An Application of Low Leakage Loading Pattern to reduce Fast Neutrons Fluence on WWER-440 Reactor Pressure Vessel in Kozloduy NPP

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Abstract

The neutron exposure of a reactor pressure vessel (RPV) is one of the key factors that have to be quantified and assess reliably to provide plant life assurance and /or an extension to operational life.

This paper summarizes the principal methods that are used in core design optimisation for WWER-440 reactors in NPP-Kozloduy in order to reduce flux of fast neutrons at the RPV. Results of fast neutron fluence changes during the all last cycles of units 1-4 with WWER-440 reactors are considered.

Results of advanced low leakage loading pattern application to reduce RPV neutron exposure are presented.

An analysis of the impact of the type of the core design (standard loading pattern, core with dummy assemblies on the periphery-reduced core, low leakage loading pattern, core with dummy assemblies and low leakage loading pattern etc.) on the neutron fluence at the RPV is performed and some conclusions are given.

Introduction

The ability to accurately predict the condition of reactor components, reactor pressure vessel etc. is becoming a key factor in nuclear safety assessment.

Decisions regarding plant lifetime and design safety margins involve a determination of energy dependent neutron fluence for a RPV (at a critical location) by combining theoretical calculations and measurements. The fluence is then used in some theoretical damage model to predict the aging.

If reliable and accurate prediction of doses incurred by RPV components is available, then utilities could verify present design lifetime of their RPV and analyze feasibility of its extension.

In Bulgaria performance of the surveillance neutron dosimetry activities for the Kozloduy WWER-440 reactors are performed by INRNE – BAS / 3,4 / and Sofia University with contribution of NPP physicists.

Fluence calculations on reactor pressure vessels of units 1 to 4 are performed for each fuel cycle taking into account operational history and fuel reload pattern.

RPV fluences obtained of different fuel cycles vary as a product of core management: fuel core loading pattern, cycle length, etc.

This paper present results of the impact of the type of core loading patterns on the neutron fluence reduction to WWER-440 pressure vessel.

I. Preconditions for core fuel loading pattern and operational regimes optimisation to reduce RPV neutron fluence in Kozloduy NPP WWER-440 reactors.

The reactor vessel metal radiation embrittlement and the prediction of RPV lifetime depend on estimation of neutron fluence.

The neutron fluence in Kozloduy NPP Units 1 to 4 (with WWER-440) has been calculated taking into account the fuel core loading patterns and cycle operation regimes for all past cycles.

The flow of fluence calculations is divided into two steps:

- detailed core calculation taking into account power history and burn-up provided by SPPS-1.6 / 2 /;
- calculations of the multi-group fast neutron fluence using transport code /4 /.

Results of Relative Neutron fluence quantities $F_{rel.unit} = F_i / F_1$ on RPV of units 1 to 4 are presented at Tables 1 to 4.

F_i is a neutron fluence of the current cycle, F_1 is a neutron fluence of the first cycle of the unit.

The analysis of results shows that the relative RPV neutron fluences obtained of different fuel cycles significantly depend on type of fuel core loading patterns.

During operational history of units 1 to 4 various fuel core loading pattern different from project design have been developed and applied.

II. Fuel Loading Patterns Type in dependence of the RPV neutron fluence reduction.

There are several type fuel loading patterns of the point of view of RPV neutron fluence reduction:

The first design fuel loading is identical for all 1 to 4 units in Kozloduy NPP /1/. The fresh fuel assemblies are placed on the core periphery in the next so called standard out-in-in fuel loading patterns. The core low-leakage loading pattern is characterized by placing burned fuel assemblies in outer core locations. There are various variations as to degree of low leakage loading application. It is depend on the number of burned assemblies placed on the core peripheral locations and its burn-up.

In the core reduced loading pattern 36 dummy (shield) assemblies made of steel are introduced in the outer core locations. The units 1 to 3 of NPP Kozloduy have been modified by 36 non- fuel dummy assemblies introduction.

Partly low leakage loading pattern with dummy assemblies is prepared when in addition to the 36 non- fuelled assemblies on the part of vacant peripheral location are placed burned fuel assemblies.

