CRITICAL LOADING CONFIGURATIONS OF THE IPEN/MB-01 REACTOR WITH $UO_2GD_2O_3$ BURNABLE POISON RODS

Alfredo Abe[1], Rinaldo Fuga[1], Adimir dos Santos[2], Graciete S. de Andrade e Silva[2], Leda C. C. B. Fanaro[2], Mitsuo Yamaguchi[2] and Rogério Jerez[2]

[1] Divisão de Física de Reatores
Centro Tecnológico da Marinha em São Paulo
Av. Prof. Lineu Prestes 2242, Cidade Universitária
05508-000 São Paulo – Capital, SP
alfredo@ctmsp.mar.mil.br

[2] Centro de Engenharia Nuclear (IPEN / CNEN – SP)
Av. Prof. Lineu Prestes 2242, Cidade Universitária
05508-000 São Paulo - Capital, SP

ABSTRACT

Since 2004, the IPEN and CTMSP jointly has been participating actively to the ICSBEP project conducted by the INEEL. A series of critical experiments with water-moderated square-pitched lattices with low-enriched fuel rods conducted at the IPEN/MB-01 reactor were submitted to the ICSBEP, those evaluations were considered as critical benchmarks. Recently, the CTMSP is conducting research and development the technology to fabricate UO_2-Gd_2O_3 fuel at the Fuel and Material Fabrication Laboratory (LABMAT). The objective driving this development is to fabricate a burnable poison pellets for the Angra I and Angra II nuclear power plants. Once the fabrication process is properly developed, some amount of qualification tests will be required. One of tests needed to be address is related to neutronic absorption efficiency of burnable poison. The UO_2-Gd_2O_3 burnable poison will be fabricated as mixed part of UO_2 and Gd_2O_3 powder. The experimental methodology to evaluate the neutronic absorption efficiency was done perfoming a set of experimental critical configurations using a few number of UO_2-Gd_2O_3 burnable poison pins. The experiments were performed in two steps, the first evaluation was carried out using only a Gd_2O_3 rods, the second evaluations was performed using the compound of UO_2-Gd_2O_3 burnable poison rods. This work presents a series of critical configurations obtained at IPEN/MB-01 research reactor using a UO_2-Gd_2O_3 burnable poison rods and compared to the Monte Carlo calculations.

1. INTRODUCTION

The IAEA funded the development of UO_2-Gd_2O_3 fuel for utilization in NPP under TC project [BRA/4/052]. The objective driving this project is to use burnable poison pellets fabricated in Brazil in the Angra I and Angra II nuclear power plants. The INB (Indústrias Nucleares do Brasil) currently fabricates UO_2 fuel elements for these power reactors and is obtaining the technology to fabricate UO_2-Gd_2O_3 fuel. Once the fabrication process is properly developed, some qualification tests will be required. One of tests needed to be adressed is related to neutronic absorption efficiency of burnable poison. The UO_2-Gd_2O_3 burnable poison is fabricated as mixed part of UO_2 and Gd_2O_3 powder. The neutronic absorption efficiency will be evaluated in two separated way, the first evaluation was carried out using only a Gd_2O_3 powder[1], another set of evaluations were performed in using the few numbers of $UO_2Gd_2O_3$ pin rods.

2. IPEN/MB-01 REACTOR AND CRITICAL EXPERIMENT

The IPEN/MB-01 is a zero power reactor controlled by only two banks of control rods, an aspect that imposes some difficulties to achieve the critical condition with all control and safety rods completely withdrawn[2]. A true critical condition is very difficult to achieve in a nuclear reactor, the reactor is always 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 core configuration has to be set a priori. A feasibility criterion has been adopted in order to define the critical configurations. First of all, only configurations that have a positive reactivity excess can be approved. Only in this case it is possible to measure the reactivity excess with a good signal-to-noise ratio. The second point is that even in this case the reactivity excess can not be very small because the waiting time to let the reactor power to reach 1 W is very long. The detector signals can be considered adequate from the signal-to-noise ratio point of view only at powers higher than 1 W. Therefore the chosen criterion consists in the acceptance as a critical configuration one whose reactivity inferred by the reactivity meters be positive but smaller than 25 pcm.

