and resonance integrals as quaudrature coefficients in the resonance cross sections. The coefficients represent homogeneous mixtures of hydrogen and the corresponding resonant absorber. The intermediate resonance approximation is then used to apply the coefficients to other isotopes. The spatial heterogeneity is described by an equivalence theorem whose dependence is determined through subsequent transport calculations.

The use of HELIOS in the new fuel management system institutes several improvements in comparison to the TRICOM's use of LEOPARD. The most visible is the geometrical representation. HELIOS models the TRIGA fuel cell exactly in hexagonal geometry with triangular pitch (see Figure 1). In the former TRICOM model, the LEOPARD input preserves areas, but changes the geometry to a circular fuel cell with a square pitch lattice. HELIOS separates the different fuel regions and performs the calculations separately thus allowing for a better thermalization model to account for energy levels in Zr-H. Homogenization is only applied at the output and is user specified. LEOPARD begins by developing a homogenous super-cell and then performs the calculations with approximations that are not valid for the TRIGA fuel.

The TRICOM method has consistently provided room temperature calculations within 2% deviations of experimental results for initial operation. Figure 2 compares K-infinity cold depletion calculations between LEOPARD and HELIOS for both TRIGA fuel cells. The HELIOS trend shows good comparison with LEOPARD implying validity for cold core calculations.

The calculation methods and cross section libraries are also much more advanced in HELIOS. HELIOS uses advanced cross section libraries (89-group and 34-group), based on ENDF/B-VI files and condensed with transport methodology. This library includes cross sections for both hydrogen and zirconium within an H-Zr mixture. This is important because the temperature dependent upscattering effect of the H-Zr crystal is now considered in the cross sections. The use of transport theory and the CCCP method in HELIOS as opposed to slowing down theory approximations in LEOPARD is also a considerable improvement.

The resonance treatment is also very different in HELIOS, especially with the TRIGA fuels. LEOPARD uses an empirical formula based on the Breit-Wigner approximation using data from mixtures of water and UO_2. HELIOS employs a detailed analytic process using the actual fuel material with their more accurate cross section data.

Figure 3 compares LEOPARD and HELIOS calculations of the initial operation fast fission factor as a function of increasing temperature. HELIOS shows the expected trend resulting from the Doppler broadening. This behavior also lends plausibility to the claim that HELIOS models the temperature dependent up-scattering effect. The LEOPARD calculations remain virtually unaffected by the change in temperature invalidating its use in temperature transient analysis.

A MCNP model of TRIGA fuel cell (Figure 1) has been developed. The model consists of cylindrical fuel rod surrounded by a hexagonal prism lattice. Reflective boundary conditions are applied to all outer boundaries to represent 2-Dl modeling. The simulation is performed by MCNP criticality mode (KCODE) with a nominal source size of 3000 particles and run a total of 50 cycles. The final k_{∞} value is 1.40395 with 0.00183 of standard deviation. The value of k_{∞} appears to be normally distributed at 95% confidence level.[5]

Since HELIOS gives the modeling flexibility to users with options for example for angular current discretization, fuel radial zoning, and which spectrum to be used, the obtained HELIOS results with the chosen options have to be confirmed. Table 1 shows the comparison between the Kinf results for MCNP, HELIOS and LEOPARD. Both the HELIOS and LEOPARD models fall within 0.5% of the value calculated using MCNP. Tables 2 and 3 compare cross section values for LEOPARD and HELIOS for each of the fuel cells. The differences can be attributed to the more advanced neutron libraries used in HELIOS as well as the contrasting calculation methods. The thermal diffusion coefficient is most noticeable since LEOPARD uses several approximations to solve for the diffusion coefficient. HELIOS solves for the transport cross section directly from the scattering term in the transport equation, then the diffusion coefficient is obtained.

