EXPERIENCE OF CR AND RCCA OPERATION IN UKRAINIAN WWER-1000: ASPECTS OF RELIABILITY, SAFETY AND ECONOMIC EFFICIENCY

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Abstract

The next topics are represented in the paper:

- A brief history of WWER-1000 control rod (CR) and WWER-1000 rod cluster control assembly (RCCA) design;
- Evolution of WWER-1000 CR manufacturing technology and design;
- Experience of RCCA operation;
- Lifetime extension of WWER-1000 boron carbide CR;
- WWER-1000 reactor core operation problems due to partial RCCA insertion;
- Designing and licensing procedures and first operational experience of WWER-1000 RCCA (CR) with a combined absorber "boron carbide-hafnium" and a chromium-nickel alloy cladding.

The main conclusions are:

- Fuel assembly (FA) bow is the main reason of partial RCCA insertion during reactor core operation. However, the use of the RCCA and its driver bar with increased dead load, alongside with other measures, allow to reduce the probability of incomplete RCCA insertion;
- The materials used in CRs of RCCA in existing reactor operating modes have been working reliably;
- The use of hafnium under an appropriate price policy can give certain economic advantages for the Ukrainian NPPs, however, additional research is needed in order to confirm the specific CR physical characteristics and reliability.

1. INTRODUCTION

The RCCAs of a reactor control protection system (CPS) are the most important elements of maintaining the safe reactor operation, ensuring control and distribution of reactor core power level and fast reactor core transfer from initial to subcritical condition during an accident. The share of RCCAs in fuel reloading cost is 1-1.2%. However, for CR materials choice it is necessary to take into account the possibility of inexpensive RCCA recovery or disposal.

2. THE SELECTION OF MATERIALS AND RCCA DESIGN, DEVELOPMENT OF RCCA

In the former USSR, the Moscow manufacturing plant of polymetals (MPP) was the designer and manufacturer of CR for almost all reactor types. The boron carbide (B_4C, with a natural mixture of isotopes) was selected as an absorber material because of it's accessible, cheap and quite effective material. Stainless steel 06 X18 N10T was selected as CR clad material. The design of the WWER-1000 RCCA is shown in a Figure 1.

Up to 1985, CRs were produced by a joint drawing method. An initial pipe with a diameter of 11 mm and wall thickness of 0.7 mm, was filled with B_4C having a density of 1.65 g/cm^3. Then it was extended through some dies. Drawing was performed till the moment when the sizes of the pipe became equal to 8.2×0.6 mm, so that the average density of the absorber became equal to 1.95 g/cm^3. The B_4C density in the central part of the pipe was 1.6 - 1.65 g/cm^3 and on the rim layer 2 - 2.1 g/cm^3.

From late1985 until now, the RCCAs are produced by a method of vibro compaction of an initial pipe 8.2 × 0.6 mm with boron carbide of 1.75 g/cm^3 density. The initial pipe is not subject to deformation [1]. The advantages of this technology are the following:

- Less absorber material is needed;
- Some technological operations are eliminated from the process;
- The smaller the density of the boron carbide (1.75 g/cm^3) in the rim (external) layer, the smaller the swelling of B_4C particles is in the layer under the same neutron flux.