The critical configurations evaluated in this work consist of the fuel rods, and UO_2-Gd_2O_3 rods appropriately distributed in the core such that criticality could be established. The burnable poison rods arrangement was the varying parameter for the set of eight critical configurations.

The UO_2-Gd_2O_3 burnable poison rods utilized in the experiment are made of sinterized powder of UO_2 and Gd_2O_3. Their dimensions and geometric layout are very similar to those of fuel rods. Particularly their cladding tubes are from spare parts of the IPEN/MB-01 fuel cladding. Consequently their as-built dimensions and compositions are assumed to be valid for the UO_2-Gd_2O_3 case. The mechanical design with dimensions and tolerances is shown in Fig. 1. The spacer 1 and 2 are acrylic and the top is sealed with an insulation rubber. Its diameter is 8.5 mm. The height of the UO_2-Gd_2O_3 rod is 1244.0 ± 0.2 mm. Its pellet diameter is 8.48 ± 0.005 cm from an average of all built pellets. A total of 9 UO_2-Gd_2O_3 rods were assembled for the set of experiments. The as-built geometric and material characteristics of the UO_2-Gd_2O_3 rods are given in Table 1.

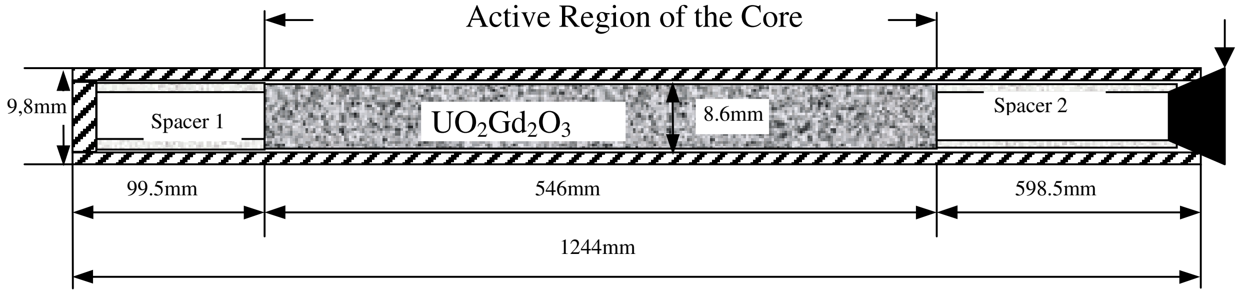

Figure 1. Mechanical Design of the UO_2-Gd_2O_3 Rods.

Table 1. As Built Data for the Assembled UO_2-Gd_2O_3 Rods.

Rod Number	**Total Length of the de UO_2-Gd_2O_3 Column (mm)**	**Total Mass Total of the UO_2-Gd_2O_3 (g)**	**Cladding Mass. (g)**	**Accessory Massa (1) (total) (g)**	**Total Mass of the UO_2-Gd_2O_3 Rod (g)**
V1	548.4±0.1	309.2±0.1	177.3±0.1	26.5±0.1	513.0
V2	548.0±0.1	310.3±0.1	173.7±0.1	26.5±0.1	510.5
V3	548.4±0.1	309.9±0.1	177.1±0.1	26.4±0.1	513.4
V4	547.1±0.1	317.6±0.1	176.4±0.1	26.4±0.1	520.4
V5	547.4±0.1	317.6±0.1	168.2±0.1	26.4±0.1	512.2
V6	548.5±0.1	317.9±0.1	172.3±0.1	26.4±0.1	516.6
V7	546.0±0.1	300.4±0.1	182.0±0.1	26.5±0.1	508.9
V8	554.0±0.1	305.1±0.1	181.3±0.1	26.5±0.1	512.9
V9	546.0±0.1	300.5±0.1	176.4±0.1	26.5±0.1	503.4
Average	548.2±0.3	309.8±0.3	176.1±0.3	26.5±0.3	512.4

