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The Mexican TRIGA Mark-III Reactor with TRIGA Fuel Type 30/20

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ABSTRACT

Mexico's TRIGA Mark-III reactor had been operating with a mixed core of low and high enriched uranium elements (20% and 70% enriched U and 8.5% of U in the fuel matrix) from November 1988 to November 2011. The studies to design a new core with low enriched elements type 30/20 (20% enriched U and 30% of U in the fuel matrix) were made with MCNP5 v 1.6. The final core has 74 elements, 4 control rods and 6 additional incore irradiation facilities. This presentation will show the technical challenges associated with the reactor conversion analysis, experimental results from the fuel loading and data from the final reactor physics testing.

Under the Global Threat Reduction Initiative, the RERTR program set an aggressive goal to complete the conversion of the Instituto Nacional de Investigaciones Nucleares reactor, before the 2012 Nuclear Security Summit held in March of 2012. The reactor conversion and subsequent HEU removal were completed by Mexico with international cooperation from the United States, Canada and was also supported by the IAEA.

1. INTRODUCTION.

The TRIGA Mark-III reactor from the Nuclear Center of México "Dr. Nabor Carrillo Flores", reached the first criticality in November 1968, since then to November 1988 the reactor used only TRIGA LEU fuel, 20% enriched and 8.5% uranium in the fuel matrix. From November 1988 to November 2011 the reactor had a mixed core with HEU and LEU fuel (70% and 20% enrichment and 8.5% of U in the fuel matrix in both cases).

At the Nuclear Security Summit held in Washington D.C in April 2010, Mexico, the United States and Canada reached agreement to work together, along with the International Atomic Energy Agency (IAEA), to convert the fuel in Mexico's research reactor. This effort will be completed under the auspices of the IAEA and it will further strengthen nuclear security on the North American continent [1].

The reactor conversion started with the reception of 85 LEU fuel type 30/20 (20% enriched U and 30% of U in the fuel matrix) in December 2011, the download of all the fuel from the mixed core was completed the same month. The HEU fuel was sent to Idaho National Lab in February 2012 and the fresh fuel loading began on February 22 and was finished on March 23, 2012.

2. REACTOR GENERAL DESCRIPTION.

The TRIGA Mark-III reactor power in the steady state operating mode is 1MW, the core is at the bottom of a large pool 25 feet long, 25 deep and 10 feet width; the pool has in its extremes experimental facilities, the Thermal Column and the Exposure Room. The core is composed by 6 circular arrays, known as rings, around a central position known as Central Thimble. Each ring is identified with a letter and the position in it by a number, the inner is B and has 6 positions, the next is C with 12, D with 18 and the last is G with 36. Figures 1-3 shows the reactor building, the reactor hall and the pool.

