CALCULATED AND MEASURED PARAMETERS OF THE TAJOURA CRITICAL FACILITY FUELED WITH LEU

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ABSTRACT

The Tajoura critical facility has been converted to low enriched uranium (LEU) fuel using the Russian manufactured IRT-4M fuel assemblies (FA). The final core containing ten 6-tube and six 8-tube IRT-4M FA was loaded to the critical facility on January 2006. During the approach to criticality and after criticality was reached many measurements were performed. In this paper measured parameters are compared with the calculated values. Two different sets of codes were used for the calculations: a) WIMS and CITATION – diffusion theory analysis; and b) MCNP – Monte Carlo analysis. The results show that there is good agreement between both calculation methods and the measured parameters.

INTRODUCTION

The fuel of the Tajoura critical facility[1,2] has been converted from 80% enriched IRT-2M ***(HEU)*** fuel to a less than 20% enriched uranium IRT-4M[3] ***(LEU)*** fuel. The IRT-4M 8-tube and 6-tube fuel assemblies were loaded to the critical facility in January 2006. Cross sections of the LEU IRT-4M fuel assemblies are shown in Figure 1, where a core diagram for the critical facility is also presented.

In this paper experimentally measured parameters are compared to the values calculated by both diffusion theory (CITATION[4, 5] code) and Monte Carlo (MCNP[6] code) methods. The MCNP model represents the core as close to exactly as feasible. For the CITATION model the fuel assemblies are homogenized and the cross sections for the homogenized regions are generated using the WIMS[3] code. Two types of cells are used for the models in WIMS[5, 7]: first the straight parts of the elements are taken as slabs while the central ring of the 8-tube and the curved corners of the fuel assembly are modelled using the annulus option.

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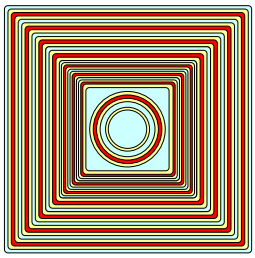
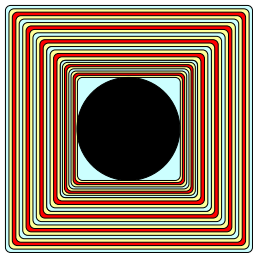


8-tube FA



6-tube FA

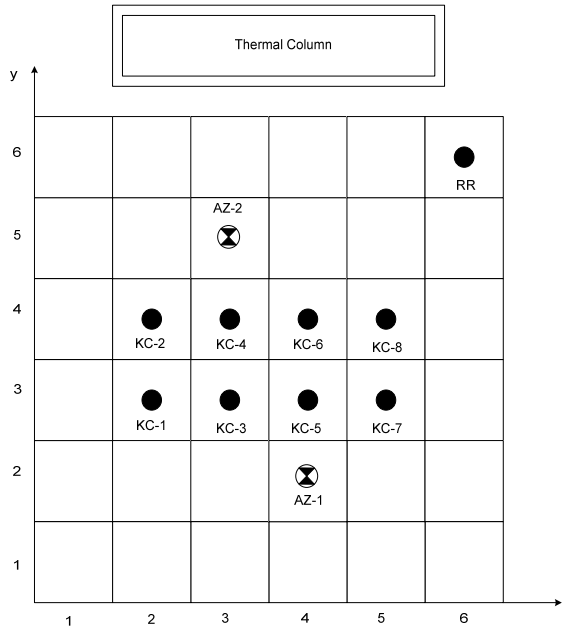


Figure 1 Cross Section of the 8-tube and 6-tube IRT-4M Fuel Assemblies and the Critical Facility Core Diagram

DATA AND RESULTS

Comparisons between measured and calculated results for different critical configurations and for total and differential control rod worth are presented in the subsections below.

Critical Configurations Comparisons

The critical facility is designed to operate with sixteen fuel assemblies (ten 6-tubes and six 8-tubes IRT-4M FA). The core has eight shim rods (KC rods in figure 1), two safety rods (AZ rods in figure 1), and one regulating rod (RR in figure 1). The core is surrounded by a Be reflector (20 moveable blocks, and a fixed Be reflector) where experiments can be loaded. If no experiments are present, Be plugs are inserted inside the Be blocks.