The procedure adopted for the experimental[2] approach was the following: An initial guess for the critical configuration was obtained from a calculational method. The control rods are completely withdrawn and the reactor system behavior is followed by the control detectors. The initial power level is determined by the strength of the start-up source. The water temperature is initially kept at around 21.0 °C. The experimental procedure adopted in this evaluation to reach criticality is based on the source insertion and withdrawn from the core. When the source is in the core and for small powers, it induces a small positive reactivity that can be used strategically to infer the reactivity excess of the configuration. In this case only positive reactivity with the source in the core is of interest and is possible. So, the procedure seeks for configurations that have a small positive reactivity excess with the source in. Then the power is allowed to increase up to a point where the detector signal-to-noise ratio is appropriate for the reactivity meter measurements. After that the source is removed and the final reactivity excess is obtained by the reactivity meter. This procedure was adopted for all configurations. If the configuration did not meet the specified criterion for the reactivity, the procedure was to increase or decrease the number of fuel rods or to change the position of a specified number of fuel and/or UO_2-Gd_2O_3 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. Table 2 summarizes all data and conditions for the eight configurations of this evaluation
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 on line to verify the acceptable conditions of the experiment.

Table 2. Experimental Data Conditions for the Eigth Critical Experiments.

Configuration	**Configuration Description (*)**	**Reactor Power (mW)**	**Water Temperature (^{0}C)**	**Reactivity (**) *With* Source(pcm)**	**Reactivity (**) *Without* Source(pcm)**
C1	Removal 36 VC Insertion 04 VUGd	1000	21.00±0.03	+34.5±0.5	+34.2±0.5
C2	Removal 48 VC Insertion 04 VUGd	100	21.00±0.03	+12.7±0.5	+12.0±0.5
C3	Removal 48 VC Insertion 04 UGd	30	21.05±0.04	+7.7±0.5	+4.0±0.5
C4	Removal 66 VC Insertion 04 UGd	1000	21.00±0.04	+26.8±0.5	+26.3±0.5
C5	Removal 52 VC Insertion 06 UGd	50	21.00±0.04	+18.6±0.5	+14.0±0.5
C6	Removal 44 VC Insertion 06 UGd	20	21.05±0.04	+1.0±0.5	-17.0±0.5
C7	Removal 22 VC Insertion 06 UGd	100	21.07±0.04	+16.0±0.5	+15.5±0.5
C8	Removal 14 VC Insertion 06 UGd	20	21.00±0.04	+3.5±0.5	-14.0±0.5

(*) Removal or Insertion of the fuel of the Reactor Core (relative to the 26x28Configuration, VC stands for fuel rod, and UGd for UO_2-Gd_2O_3 rod.

(**) Neutron Source (start-up source) of the Reactor.

All configurations were based on the 30 x 30 array of available positions in the grid plates. For all the configurations considered, the control and safety rods were kept totally removed from the core. By the design criteria, the safety rods are kept in a removal position 35 % (~19 cm) above the active core. The control rods are also totally removed, but, as mentioned previously, when the control rods are at their uppermost position the bottom surface of the absorber coincides with the top of the active core. The bottom plug remains inside the active core.

In all cases, the temperature of the system is in the range 21.0 ± 0.4 °C and with exception of configuration 1 and 4, the absolute value of the reactivity was less than 25 pcm. Configurations 1 and 4, even though exceed the reactivity criteria, were considered acceptable configurations because they did not introduce any additional uncertainties or bias.
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Table 3 shows the number of each rod type in the eigth critical experiments. Also, the lat column is listed the figure number that shows the configuration for each experiment.

Table 3. Numbers of Each Type of Rod in the Eigth Critical Experiments.

Case	**Fuel Rods**	**UO_2-Gd_2O_3 Rods**	**Empty Positions (a)**	**Control Rods (b)**	**Safety Rods (b)**	**Figure**
1	644	4	204	24	24	2
2	632	4	216	24	24	3
3	632	4	216	24	24	4
4	614	4	234	24	24	5
5	628	6	218	24	24	6
6	636	6	210	24	24	7
7	658	6	188	24	24	8
8	666	6	180	24	24	9

(a) Each configuration is based on a 30 x 30 array. The empty positions are those positions that are not occupied by a fuel, control, safety, or UO_2-Gd_2O_3 rod. The empty positions are filled with water.
(b) At their fully withdrawn positions.