Figure 1 Reactor building

Figure 2. Reactor hall

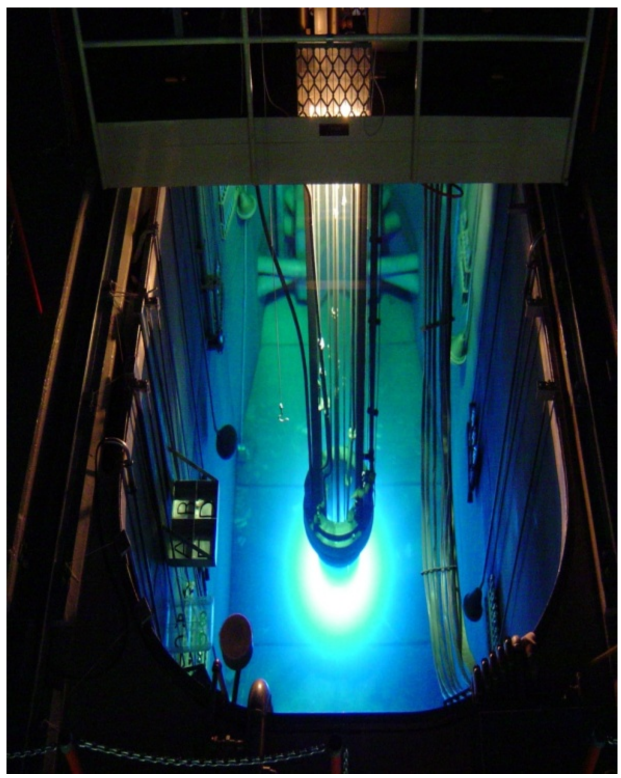


Figure 3. Reactor pool

2.1 Reactor core with HEU and LEU fuel.

The HEU and LEU fuels were type FLIP and 104 respectively (according to GA catalogue). The LEU fuels were in B, E and F rings (total 59 fuels), the HEU fuels were in C and D rings (total 26). The core had 4 control rods, 1 with air follower locate in C-4 and 3 with HEU fuel follower, they were located in C-10, D-1 and D-10; the control rod in C-4 is kwon as Transient, in C-10 as Regulating, in D-1 as Shim and in D-10 as Safety. The Figure 4 shows the mixed core, the yellow circles represent LEU fuel, the red HEU fuels, and the blue graphite dummy elements.

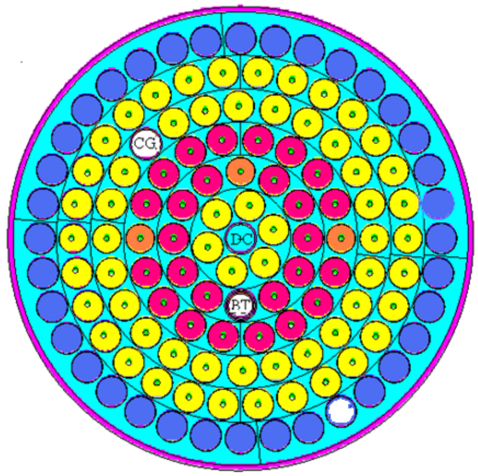


Figure 4. Reactor core with HEU and LEU fuel

3. CORE DESIGN WITH LEU FUEL TYPE 30/20.

The requirements for the design of the reactor core with LEU fuels were taken from Safety Analysis Report, the new core must satisfy the reactivity excess and the shutdown margin establish in the Technical Specifications (SAR Chapter 14).

3.1 LEU fuel and control rod characteristics study.

The existing MCNP v 1.6 models for the mixed core were prepared with the dimensions and geometry taken from the reactor manuals and compositions from some information provided by GA. When we received from TRIGA International the characteristics for the new LEU fuel, we noticed that in our model for the fuel and the control rods there were missed some components and regions. The new fuels have in addition to the fuel meat and the top and bottom graphite reflectors a region with air, and the control rods don't have top and bottom reflectors but they have some air regions and steel spacers inside. It was necessary to analyze the characteristics and compositions for the new fuel and the control rods and make a new MCNP v1.6 model for them. The Figure 5 shows the fuel and the control rod regions.

