THE SUB CRITICAL CORE OF IPEN-MB-01 DRIVEN BY A NEUTRON SOURCE IN THE FRAMEWORK OF THE IAEA COLLABORATIVE WORK ON LOW ENRICHMENT URANIUM(LEU) FUEL UTILIZATION IN ACCELERATOR DRIVEN SUB ASSEMBLY SYSTEM

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ABSTRACT

In the framework of the International Atomic Energy Agency (IAEA) Coordinated Research Projects (CRP) on i) Analytical and Experimental Benchmark Analysis on ADS and ii) Collaborative Work on Low Enriched Uranium Fuel Utilization, a benchmark was proposed to study the feasibility to introduce a compact neutron generator to produce a D-D and a D-T neutron source in a sub critical core of the Brazilian Zero Power Reactor, IPEN-MB-01, for two configuration, i) without control rods (phase I), ii) with control rods (phase II). Technical Specifications were distributed for the participants, in which a complete description of the facility was made as well as the tasks to be performed. Participated in this benchmark the following countries: Argentina, Brazil, China, Republic of Korea, and Spain. The paper summarizes the motivation for the work, the description of the facility, the tasks to be performed, the results obtained by the participants up today, and the conclusions.
1. Introduction

A first Workshop on LEU Fuel Utilization in ADS Experimental Facilities took place at IAEA in 2005, where the concern of the US RERTR program and the IAEA (Nuclear Fuel Division) with the utilization of HEU in Source Driven Experimental Facilities was presented. A second workshop on “Low Enriched Uranium (LEU) Fuel Utilization in Accelerator Driven Sub-Critical Assembly (ADS) System”, promoted by the Nuclear Fuel Cycle and Waste Technology, took place from 6 to 9 November 2006. During this Workshop, we present a paper on the utilization of a compact neutron generator to drive a sub-critical core of the IPEN-MB-01 facility for reactor physics experiments, as a preliminary proposal to install a compact neutron generator developed by The Plasma and Ion Source Technology Group at the Lawrence Berkeley National Laboratory into a sub critical core of the Zero Power Facility, IPEN-MB-01, at Instituto de Pesquisas Energética e Nucleares, aiming to perform Reactor Physics benchmark measurements of source driven systems.[1]. This preliminary proposal becomes a benchmark in the collaborative work. Also it was in this workshop that the activities to be realized in the framework of the collaborative work were defined, and commitments were made by the interested participants: Argentina, China, Republic of Korea, and Spain. In short, we defined two phases as scope of the work, the first was a configuration without control rods, and the second with control rods partially inserted. The technical specifications for the facility and the tasks to be performed were distributed to the participants[2, 3]. Finally in the two last meetings, which were joint meetings with the Coordinated Research Project on Analytical and Experimental Benchmark Analysis on ADS, the first held in Rome, 12-16 November 2007, and the second in Vienna, 26-30 January 2009, progress reports were presented containing preliminaries inter comparisons among the participants. Here, we wish to report the results for this benchmark exercises obtained up today. The structure of the paper contains the description of the problem/facility; the preliminary results obtained by the participants (inter comparison) as well as a short summary of the methodologies used by them, and the conclusions obtained by solving this benchmark.

2. Description of the IPEN-MB-01 facility

The IPEN-MB-01 is a Zero Power Reactor (100 watts), light water tank type, consisting of a 28x 26 rectangular array of LEU UO2 fuel pins, 4.3 w/o, with a clad of SS-304. The pitch (1.5 cm) was chosen to give an optimum moderator ratio. Figure 1, illustrates a pin of the IPEN-MB-01, and figure 2, illustrates an axial (A), and radial cross sections (B), of the facility.
**Figure 1: IPEN-MB-01 Fuel Pin**

Cladding  
- Thickness 0.060
- Outer diameter 0.980 ± 0.005
- Inner diameter 0.860 ± 0.004

Spacer Tube  
- Inner diameter 0.730 ± 0.005
- Outer diameter 0.850 ± 0.005

Al₂O₃ Pellets  
- Diameter 0.847 ± 0.007

UO₂ Pellets  
- Diameter 0.849 ± 0.001

Upper plug  
- 1.3 (+0.0, -0.02)

Spring  
- 9.2 ± 0.02

Spacer tube  
- 38.6 ± 0.05

Al₂O₃ pellets  
- 5.4 ± 0.012

UO₂ pellets  
- 54.6 (+0.8, -0.25)

Al₂O₃ pellets  
- 9.0 ± 0.005

Bottom plug  
- 1.3 (0.00, -0.02)

Dimensions in cm  
Drawing not to scale

**Figure 2: Cross Sections of IPEN-MB-01: axial (A), and radial (B).**
The facility is controlled by control banks (2), composed by 12 Ag-In-Cd pins. Also there are 2 banks of Safety Rods, composed by 12 B₄C pins, which are kept out of the core. Geometrical data for the fuel pins, and control rod pins are show in Table 1. A complete description of the IPEN-MB-01, can be find in the NEA/NSC/DOC (95)03/IV [2], since the facility is in the International Reactor Physics Evaluation Project.