The measured k_{eff}'s (i.e., k_{eff}'s calculated from measured reactivities) along with the final average temperatures are given in Table 4. The experimental uncertainties shown in Table 4 do not include the effects of geometrical and material composition uncertainties. The uncertainties here are only those due to the statistical events of the critical measurement itself.

Table 4. Measured k_{eff} and Temperature of the Critical Configurations.

Case	**k_{eff}**	**Temperature (^oC)**
1	1.00034±0.00001	21.00±0.03
2	1.00012±0.00001	21.00±0.03
3	1.00004±0.00001	21.05±0.04
4	1.00026±0.00001	21.00±0.04
5	1.00014±0.00001	21.00±0.04
6	0.99983±0.00001	21.05±0.04
7	1.00016±0.00001	21.07±0.04
8	0.99986±0.00001	21.00±0.04

Figures 2-9 shows the final critical configurations obtained according to the experimental procedure mentioned before.

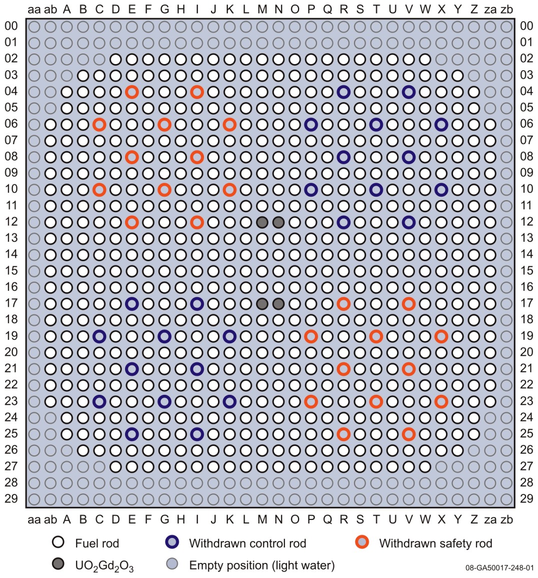

Figure 2. Experimental Core Case 1

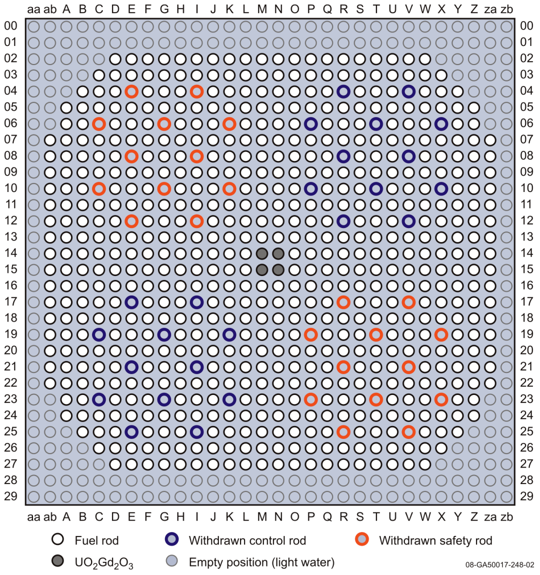

Figure 3. Experimental Core Case 2

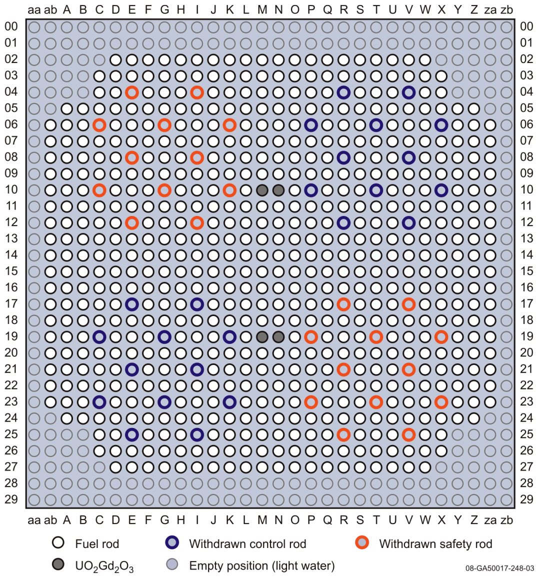

Figure 4. Experimental Core Case 3

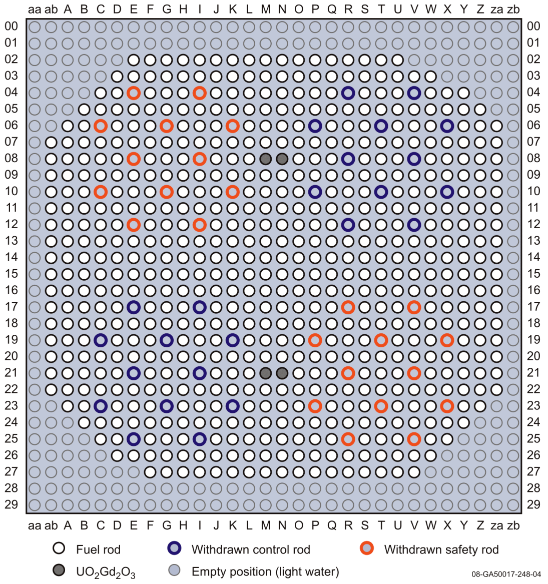

Figure 5. Experimental Core Case 4

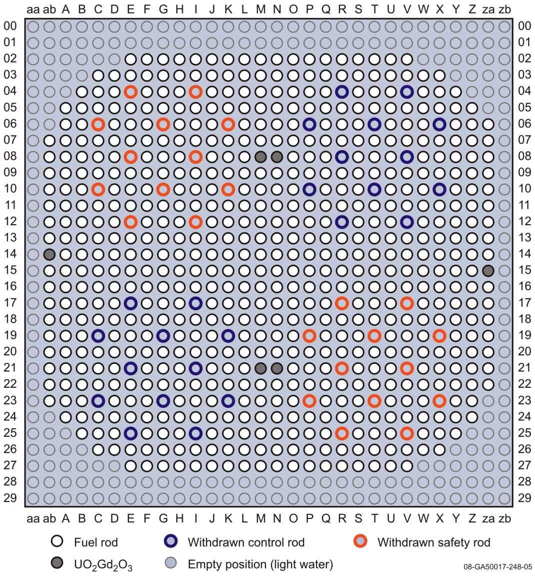

Figure 6. Experimental Core Case 5

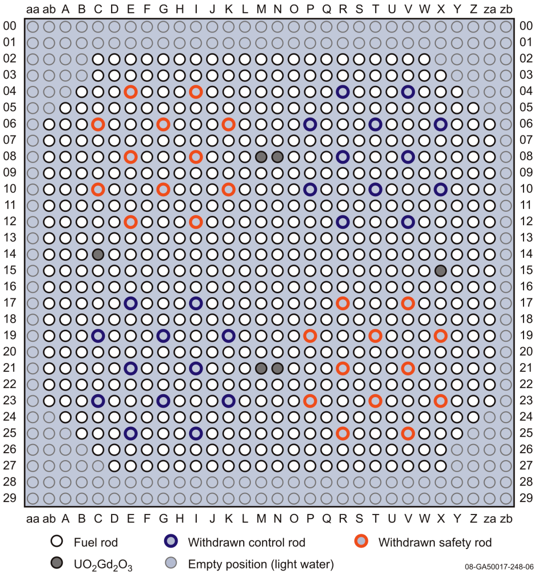

Figure 7. Experimental Core Case 6