Low-leakage loading pattern with dummy assemblies is prepared when on all the vacant peripheral locations are placed high burned assemblies in addition to 36 dummy assemblies.

III. Obtained results of the impact of the type of used fuel core loading pattern on the RPV neutron fluence reduction.

Relative neutron fluences on RPV of in dependence of the core loading pattern types and cycle length for all past cycles of units 1 to 4 are given in Tables 1 to 4.

The evolution of the different type of core loading pattern application for units 1 to 4 is demonstrated on Fig.1 to 4.

The influence of the different types of low leakage loading patterns application and dummy assemblies introduction on reduction of RPV neutron fluence is presented in Fig.5 and 6.

It is shown that maximum reduction of the RPV neutron fluence is reached in the case of low leakage loading pattern with dummy assemblies application (21,22 cycle of unit 1). This type of loading pattern was called "low fluence".

The application of low leakage loading pattern for fuel core with 349 fuel assemblies (unit 4 in NPP Kozloduy) allow an reduction RPV neutron fluence with about 40% in comparison with standard loading pattern. In this case maximum reduction is achieved by placing on the core periphery high burned assemblies (30 MWD/kg).

Conclusions

Although, the presented results and analyses have mostly qualitative character, it is evident that fuel core loading patterns optimisation can contribute to reduction of RPV neutron exposure.

The additional studies and quantitative analyses will allow to consider minimization of RPV neutron fluence as a criterion of choosing the appropriate loading patterns.

References

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Table 1

№ cycle	Date of beginning and end of Cycle	Cycle length (FPD)	Fluence rel.units F_1/F_1	Type of Fuel Loading Pattern	Type of Assemblies on the periphery
1	1.09.74-31.10.75	289.7	1.00	Project	1A-60; 1B-6
2	21.02.76-27.06.77	357.4	1.22	Standard out in in	1A-60; 1C-6
3	15.07.77-30.06.78	303.6	1.01	Standard out in in	1A-60; 2B-6
4	15.09.78-8.08.79	311.7	1.08	Standard out in in	1A-60; 3B-6
5	1.10.79-11.09.80	317.8	1.13	Standard out in in	1A-60; 2B-6; 1C-1
6	12.10.80-8.09.81	308.3	1.12	Standard out in in	1A-60; 1B-6
7	21.10.81-8.09.82	297.7	1.04	Standard out in in	1A-60; 1B-6
8	31.10.82-14.09.83	302.7	1.04	Standard out in in	1A-60; 1B-6
9	12.10.83-11.09.84	312.9	1.04	Standard out in in	1A-60; 1B-6; 3B-5
10	9.10.84-24.09.85	329.2	0.93	Standard out in in	1A-60; 1B-6
11	17.10.85-9.09.86	310.3	0.96	Partly low leakage	1A-36; 2A-12; 4A-12; 2B-6
12	25.11.86-03.10.87	293.7	0.72	Low leakage (LL) in in out	1A-24; 3A-12; 4A-24; 3B-6;
13	31.10.87-9.08.88	270.6	0.26	Dummy ass.+ L.L.	DA-36; 1A-12; 4A-12; 3B-6
14	8.09.88-24.07.89	304.5	0.26	Dummy ass.+ L.L.	DA-36; 3A-12; 4A-12; 3B-6
15	annealing 15.11.89-12.09.90	277.0	0.20	Dummy ass.+ p.L.L.	DA-36; 1A-12; 4A-11; 3B-6;3A1
16	18.10.90-04.09.91	274.0	0.23	Dummy assemblies	DA-36;1A-24; 3B-6
17	29.12.93-27.02.95	339.7	0.28	Dummy ass.+ p.L.L.	DA-36; 1Д-12; 3A-5; 3B-9;4A-4
18	4.10.95-17.05.96	203.0	0.15	Dummy ass.+ L.L.	DA-36; 3A-10; 4A-6; 2B-6;2E-7
19	17.01.97-16.03.98	296.2	0.19	Dummy ass.+ L.L.	DA-36; 4A-24; 3B-4;4B-2
20	20.06.98-17.0899	288.5	0.18	Dummy ass.+ L.L.	DA-36; 4Д-23; 3E-1;4B-6
21	22.02.00-1.3.2001	293.4	0.23$^{\text{пр}}$.	Dummy ass.+ L.L.	DA-36; 4Д-24; 3B-16;

Relative Neutron Fluence $F_{rel.units}$=Fi/F1 on Reactor Vessel of unit 1 in dependence of Fuel Loading Patterns Type and Cycle Length.

