TR-2 REACTOR CALCULATIONS

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ABSTRACT

The preliminary design calculations for the TR-2 research reactor has been made at France in 1974. First criticality was achieved in Dec. 10^{th}, 1981; with the available HEU fuels. It has been operated at different power levels for different time intervals in the first cycle. After a 186.87 MWD's of operation, the second cycle has begun. The Xe-poisoning problem has arised in the second cycle after 80 MWD's of operation. This problem has been solved by replacing two Al blocks with two Be ref-lectors.

In the meantime, core conversion activities has been initiated with the investigation of appropriate fuel type for the TR-2 reactor in 1980's. All possible LEU fuel types have been tested and optimization calculations have been covered for a new fuel design. The siliside fuels have been chosen on basis of these various design calculations and the recent developments in this type of fuels. No enlargement was necessary in the core loading, and especially, no modification was needed in the fuel element geometry, since the density of the siliside fuels could be very high.

Density search calculations has been carried out to find a suitable density for the new (siliside) LEU fuels in order to achieve at least the same core performance obtained with the HEU fuels. An uranium density of 4.8 g/cc was preferred among many possible choises because of available production, which increased the core performance. 3D diffusion-burnup calculations have been made with the HEU fuels to update the core status. Many equilibrium core designs have been studied for the optimum utilization of the existing HEU and chosen LEU fuels. Mixed and fully converted equilibrium core calculations have been performed. Some of the LEU fuels have already been loaded to the TR-2 core without any operational or safety related problems. The agreement between the calculations and the experiments are quite good for the operated 13 cycles.

INTRODUCTION

TR-2 is a 5 MW, MTR-type research reactor, which has been in operation since Dec. 10^{th}, 1981. The preliminary design calculations has been made at France in 1974 **[1,2]**. The fuel procured for the first core loading (Fig.-1) is 93 % enriched UAl alloy fuel, containing 280 gr of U-235 per 23 plate standard element. The energy production was 186.87 MWD's in the first cycle. Two irradiation facilities have been inserted to core positions 25 and 74 in this cycle; and one one at position 72 in the second cycle. There arised a Xe-poisoning problem in the 2^{nd} cycle after 80 MWD's operation. This shortage in the excess reactivity has been solved by replacing 2 Al blocks with 2 Be reflectors in the 3rd cycle **[3]**.

Core conversion activities started with the investigation of possible fuel types; UAl-alloy, UAl_x-Al, U_3O_8-Al, $UZrH_{1.6}$ (TRIGA), U_3Si-Al, U_3Si_2-Al for the TR-2 reactor **[4]**. Number of plates per standard fuel element varied from 18 to 23, and the meat thicknesses from 0.51 to 1.2 mm; in order to find an optimum core design. After many optimization calculation and taking into account the developments in the siliside fuels, it has been decided to use U_3Si_2-Al fuel; since there would be modification necessary in the fuel element designs for the conversion from HEU to LEU fuels. Density search calculations had been carried out to find a suitable density for the siliside fuels, to achieve the same core performance with the HEU fuels **[5]**. An uranium density of approximately 4.0 g/cc seemed to satisfy the above criteria for the HEU equilibrium core.

32+ Be	42 Be	52 Be*	62 Be
33 1**	43 SR-1	53 FE	63 SR-2
34 CR-1	44 FE	54 FE	64 2
35 4	45 3	55 CR-2	65 5
36 Al	46 7	56 6	66 Al

1.step: A fuel is placed at core position 33; reactor not critical

2.step: A fuel is placed at core position 64; reactor not critical

3.step: A fuel is placed at core position 45; reactor not critical

4.step: A fuel is placed at core position 35; critical; SR1, SR2, CR1 out, CR2 at 683

5.step: A fuel is placed at core position 65; critical; SR1, SR2, CR1 out, CR2 at 441

6.step: A fuel is placed at core position 56; critical; SR1, SR2, CR1 out, CR2 at 271

7.step: A fuel is placed at core position 46; critical; SR1, SR2 out, CR1 at 780, CR2 in

Figure-1 : The initial core loading of the TR-2 reactor

An uranium density of 4.8 g/cc was preferred because of available production for the French OSIRUS reactor, which increased the performance of TR-2. This fuel is identical with our HEU fuels, except there is no extra cladding on the 2 outer plates, which is unnecessary for todays technology. The main steps of these conversion studies are :

- optimization of the usage of available HEU fuels until the import of LEU fuels,
- mixed core calculations to figure out a fuel shuffling strategy for the maximization of the discharge burnup levels for the HEU fuels,
- equilibrium core calculations with LEU fuels that will satisfy the operational needs.