During the approach to the normally operating configuration (16 FA), the critical facility reached its first critical configuration when its core contained eleven fuel assemblies (ten 6-tube IRT-4M and one 8-tube IRT-4M FA). After that configuration was reached the loading of the other five fuel assemblies continued until the final configuration with sixteen fuel assemblies was reached. Table 1 presents the critical configurations for all cases from 11 to 16 fuel assemblies, with the respective control rods positions. The MCNP results for those

configurations are also presented in Table 1, where it can be seen that the agreement between measured and calculated results is good.

Diffusion theory and Monte Carlo analyses for those configurations (11 through 16 FA) with the control rods withdrawn were performed and the results are presented in Table 2. The results show that the CITATION and MCNP results are close only for the configurations with higher number of fuel assemblies (14 through 16 FA). This seems to indicate that the WIMS cross sections for the water between the fuel assemblies and the beryllium reflector need improvement. However, this is not a problem for the critical facility because it is only going to be operated with a load of 16 FA; in that case the diffusion calculation provides acceptable results.

Control Rods	**Number of Fuel Assemblies in Core**					
	11 (Ten 6-tube/ One 8-tube)	**12 (Ten 6-tube/ Two 8-tube)**	**13 (Ten 6-tube/ Three 8-tube)**	**14 (Ten 6-tube/ Four 8-tube)**	**15 (Ten 6-tube/ Five 8-tube)**	**16 (Ten 6-tube/ Six 8-tube)**
AZ-1/AZ-2	**0**	**0**	**0**	**0**	**0**	**0**
KC-1/KC-2	**0**	**0**	**0**	**0**	**313**	**443**
KC-3/KC-4	**115**	**315**	**447**	**607**	**650**	**650**
KC-5/KC-6	**115**	**315**	**447**	**607**	**650**	**650**
KC-7	**115**	**0**	**0**	**0**	**313**	**443**
KC-8	**100**	**0**	**0**	**0**	**313**	**443**
RR	**650**	**589**	**589**	**589**	**589**	**589**
	MCNP Results (reactivity in $)					
	-0.31	**-0.27**	**-0.17**	**-0.13**	**+0.27**	**-0.30**

Table 1 Critical Configurations for Intermediate and Final Core (Control rods fully inserted = 650 mm)

Configurations	***Core Excess Reactivity ($)***	
	CITATION	***MCNP***
11 Fuel assemblies (10 of 6 tube type & 1 of 8 tube type)	**3.53**	**0.91**
12 Fuel assemblies (10 of 6 tube type & 2 of 8 tube type)	**8.34**	**6.18**
13 Fuel assemblies (10 of 6 tube type & 3 of 8 tube type)	**12.40**	**10.89**
14 Fuel assemblies (10 of 6 tube type & 4 of 8 tube type)	**15.23**	**14.25**
15 Fuel assemblies (10 of 6 tube type & 5 of 8 tube type)	**18.38**	**17.75**
16 Fuel assemblies (10 of 6 tube type & 6 of 8 tube type)	**21.08**	**20.07**

Table 2 Calculated Core Excess Reactivity (Diffusion and Monte Carlo)

Several other configurations in which the core had sixteen fuel assemblies but the position of the shim and regulating rods were modified were also used to perform measurements and to evaluate the comparative worth of different rods. An example of another set of measurements and the comparison of measured and MCNP-calculated results are presented in Table 3 below, where it can be seen, again, that the agreement between measured and calculated results is very good. Note that in all Monte Carlo results presented in this paper the uncertainty is less than $0.02.

	Shim Rod (KC-2,KC-7 and KC-8) Insertions at Critical State (mm)			
KC-1	**71**	**625**	**650**	**650**
KC-2	**650**	**0**	**650**	**650**
KC-3/KC-6	**650**	**650**	**650**	**650**
KC-5/KC-6	**650**	**650**	**650**	**650**
KC-7	**650**	**650**	**71**	**590**
KC-8	**650**	**650**	**650**	**0**
RR	**650**	**650**	**650**	**650**
	MCNP Results (reactivity in $)			
	-0.22	**-0.28**	**-0.22**	**-0.21**

Table 3 Comparison of the Reactivity Worth of KC-2, KC-7 and KC-8 Shim Rods with KC-1 Shim Rod for the 16 FA Core (Control rods fully inserted = 650 mm)

Measurements and calculations were also performed for configurations with and without some of the Be plugs located inside the moveable Be reflector blocks. Two of those measurements are shown in Table 4, where the agreement between calculated and measured values is also good.