Table 2

№ cycle	Cycle length (FPD)	Fluence rel.units F_i / F_1	Type of Fuel Loading Pattern	Type of Assemblies on the periphery
1	290.0	1.0	Project	1A-60; 1B-6
2	286.0	0.99	Standard out in in	1A-60; 2B-6
3	345.0	1.18	Standard out in in	1A-60; 1B-6
4	312.0	1.10	Standard out in in	1A-60; 1B-6
5	213.0	0.77	Standard out in in	1A-60; 2B-6
6	290.4	1.08	Standard out in in	1A-60; 1B-6
7	328.7	1.17	Standard out in in	1A-60; 2B-6
8	278.0	0.97	Standard out in in	1A-60; 1B-6
9	298.9	1.02	Standard out in in	1A-60; 2B-6
10	339.2	0.98	Partly low leakage	1A-36; 4A-24; 3B-6;
11	310.5	0.98	Partly low leakage	1A-36; 4A-24; 2B-6;
12	322.0	0.81	Low Leakage (LL) out in in	1A-24; 3A-12; 4A-23;3B-7
13	320.2	0.80	Low Leakage (LL) out in in	1A-12; 3A-24; 4A-24;2B-6
14	303.1	0.17	Dummy ass.+ part.L.L.	DA-36; 1A-12; 3A-6; 4A-6; 3B-6
15	280.6	0.18	Dummy ass.+ part.L.L.	DA-36; 1A-12; 3A-6; 4A-6; 3B-6
16	300.0	0.16	Dummy ass.+ part.L.L.	DA-36; 1D-4; 1A-8; 3A-11; 4A-1; 3B-6
17	293.4	0.24	Dummy ass.+ part.L.L.	DA-36; 1D-12; 3A-6; 4A-14; 2B-2; 3B-6
18	294.2	0.23	Dummy ass.+ part.L.L.	DA-36; 1D-12; 3D-4; 3A-1; 4A-5; 3B-8
19	295.0	0.23	Dummy ass.+ part.L.L.	DA-36; 1D-12; 3D-11; 3E-1; 2B-8
20	289.2	0.19	Dummy ass.+ L.L.	DA-36; 4D-23; 3B-6; 3E-1;
21	294.6	0.23*	Dummy ass.+ part.L.L.	DA-36; 1G-12; 4D-11; 4E-1; 3B-6
22	279.7	0.19*	Dummy ass.+ part.L.L.	DA-36; 3D-8; 4D-12; 2E-4; 4B-6

Relative Neutron Fluence $F_{rel.units}$=Fi/F1 on Reactor Vessel of unit 2 in dependence of Fuel Loading Patterns Type and Cycle Length.

