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Title: Summary of Results for the Uranium Benchmark Problem of the American Nuclear Society Ad Hoc Committee on Reactor Physics Benchmarks

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ABSTRACT

This paper presents a summary of the results obtained by all of the contributors to the Uranium Benchmark Problem of the ANS Ad Hoc Committee on Reactor Physics Benchmarks. The benchmark problem was based on critical experiments which mocked-up lattices typical of PWRs. Three separate cases constituted the benchmark problem. These included a uniform lattice, an assembly-type lattice with water holes and an assembly-type lattice with pyrex rods. Calculated results were obtained from eighteen separate organizations from all over the world. Some organizations submitted more than one set of results based on different calculational methods and cross section data. Many of the most widely used "assembly physics" and "core analysis" computer codes and neutron cross section data librairies were applied by the contributors.

I. INTRODUCTION

In 1994, the ANS Ad Hoc Committee on Reactor Physics Benchmarks was organized through the joint efforts of the ANS-19 Standards Committee of the Reactor Physics Division and the Computational Benchmark Problem Committee of the Mathematics and Computations Division. Both committees foresaw a need to formulate benchmarks based on measured data to supplement the LWR computational benchmarks that had been promulgated in the past. The efforts of the ANS Ad Hoc Committee on Reactor Physics Benchmarks were anticipated to be conducted in four phases. These were as follows: 1) identification of suitable experimental benchmarks, 2) dissemination of problem specifications that would allow modeling of the experimental configurations[1], 3) performance of calculations by the reactor physics community and 4) reporting and comparison of the results.

The availability of the benchmark problem's specifications was publicized through the RPD newsletter and routine communications of the NEA. Phases 1 and 2 were completed by early 1996 and Phase 3 was completed in December 1997. Phase 4 is nearly complete and will be finished with the presentations and publication of this summary of results and individual results from some of the benchmark participants at this meeting.

The uranium benchmark problem's specifications were based on three criticality measurements from a series of experiments carried out by Babcock & Wilcox Co. at their critical facility with support from the Atomic Energy Commission[2]. The three experiments chosen for the uranium benchmark problem all utilized a central core composed of a 3x3 array of 15 x 15 rod PWR assemblies centered inside an annular driver region containing 2936 PWR fuel rods forming a roughly cylindrical outer shape. A top view of the experimental configuration is shown in Fig. 1. The contents of the central core (consisting of a 3x3 array of 15x15 rod assemblies) were varied in the three experiments selected for the benchmark problem. Both the central core and driver regions were laid out on a square pitch of 1.63576 cm and were submersed in water to a height of 145 cm. Criticality was achieved by varying the soluble boron concentration. A side view showing one rod of the experimental configuration is presented in Fig. 2.