Rod	**Control Rod Insertions at Critical State (mm)**	
	Before Unloading Be Plugs from Cells 1-1, 1-6 and 6-1	**After Unloading Be Plugs from Cells 1-1, 1-6 and 6-1**
KC-1/KC-2	**438**	**429**
KC-3/KC-6	**650**	**650**
KC-7/KC-8	**438**	**429**
RR	**650**	**650**
	MCNP Results (reactivity in $)	
	-0.10	**-0.17**

Table 4 Change of KC-1, KC-2, KC-7 and KC-8 Shim Rods after Unloading Some of the Be Plugs in the 16 FA Core (Control rods fully inserted = 650 mm)

Reactivity Worth of Control Rods: Integral and Differential

The reactivity worth of each of the control rods was measured with the 16 FA core configuration with and without the Be plugs in place. The Be plugs are positioned in side the Be blocks in the reflector when no experiments are located there. Comparison of the measured results with calculated results using CITATION and MCNP are provided in Table 3 below for the case with the Be plugs in place. The calculated results, both diffusion and Monte Carlo, are essentially within about 10% of the measured results, which is considered a good agreement given that there some differences between the way the reactivity worth of the control rods are measured and calculated:

- Experimental values are based on the measured worth of the regulating rod but the calculated results are not.

- Criticality is being adjusted after each step in the experimental calibration but not in the calculations.
- For the diffusion analysis it was assumed that the 60 cm of the absorbing material (B_4C) is placed on the 60 cm active part of the fuel assembly.
- For the diffusion analysis the design value of the ^{235}U mass for the fuel assemblies was used. For the Monte Carlo Analysis the average ^{235}U mass for the actual core was used for both the 6-tube and the 8-tube fuel assemblies.

Rod	Calculated Results		Experimental Results
	CITATION (β_{eff})	MCNP (β_{eff})	(β_{eff})
Safety Rod AZ1	**3.31**	**3.0**	**3.0**
Safety Rod AZ2	**2.87**	**2.89**	**2.5**
Regulating R	**0.58**	**0.61**	**0.62**
Shim Rod KC-1	**3.12**	**3.08**	**3.25**
Shim Rod KC-2	**2.96**	**2.98**	**3.1**
Shim Rod KC-3	**3.55**	**3.43**	**3.8**
Shim Rod KC-4	**3.36**	**3.37**	**3.7**
Shim Rod KC-5	**3.48**	**3.41**	**3.8**
Shim Rod KC-6	**3.31**	**3.36**	**3.65**
Shim Rod KC-7	**3.0**	**3.08**	**3.25**
Shim Rod KC-8	**2.77**	**2.98**	**2.95**
Shutdown Margin	**-5.05**	**-3.23**	**-3.25**

Table 4 **Control Rods Total Worth for a Compact LEU Core with 16 Fuel Assemblies (With all Be plugs in place)**

Comparisons between diffusion theory and Monte Carlo for the 16 FA core with rods fully withdrawn, all shim rods and regulating rod fully inserted (shutdown criterion), and all rods (shim, regulating and safety fully inserted) are presented in Table 5. The results of this table show an acceptable agreement between the two methods, except for the shutdown margin criterion case in which both methods have a large difference. Note that for this case the MCNP result is essentially the same as the measured value (see last row of Table 4).

	Reactivity ($)	
	CITATION	MCNP
All Rods Out	**21.08**	**20.07**
All Shim and Regulating Rods Inserted	**-5.05**	**-3.23**
All Rods Inserted	**-11.08**	**-10.77**

Table 5 Reactivity for 16 FA Core with Different Sets of Rods Fully Inserted

Finally, measurements were performed to determine the differential worth of several control rods. The MCNP model was also used to calculate the differential worth of the regulating rod RR) and of the KC-1 shim rod. A comparison of the measured and calculated results is presented below in Figures 2 and 3, where the good agreement between measured and calculated results is clear.