3. Benchmark Exercise Description

The benchmark exercise was divided in two parts:

BENCHMARK-PHASE I: Sub Critical Core without control rods, one point source

Within the framework of the collaborative work on the utilization of LEU in ADS, we consider in phase 1 exercise the analyses of a sub critical configuration of the IPEN-MB-01, by removing all control rods, and two rows and lines of the critical configuration, with a point source D-D (E= 2.45 MeV), and D-T (E=14.1 MeV), isotropic and mono energetic, located in the position M14 (see Fig. 3). The tube guide of the source is to be considered as an empty space. The positions of the control and safety rods are to be considered as tube guides filled with water. The matrix considered for the exercise is a configuration (24x 22) positions in the matrix, as illustrated in figure 3.

The parameters requested in the benchmark specifications, and evaluated by the participants, are listed below

Phase 1:

- Static Parameters: a) Keff, ks, b) total flux distribution axially averaged in each cell, in the active fuel length of the sub critical configuration, c) total power, total flux at the experimental detectors, c) Neutron spectra (averaged in spaced) at cells (N,14) (R,14) (P,10) (O,11) (R,8), d) axial distribution of the total flux at the same cells as in the previous item in c in the complete rod (active and non active)
- Dynamic and kinetics Parameters: Given a rectangular pulse of 10 µs width, and with amplitude 10 times the CW, calculate: a) the time evolution of the total flux in the x position 14, starting from the source position up to the experimental detector for t=50, 102, 103, 104, 105,106 µs. b) Calculate at the detector position, plot the total flux (counts) versus time, c) using this data estimate $\rho$ [$\$] using the area method.
**Table 1: Geometrical Data of IPEN-MB-01**

<table>
<thead>
<tr>
<th>Region</th>
<th>Fuel</th>
<th>Diameter</th>
<th>Cladding Outer Diameter</th>
<th>Cladding Thickness</th>
<th>Pitch (Square)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active Region</strong></td>
<td>UO₂</td>
<td>0.84894 cm</td>
<td>0.98074 cm</td>
<td>0.06164 cm</td>
<td>1.5037 cm</td>
</tr>
<tr>
<td><strong>Alumina Region</strong></td>
<td></td>
<td>0.847 cm</td>
<td>0.98074 cm</td>
<td>0.06164 cm</td>
<td></td>
</tr>
<tr>
<td><strong>SS Spacer Tube Region</strong></td>
<td></td>
<td>0.730 cm</td>
<td>0.850 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Control Rod Data</strong></td>
<td>Ag-In-Cd</td>
<td></td>
<td>0.98074 cm</td>
<td>0.06164 cm</td>
<td></td>
</tr>
<tr>
<td><strong>Guide Tube Outer Diameter</strong>(a)</td>
<td></td>
<td>1.200 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Guide Tube Thickness</strong>(a)</td>
<td></td>
<td>0.035 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **Bottom Grid Plate Dimensions** | | |
| Square Side                  | 58.8 cm |
| Thickness                    | 2.2 cm  |
In the phase II, we are proposing to calculate the parameters described for a configuration typically used for critical measurements consisting of a 28x 26 rectangular array of UO2 fuel pins, 4.3 w/o, with a clad of SS-304. For this Configuration, the reactor is controlled by inserting the control rods. In this phase we are considering that the reactor would be sub critical by keeping fix one bank (BC1) half height inserted, and find several degrees of sub criticality by moving the second bank. Then for each degree of sub criticality a point source will be inserted in the position (L14), and for each degree of sub criticality, static and kinetics parameters will be calculated.

Figures 1 and 2, define the phase II configuration. The BC1 and BC2 symbol refersers to the control bank consisting of 12 Ag-In-Cd rods each. The control bank position is given in % withdrawn, being the reference level or 0% when the bottom of the active absorber length (excluding the bottom plugs) is aligned with the bottom of the active core. During the reactor operation both the safety banks are 135% withdrawn, and could be neglected.

Figure 4: Phase II configuration (radial)
Figure 5: Axial View of the IPEN-MB-01 core (schematic)

The tasks to be performed are defined as:

1. Without source, calculate the keff versus the position of BC1, keeping BC2=50%.
2. ks (source multiplication factor), with the source for keff=0.9990, 0.9900, 0.9800.
3. Total Power (CW): \[ P = \int \int dE dV \sum f(r,E) \phi(r,E) \text{ fissions/sec for Keff=0.9990, 0.9900, 0.9800.} \]
4. The Integral Kinetics Parameters (\( \rho \), \( \beta \), \( \Lambda \)) for Keff=0.9990, 0.9900, 0.9800.