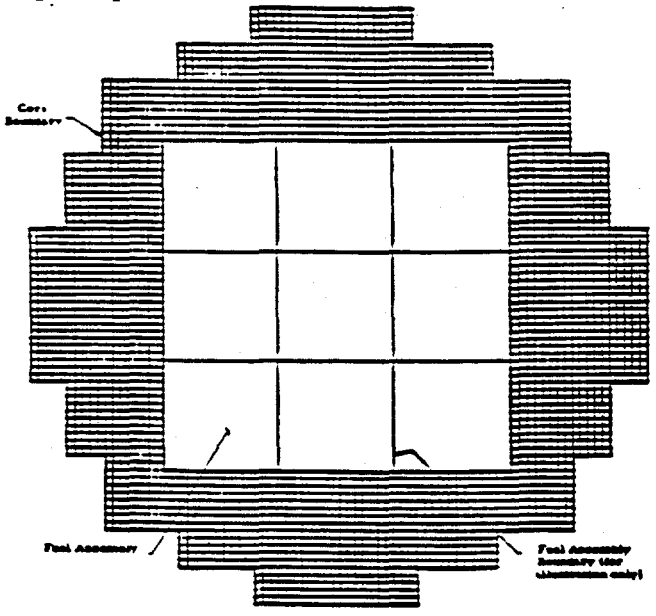


Fig. 1 Top View of the Critical Experiment

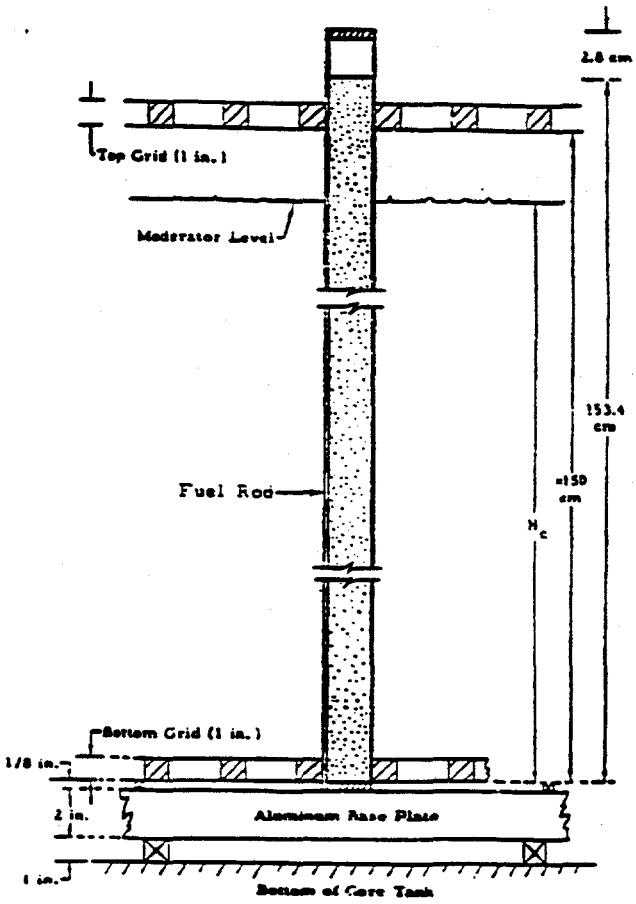
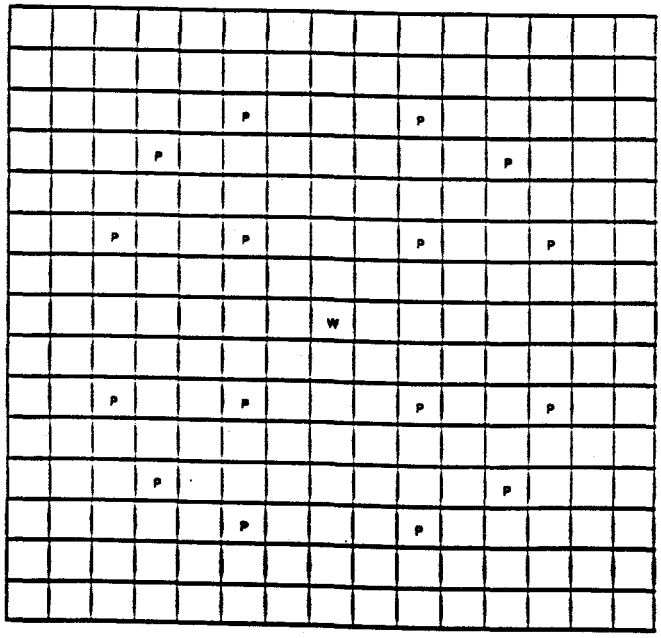


Fig. 2 Side View of the Critical Experiment

The uranium fuel rods both in the central core (nine assemblies) and in the driver region had an enrichment of 2.459 w/o ^{235}U. Each uranium fuel pellet in the rods had an OD of 1.0297 cm. The fuel rods were clad with a 0.0813 cm thickness of Al-6061 and had an OD of 1.206 cm. The three criticality measurements chosen for inclusion in the uranium benchmark problem included nine PWR (15x15) assemblies in the central region that contained 1) all uranium fuel rods (denoted as core type A), 2) 153 water holes (lattice locations from which fuel rods were removed) (denoted as core B) and 3) 9 water holes and 144 pyrex pins (denoted as core C).

The water holes and pyrex pins were distributed throughout each of the simulated 15x15 PWR assemblies so as to represent the locations of control thimbles/burnable poisons in standard assemblies. The locations of the water holes/pyrex rods for each of the three types of assemblies used in each of the cores are shown in Fig. 3. For each of the critical configurations, the measured k_{eff} was 1.0007 +/- .0006. The critical soluble boron concentrations were reported to be 1511, 1335.5 and 794 ppm, respectively. The error in the critical boron concentrations was given as +or - 3ppm. According to the problem specifications, two dimensional calculations of the experimental configurations were to use an experimentally determined axial buckling value of .00037 cm^{-2}. Both two dimensional and three dimensional calculations for the core configurations were contributed by the participants. Measured rod powers for the central assemblies of cores B and C were also included in the benchmark problem specifications.