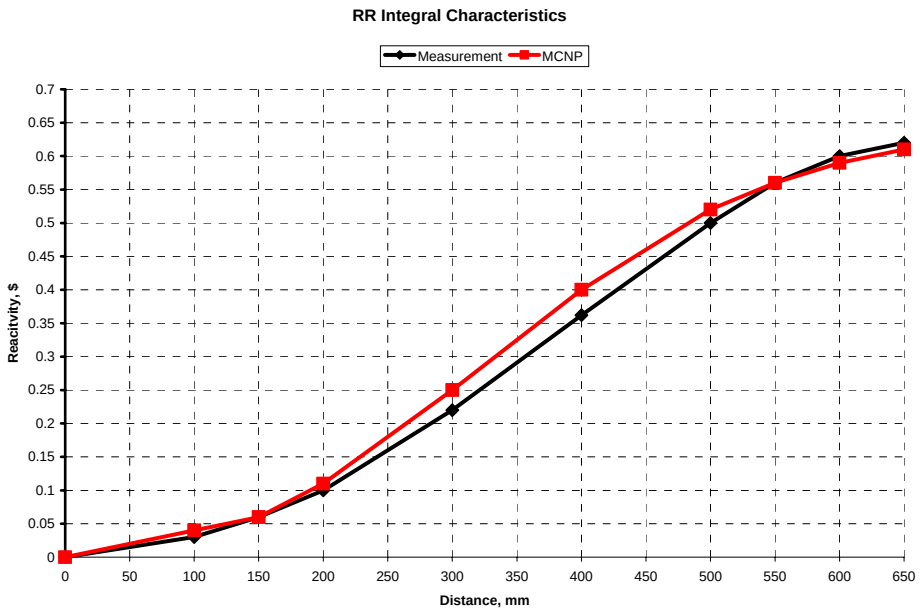


Figure 2 Regulating Rod Reactivity Worth: Measurement Vs Calculated

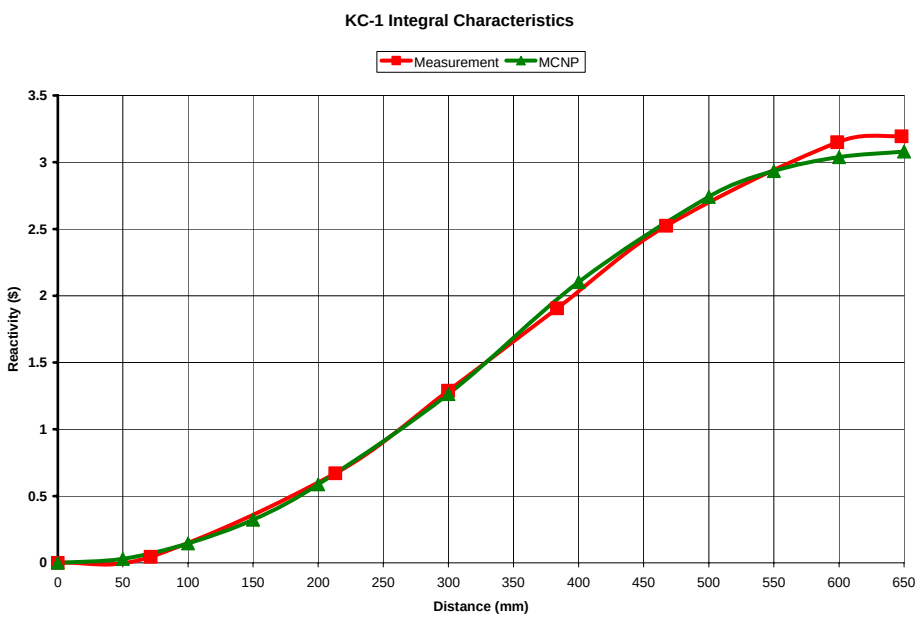


Figure 3 Shim Rod KC-1 Reactivity Worth: Measurement Vs Calculated

SUMMARY

The Tajoura critical facility was recently converted to LEU (Jan/2006) using the Russian-designed IRT-4M FA (6-tube and 8-tube FA). During the conversion process many measurements were carried out, and comparisons between measurements and calculated results using both diffusion theory (CITATION code) and Monte Carlo (MCNP code) methods were presented. These results show a very good agreement between calculated and measured data.

Note that even though the facility is operated using a compact core with 16 FA (10 of 6-tube and 6 of 8-tube) the minimum number of IRT-4M type fuel assemblies needed to reach a critical system is 11 assemblies. The shutdown margin of $\boldsymbol{-3.25}\,\beta_{eff}$ for the 16 FA compact core is enough to keep the critical facility in a sub critical state.

ACKNOWLEDGEMENTS

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