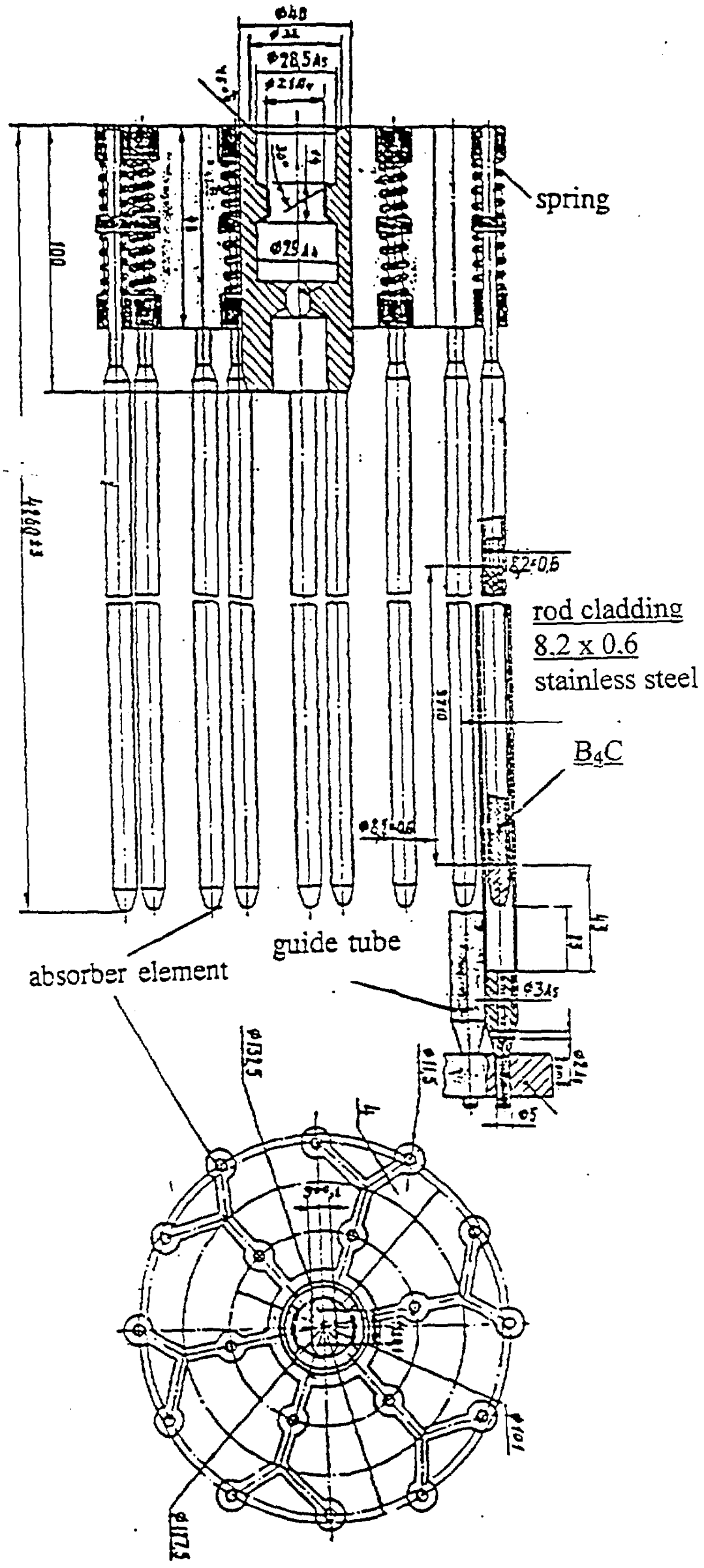


FIG. 1. WWER-1000 Rod cluster control assembly (RCCA) design

The change of B_4C density from 1.95 g/cm^3 up to 1.75 g/cm^3 has not reduced the efficiency of the RCCA. The RCCA efficiency measurements, with respect to various B_4C densities, have been made by using WWER-1000 critical assemblies. In the first case, the critical assembly was the fuel assembly (FA) from the first loading of unit-1 of the South Ukrainian NPP (49 RCCAs). In the second experiment, the critical assembly was the FA from the first loading of unit-1 of the Kalinin NPP (61 RCCAs). The results of the measurements [3] are shown in Table I.

TABLE I. RCCA EFFICIENCY MEASUREMENTS

Number	**B_4C density in CR g/cm^3**	**Efficiency of RCCA %**	**RCCA relative efficiency (%)**	**Comments**
1	1.80	9.8x10^{-2}	100%	
2	1.67	9.8x10^{-2}	100%	
3	1.14	9.4x10^{-2}	96%	there corresponds to burnup ^{10}B 33% for initial density B_4C - 1.75 g/cm^3
4	0.95	9.2x10^{-2}	93,7%	there corresponds to burnup ^{10}B 45% for initial density B_4C - 1.75 g/cm^3
5	0.69	8.6x10^{-2}	87.6%	there corresponds to burnup ^{10}B 60% for initial density B_4C - 1.75 g/cm^3

The initially RCCA lifetime was determined to be 1 year for control (regulating) groups (CGs) and 5 years for shut down (scram) groups (SGs).

3. EXTENDED RCCA OPERATION AND POST-IRRADIATION EXAMINATION

The results of high flux tests of an RCCA model in a material test reactor and commercial operation experience have created premises for RCCA lifetime extension. In order to provide lifetime extension, the RCCAs of unit-5 of the Novovoronezh NPP had been operated for longer time comparing with the period given by the project. After irradiation, these RCCAs have been examined at the Research Institute of Atomic Reactors (RIAR) and the Novovoronezh NPP hot cells. The research was performed and paid by the Russian and Ukrainian utilities (ROZENERGOATOM and GOSKOMATOM) [1-3].

The value of the neutron flux was checked up by means of ^{10}B burnup and accumulation of activation products (^{60}Co). The main results are given in Table II [1-3]. Completed tests and further research on CRs from CG have confirmed the expected outcome. Vibre compacted CRs have the best operating performances in comparison with joint drawn CRs.

The divergence in maximum thermal neutron flux (F^{max}) in CRs between calculated data (2.1×10^{21} by the Kurchatov Institute and OKB GP) based on ^{10}B burnup (4.5×10^{21}) and data based on ^{60}Co accumulation in the steel cladding of the CR (6.0×10^{21}) has been determined through SG CR research. The calculated results appeared to be underestimated.

The analysis of all research, resulted in establishing the values for several parameters, i.e. the maximum allowable ^{10}B burnup for vibro compacted CRs was 57.5%, the CR swelling ($\Delta\Phi$) was less than 1.2 % (implying that there were safety and plasticity margins of the cladding material) and the relative thermal neutron flux was 3.6×10^{21}.

TABLE II. RESULTS OF RCCA RESEARCH

Characteristic, parameter	**CR vibrating filling mode (Absorber of vibrating packed type)**		**CR joint drawing mode**
Time of operation, maximal neutron fluence, $F^{max} \times 10^{21}$	CG 2 y, 491 eff. days, neutron energy: E>08MeV ~3.3 E>01MeV ~5.4 thermal ~1.5	CG 3 y, 819 eff. days, neutron energy: E>08MeV ~7.6 E>01MeV ~12.5 thermal ~3.2	SG 7 y, 2028 eff. days, neutron energy: E>08MeV ~4.5 E>01MeV ~6.1 thermal ~4.5
General state of the CR	All of CR have saved the form and tightness. There is black dense oxide film the thickness of which 4 - 7 microns on a surface		Longitudinal cracks (L=10mm) are detected at the bottom CR
CR swelling in the area of F^{max} (Δ⌀)[mm, /%]	0	0.02 - 0.06 0.24 - 0.72	0.11 - 0.16 1.35 - 2.0
Burnup of ^{10}B, %	max. ~32.5	max. ~53.2	max. ~72 - 77
Helium release under cladding	70-130 [cm^3]	260-350 [cm^3]	~100[cm^3], part of gas has left through cracks
Pressure of gas under cladding	at 20°C 2-4 bar at 333°C 4-8 bar	at 20°C 15-25 bar at 333°C 35-56 bar	2-9 bar, ,Part of gas has left through cracks
Absorbing material B_4C state	Powder B_4C freely hailed down under cutting of cladding on samples	At the CR bottom there was a sintering of a powder, which densely adjoins to the cladding. Change of cladding diameter + 0.2 - 0.7%	swelling of the CR bottom B_4C lead to the open cracks
Mechanical properties of cladding in the area of F^{max} σ_b[MPa] σ_{02}[MPa] δ_0 [%]	σ_b at 20°C - 820 σ_b at 350°C - 520 σ_{02} at 20°C - 500 σ_{02} at 350°C- 290 δ_0 at 20°C - 14.2 δ_0 at 350°C - 7.1	σ_b at 20°C - 893 σ_b at 350°C - 630 σ_{02} at 20°C - 670 σ_{02} at 350°C - 580 δ_0 at 20°C - 18.6 δ_0 at 350°C - 1.1	σ_b at 20°C - 830 σ_b at 350°C - 580 σ_{02}at 20°C - 640 σ_{02} at 350°C - 480 δ_0 at 20°C - 26,4 δ_0 at 350°C - 3.9
General conclusion on spent CR state	CR condition is satisfactory. It is probable to continue their operation within one more year (fuel cycle)	CR are close to extreme allowable condition. CR swelling makes 0.24-0.72 % in the area of F^{max}	Actual duration of operation has exceeded allowable time for this CR type, that has caused the excessive swelling of B_4C and cladding, of cracks, washing away of B_4C