Type A – Both P and W denote locations that contain fuel rods
Type B – Both P and W denote locations filled with water
Type C – P denotes locations that contain pyrex rods and W denotes a location filled with water

Fig. 3 Assembly Configurations

II. DESCRIPTION OF THE CONTRIBUTIONS AND SUMMARY FILE

A total of 18 different organizations submitted 29 sets of calculational results to the uranium benchmark problem. Six of the participating organizations were from the US and these included national laboratories, universities and commercial enterprises. Nine organizations from Europe submitted results for the benchmark problems, including two each from France and Germany and one organization from each the following countries: Switzerland, Netherlands, Russia, Belgium and Italy. Three organizations from Asia contributed results including two from India and one from Korea. The calculated results were nearly evenly split with about one-half generated from Monte Carlo analyses and about one-half obtained using deterministic methods. The neutron cross section librairies used by more than one contributor to calculate results were ENDF/B-V, JEF2.2, ENDF/B-VI, the WIMS-69 group set and the ABBN multigroup set. Widely used Monte Carlo and reactor analysis codes, such as MCNP, VIM, TRIPOLI, CASMO, WIMS, HELIOS, APOLLO and SCALE are represented in the contributed results. Reported results included k_{eff} for the three core configurations, relative rod powers for the central assembly for the two cores that included water holes and pyrex rods, k_{inf} for the three assembly types (based on infinite lattice configurations and zero axial bucklings), relative rod powers for the two assemblies with water holes and pyrex rods, and miscellaneous assembly average quantities, such as, the conversion ratio, pyrex rod aborption fraction, the ^{235}U epithermal to thermal fission ratio, the ^{238}U to ^{235}U fission ratio and the epithermal to thermal capture ratios for ^{238}U and ^{235}U.

The results from each participant have been entered into separate folders in an EXCEL spreadsheet file. Each participant was given the opportunity to review the contents of the folders to verify that all of the results have been entered

correctly. The benchmark problem specifications allowed each participant to submit all, or as many of, the requested parameters as the participant judged to be practical. When an organization contributed results based on more than one calculational method, or on different sets of cross section data, each contribution was stored in a separate folder. The contributions were assigned identifiers according to the organization making them and the order in which they were received. For example, LANL 3 refers to the third set of results submitted by Los Alamos National Laboratory. Detailed information, like the name, address, etc. of the individual making the contribution are available in the folders for each contribution. After verification of the correctness of the data entered into each folder, calculations of average values, calculational to experimental differences, standard deviations, etc, were performed based on the results from all of the participants and these results were stored in "summary" folders that are included in the EXCEL file. The complete EXCEL file, including the individual folders and the "summary" folders, was sent to each participant for comment. Following incorporation of the feedback from the participants, a final EXCEL file containing the "official' results for the benchmark exercise was produced. The "summary" folders contain tables and plots of the summaries of the participants' results for k_{eff}, and the other requested parameters. These figures and tables are too numerous to recount completely in this paper. However, the final EXCEL file can be obtained by making a request to tap@trinity.tamu.edu.

III. BENCHMARK PROBLEM RESULTS

A total of twenty-nine sets of results were contributed by eighteen different organizations. Tables I and II describe the benchmark problem results that were submitted. Table I characterizes the 17 submittals based on deterministic codes, while Table II characterizes the 12 submittals based on Monte Carlo codes.

A summary of the calculated k_{eff} values for the three experimental configurations is presented in Table III. The average values of k_{eff} based on the contributions from all of the participants for experimental cores A, B and C were .99963, .99994 and .99750, respectively. As mentioned earlier, the experimental value of k_{eff} was 1.0007 for all three cores. The standard deviations (based on calculated minus experimental values) for all of the contributed values of k_{eff} were .00300, .00320 and .00468 for cores A, B and C, respectively. Additional statistical summaries were computed for various subsets of the contributions, for example, those results obtained using Monte Carlo codes, deterministic codes or those based on using a particular cross section library, such as ENDF/B-VI or JEF2.2. Average values for various subsets and the complete set of k_{eff} values are given in Table IV. In general, out of the subsets considered, the average k_{eff} values obtained using the deterministic codes and the JEF2.2 library were closest to the experimental values for all three cores. It is also interesting to note that the effective neutron multiplication factors from all of the Monte Carlo codes and all of the cross section libraries were less than 1.0 for all three of the experimental cores. The k_{eff} values from the deterministic codes were both greater and less than the experimental values. Also one can see from these figures that, in general, the differences (calculation minus experiment) in k_{eff} are greatest for both the Monte Carlo and deterministic codes for core C which contained the pyrex absorber rods.