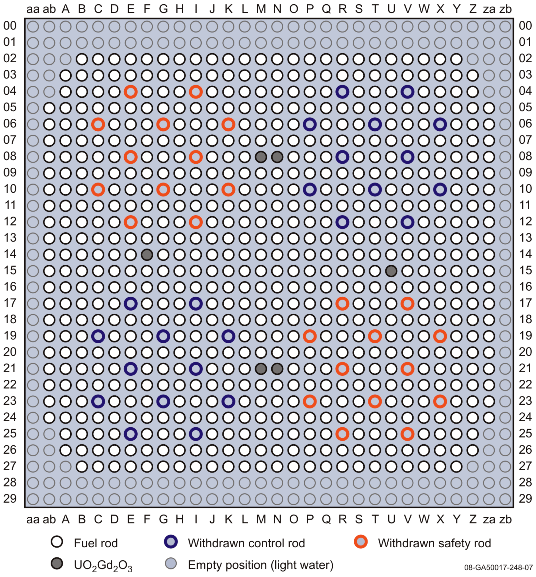

Figure 8. Experimental Core Case 7

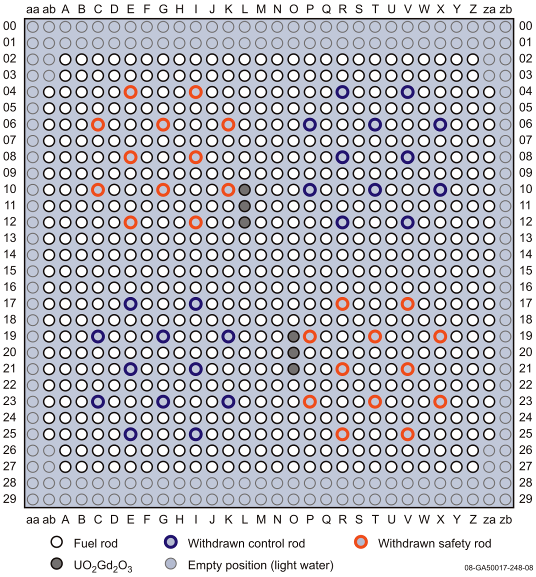

Figure 9. Experimental Core Case 8

3. RESULTS

The eight critical configurations were modeled in the MCNP[2] and KENO-V.a[3] Monte Carlo codes, the modeling considered all representative part of the core in a very fashion, very minor simplification were adopted, the calculated k_{eff} values using MCNP and KENO-V.a are given in Table 5. The dimensions and material data for modeling can be found in the reference [2]:

Table 5. Sample Calculations Results

Code (Cross Section Set) Case Number ↓	**MCNP-5 (Continuous Energy ENDF/B-V and VI) [(a)]**	**KENO-V.a (238-GROUP ENDF/B-V)[(b)]**
1	0.9988 ± 0.0001	0.9970 ± 0.0001
2	0.9987 ± 0.0001	0.9967 ± 0.0001
3	0.9987 ± 0.0001	0.9967 ± 0.0001
4	0.9988 ± 0.0001	0.9965 ± 0.0001
5	0.9991 ± 0.0001	0.9966 ± 0.0001
6	0.9984 ± 0.0001	0.9963 ± 0.0001
7	0.9982 ± 0.0001	0.9966 ± 0.0001
8	0.9979 ± 0.0001	0.9961 ± 0.0001

(a) Indium, ^{17}O, and ^{nat}P are ENDF/B-VI cross sections. All others are ENDF/B-V.
(b) ^{nat}O used in all cases.

4. CONCLUSIONS

As a part of the qualification process of the burnable poison rods fabricate at CTMSP, a critical experiment was carried out in the IPEN/MB-01 reactor. Eight different configurations are considered in this evaluation. The