4. EXPERIENCE OF RCCA LIFETIME EXTENSION

4.1. Operation time

The operation time of RCCAs for CG was enlarged from 1 to 2 fuel cycles [3].

4.2. Life extension

The unconditional specification of the RCCA lifetime extension for SG from 5 to 6 years (and even to 7 years) was not possible, based on the results of the research, as the calculated thermal neutron flux density above the reactor core was lower than the actual value.

In order to be able to specify the SG RCCA lifetime extension, the exact position of the RCCA lower flat end above the reactor core for each unit in each fuel cycle is needed. The lower flat end of RCCA would be within the 0.9 - 14.9 cm above the core in serial WWERs-1000 (e.g. for unit-5 of Novovoronezh NPP - 7.7-8.7 cm). The thermal neutron flux density within the same range should not be a constant value. The dependence of the allowable time of SG RCCA operation according to the position of the lower flat end is given in Table III [2].

TABLE III. ALLOWABLE OPERATING TIME OF RCCAs

Position of the lower flat end B_4C above the core h (cm)	**^{10}B burnup for 1 year of operation (300 eff. days) (%)**	**allowable time of SG RCCA operation (eff. days/years)**
0.9 - 8	11.4	1530\5
9	11.1	1570/5
10	10.7	1630/5
11	10.0	1735/5
12	9.3	1870/6
13	8.7	2000/6
14	7.85	2210/7
14.9	7.23	2400/8

Approximately 10 - 15 % of Ukrainian WWER-1000 SG RCCAs have been operated during the 6 fuel cycles. The total duration of operation did not exceed 1700 -1790 effective days. The experience of SG RCCA lifetime extension to 6 and more years has not received broad attention for the reason of difficulties related to monitoring of the RCCA lower flat end position. During the whole period of operating WWERs-1000 in the Ukraine, there occurred no RCCA damage. The materials used in the RCCAs performed reliably.

5. RESULTS OF IMPROVED RCCAs BASED ON A COMBINATION OF Hf AND B_4C

The cost, allowable time of operation, and possibility of inexpensive disposal are the main consumer features of RCCAs. In order to increase the RCCA lifetime, it is required to replace the bottom (300-500 mm) n/α absorber B_4C by an n/γ absorber (Hf, Dy_2TiO_5or In-Ag-Cd, which doenot swell) and to use cladding material that will be more stable to radiation embrittlement.

12 RCCAs with combined Hf-B_4C absorber were designed, manufactured and accepted by an interdepartmental commission. In 1997, they were loaded in the WWER-1000 of the Rovno NPP for the operation according to a joint decision of GOSKOMATOM and MPP (with participation of Kurchatov institute, RIAR, OKB GP). The CR cladding was made from Cr-Ni alloy EP-630Y. The design of the combined absorber CR is shown in Figure 2. It was decided to use the new designed RCCA in SG.

The ingots made in the Ukrainian zirconium plant, based on the calcium-thermal recovery technology and further double electronic radial remelting, were used as raw Hf source material. Further processing and manufacturing of Hf rods for CRs were carried out in Russia. Samples of Hf pipes with a diameter (⌀) 9.6 mm, wall thickness of 2 mm, length 100 mm (9.6×2 mm) and rods with a diameter of 8.2 mm, length 10 mm were stage by stage irradiated and investigated in RIAR for the period 1993 - 1997.

Irradiation of samples located in ampoules were made in the material test reactors (BOR-60, in a sodium environment at a temperature of 340 - 360°C, and in CM-2, in water at 60 - 80°C). At the first stage, the irradiation was performed in BOR-60 by a fast neutron flux of (E>1 MeV) 1×10^{22}.

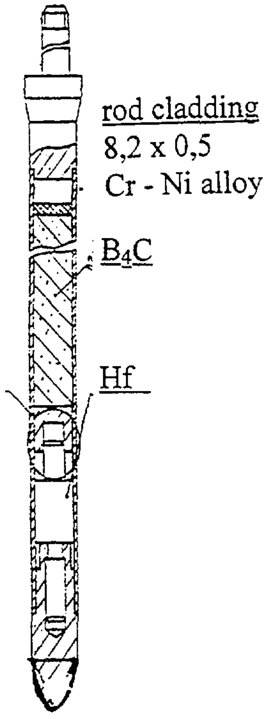


FIG. 2. Combined absorber rod design (Hf + B_4C)

The diameter of the pipe decreased by 0.3% and that of the rod by 0.8%. The lengths of the pipe and rod were increased by 0.3% and 1%, respectively after the irradiation. The densities of the pipe and rod have decreased by 0.42% and 0.55%, respectively. The pipe has plasticity at the level of 1-2% and there was no damage. Two longitudinal radial cracks, which could have occurred at the rod manufacturing stage, were detected. The Hf rod was damaged (an = 4 kgm/cm^2) [4] by shock tests. For that reason the Hf rod has been located inside the cladding. As cladding material, the Cr-Ni alloy (Cr-42%, Ni-56%, Mo-1%) was used. This material named as EP-630Y has a high plasticity after long irradiation and a high corrosion stability (resistance) in a water environment. At the second stage, the irradiation was performed in BOR-60 and CM-2 by a fast neutron flux of (E>1 MeV) 3.4×10^{22}. The average radiation growth of the sample was 3%. After the first stage of irradiation, cracks of the same form and size were detected in the rods [5]. The mechanical properties of EP-630Y are given in Table IV [6].