Table 3

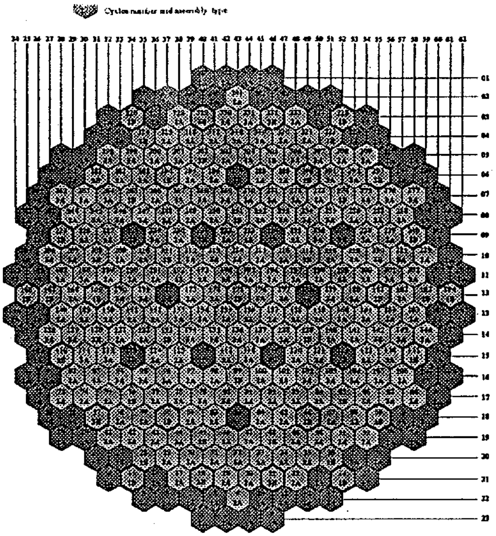
№ cycle	Cycle length (FPD)	Fluence rel.units F_I/F_1	Type of Fuel Loading Pattern	Type of Assemblies on the periphery
1	406.0	1.00	Project	1A-60; 1B-6
2	270.1	0.63	Standard out in in	1A-60; 2B-6
3	289.8	0.68	Standard out in in	1A-60; 1B-6
4	330.9	0.69	Partly low leakage	1A-36; 4A-24;2B-6
5	335.8	0.65	Partly low leakage	1A-36; 4A-24;2B-6
6	293.8	0.45	Low leakage out in in	1A-24; 3A-12;4A-24;3B-6
7	300.5	0.17	Dummy ass.+ part.L.L.	DA-36; 1A-12; 3A-12;2B-6
8	326.3	0.16	Dummy ass.+ L.L.	DA-36; 3A-24;3B-6
9	322.5	0.20	Dummy ass.+ part.L.L.	DA-36; 1A-12; 3A-12; 3B-6
10	292.1	0.17	Dummy ass.+ L.L.	DA-36; 3A-24; 2B-6
11	310.4	0.19	Dummy ass.+ L.L.	DA-36; 3A-24; 3B-6
12	327.0	0.21	Dummy ass.+ L.L.	DA-36; 3A-26; 3D-1;4A-3
13	321.5	0.24	Dummy ass.+ modif.L.L.	DA-36; 1D-24; 3B-6
14	329.8	0.20	Dummy ass.+ L.L.	DA-36; 3D-19; 3A-7;3B-1; 2E-3
15	279.3	0.17	Dummy ass.+ L.L.	DA-36; 3D-9; 4D-11;3A-6; 4A-1; 3E-3

Relative Neutron Fluence $F_{rel.units}$=Fi/F1 on Reactor Vessel of unit 3 in dependence of Fuel Loading Patterns Type and Cycle Length.

Table 4

№ cycle	Cycle length (FPD)	Fluence rel.units F_I/F_1	Type of Fuel Loading Pattern	Type of Assemblies on the periphery
1	390.1	1.00	Project	1A-60; 1B-6
2	241.2	0.56	Standard out in in	1A-60; 2B-6
3	348.8	0.72	Partly low leakage	1A-36; 2A-12;1B-6;3B-12
4	313.7	0.68	Partly low leakage	1A-36; 2A-12;4A-12;2B-6
5	354.4	0.54	In-in-out low leakage	1A-24; 3A-12;4A-24;3B-6
6	309.5	0.47	In-in-out low leakage	1A-12; 3A-30;4A-18;2B-6
7	244.0	0.33	In-in-out low leakage	1A-12; 3A-18;4A-30;2B-6
8	350.4	0.50	In-in-out low leakage	1A-12; 4A-48;2B-6
9	295.0	0.40	In-in-out low leakage	1A-3; 1D-9;4A-48;3B-6
10	309.3	0.42	In-in-out low leakage	1A-12; 4A-48; 3B-6
11	332.0	0.43	In-in-out low leakage	1D-12; 3A-12;4D-36;3B-6
12	356.4	0.55	In-in-out low leakage	1D-12; 3A-12;4D-36;3B-6
13	358.7	0.50	In-in-out low leakage	1D-12; 3D-12;4A-36;3B-6
14	295.7	0.41	In-in-out low leakage	1G-12; 3A-6;3D-18;4D-30

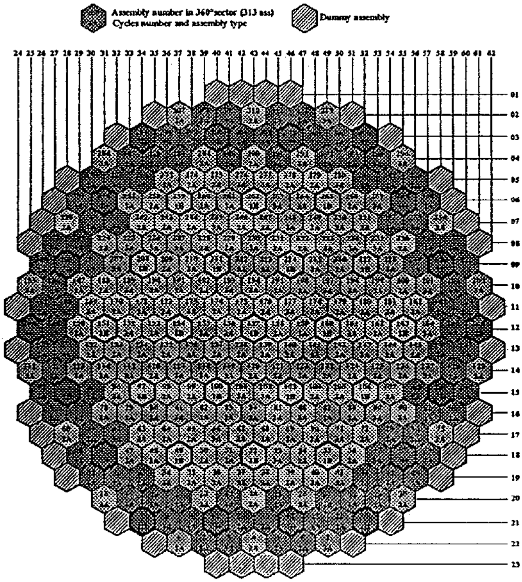
Relative Neutron Fluence $F_{rel.units}$=Fi/F1 on Reactor Vessel of unit 4 in dependence of Fuel Loading Patterns Type and Cycle Length.