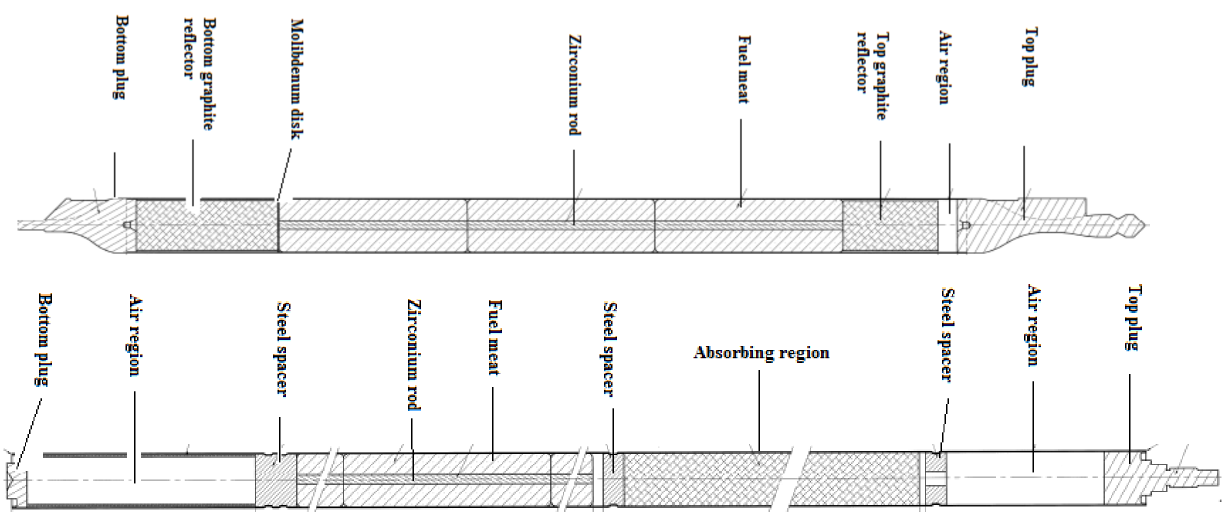


Figure 5. Fuel and the control rod schematic views.

3.2 MCNP models for the fuel and the control rod.

The model for these components were realized trying to preserve as far as possible all the characteristics related with the geometry, dimensions and compositions. The Figures 6 and 7 show the model for the fuel and the control rods

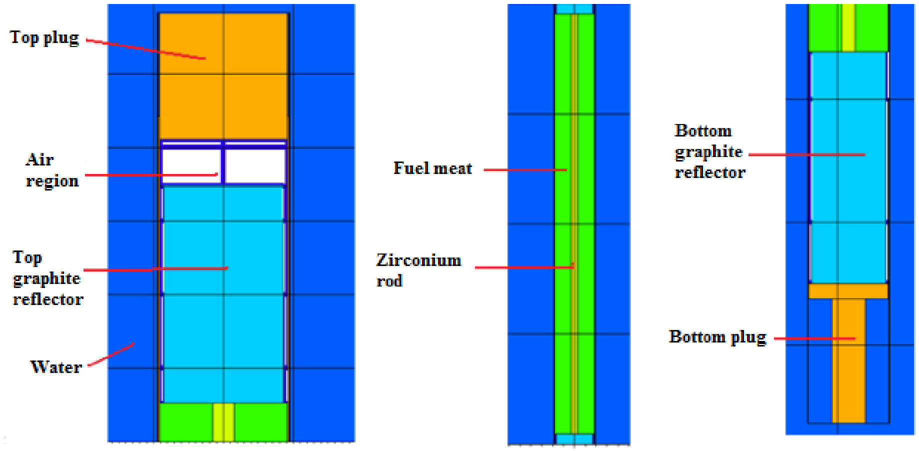


Figure 6. The model for the fuel.

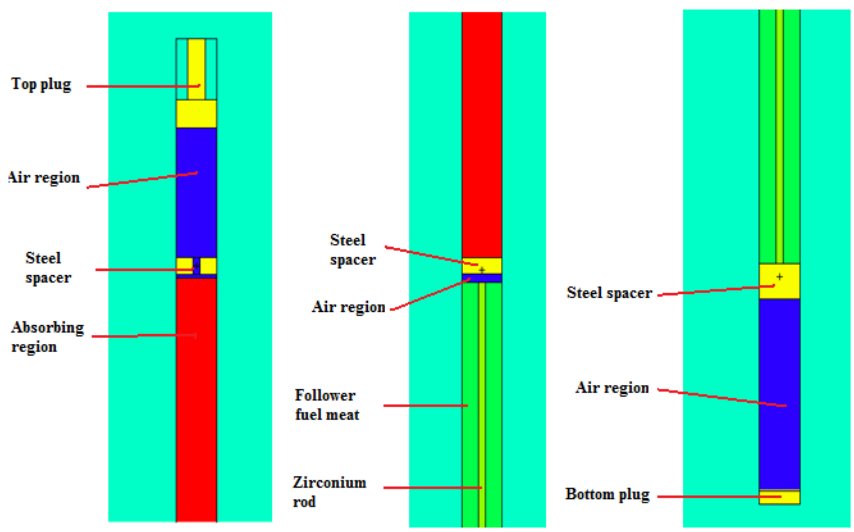


Figure 7. Model for the control rod with fuel follower.