TABLE IV. MECHANICAL PROPERTIES OF EP-630Y

Temperature [°C]	Neutron fluence$\times10^{22}$ E>8MeV [cm^{-2}]	σ_{02} [MPa]	σ_b [MPa]	δ_p [%]
20	0	360	770	53
	0.7	640	840	50
	2.7	750	870	44
	6.8	820	910	22
300	0	250	640	52
	0.7	480	800	40
	2.7	540	660	39
	6.8	660	680	16

The behaviour of modelled CR was investigated under accident conditions:

- B_4C, Hf, Dy_2TiO_5 absorbers do not affect the EP-630Y cladding at temperatures between 350 and 500°C during 1000 hours;
- The CR research under simulated cladding leakage conditions (temperature of overheated steam of 1150°C) has shown, that there is reliable compatibility of Hf and Dy_2TiO_5. The Hf modelled CR surface damage was revealed at a level of 400μm. The melting occurred in the Hf cladding contact area under a vapour temperature of 1250°C [10].

6. SOME LICENSING REQUESTS

In order to obtain the licence of the nuclear regulatory administration (NRA) for CR test performance, it should be shown that, at the time of the RCCA insertion, the reactivity derivative ($\partial\rho/\partial\tau$) will be negative (the accident factor of the Chernobyl NPP). This condition is always required if the CR lower part has the lowest differential efficiency.

7. EXPERIMENTAL RESULTS OF THE COMBINED Hf-B_4C ABSORBER EFFICIENCY.

The Hf efficiency has been calculated and is 80% of the B_4C efficiency. The use of more durable cladding material allows to decrease the wall thickness from 0.6 mm down to 0.5 mm and consequently to increase the absorber diameter from 7 mm to 7.2 mm. The calculated combined Hf-B_4C RCCA efficiency is equal to 1.025 of the ordinary RCCA [6, 7].

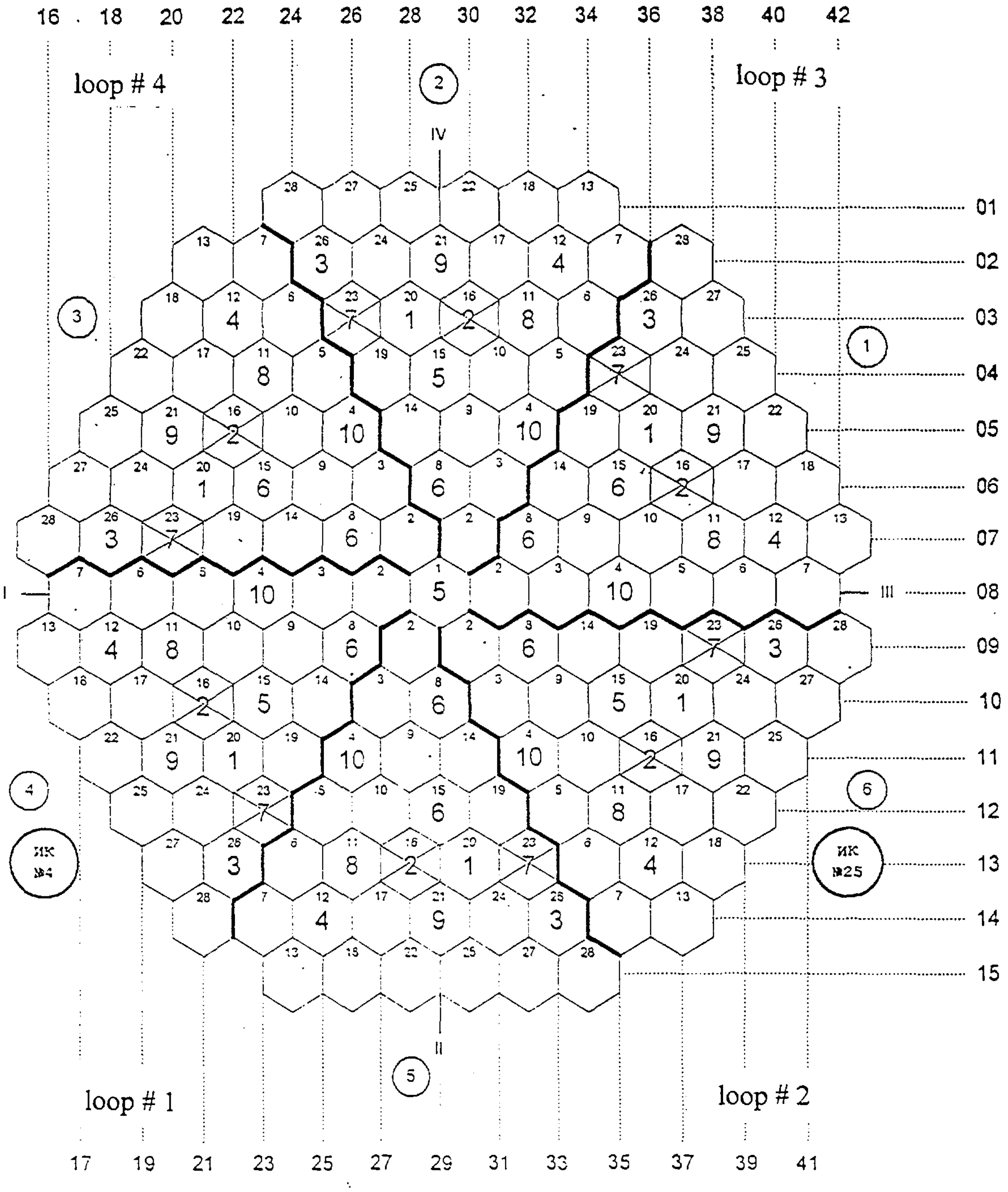
Efficiency measurements have been made in the beginning of cycle (BOC) at a level of 1-2% of $N_{nominal}$, with a temperature of 280°C and a pressure of 160 bar. The location of the RCCA groups, including the combined groups (#2 and #7), is shown on Figure 3. The Rovno WWER-1000 reactor core parameters in the BOC (for the 11th fuel cycle) are presented in Table V.