CODES AND NEUTRONIC CALCULATIONS

Few group crosssection libraries for HEU and LEU fuels were generated for different regions in the core with EPRI-CELL code **[6]**. The RABANL integral transport option of MC^2-2 code **[7]** was used to accurately account for the resonance self-shielding of U-238. Two and 3 dimensional diffusion and burnup calculations were carried out by DIF3D and REBUS-3 codes **[8,9]**. 10 ppm Bo equivalent was taken to account for the impurities inside the fuel materials. It corresponds to approximately 300 pcm anti-reactivity for the TR-2 initial core loading.

Burnup calculations were updated by tracing the TR-2 history. The initial core loading was conserved during the first 9 cycles. Only the replacement of 2 Al blocks with 2 Be reflectors were made in the 3rd cycle. Three dry irradiation facilities were inserted during the first 2 cycles and 2 of them were removed during cycles 7 and 8. The experimental and calculated burnup values for control and standard elements are given in Table-1 for the first 9 cycles. The CR-2 control rod was assumed to be 50 % inserted in 3D burnup calculations, in order to simulate the operational blade movements. The 2 Be blocks were replaced by 2 standard fuel elements, one fuel element at core position 45 was replaced by an irradiation element and 4 additional Be reflectors were inserted at core positions 37, 47, 57 and 67; in the 10th cycle.

Table-1 : The calculational (C) and experimental (E) burnup values of the standard and control fuel elements during 9 cycles

Fuel element ID. No.		Burnup values (in percent) during the cycles								
		1	2	3	4	5	6	7	8	9
S101	E	7.91	13.80	20.16	-	-	23.20	25.19	26.95	-
	C	8.02	14.02	21.35	-	-	24.46	26.82	28.81	-
S102	E	7.04	12.37	20.58	-	-	22.86	25.50	-	-
	C	6.79	11.90	20.28	-	-	23.07	25.70	-	-
S103	E	7.70	13.12	-	14.80	17.31	19.96	22.69	24.76	26.27
	C	8.19	14.29	-	16.01	18.44	20.89	23.17	25.25	27.30
S104	E	6.84	11.56	19.43	21.12	-	23.95	-	-	-
	C	7.33	12.82	21.08	23.03	-	26.03	-	-	-
S105	E	-	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-	-	-
S106	E	6.38	10.41	17.14	19.08	22.04	-	-	-	-
	C	6.20	10.93	17.47	19.26	22.29	-	-	-	-
S107	E	5.60	-	-	7.51	10.14	12.59	15.19	17.30	19.50
	C	6.25	-	-	8.06	10.85	13.66	15.86	17.70	20.13
S108	E	5.52	10.03	17.59	19.66	22.07	-	-	-	-
	C	5.09	8.85	15.85	17.91	20.68	-	-	-	-
S109	E	4.71	9.27	15.67	17.11	19.67	-	-	-	-
	C	4.18	8.08	13.94	15.53	18.21	-	-	-	-
S110	E	5.43	10.54	17.17	19.11	22.20	-	-	-	-
	C	4.92	9.65	16.61	18.33	21.47	-	-	-	-
S111	E	6.04	10.42	18.24	-	-	21.18	23.89	25.34	27.11
	C	6.17	10.84	17.98	-	-	20.64	25.35	25.20	27.50
S112	E	-	4.09	-	5.89	8.13	10.51	12.73	14.74	16.44
	C	-	3.31	-	4.80	6.81	8.88	10.95	12.82	14.93
S113	E	-	-	6.27	7.65	9.98	12.48	15.14	16.91	18.75
	C	-	-	5.24	6.55	8.90	11.30	13.70	15.56	17.50
S114	E	-	-	6.49	8.02	11.05	13.88	16.12	17.76	19.89
	C	-	-	6.04	7.56	10.34	13.13	15.52	17.22	19.30
S115	E	-	-	-	-	2.48	4.81	7.18	8.75	10.95
	C	-	-	-	-	2.35	4.73	6.54	8.18	10.33
S116	E	-	-	-	-	-	-	2.33	3.94	5.63
	C	-	-	-	-	-	-	2.09	3.52	5.38
S117	E	-	-	-	-	-	-	-	1.78	3.57
	C	-	-	-	-	-	-	-	1.64	3.25
S118	E	-	-	-	-	-	-	-	-	1.99
	C	-	-	-	-	-	-	-	-	1.87
C011	E	-	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-	-	-
C012	E	-	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-	-	-
C013	E	-	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-	-	-
C014	E	-	-	-	-	-	-	-	-	-
	C	-	-	-	-	-	-	-	-	-
C015	E	8.52	14.55							
	C	8.99	15.65							
C016	E	6.98	11.95							
	C	7.06	12.34							
C017	E	7.20	12.33							
	C	7.59	13.28							
C018	E	5.12	9.23							
	C	4.69	8.26							