Fig. 4 presents some (calculated minus experimental) relative rod power results for core B. For all of the contributors the rms value of the rod power differences was less than 0.02. From Fig. 4, it can be seen that there is a consistently higher rod power from the calculations than from the experiment for rod 23. The low measured value for the rod power in this rod is also inconsistent with the measured rod powers in this rod location for other similar experiments.

#	Team Name	Name(s)	Organization	Code	Library
1	LANL 4	Mosteller	LANL	HELIOS	ENDF/B-VI.3
2	LANL 5	Mosteller	LANL	HELIOS	ENDF/B-VI.3 (Modified U-238)
3	IGCAR	Mohanankrishnan	Indira Gandhi Centre for Atomic Research	IGC-SMAXY/CEMESH	
4	BARC	Krishnani	Bhabha Atomic Research Center	LWRBOX/3D-FAST	
5	PSI 1	Stanculescu	Paul Scherer Institute	ETOBOX/BOXER (ELCOS)	
6	PSI 2	Hollard	Paul Scherer Institute	CASMO-4	
7	TUD 2	Hersman, de Leege	DUT	XSDRNPM-S	
8	TUD 3	Hersman, de Leege	DUT	DORT	
9	KAERI	Kim	KAERI	HELIOS/AFEN	
10	ANL 2	Taiwo, Palmiotti, Deen	ANL	WIMSD4m, DIF3D-VARIANT	
11	ANL 3	Taiwo, Palmiotti, Deen	ANL	WIMSD4m, DIF3D-NODAL	
12	EDF	Kerkar	EDF	APOLLO2	
13	GRS	Zwermann	GRS	XSDRNPM-S/TWODANT	
14	FCF 1	Hobson	Framatome Cogema Fuels	CASMO-3/NEMO	
15	FCF 2	Hobson	Framatome Cogema Fuels	SCIENCE	
16	TRCTBL	Maes	TRACTEBEL	LWRWIMS	
17	DES 1	Paulson	Duke Engineering & Services	CASMO-3	

Table I Benchmark Problem Contributions --- Deterministic Codes

#	Team Name	Name(s)	Organization	Code	Library
1	LANL 1	Mosteller	LANL	MCNP-4A	ENDF/B-V
2	LANL 2	Mosteller	LANL	MCNP-4A	ENDF/B-VI.2
3	LANL 3	Mosteller	LANL	MCNP-4A	ENCF/B-VI.3
4	VKTA	Seifert	VKTA	OMEGA (Monte Carlo)	
5	UC-Berkley	Kuo, Verbeke, Vujic	UC-Berkeley	MCNP-4A	
6	TUD 1	Hersman, de Leege	DUT	KENO Va	
7	RRC-KI	Bryzgalov, Yudkevich	Russian Research Center-Kurchatov Institute	MCU-RFFI	
8	ANL 1	Blomquist	ANL	VIM	
9	CEA 1	Yi-Kang Lee	CEA	TRIPOLI-4	JEF 2.2
10	CEA 2	Yi-Kang Lee	CEA	TRIPOLI-4	ENDF/B-VI
11	ENEA	Siciliano	ENEA	MCNP-3A	
12	DES 2	Paulson	Duke Engineering & Services	KENO Va	ENDF/B-V