TABLE V. ROVNO REACTOR CORE PARAMETERS

Date of experiment	Effective days	CG position %	H_3BO_3 concentration g/kg	Xe
6 Nov. 97	0	0 - 90	8.5 - 9.3	no
17 Nov. 97	7	55 - 57	7.7	yes
18 Nov. 97	7	36 -50	7.7 - 8.0	yes

On 6 November 1997, differential and integral RCCA efficiencies were measured at the time of RCCA insertion by means of a reactivity meter. The inserted reactivity was compensated by CG (#10) movement. Separated RCCA movement, combined groups (#2 & #7) movement, and groups (#1 and #8) movement have been made step by step (in turn) from upper position (H=100%) down to lower position (H=0%) by steps of 5%. The reactor criticality was maintained constant, as well as the coolant pressure, temperature and H_3BO_3 concentration. The measurement results are presented in Figures 4 and 5.

On 18 November 1997, differential and integral RCCA efficiencies were measured at the time of RCCA insertion by means of a reactivity meter. Inserted reactivity was compensated by H_3BO_3 concentration change. Separated RCCA movement, combined groups (#2 & #7) movement, and groups #1 and #8 movement have been made step by step (in turn) from upper position (H=100%) down to lower position (H=0%) by step of 5%. The reactor criticality was maintained constant, as well as the coolant pressure and temperature, and the CG position was at the level of H=55%.



FA Number in 60° symmetry sector
Number of RCCA group (X - Hf RCCA)

FIG. 3. Reactor core of the Rovno unit-3, 11th fuel cycle

In addition, the measurements of combined group (#2 & #7) 10% insertion efficiency (that corresponds to the height of Hf absorber) alongside with insertion of groups #1 and #8 were completed. The same was done for 20% of separate RCCA insertion. The results are shown on Figures 6 and 7.

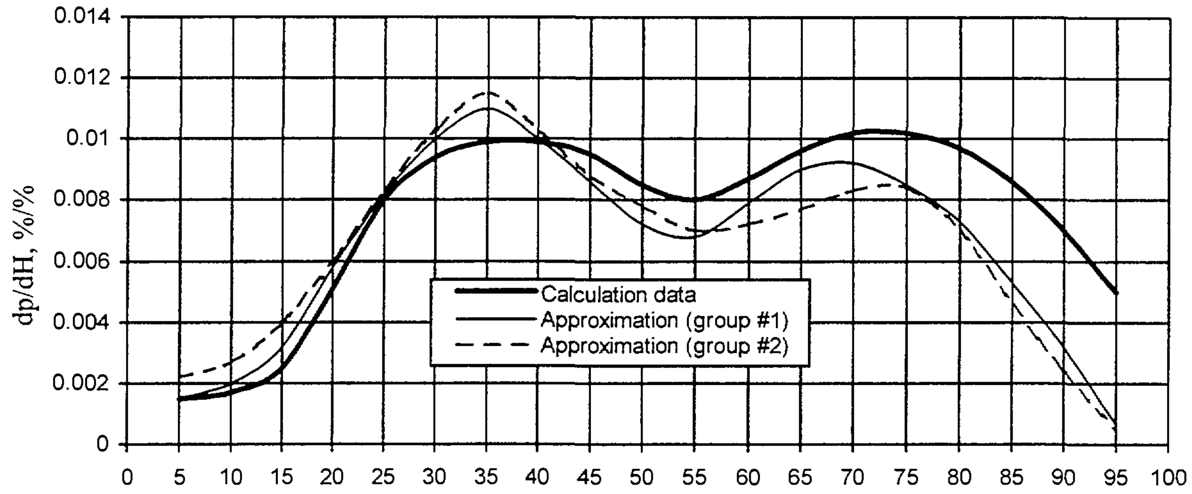


FIG. 4. Differential characteristics of RCCA group (#1 and #2 (Hf)),
The reactivity was compensated by control group (CG)