A - 3.6% wall thickness 2.0mm

B - 2.4% wall thickness 2.0mm

Unit III Cycle 3

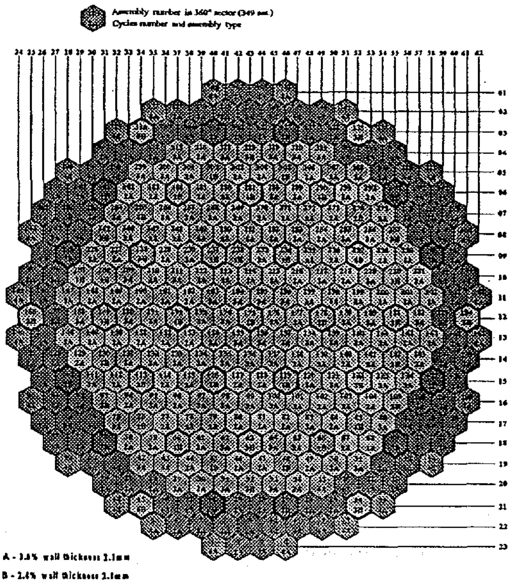


A - 3.6% wall thickness 2.1mm

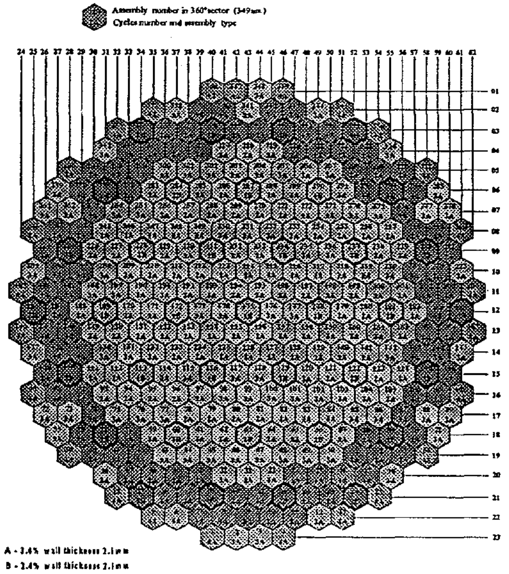
B- 2.4% wall thickness 2.1mm

Unit III Cycle 7

Fig.1 Charts of 3-d and 7-th core fuel loadings of Unit 3

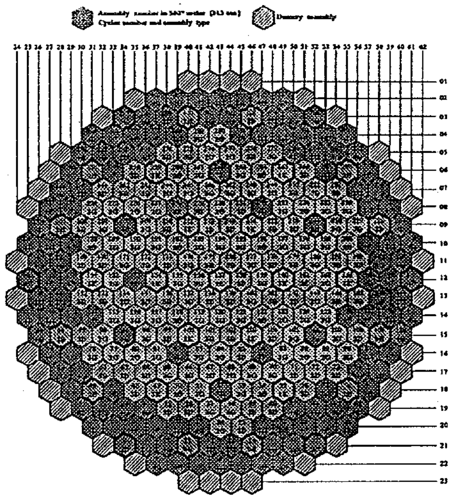


Unit II Cycle 10



Unit II Cycle 13

Fig.2 Charts of 10-th and 13-th core fuel loadings of Unit 2

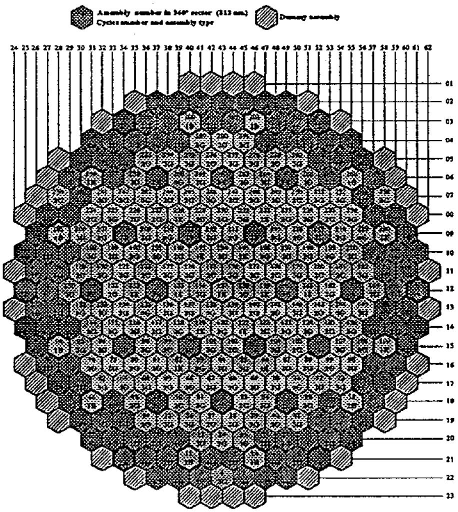


B* - 2.4% wall thickness 2.1mm
D* - 3.6% wall thickness 1.5mm
A* - 2.4% wall thickness 1.5mm
F* - 1.6% wall thickness 1.5mm