Table II Benchmark Problem Contributions --- Monte Carlo Codes

Submissions	Effective Multiplication Factor		
	Assembly		
	A	B	C
LANL 1 MCNP4A (ENDF/B-V)	0.9981 0.0003	0.9986 0.0003	0.9965 0.0003
LANL 2 MCNP4A (ENDF/B-VI.2)	0.9963 0.0003	0.9964 0.0003	0.9944 0.0003
LANL 3 MCNP4A (ENDF/B-VI.3)	0.9956 0.0003	0.9957 0.0003	0.9940 0.0003
LANL 4 HELIOS-ENDF/B-VI.3	0.9956	0.9971	0.9917
LANL 5 HELIOS-ENDF/B-VI.3 (modified U-238)	0.9992	1.0004	0.9951
IGCAR CEMESH	0.9990	0.9998	0.9921
VKTA OMEGA	0.9981 0.0006	0.9982 0.0006	0.9984 0.0006
BARC 3D-FAST	1.0055	1.0032	1.0055
PSI 1 BOXER	1.0043	1.0044	1.0028
ENEA MCNP3A	1.0005 0.0075	0.9922 0.0027	not submitted
UC-B MCNP4A	0.9979 0.0002	0.9980 0.0002	0.9963 0.0002
TUD 1 KENO	0.9968 0.0002	0.9973 0.0002	0.9966 0.0002
TUD 3 DORT	1.0042	1.0036	1.0029
KAERI HELIOS/AFEN	1.0024	1.0048	0.9991
RRC-KI MCU-RFFI	0.9982 0.0011	0.9983 0.0006	0.9950 0.0006
ANL 1 VIM	0.9978 0.0003	0.9979 0.0001	0.9982 0.0001
ANL 2 DIF3D-VARIANT	1.0003	1.0014	0.9998
ANL 3 DIF3D-NODAL	0.9997	1.0015	0.9964
EDF APOLLO2	1.0024	1.0001	0.9988
CEA 1 TRIPOLI-4/JEF 2.2	0.9992 0.0003	0.9995 0.0003	0.9983 0.0004
CEA 2 TRIPOLI-4/ENDF/B-VI	0.9948 0.0002	0.9957 0.0003	0.9943 0.0003
GRS TWODANT	1.0005	1.0030	0.9980
PSI 2 CASMO4	1.0010	1.0015	0.9999
FCF 1 CASMO3/NEMO	1.0026	1.0042	1.0024
FCF 2 SCIENCE	1.0029	1.0038	0.9999
TRCTBL LWR-WIMS	0.9999	1.0022	0.9934
DES 2 KENO V.a/ENDF/B-V	0.99711 0.00047	0.99953 0.00048	0.99517 0.00053

For MC calc. the standard deviations are included below the k_{eff} values.

Table III Summary of k_{eff} Results for the Uranium Benchmark Problem Core Calculations

Parameter	Assembly		
	A	B	C
Avg k_{eff} from all Methods and Cross Sections	0.99963	0.99994	0.99750
Avg k_{eff} from Deterministic Methods	1.00130	1.00206	0.99851
Avg k_{eff} from Monte Carlo Methods	0.99754	0.99729	0.99611
Standard Deviation of (Calculated-Experimental) for all	0.00300	0.00320	0.00468
Standard Deviation of (Calculated-Experimental) for	0.00253	0.00244	0.00454
Standard Deviation of (Calculated-Experimental) for Monte	0.00349	0.00394	0.00486
Avg k_{eff} from JEF2.2 Cross Sections	1.00080	1.00021	0.99826
Avg k_{eff} from ENDF/B-V Cross Sections	0.99848	0.99951	0.99706
Avg k_{eff} from ENDF/B-VI Cross Sections	0.99695	0.99795	0.99470
Avg k_{eff} from ABBN Cross Sections	0.99815	0.99825	0.99670
Standard Deviation of (Calculated-Experimental) for JEF2.2 Cross Sections	0.00219	0.00372	0.00364
Standard Deviation of (Calculated-Experimental) for ENDF/B-V Cross Sections	0.00248	0.00190	0.00394
Standard Deviation of (Calculated-Experimental) for ENDF/B-VI Cross Sections	0.00386	0.00396	0.00592
Standard Deviation of (Calculated-Experimental) for ABBN Cross Sections	0.00255	0.00245	0.00435

Table IV Average Values and Standard Deviations of the k_{eff} Values for the Uranium Benchmark Problem Core Calculations