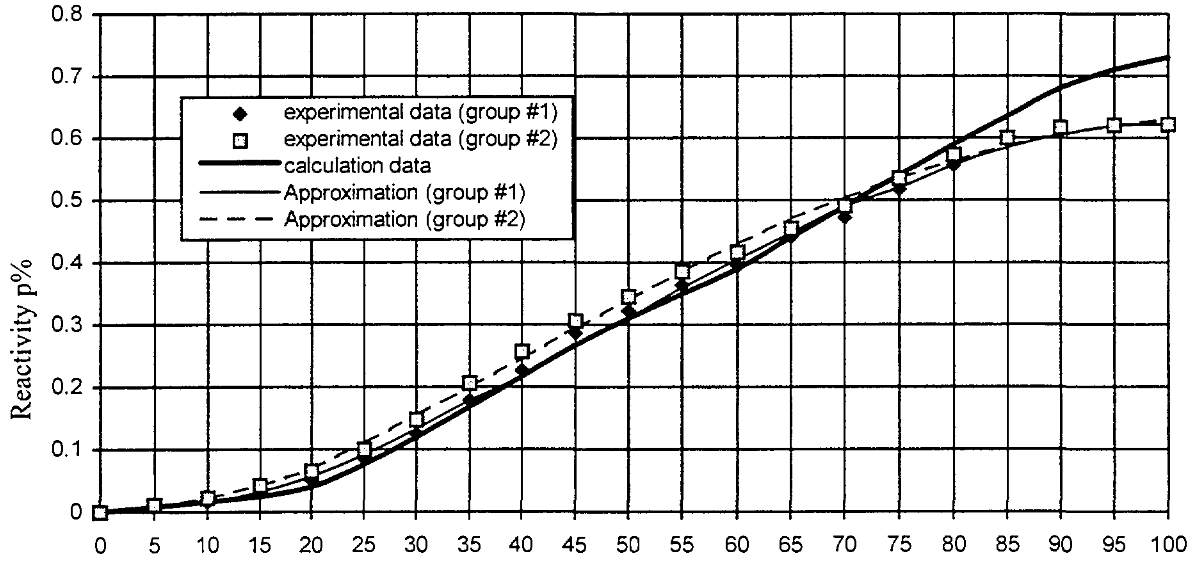


FIG. 5. Integrated characteristic of RCCA group (#1 and #2 (Hf)),
The reactivity was compensated by control group (CG)

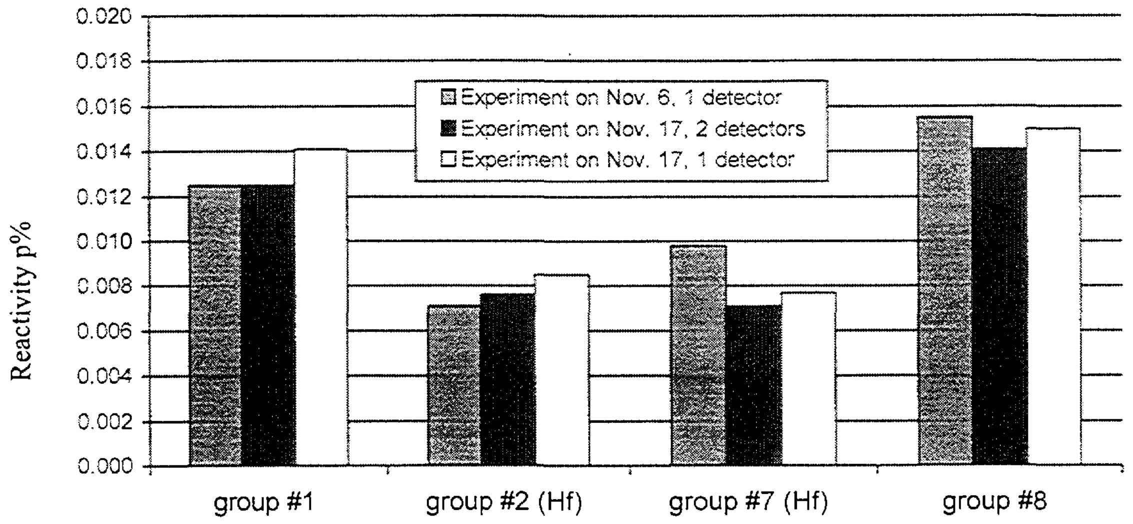


FIG. 6. Integrated efficiency of 10 % of groups RCCA (groups #1, #2(Hf), #7(Hf), #8),
the RCCA lower flat end position in core (H%) was changed from 100% up to 90%

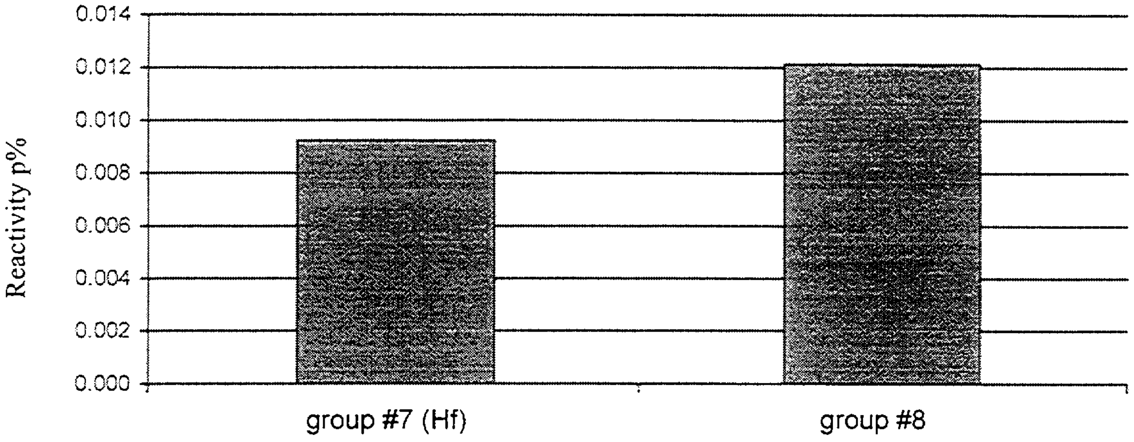


FIG. 7. Integrated efficiency of 20% separate (one) of RCCA in group (group #7(Hf), #8), the RCCA lower flat end position in core (H%) was changed from 100% up to 80% (experimental data)

By the 13th of September 1998 at the end of cycle (EOC), the measurements have been made at the power level of 50% $N_{nominal}$. According to the preliminary data, the results were similar to those obtained earlier. The results allow to conclude:

- integral characteristics of RCCA with and without Hf are almost the same (Figure 8);
- at the moment of 20% insertion, the integral efficiency of the lower part of the RCCA with Hf was 24% less then the ordinary RCCA;
- at the moment of 10% insertion, the efficiency of the RCCA with Hf was equal to 0.53-0.58 against the ordinary RCCA efficiency (the calculated value was 0.8);
- at the moment of reactor scram, the summary efficiency of the RCCA was equal to 8.7% and exceeded the calculated value (7.5%).