3.3 Reactor core model.

To model the reactor core including the structural components, the fuel elements and the control rods, it is very important to place these components in its right place. This information was taken from the design information provided by the reactor constructor [2]. The first model was for a core like the mixed one (85 fuels, 3 control rods with fuel follower and 1 control rod with air follower). The Figure 8 shows the model.

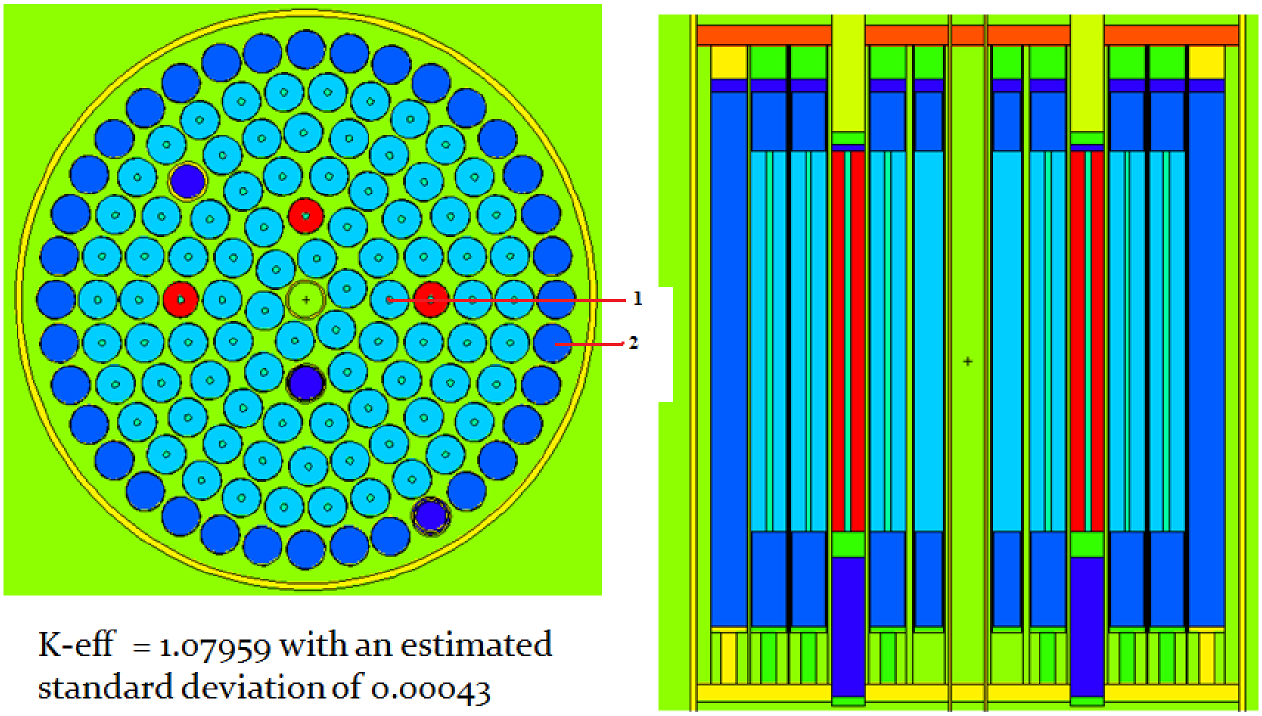


Figure 8. The reactor core with 85 fuels and three control rods fuel followers completely inside the core.

