A Set of Critical Loading Configurations of the IPEN/MB-01 Reactor

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Abstract. A new set of critical loading configurations has been performed at the IPEN/MB-01 research reactor facility. The configurations were submitted to ICSBEP and have been approved for publication in the coming September edition, 2004. The final k_{eff} uncertainty is judged to be 100 pcm for all configurations and suitable for a benchmark experiment. The k_{eff} results using the currently released nuclear data libraries ENDF/B-VI.8 and JEF3.0 are in very good agreement with the experimental values. JENDL3.3 overestimates k_{eff} by around 200 pcm.

INTRODUCTION

During 15 years, the IPEN/MB-01 research reactor has been operated jointly by IPEN and CTMSP to perform several experiments in order to validate calculational methods and related nuclear-data libraries. Recently, IPEN has been invited to participate in the ICSBEP (International Criticality Safety Benchmark Evaluation Project). As a first task, IPEN has been engaged in a series of experiments in the IPEN/MB-01 core in order to evaluate critical configurations for a great number of applications. The main purpose of this work is to contribute to the ICSBEP proposing such a set of configurations as benchmarks. The selected five configurations comprise the IPEN/MB-01 core surrounded by a stainless-steel baffle and for some configurations consider the presence of burnable-poison rods (Al_2O_3-B_4C; Boron mass content is 27.04 mg/cm^3). The final data take care of the uncertainty due to the manufacturer (input data) and due to the experimental procedure and were considered to be less than 100 pcm. The calculational approach of the five critical configurations employs MCNP-4C [1]. The nuclear-data libraries considered are: ENDF/B-VI.8 [2], JENDL3.3 [3], and JEF3.0 [4]. A complete description of the IPEN/MB-01 [5] reactor as well as complete details of the experiment and evaluation can be found in [5]. The intention here will be just to show the main aspects of the evaluation and to complete the analysis with the utilization of more recent released libraries.

EXPERIMENTAL PROCEDURE

The experiment was set up in the following way. Initially, two experimental detectors were placed on the west and east faces of the reactor. The intention here was to monitor the reaction chain events and also to transform the detector current into reactivity by means of the reactivity meter. An inverse-kinetics mathematical model performed this transformation. The signals of both detectors were transformed individually into reactivity in order to detect any possible spatial effect. The IPEN/MB-01 reactor is controlled by two banks of control rods, an aspect that imposes some difficulties in achieving the critical condition with all control and safety rods completely withdrawn. Strictly speaking, a true critical condition is very difficult to achieve in a nuclear reactor. The reactor is always either slightly supercritical or slightly subcritical. In the case of these experiments in the IPEN/MB-01 reactor, because reactivity is not controlled by water level, and control and safety rods are completely withdrawn from the core, achieving a critical condition is more difficult. The number of fuel and burnable-poison-rod configurations has to be set a priori. This configuration, even in the best case, will already have reactivity different from zero when the control and safety rods are fully withdrawn. In order to overcome this hurdle, a feasibility criterion has been adopted. This criterion consists of the acceptance as a critical configuration one whose reactivity inferred by the reactivity meters stands in the range - 10 pcm to ±10 pcm. Therefore, what is meant by

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"critical configuration" is the one that attains the abovementioned criterion.