EQUILIBRIUM CORE CALCULATIONS

Three major equilibrium core designs were considered with the LEU fuels. Different shuffling schemes and different loading strategies were investigated for the minimization of power peaking factors and for the maximization of the discharge burnup levels. The first one had 4 control, 2 irradiation and 14 standard fuel elements. It is reflected on both opposite sides by 10 Be elements. The shuffling scheme and the fuel loading strategies for the different fuel elements are given in Fig-2. The discharge burnup levels of the different fuel elements for a cycle length of 260 MWD's are given in Table-2.

Be	Be	Be*	Be	Be
6 **	9	11	d	5
1	b ++	12	0 0 A+	4
3	13	14	c	2
7	0 0 B	a	10	8
Be	Be	Be*	Be	Be

**) 1, 2, 3, … : standard fuel element shuffling positions

++) a, b, c, … : control fuel element shuffling positions

+) A, B, C, … : irradiation fuel element shuffling positions

Be, Be* : Be blocks without and with hole

Figure-2 : TR-2 equilibrium core (Design No : 1)

Table-2 : The discharge burnup levels of the different fuel elements for the TR-2 equilibrium cores (Design No : 1 and 2)

LEU core	Design No : 1	Design No : 2	
Fuel loading strategy	$1SE + \frac{2}{7} CE + \frac{1}{10} IE$*	$1SE + \frac{2}{4} CE + \frac{1}{13} IE$	
Cycle length	260 MWD	200 MWD	250 MWD
Standard fuel element (SE)	55.2	46.4	57.2
Control fuel element (CE)	63.3	50.9	62.1
Irradiation fuel element (IE)	48.8	56.1	67.5

*) $1SE + \frac{2}{7} CE + \frac{1}{10} IE$: 1 standard fuel element per cycle
2 control fuel element per 7 cycles
1 irradiation fuel element per 10 cycles

The second equilibrium core had 4 control, 1 irradiation and 16 standard fuel elements. It is also reflected by 10 Be elements on both sides. The discharge burnup levels of the different fuel elements for the cycle lengths of 200 and 250 MWD's are given also in Table-2 .

The 3rd equilibrium core had 4 control, 2 irradiation and 16 standard fuel elements. One Be block is located inside the core for the irradiation purposes. The BOC and EOC k-effective values, power peaking and discharge burnup levels for different fuel elements, for cycle lengths of 250 - 280 MWD's are given in Table-3.

Table-3 : The excess reactivities, power peaking values and discharge burnup levels of the different fuel elements for the TR-2 equilibrium core (Design No : 3)

Cycle length [MWD]	Excess reactivity [pcm]		P_{max} [w/cm^3]	Discharge* burnup levels (%)		
	BOC	EOC		SE	CE	IE
250	7310	2600	251.5	54.2	63.3	46.0
260	6831	2026	253.5	56.4	65.6	47.8
270	6388	1435	255.8	58.4	67.6	49.6
280	5929	796	257.9	60.3	69.5	51.3

*) Fuel loading strategy : $1SE + \frac{1}{4} CE + \frac{1}{4} IE$

Mixed core calculations were made for the second equilibrium core. The same shuffling schemes were followed for HEU and then LEU fuel elements. The power peaking values are sligthly higher in mixed core then HEU and LEU equilibrium cores, but still below the safety margins. The maximum power peaking value was observed when a fresh irradiation element was inserted into the middle of the core, as can be expected.