The K-effective calculated was high, that means there are many fuels in the core and the reactivity excess is high compared with the established in the Tech Specs. The next step was to analyze some core configurations with less fuel and some free positions. The first option had 75 fuels plus 3 control rods with fuel follower, 10 fuels were removed from the F ring (F-3, F6, …F-28), the K-effective was again high and a new model with 70 fuels was prepared. In the Table 1 are presented the results for these models and in the Figure 9 are shown these models.

Table 1. Results for the core withe 75 and 70 fuels and 3 control rods with FF**.**

Core	K-effective	Remarks
75+3	1.06606±0.00045	The 3 control rods FF are inside
70+3	1.05852±0.00042	The 3 control rods FF are inside
70+3 (shutdown margin calc.)	0.99501±0.00044	The Regulating control rod is out the core and the other three are in the core

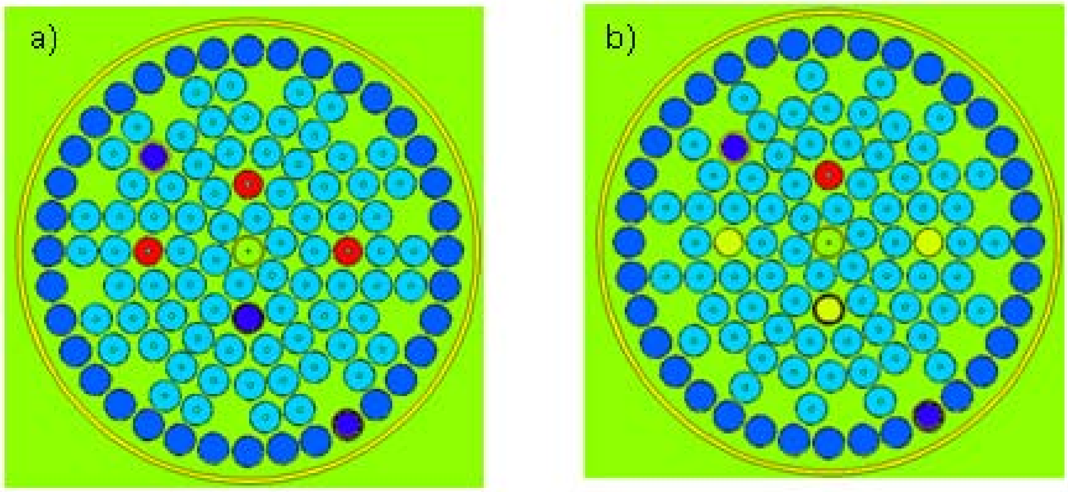


Figure 9. The models with 75 and 70 fuels.

3.4 Optimizing studies and the final core design.

The purpose of these studies was to design a reactor with more in-core experimental facilities, to increase the capabilities for radioisotopes production and satisfy some research needs at the Institute, for instance there is a project to make studies for the life extension of Laguna Verde nuclear power plant, for this project it's necessary to have a place to irradiate steel, similar to the LVNPP's vessel, with high energy neutrons to evaluate the mechanical changes in the steel properties. Several options were studied and the selected design includes 6 new experimental facilities, 2 in B ring (B-1 and B-2) and 4 in E ring (E-4, E-10, E-16 and E-22) and 6 free spaces in F ring. For this core we calculate: a) the critical configuration, b) the reactivity excess, c) shutdown margin, d) β effective and e) the control rod worth. The results are presented in the Table 2, the selected core and the intended uses for the new in-core facilities are presented in Figure 10.

Table 2. Calculated parameters for the selected configuration.