G - 3.6% wall thickness 1.5mm and Zr spacer grids
K - 2.4% wall thickness 2.0mm and Zr spacer grids
L - 1.6% wall thickness 2.0mm and Zr spacer grids

* - with Steel spacer grids

Unit I cycle 21



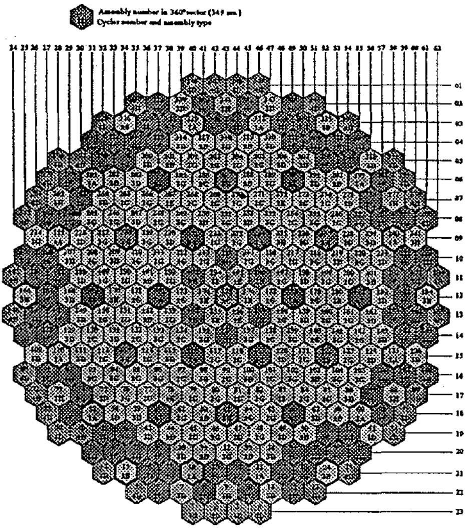
B* - 2.4% wall thickness 2.1mm
D* - 3.6% wall thickness 1.5mm
A* - 2.4% wall thickness 1.5mm

G - 3.6% wall thickness 1.5mm and Zr spacer grids
K - 2.4% wall thickness 2.0mm and Zr spacer grids
L - 1.6% wall thickness 2.0mm and Zr spacer grids

* - With Steel spacer grids

Unit I cycle 22

Fig.3 Charts of 21-st and 22-d core fuel loadings of Unit 1



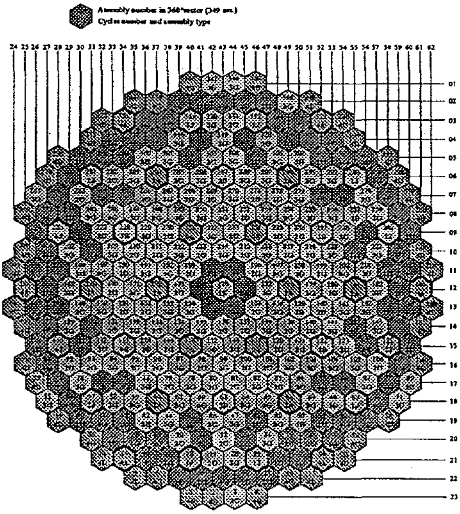
A* - 3.6% wall thickness 2.1mm
B* - 2.4% wall thickness 2.1mm
C* - 1.6% wall thickness 2.1mm
D* - 3.6% wall thickness 1.5mm
A* - 2.4% wall thickness 1.5mm

G - 3.6% wall thickness 1.5mm and Zr spacer grids

H - 2.4% wall thickness 1.5mm and Zr spacer grids

* - With Steel spacer grids

Unit IV Cycle 15



A* - 3.6% wall thickness 2.0mm
B* - 2.4% wall thickness 2.0mm
D* - 3.6% wall thickness 1.5mm
A* - 2.4% wall thickness 1.5mm

G - 3.6% wall thickness 1.5mm and Zr spacer grids
H - 2.4% wall thickness 1.5mm and Zr spacer grids
J - 3.6% wall thickness 2.0mm and Zr spacer grids
K - 2.4% wall thickness 2.0mm and Zr spacer grids

