KOZLODUY NUCLEAR POWER PLANT PLC

EXPERIENCE OF RWFA FUEL IMPLEMENTATION AT KOZLODUY NPP UNIT 5

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1. INTRODUCTION

- The loading of Westinghouse **RWFA** VVER-1000 fuel in Kozloduy NPP and start of mixed core operation with **RWFA** and TVSA fuel, marks the completion of the qualification and licensing process for **RWFA** in Bulgaria.
- The qualification and licensing process of **RWFA** for KNPP started in 2018 with a feasibility study.
- After completion of the feasibility study, it was decided to continue with full licensing of **RWFA** for unit 5 and a contract was signed between KNPP and Westinghouse.
- On April 22nd BNRA issued a license for **RWFA** implementation on Unit 5, and in May 2024 the first 43 fresh **RWFA** were loaded in a mixed core with the resident TVSA for the cycle 31.
- The advanced **RWFA** assembly distinguishes itself with increased uranium content and enrichment up to 4.75wt%.
- This enables the safety and effectiveness of the fuel cycles to be increased.
- Neutron-physics characteristics for cycle 31st of Unit 5, calculated by **APA-H** and **HELHEX** code packages have been compared with relevant measured/reconstructed data.

2. RWFA – DESIGN FEATURES

Fig. 1. RWFA

Table 1. RWFA features

Fuel mass in Assembly, UO_2, kg	551
Number of Fuel Assemblies	163
Number of Fuel Rods and Gd-rods	300, 306 / 12, 6
Fuel mass in FR/GdR, UO_2, kg	1.766 / 1.737
Fuel pellet outer diameter, cm	0.7844
Fuel pellet hole diameter, cm	0
Cladding outer diameter, cm	0.9144
Cladding inner diameter, cm	0.800
Average enrichment, wt%	4.59, 4.19, 3.01
Number of GdR	12, 12, 6
Fuel Rods max enrichment, wt%	4.75 / 4.3 / 3.1
Gd-rods enrichment, wt%	3.6, 3.2, 2.3
Gd-rods Gd_2O_3 content, wt%	5.0