The cross sections generated are then imported into MCRAC for core optimization. MCRAC is the two-dimensional nucleonic core optimization code used in the TRICOM system. It is the modified version of the SCAR code (based on EXTERMINATOR-II) with improvements in flux distribution and depletion analysis. MCRAC uses finite-difference techniques for spatial discretization of the two-group diffusion equation. Table 4 shows a comparison between Keff calculations using the LEOPARD generated cross section library and the HELIOS generated cross section library for initial cold core conditions. Several test core configurations have been analyzed using both generated cross section data. In each case, less than 1% deviation was seen in comparing Keff values for the HELIOS and LEOPARD cases. More noticeable discrepancies are observed in predicted normalized power (NP) distributions with maximum absolute difference of 6.57% at the periphery (see Figure 4). The accuracy of local parameter predictions is important for precise depletion and experiment simulations.

ADMARC-H is a hexagonal geometry two-group 2-D nodal diffusion code. The hexagonal nodal flux solution, following a semi analytic approach, has been developed in the framework of original interface net current formulation with limited modifications. Multi-level iterative strategy for upgrading nodal coupling coefficients and acceleration techniques to inner and outer iterations are applied in the framework of a semi-implicit macroscopic depletion method.[6]

The ADMARC-H methodology is superior to MCRAC in that it uses the more advanced nodal methods for solving the diffusion equation. The finite-difference techniques used in MCRAC tend to introduce significant errors in describing the flux gradients. ADMARC-H is designed for an explicit treatment of hexagonal lattice where MCRAC models the standard Cartesian geometry. The errors associated with this geometric approximation will be eliminated with the use of ADMARC-H. In addition, MCRAC only solves for ¼ core models, where ADMARC-H can solve for different symmetry as well as full core models.

Benchmark calculations were performed for the modified Atomic Energy Agency 2-D benchmark problem to validate ADMARC-H for steady state analysis. Depletion calculations for the VVER-1000 two-cycle burnup benchmark have been performed demonstrating very good agreement with the reference solutions. The code is currently being modified to accommodate the TRIGA reactor as the next phase of this project.

CONCLUSION

Cross sections have been generated for TRIGA 8.5wt% and 12wt% fuels using the HELIOS code. Detailed comparisons with LEOPARD as well as a benchmark comparison with MCNP validate the use of HELIOS for cold initial core calculations. Depletion calculations are shown to correspond with LEOPARD results and further tests with whole core analysis will have to be performed for validation. Temperature studies were also performed showing HELIOS to provide correct behavioral output. HELIOS is then a candidate for validation in temperature transient analysis. Because of the advanced characteristics of the HELIOS code, improved performance over LEOPARD is probable for the future of the PSBR.

In the next phase, the ADMARC-H code will be completely modified for use in the TRIGA reactor. Detailed comparisons will then be made with the MCRAC code using HELIOS generated cross sections. The next step will be to compare with MNCP calculations for the whole core. The new fuel management plan project will be completed with comprehensive experimental testing and code benchmarking.