PARAMETER		
Critical core		50 EC + 3 SC
Control rod worth	Transient	3.08 $
	Safety	2.80 $
	Shim	2.82 $
	Regulating	4.05 $
	TOTAL	12.75
Reactivity excess (β = 0.00779)		6.96 $
Shutdown margin		0.51$

NOTE. The control rod worths were calculated with the help of Eric Wilson from ANL

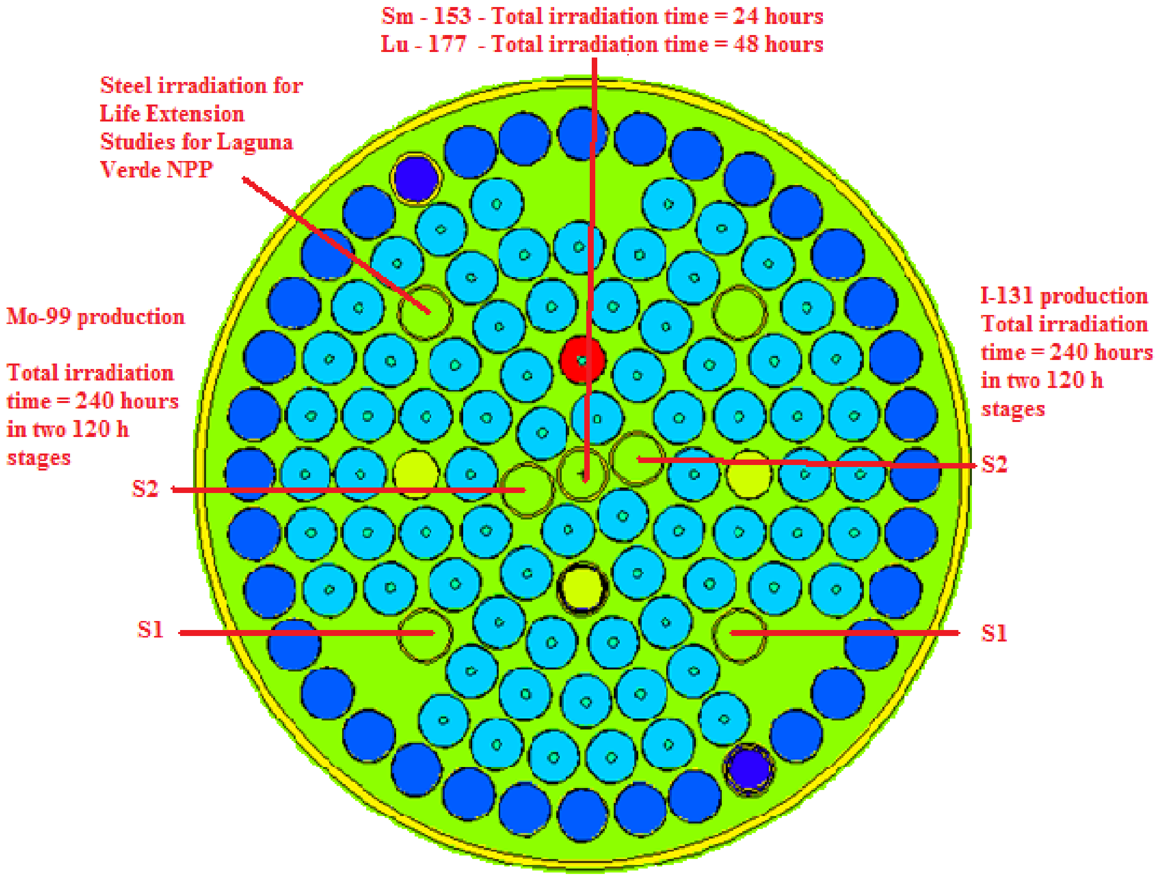


Figure 10. The selected design and the intended uses for the new in-core facilities.