The procedure adopted for the experimental approach was based on the Isothermal-temperature reactivity coefficient. An initial guess for the critical configuration was obtained from a calculational method [1]. The reactor power was maintained at 1 W in all cases. This power was found to be adequate for the experimental purposes, i.e., the detectors had a good signal-to-noise ratio and the time elapsed to increase the power from nearly 100 mW to 1 W was less than 5 minutes. To achieve criticality with all the control rods nearly in the fully withdrawn position and the reactivity very close to zero, the reactor core had to be cooled down to 14°C. The IPEN/MB-01 reactor core surrounded by a baffle possesses an average isothermal-temperature reactivity coefficient of around -6.1 pcm/°C in the range 14.0°C through 20.5°C. In this sense when the core temperature is reduced by 6.5°C, the system reactivity increases approximately 40 pcm. This reactivity gain was utilized to enable the reactor to become critical at 14°C and to reach the power of 1 W. If criticality was not achieved with this initial guess, another core configuration obtained by a rearrangement of the fuel rods or even by the addition of extra fuel rods was tried with the intent to get a more reactive condition. This process was repeated until the reactor became critical. Once the reactor became critical and its power reached 1 W, the system was initially stabilized, and soon after that, the temperature was increased to 20.5°C by the reactor cooling/heating system. The most important part of the experiment lies at this point of the procedure. When the temperature reached 20.5°C, the reactivity criterion might not have been satisfied with all control rods withdrawn. If the configuration did not meet the specified criterion for the reactivity, the procedure was to increase or decrease the number of fuel/burnable-poison rods or to change the position of a specified number of fuel/burnable-poison rods in order to satisfy the chosen criterion. Whenever it was possible, symmetry was preserved, as it is a desirable condition. This process was repeated by a trial-and-error approach until the desired criterion was satisfied. The temperature in the fuel region was monitored by the 12 thermocouples strategically located in the reactor core. Extreme care was taken to homogenize the temperature in the reactor core in order to guarantee that uncertainties in the final average temperature were small. For each step of the experiment, the reactor system was allowed to reach thermal equilibrium, and the experimental data (temperature from all thermocouples, detector current, and reactivities) were analyzed online to verify the acceptable conditions of the experiment. The multiplication factor, k_{eff}, is obtained from the reactivity as: $k_{eff} = 1/(1-\rho)$, where ρ is the inferred reactivity.

EVALUATION OF THE EXPERIMENTAL DATA

The experiments performed at the IPEN/MB-01 reactor were carefully conducted and well documented. All the details of the experiments are archived in the internal reports of IPEN and in the logbooks of the reactor. There were no significant omissions of data.

The uncertainty in final value of k_{eff} for each configuration is evaluated by a combination of the experimental uncertainties derived from the acquired data and those arising from the geometrical and material composition data, which were evaluated by computational codes.

The experimental uncertainties in the k_{eff} are the ones arising from the measurements of the reactivity given by the reactivity meter and from the measurements of the average temperature given by the thermocouples. There are two components in each one of these uncertainties: statistical and systematic. The statistical component has its origin in the spread of the experimental data around a mean value. It is given in terms of one standard deviation (1σ). The systematic component arises from the uncertainties in the effective delayed-neutron parameters used by the reactivity meter and in the calibration of the thermocouples. Considering first the case of the uncertainty in the effective delayed-neutron parameters, this uncertainty has been estimated to be 5% of the measured reactivity, and since it is a number very close to zero, this component has been neglected because it accounts for a small contribution compared to that of a statistical nature. Considering now the absolute value of the temperature, its systematic uncertainty component, arising from the calibration of the thermocouples, results in an uncertainty of 0.02°C. Once again, this systematic component introduces a small contribution compared to that of a statistical nature. Therefore it is also neglected.

Not only was the uncertainty in the temperature transferred to that of k_{eff}, but also the difference of the temperature from the value of 20.5°C for all configurations is transformed into reactivity and added to the respective k_{eff}. This transformation is done by multiplying the average isothermal-temperature reactivity coefficient (-6.1 pcm/°C) by the temperature uncertainty or difference.

The uncertainty due to the geometrical and material-composition data was obtained in the companion HAMMER-TECHNION/CITATION codes. HAMMER-TECHNION [6] is used for the few-group cross-section generation and CITATION [7] (a 3-D deterministic diffusion theory code) is used for the neutron diffusion into the reactor core. The model included all details of the fuel region, control rods, reflector, etc. The convergence criterion used was 10^{-6}. Since the uncertainties in the majority of cases are rather small, the use of a Monte