In order to clarify the reasons of low Hf efficiency in existing RCCAs, it is useful to perform calculation of:

- burnup effect (neutron spectrum influence);
- research on geometry effect on the RCCA lower part efficiency;
- safety analysis of RCCA with Hf as CG.

When RCCA with Hf are used as SG all safety requirements are met.

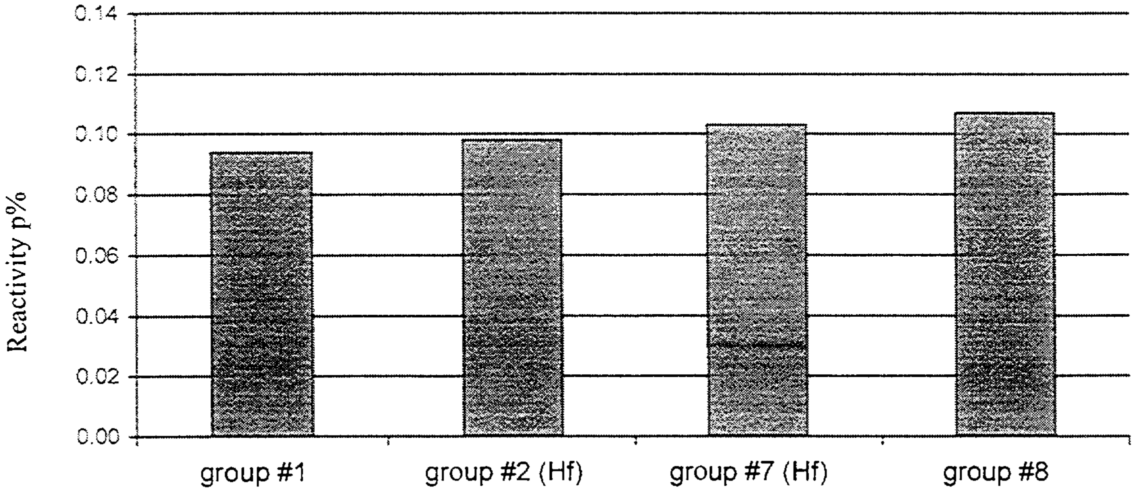


FIG. 8. Integrated efficiency of separate (one) RCCA in groups (groups #1, #2 (Hf), #7 (Hf), #8) (experimental data)

8. SAFETY PROBLEMS OF REACTOR OPERATION WITH INCOMPLETE RCCA INSERTION

During 1992 and 1993, almost at all WWER-1000 in Ukraine, Russia and Bulgaria incomplete RCCA insertion occurred, i.e. an RCCA stuck in an intermediate position and RCCA drop time exceeding 4 s (design time). A programme of additional quarterly measurements of RCCA drop time was developed and implemented. In the case of RCCA operation violation (and when there was no chance to cease one) the unit had been transferred to the operational mode with three loop coolant circulation and with preliminary power reduction to 67% of $N_{nominal}$.

The following Ukrainian units were transferred to the 3 loop operational mode:

- Zaporozye NPP unit 1; fuel cycle # 7 and 8; Generation loss- $2,1\times10^9$ kWh;
- Zaporozye NPP unit 3; fuel cycle # 7 , 8 and 9; Generation loss-$3,3\times10^9$ kWh;
- South Ukraine NPP unit 2; fuel cycle # 7; Generation loss-$1,0\times10^9$ kWh.

In 1993, the chief reactor designer had calculated the neutron physical and thermal hydraulic characteristics of the reactor core for the RCCA drop time up to 10 s, keeping in mind the case when all RCCA are inserted except the most effective RCCA. It was shown that the design safety criteria were met. However, the results obtained were not used to cancel operational restrictions according to the conservative principle. Fuel assembly (FA) bow is the main reason of incomplete RCCA insertion during reactor core operation. Complicated form of FA bow results in:

- appearance of additional friction force between CR and guide thimble clad;
- either RCCA drop time increase in scram mode or RCCA jam in intermediate position;

In order to reduce the probability of incomplete RCCA insertion, to decrease the size of FA bow and to ensure the reactor's safe operation, the following compensatory measures have been performed during the scheduled repairs in 1993-1997:

1) New designed heavier RCCAs with gafnium or titanat of dysprosium were used in the Rovno and Zaporozye NPP;
2) The dead load of the RCCA driver bar was increased;
3) In order to decrease losses of the RCCA kinetic energy during RCCA insertion (the pump effect), holes in the RCCA driver bar have been drilled;
4) The position of the bundle safety tube (BST) was updated with the purpose of maintaining the spring block of the FA, without exceeding the compress maximum (axial compression of FA head).

Figure 9 shows the curves of RCCAs (both of original and advanced design) drop speed [9].