UO_2-Gd_2O_3 rods were properly positioned in the reactor core to obtain a critical configurations. Besides reactivity measurements, the performance of burnable poison under irradiation should be evaluated in the future. Due to the high quality of the experimental data, as well the evaluations proceeded, those eight critical configurations were submitted as benchmark to the ICSBEP project.

REFERENCES

1. Abe.Y, A. dos Santos; R. Fuga; R. Jerez, G. S. de Andrade e Silva, M. Yamaguchi, and L.C.C.B. Fanaro "Critical Loading Configurations of the IPEN/MB-01 Reactor with UO_2, Stainless Steel and Gd_2O_3 rods", International Nuclear Atlantic Conference 2007- Brasil.
2. A. dos Santos, A. Abe, G. S. de Andrade e Silva, M. Yamaguchi, L.C.C.B. Fanaro, R. Fuga and R. Jerez, "Critical Loading Configurations of the IPEN/MB-01 Reactor with UO_2 and Borated Stainless Steel Plates", LEU-COMP-THERM-089, ICSBEP Handbook version 2007.
3. J. F. Briesmester, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 4C", LA-13709-M, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, 2000.
4. D. F. Hollenbach, L.M. Petrie, and N. F. Landres, "KENO-VI: A General Quadratic Version of the KENO Program", Vol. II Sect. F17, of Scale : A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation, NUREG/CR-0200, Rev7., April 2004.