4. Results

The results obtained by the participants were obtained using the following libraries and codes:

- Argentina (A. Cintas, E. Lopasso, J. Ignácio-): ENDF/B-VI & V, MCNP5
- Brazil (T. Carluccio, J.R. Maiorino): ENDF/B-VII & MCNP5 1.4
- China (Xia Pu): MCNP/ENDF/B-VI
- Republic of Korea (Ho Jin Park & Chang Hyo Kim): ENDF/B-VII/ McCARD
- Spain (F. Sordo, A. Abanades): ENDF/B=VI/ MCNPX

Tables 2 and 3 show the integral parameters for phase 1 and 2, respectively. It is important to emphasis that still some results are on going, mainly for phase II, and are preliminary. Final results will be available at the end of the collaborative work.
Table 2: Integral Parameters for phase I (statics and dynamics)

<table>
<thead>
<tr>
<th>Country</th>
<th>Keff</th>
<th>(\beta_{\text{eff}})</th>
<th>Ks</th>
<th>Total Power</th>
<th>Reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain</td>
<td>0.96868</td>
<td>0.97233</td>
<td>0.96883</td>
<td>2.13E+01</td>
<td>-3063</td>
</tr>
<tr>
<td>Brazil</td>
<td>0.97015</td>
<td>0.97015</td>
<td>0.97015</td>
<td>18.46E+00</td>
<td>-152</td>
</tr>
<tr>
<td>China</td>
<td>0.97277</td>
<td>0.97277</td>
<td>0.97277</td>
<td>16.50E+00</td>
<td>-105</td>
</tr>
<tr>
<td>ROK</td>
<td>0.9728</td>
<td>0.9728</td>
<td>0.9728</td>
<td>16.56E+00</td>
<td>-2016</td>
</tr>
</tbody>
</table>

**Table 3: Integral Parameters for phase II (statics and dynamics)**

<table>
<thead>
<tr>
<th>Country</th>
<th>Keff</th>
<th>(\beta_{\text{eff}})</th>
<th>Ks</th>
<th>Total Power</th>
<th>Reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spain</td>
<td>0.99855</td>
<td>0.99855</td>
<td>0.99855</td>
<td>486.60</td>
<td>-152</td>
</tr>
<tr>
<td>Brazil</td>
<td>0.98958</td>
<td>0.98958</td>
<td>0.98958</td>
<td>67.10</td>
<td>-991</td>
</tr>
<tr>
<td>China</td>
<td>0.97901</td>
<td>0.97901</td>
<td>0.97901</td>
<td>32.90</td>
<td>-2086</td>
</tr>
<tr>
<td>ROK</td>
<td>0.97901</td>
<td>0.97901</td>
<td>0.97901</td>
<td>2086</td>
<td>791</td>
</tr>
</tbody>
</table>

Figures 6 and 7 report the results for the flux map for the phase I. We would like to emphasize that these results are not final yet. Also we did not report the results obtained by Spain, due to they are still in analysis. The results for phase II are also still in analysis, and will not be reported here.

The neutron spectrum for positions N-14, P-10, R-8, and R-14 are illustrated in Figure 8 for D-D reaction (phase I). Although we have the results for D-T source they are discrepant, and are under investigation. Also the results for phase II, are in analysis. Finally, in the Figures 9 and 10 we illustrate the results for the axial flux distribution for selected positions, for phase I.
Figure 6: Flux Map for Phase I (D-D)
Figure 7: Flux Map for Phase I (D-T)
Figure 8: Neutron Spectrum –D-D (Phase I) in the positions N-14; P-10, R-8, R-14
Figure 9: Axial Flux Distribution at selected positions. D-D Source- Phase I.
4. Analysis and Conclusions

Although the benchmark exercise is still on going, the results obtained up today allow some preliminary conclusions. First, it is clear that the inter comparison made, allows us to conclude that the integral parameters, such as $k_{\text{eff}}$, are in relative good agreement up to 2 significant figures (e.g. for phase I, we may guaranty that $k_{\text{eff}}=0.97$), however $k_s$ still have a discrepancy among the participants, indicating clearly that source driven system are not yet a well established benchmark, and need further investigation. For integral parameters such as power, there are a good agreement between Brazil and Korea, for instance the total power in fissions per source neutron/s, was obtained 18.6(D-D), and 16.5(D-T) by Brazil, and 18.4(D-D), and 16.4 by Korea, whereas Argentina obtained 21.3 and 18.7 respectively, indicating a systematic deviation. The results of China and Spain need to be reviewed. Moreover, the total flux at the experimental neutron detector positions in n/cm$^2$ per source neutrons/s, are also in agreement among the participants ($\sim 5 \times 10^{-4}$). These two parameters with the $k_{\text{eff}}$, are the bases to establish the feasibility to introduce a neutron source in a sub critical core of the IPEN-MB-01. Thus, we may conclude that it is feasible to turn IPEN-MB-01
in a sub critical experimental facility driven by a neutron generator which produces $10^8$-$10^9$ n/s, quite common in nowadays. Then, the total power would be of the order of mile Watts, below of the cooling capability (100 W) of the critical system, and the fluxes in the experimental positions will be $\sim 10^4$-$10^5$ n/cm$^2$.s inside the range of the neutron detection.

5 References


4 A.Santos et al, NEA/NSC/DOC (95)03/IV, Volume IV, LEU-COMP-THERM-090, 2006

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