Carlo approach has been discarded because it would require a very large number of neutron histories in order to reduce the standard deviation to a level smaller than the uncertainty itself. The approach adopted based in the deterministic code has been found to be adequate. The uncertainties considered are those arising from the ^{235}U enrichment, UO_2 density, UO_2 pellet diameter, cladding outer and inner diameters, pitch, active core height, cladding density and composition, ^{234}U content, UO_2 stoichiometric factor, water density, and bottom alumina height. The uncertainties on the burnable-poison density and baffle distance and thickness will be considered further in Table 1. The effect of the impurities in the fuel on the reactivity was estimated to be of the order of 1 pcm, which is negligible for the analysis considered here. The effect of the water impurities is also small (<1 pcm). Reference [5] gives the complete characterization and evaluation of all uncertainties. Here it will be considered the final values. A total uncertainty of 100 pcm will be applied to all cases. Since the total uncertainty is small and well understood, all cases are acceptable as benchmarks.

The benchmark-model k_{eff} values and their estimated uncertainties (1σ) arising from the uncertainty on the experimental data as well as from the geometrical and composition parameters are shown in Table 1.

TABLE 1. Final values of k_{eff} and their respective uncertainties.

Case	k_{eff}	Temperature(°C)
1	1.0003±0.0010	20.50
2	1.0004±0.0010	20.50
3	1.0004±0.0010	20.50
4	1.0004±0.0010	20.50
5	1.0003±0.0010	20.50

RESULT OF SAMPLE CALCULATIONS

The calculated k_{eff} values using MCNP-4C are given in Table 2. The MCNP-4C model for the IPEN/MB-01 core considers the full geometric model. The model includes the description of the fuel rod, the guide tube, the Burnable-poison rods, the control rods at the top of the reflector, etc. Only the upper part of the fuel rod is neglected due to its small effect on k_{eff}. Table 2 shows that the nuclear data files ENDF/B-VI.8 and JEF3.0 are in very good agreement with the experimental values. JENDL3.3 overestimates k_{eff} by around 200 pcm. The general agreement is fairly good for all libraries.

TABLE 2. Calculated results using the currently released libraries.

Case	ENDF/B-VI.8	JEF3.0	JENDL3.3
1	1.00001(7)	1.00058(7)	1.00251(7)
2	0.99913(7)	1.00003(7)	1.00196(7)
3	0.99977(7)	1.00031(7)	1.00196(7)
4	1.00004(7)	1.00046(7)	1.00228(7)
5	1.00005(7)	1.00063(7)	1.00247(7)

CONCLUSIONS

The new set of critical loading configurations has been successfully performed at the IPEN/MB-01 research reactor facility. The configurations were submitted to ICSBEP and have been approved for publication in the coming September edition, 2004. The configurations considered the IPEN/MB-01 core surrounded by a baffle and some of them considered the presence of burnable-poison rods (Al_2O_3-B_4C; Boron mass content is 27.04 mg/cm^3). The final uncertainty on k_{eff} is judged to be 100 pcm for all configurations. This uncertainty is suitable for a benchmark experiment. The k_{eff} results using the currently released nuclear libraries ENDF/B-VI.8 and JEF3.0 are in very good agreement. JENDL3.3 overestimated slightly (around 200 pcm) the k_{eff} for all configurations.

REFERENCES

1. MCNP4C, Monte Carlo N-Particle Transport Code System - RSICC Computer Code Collection, Technical Report CCC-70 MCNP4C, Oak Ridge National Laboratory, 2001.
2. P. F. Rose, ENDF/B-VI Summary Documentation, Technical Report BNL-NCS-17541, National Nuclear Data Center, Brookhaven National Laboratory, 2002 (4 Ed., Release-8).
3. K. Shibata, Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDL3.3, *J. Nucl. Sci. Technol.* **39**, 1125 (2002).
4. Cross Section Evaluation Working Group Benchmark Specification, USAEC Report, Technical Report 19302, Brookhaven National Laboratory, 1974 (ENDF-202).
5. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03/I, Nuclear Energy Agency, Paris, 2003.
6. J. Barhen, W. Rhotenstein, and E. Taviv, The Hammer Code System, Technical Report NP-565, Technion-Israel Institute of Technology.
7. T. B. Fowler, D. R. Vondy, and G. W. Cunninghan, Nuclear Reactor Core Analysis Code: CITATION, Technical Report ORNL-2496, 1971.