4. FUEL LOADING

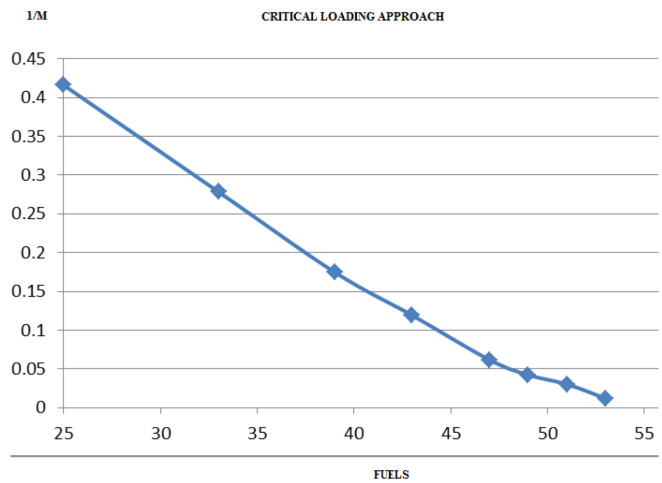
When the rod extensions for the control rods, the instrumented fuel was ready to be install and the two counting systems, to follow the criticality loading approach, were tested and installed, we began the reactor core fuel loading, this activity was realized in about 1 month (February 22 to March 23, 2012). The installation and testing for the counting system was done according to [4] and the loading according to [5].

4.1 Critical reactor core.

The loading began with the installation of the control rods and the instrumented fuel, then the background and the source counting were obtained in the counting systems. The critical loading was done in 12 steps from February 22 to March 17. After each stage we made estimation for the critical load and define how many fuel will load in the next step. The final critical core was with 51 fuels and “almost” the three control rod fuel followers. The calculated number was 50+3 fuel followers, this calculation was done with water surrounding the core and the measurement was done with the “Lazy Susan” in the down position, this condition changes the surroundings for the core. Table 3 shows some the results for the criticality approach.

Table 3. Critical approach

STEP	No. Comb.	1/M
C4	25 (22+3)	0.415855355
C5	33 (30+3)	0.278268962
C6	39 (36+3)	0.174751607
C7	43 (40+3)	0.11918286
C8	47 (44+3)	0.061786434
C9	49 (46+3)	0.04237378
C10	51 (48+3)	0.03031071
C11	53 (50+3)	0.01199034



With 50+3 fuels loaded we decided to load 2 additional fuels and check the criticality condition with the shim control rod, the process was: a) withdrawn completely the transient, regulating and safety rods, b) get the source count, c) made several 5 cm withdraws with the shim rod and d) make an estimation for the criticality rod position. The results shown a shim rod position too down that's why we decided to remove 1 fuel from the core and check again for the criticality condition. The results are in Tables 4 and 5

Table 4. Criticality condition test with the shim rod for 52+3

	0	5	10	15	20	25	27.5	27.5 no S	26.8	27
C1	2414	2630	3042	3780	6075	13041	29350	67463	162968	138373
C2	2360	2585	3104	3852	6046	15317	36503	84096	155241	143590
C3	2467	2634	3029	4092	6190	15983	40873	106570	147455	148221
C4	2396	2620	2966	3823	6570	16296	43153	135004	139105	152929
C5	2505	2627	2989	3867	6237	16371	45145	170159	132658	159791
AV.	2428	2619	3026	3883	6224	15402	39005	112658	147485	148581
1/M	1	0.9271	0.8025	0.6254	0.3902	0.1577	0.06226	0.0216	0.0165	0.01634

Table 5. Criticality condition test with the shim rod for 51+3

	0	5	10	15	20	25	30	32.5	35	37.8	37.8 no S	33.1 c
C1	2051	2134	2286	2903	4041	6648	13563	23474	40554	53982	141927	2117268
C2	2054	2090	2420	2909	4089	7040	15043	25134	42381	58662	252079	2114616
C3	2023	2207	2342	3007	3993	7343	15350	26090	43755	62480	437527	2109430
C4	2102	2136	2431	3029	4153	7088	15929	26490	44502	64182	762596	2100779
C5	2078	2134	2390	3016	4183	7301	15881	26417	44687	66261	1262261	2112669
AV	2062	2140	2374	2973	4092	7084	15153	25521	43176	61113	571278	2110952
1/M	1	0.9633	0.8685	0.6935	0.5038	0.2910	0.1361	0.0808	0.0477	0.0337	0.0036	0.0010

The conclusion from these results is that the critical reactor core was with 51 fuel and 2 fuel followers and the shim rod almost completely out (33.1 cm out)

4.2 Operational core loading.

The fuel loading to get the operational reactor core was from March 17-23, it was done in 7 stages; at the end of each stage an estimation of the core reactivity excess was made and the load for the next stage was established. The regulating rod in all the stages was completely withdrawn to satisfy the shutdown criteria "the reactor can be shut down even with the worthiest rod completely out".