* - With Steel spacer grids

Unit IV Cycle 16

Fig.4 Charts of 15-th and 16-th core fuel loadings of Unit 4

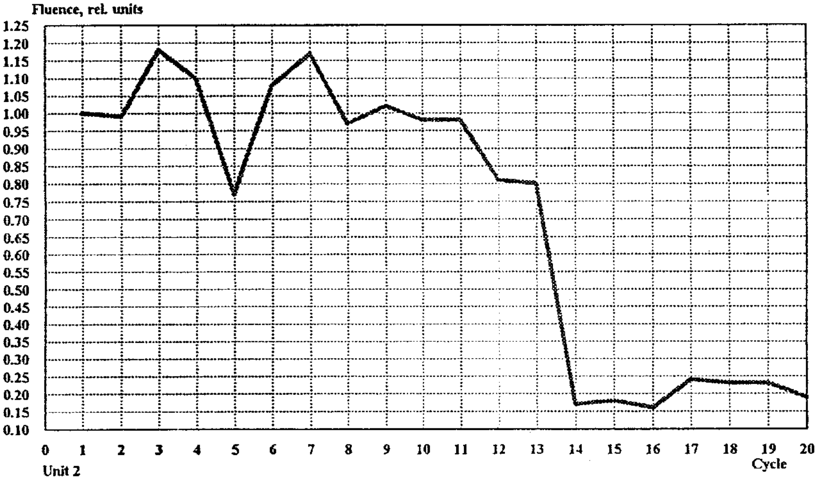
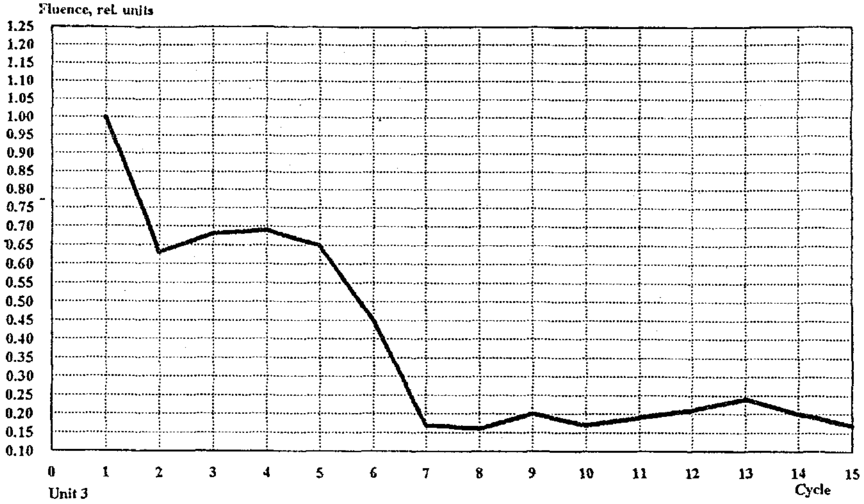


Fig.5. Change of the Relative Neutron Fluence $F_{rel.units}$ = Fi/F1 On Reactor Vessel during all past fuel Cycles of units 1 and 2



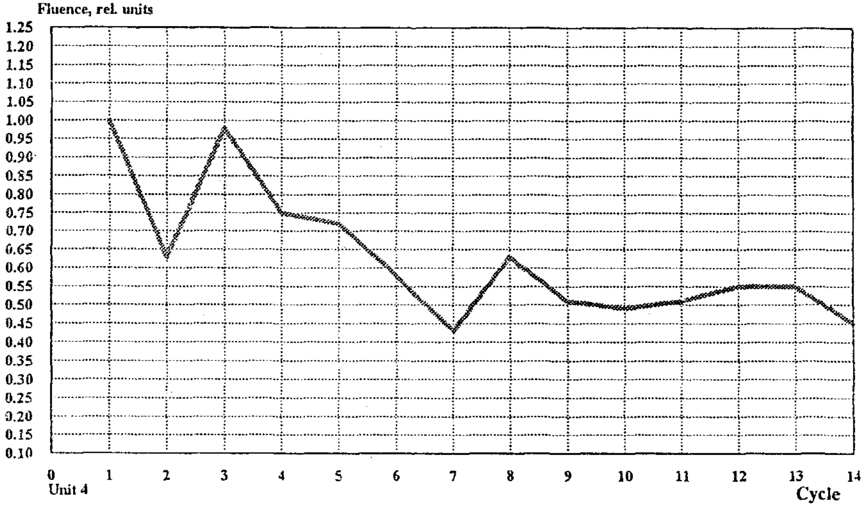


Fig.6. Change of the Relative Neutron Fluence $F_{rel.units} = Fi/F1$ on Reactor Vessel during all past fuel Cycles of units 3 and 4.