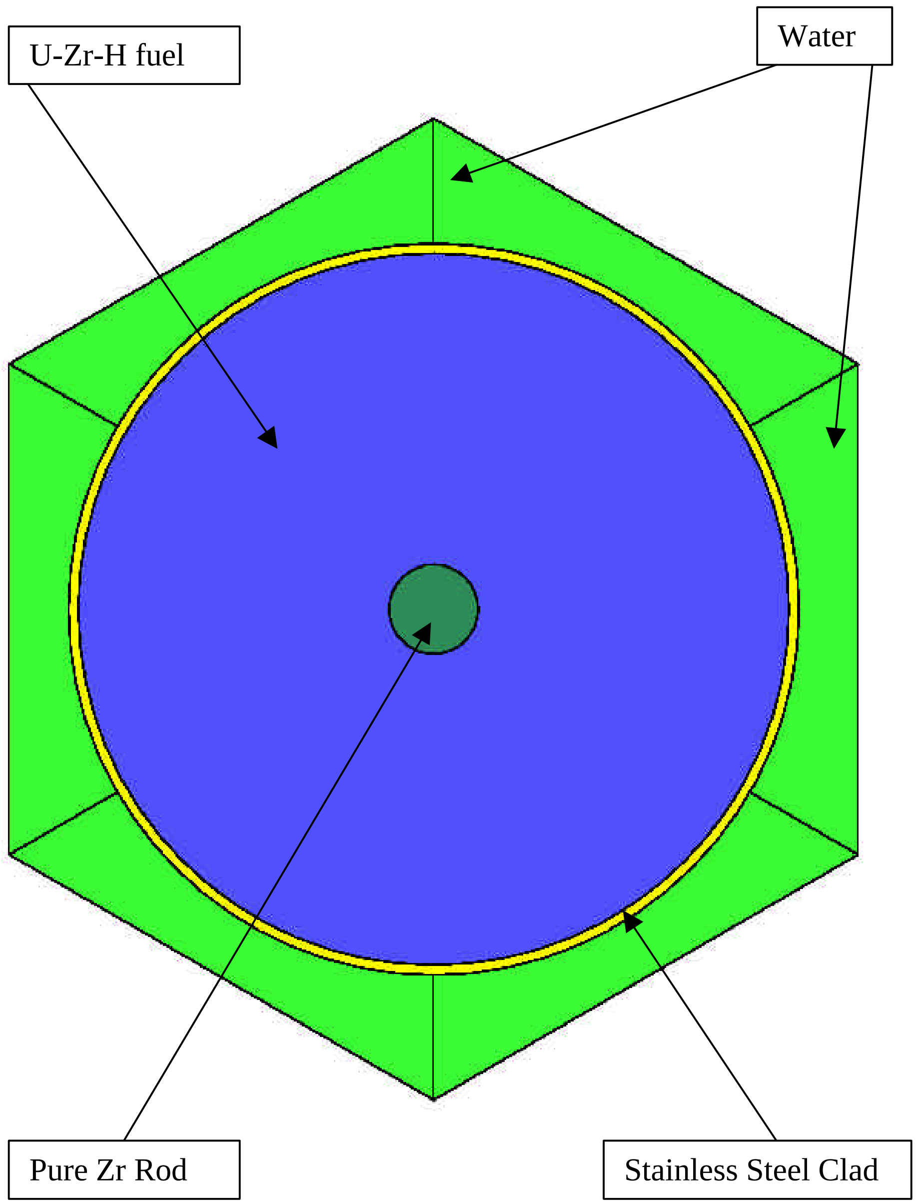

Figure 1: Unit Fuel Cell as Represented by HELIOS and MCNP

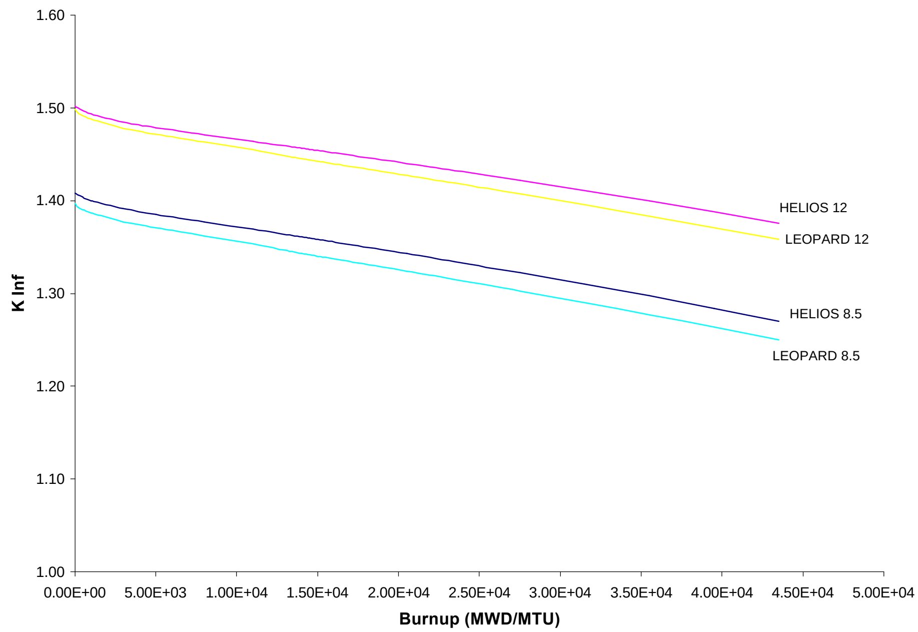

Figure 2: K Infinity as A Function of Burnup

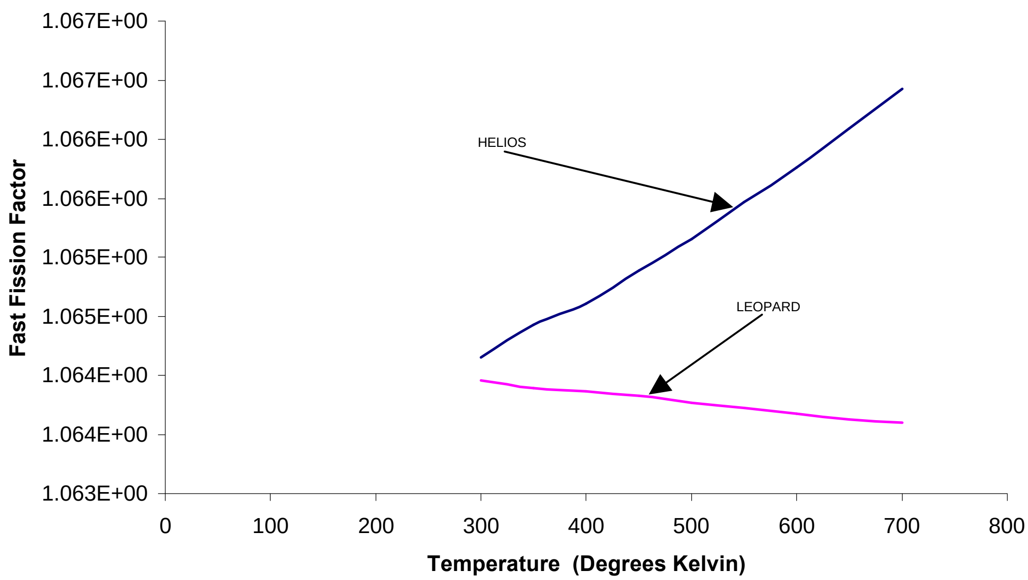

Figure 3: Fast Fission Factor as a Function of Temperature

Table 1: Initial Cold K-Infinity Values for TRIGA 8.5wt% Fuel

MCNP K-Inf	HELIOS K-Inf	LEOPARD K-Inf
1.40395	1.40794	1.39699

Table 2: Initial Cold Cross Sections for TRIGA 8.5wt% Fuel Cell

Group Constant	LEOPARD	HELIOS	% Difference
Fast Absorption	0.00502	0.00579	13.36
Thermal Absorption	0.09336	0.09181	1.69
Fast NuF	0.00357	0.00376	5.11
Thermal NuF	0.13851	0.14010	1.13
Fast Fission	0.00144	0.00153	5.44
Thermal Fission	0.05680	0.05756	1.33
Fast Diffusion	0.98483	1.02880	4.27
Thermal Diffusion	0.17518	0.21139	17.12
Removal	0.03876	0.03720	4.17

Table 3: Cold Initial Core Cross Sections for TRIGA 12wt% Fuel Cell