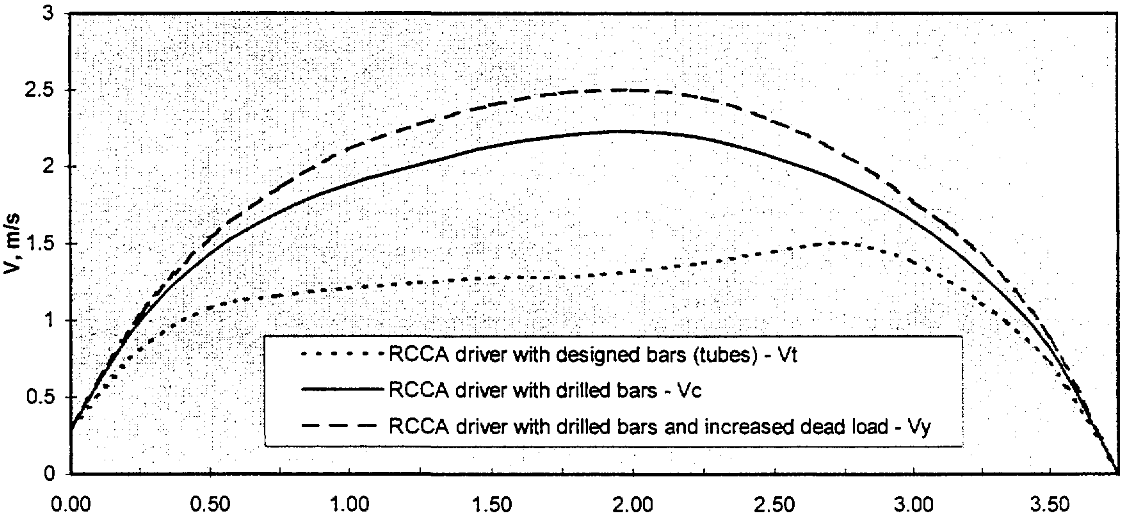


FIG. 9. Curve of average speed of RCCA drop

In Figure 10, the curves of the RCCA drop time change for the period 1993 - first quarter of 1998 are represented as an example for Zaporozhe NPP-2. Before the implementation of compensatory measures for Ukrainian WWERs-1000, the average RCCA drop time (τ average) was 3.3 s, 200 RCCAs had a drop time larger than 4 s and 28 RCCAs were jammed. After implementation of measures, the average RCCA drop time was 2.5 s, whilst 11 RCCAs had a drop time larger than 4 s and only 1 RCCA was jammed.

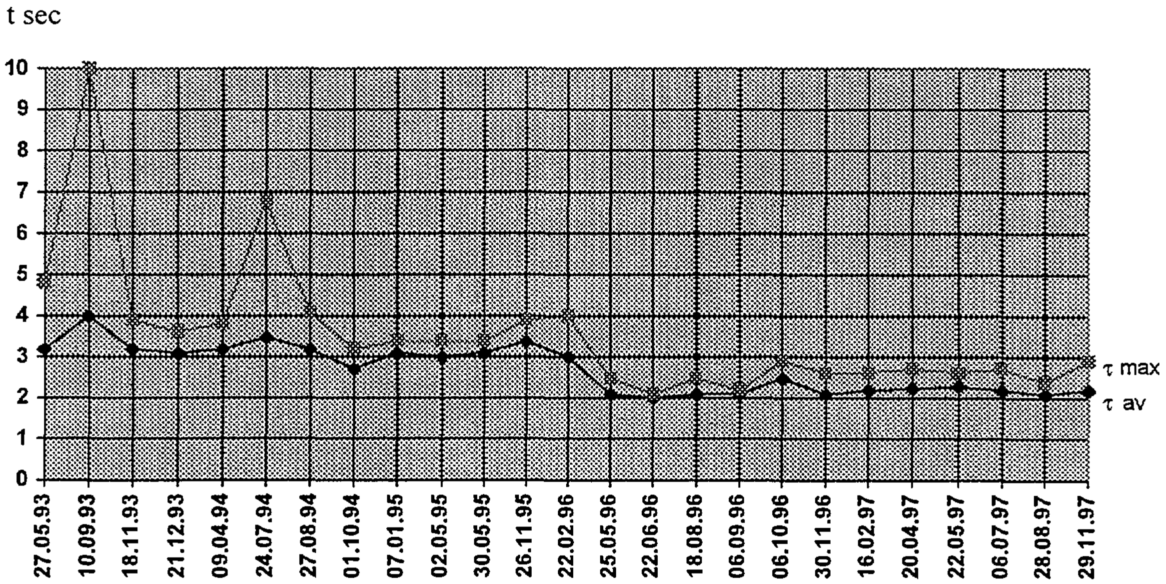


FIG. 10. Measurement of RCCA drop time on ZNPP-2

Only after the beginning of the implementation of compensatory measures for the period 1995 - first quarter of 1998, 140 RCCA drop tests have been performed, from which 18 have been performed at 40-50% $N_{nominal}$ power level, some measurements have been done at power level of 20-30% $N_{nominal}$ and the rest was performed under "hot shutdown" conditions. The results of "under power" tests have complied with the design requirements. The average results of the RCCA drop time measurements on all Ukrainian WWER-1000 units before and after compensatory measures are presented in Table VI.

TABLE VI. SUMMARIZED RESULTS OF RCCA DROP TEST

NPP/UNIT	**τ average (s)/Number of RCCAs with τ > 4s/Number of jammed RCCAs**	
	For the period before compensatory measures were applied (1993-1995)	For the period after compensatory measures were applied (1995 - first quarter of year 1998)
Zaporozhe NPP 1	3.22 / 34 / 8	2.31 / 0 / 0
Zaporozhe NPP 2	3.18 / 30 / 0	2.18 / 0 / 0
Zaporozhe NPP 3	3.17 / 29 / 6	2.61 / 0 / 0
Zaporozhe NPP 4	3.21 / 11 / 0	2.52 / 0 / 0
Zaporozhe NPP 5	3.28 / 9 / 8	2.85/ 2 / 1
Zaporozhe NPP 6	3.15 / 1 / 0	2.68 / 2 / 0
South Ukraine NPP 1	3.5 / 0 / 0	2.51/ 0 / 0
South Ukraine NPP 2	3.72 / 32 / 1	2.48 / 0 / 0
South Ukraine NPP 3	3.55 / 19 / 0	2.35 / 3 / 0
Rovno NPP 3	3.465 / 35 / 5	2.74/ 3 / 0
Khmelnitski NPP 1	3.72 / 12 / 0	2.53 / 1 / 0

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