CONTROL ROD WORTHS

The control rod worths for different cores (small, intermediate, equilibrium) loaded with HEU or LEU or mixed fuels were calculated by diffusion theory using effective cross-sections **[10]** for the control rod regions. The difference between full and half-symmetric core calculations in 3D differ only by less then 4 %, so half-symmetric core model was used in most of the calculations. Results are summarised in Table-4. In general, rod worths increase from BOC to EOC. The decrease in the anti-reactivity values of the control rods for the LEU cores is not important since the excess reactivities are also decreased for these cores.

Table-4 : The control rod worths for different TR-2 cores loaded with HEU; or LEU; or HEU and LEU mixed fuels

Control Rod	Small core Fuel: HEU	Cycle 10 HEU	Equilibr. core 2* HEU	Equilibr. core 2 HEU	Equilibr. core 2 HEU+LEU	Equilibr. core 2 LEU
SR-1	5939	4191	4133	4290	4164	3368
SR-2	3268	2402	4145	4230	4051	3344
CR-1	4223	3536	4279	4592	4142	3568
CR-2	5945	6906	4200	4340	3835	3324

*) 4 Be blocks at the corners are removed

CALCULATION OF SAFETY PARAMETERS

Safety related neutronic parameters needed for transient analysis of the TR-2 reactor cores loaded both with HEU and LEU fuels have been calculated. Ten group structure was used in the generation of cross-sections, with 4 thermal groups below 0.625 eV, which is the upper energy limit of group 5 in the standard 5-group set, to increase the accuracy of the coefficient of spectral feedback caused by increasing the water temperature. Reactivity feedback coefficients were calculated for HEU and LEU fuel loaded small, intermediate and equilibrium cores.

The Doppler effect has not been calculated for HEU fuels, because of the low U-238 content. Also, reactivity effects associated with the expansion of fuel and structural materials have not been encountered. Cross-sections generated for various water and fuel temperatures were used to evaluate the feedback coefficients. The reactivity effect of % void in the moderator also calculated for both HEU and LEU fuels. There is a slight change in the feedback coefficients from BOC to EOC. There is almost no change in reactivity between BOC and EOC cores due to changes in water density, and fuel temperature, but there is a slight increase from BOC to EOC due to changes in water temperature.

Kinetic parameters such as prompt neutron generation times, delayed neutron fractions for different TR-2 cores were calculated using 3D diffusion theory perturbation capability of the ARC system. Two calculations were made for HEU fuel loaded TR-2 small core. The first one was made for all rods out situation in 3D half-symmetric core. The first one was made for all rods out situation in 3D half-symmetric core. The second one was made for the control rods CR-1 and CR-2 % 50 inserted situation in full 3D geometry. Except the neutron generation time, the variation between the two cases is not considerable. The kinetic parameters were also calculated for LEU fuel loaded small, half-symmetric core for all rods out situation. They were calculated for BOC and EOC of the half-symmetric, LEU fuel loaded 3rd equilibrium core for CR-2 fully inserted situation. The kinetic parameters for cycle 10, mixed and other TR-2 equilibrium cores were also calculated.

SUMMARY

The main objectives attained in these core conversion calculations can be summarised as follows :

- Safe operation of the reactor during all phases (HEU small- HEU intermediate-HEU and LEU mixed-LEU equilibrium cores) : The fuel shuffling and loading strategies were optimised in all stages. The power peaking factors became impor-tant, especially for mixed cores.
- Economical usage of the HEU and LEU fuel elements : Be reflectors were used in two opposite sides of the TR-2 reactor core to increase the burnup levels. Diffe-rent loading patterns and cycle lenghts were used to optimize the discharge burnup levels of different type of fuel elements. In this way the discharge burnup levels were increased up to % 60.
- Establisment of the best irradiation positions : The irradiation element and Be block positions were optimized in order to obtain the maximum efficiency for the irradiation samples.
- Facilitate the operation of the reactor : The loading patterns were adjusted in such a way that the BOC and EOC excess reactivities don't differ much from cycle to cycle and also able to compansate the Xe+Sm anti-reactivity for continious operation of the reactor during

the whole cycle. Since there is a fixed shuffling scheme for each type of element, the flux values throughout the reactor will remain nearly the same at each cycle.

One irradiation and 2 standard LEU fuel elements have already been loaded to the TR-2 core without any operational or safety related problems. The agreement between the calculations and the experiments are quite good for the operated 13 cycles.

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