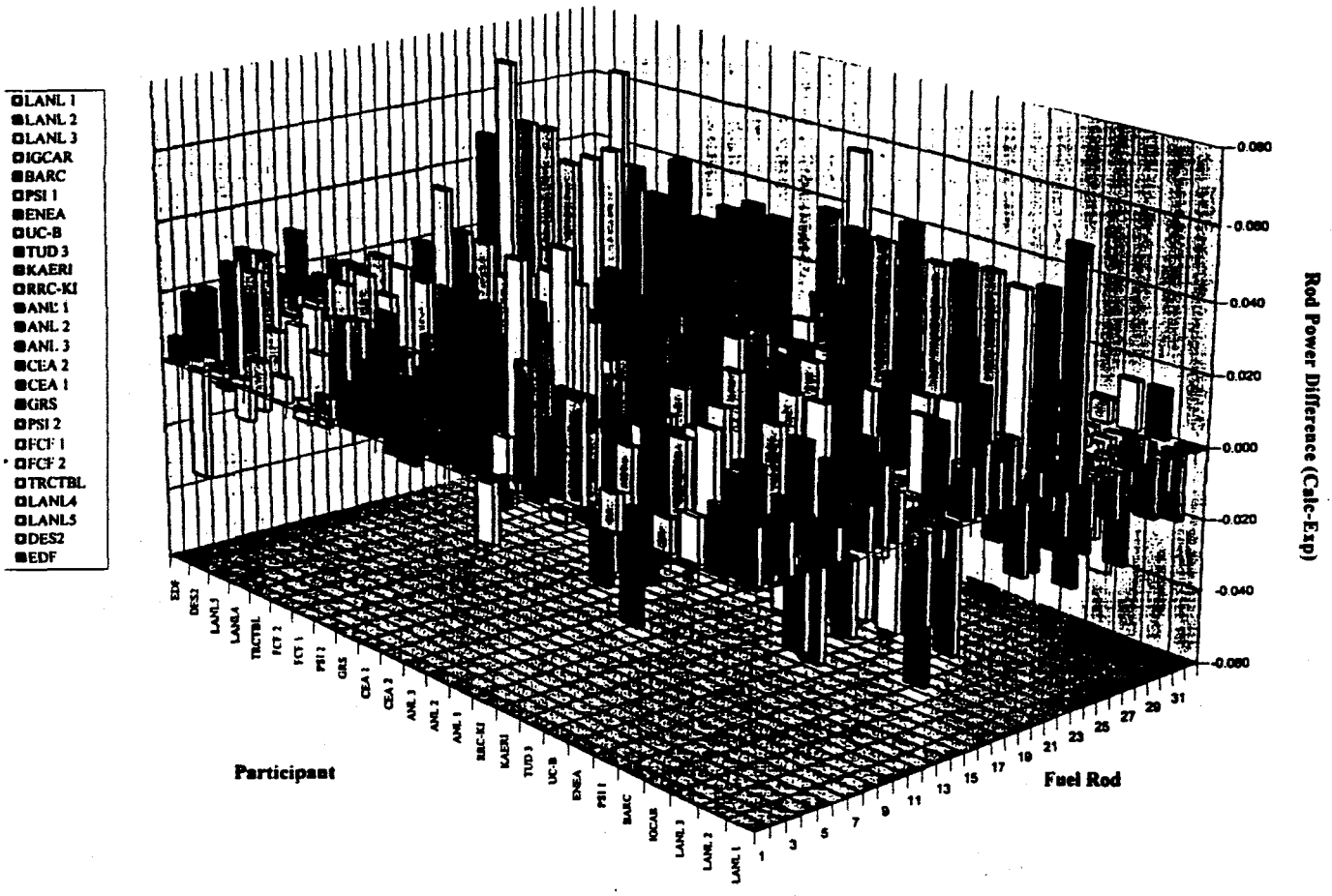


Fig. 4 Differences Between Calculated and Measured Rod Powers for Core B

IV. CONCLUSIONS

The uranium benchmark problem results should be useful to those people in the reactor physics and mathematics and computation communities who are engaged in neutronic and in-core fuel management modelling. The results from this benchmark problem should also be useful to those organizations who are carrying out computer code validation activities. Interested parties should request the final EXCEL file.

REFERENCES

1. J. C. Gehin, "PWR Lattice Benchmark Problems," Ad Hoc Committee on Reactor Benchmarks, Reactor Physics Division, American Nuclear Society, 1996.

2. M. N. Baldwin and M. E. Stern, "Physics Verification Program, Part III, Task 4, Summary Report," Babcock & Wilcox Company Report, BAW-3647-20, 1971.