The process to calculate the reactivity excess was as follows:

1. The transient rod was withdrawn completely or until the reactor was critical.
2. The safety rod was withdrawn completely or until the reactor was critical.
3. The shim rod was withdrawn until the reactor was critical.
4. Measure the rod worth from the critical position to completely out, with the positive period method.
5. The reactor reactivity excess was the total worth for all the rods that are partially or totally inside the core.

In the first stage the criticality condition was reached with the regulating, transient and safety rods completely out and the shim rod at 169 u (the rods runs from 0 to ≈380 u). In the Table 6 are the rod positions for the criticality condition.

Table 6. Fuel loading for the operational core.

S	Add. fuel	Total	Control rod positions				Estim. excess	Excess
			Reg.	Tr.	Saf.	Sh.		
1	5	59	out	out	out	169	1.3897	Shim from 169 to out
2	6	65	out	out	277	in	3.3515	Full shim + safety from 277
3	4	69	out	out	153	in	4.7162	Full shim + safety from 153
4	3	72	out	321	in	in	6.1505	Full shim+saf+tr. from 321
5	2	74	out	246	in	in	6.7540	Full shim+saf+tr. from 246
6	1	75	out	229	in	in	6.9785	Full shim+saf+tr. from 229
7	2	77	out	148	in	in	7.91	Full shim+saf+tr. from 148

The shutdown margin is the transient rod worth from 0 to 148 u.

5. FINAL REACTOR TESTING.

The experimental measurements made with the operational core are: a) control rod calibration using the positive period method, b) core reactivity excess and shutdown margin, c) power defect (reactivity loss from cold to hot) and d) thermal power measurements.

Table 7. Control rod worth, reactivity excess and shutdown margin.

CR- woth	**Calculated**	**Measure**	**Diff.**
Regulating	4.05 $	4.00 $	-1.25 %
Transient	3.08 $	3.07 $	- 0.33%
Safety	2.80 $	2.68 $	4.48%
Shim	2.82 $	3.11 $	+ 9.32 %
Reactivity escess	6.96 $	7.95 $	+ 12.45%
Shutdown margin	0.51 $	0.91 $	+ 43.96%

Table 8. Reactivity loss from cold to hot

	2 W		500 kW		1000 kW	
Rod	Pos.	Worth	Pos.	Worth	Pos.	Worth
Regulating	152	243.30	177	204.13	185	191.54
Transient	156	197.01	181	166.94	191	154.76
Safety	152	158.64	179	129.50	190	117.85
Shim	152	180.24	179	145.82	190	132.12
Excess $		7.79		6.46		5.96
Temp °C	11.5		286.7		382.7	
Δρ ($)			1.33		1.83	

Table 9. Thermal power measurements and reactivity loss due to poisons.

	Reactor run for 20 h		Reactor run for 36 h	
	Rod pos. Beginning	Rod pos. End	Rod pos. Beginning	Rod pos. End
Regulating	185	202	159	185
Transient	191	202	198	216
Safety	190	202	204	217
Shim	190	203	204	217
Excess	5.96 $	5.30 $	5.96 $	5.06 $
Δρ ($)	0.66 $		0.90	
Measure thermal power = 905.15 kW			MTP = 991 kW	

The thermal power measurements were done using the calorimetric method in both cases, after the first one the compensated ion chambers for the logarithmic and linear channels were replace to adjust the power of the reactor.

6. REFERENCES

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