Group Constant	LEOPARD	HELIOS	% Difference
Fast Absorption	0.00617	0.00706	12.55
Thermal Absorption	0.11678	0.11523	1.34
Fast NuF	0.00512	0.00533	3.95
Thermal NuF	0.18763	0.19048	1.50
Fast Fission	0.00207	0.00216	4.30
Thermal Fission	0.07694	0.07826	1.70
Fast Diffusion	0.96922	1.03190	6.07
Thermal Diffusion	0.17778	0.22157	19.76
Removal	0.03726	0.03486	6.87

Table 4: K-Effective Values From MCRAC

LEOPARD	HELIOS
1.0762850	1.0747470

HEL	.000	1.629	1.310	1.071	.795	.665
LEO	.000	1.642	1.340	1.091	.794	.624
HEL	1.596	1.364	1.161	.905	.741	
LEO	1.611	1.394	1.185	.912	.711	
HEL	1.363	1.307	1.160	.945	.812	
LEO	1.393	1.337	1.186	.953	.782	
HEL	1.161	1.070	.905	.813		
LEO	1.186	1.090	.912	.782		
HEL	.945	.904	.795	.742		
LEO	.953	.911	.793	.711		
HEL	.814	.743	.674			
LEO	.782	.711	.632			

Figure 4: Normalized Power Comparison for TRIGA ¼ Core

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