2. RWFA – DESIGN FEATURES

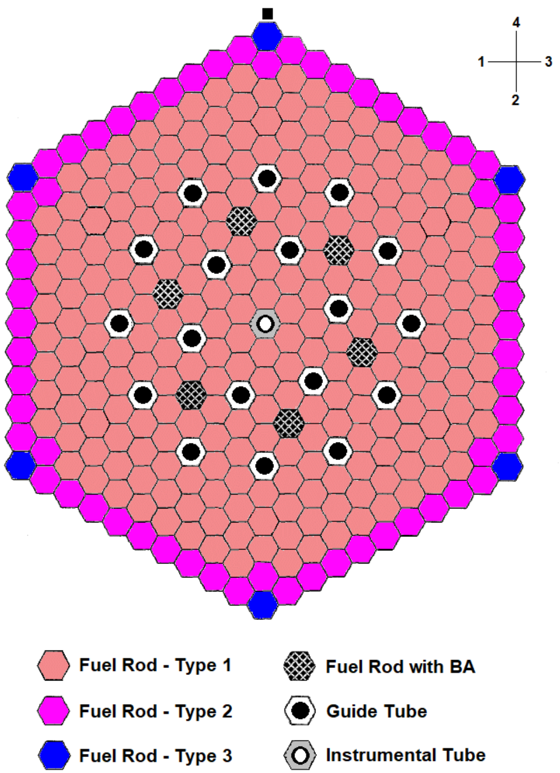


Fig. 2. 301WR layout

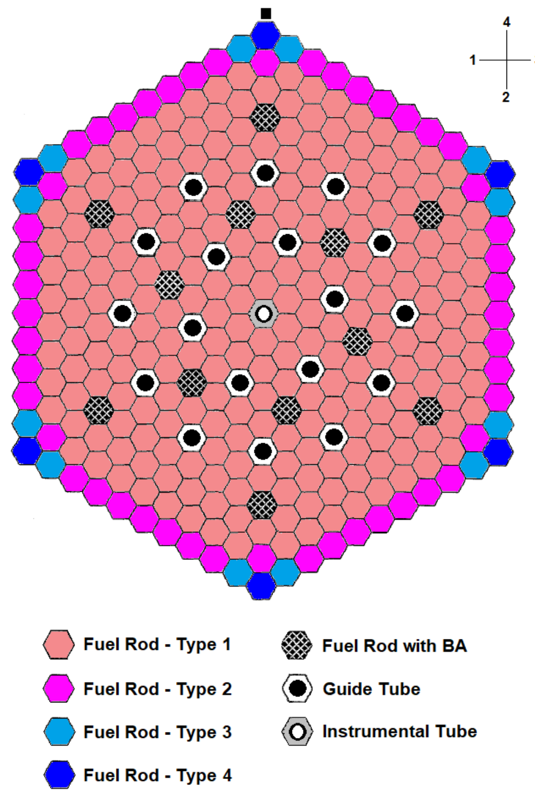


Fig. 3. 400WR / 419WR layout

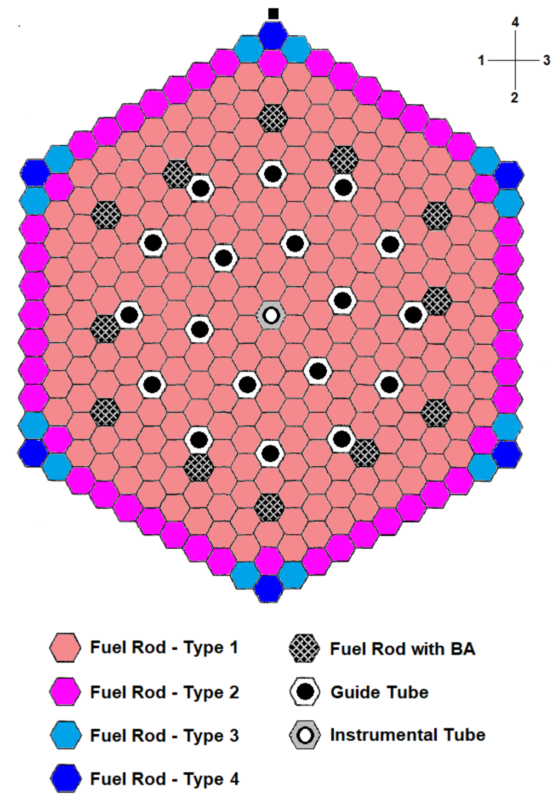


Fig. 4. 459VR layout

3. CYCLE 31 WITH TVSA and RWFA

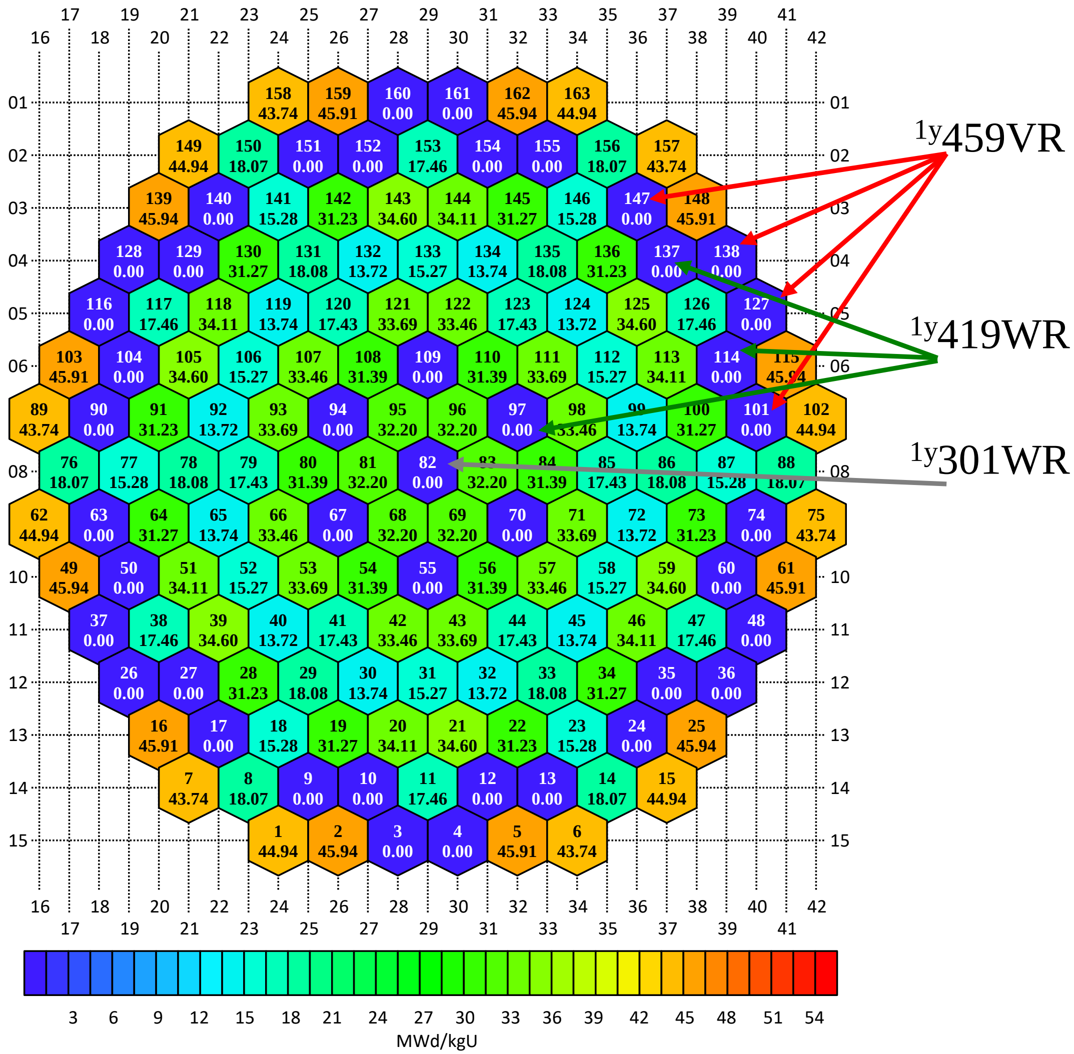


Fig. 5. Fuel assembly Burn-up at the beginning of cycle 31

4. CODES USED – APA-H and HELHEX

- **APA-H** code package developed in Westinghouse (ALPHA-H 8.10.3 / PHOENIX-H 8.8.2 / ANC-H 8.7.13) is used for core design and neutron-physics calculations. The neutronic cross-sections were prepared by the PHOENIX-H code using the 70-group cross-section library based on ENDF/B-VII.1.
- **HELHEX** code package developed at the Sofia University in 2013 is also used for neutronic calculations. **HELHEX** consists of a 3D two-group nodal diffusion code **HEX3DA** and a 3D two-group pin-by-pin diffusion code **HEX3DP**.
- **HEX3DA** employs the nodal method **HEXNEM3** (Christoskov, Petkov, 2012) which is an extension to the HEXNEM2 method implemented in the DYN3D code.
- **HEXNEM3** is based on transverse integration and a specific two-dimensional expansion of the intranodal fluxes in the hexagonal plane.
- The XS-libraries for **HELHEX** code package are generated using the **Helios-1.5** lattice code.
- The albedo side-group to side-group boundary conditions for the radial boundaries and group to group for the axial boundaries are calculated with the **Helios-Mariko** system.

4. CODES USED – APA-H and HELHEX

- The two group diffusion equations in the 3D pin-by-pin code **HEX3DP** are solved using the finite difference method.
- The boundary conditions are practically the same as for the nodal code **HEX3DA**, but the net current on the macro-cell boundaries is calculated for each micro-cell side, separately.
- The energy collapsed and spatially homogenized diffusion parameters are corrected using the SPH-method (SuPerHomogenization, Kavenoky 1978, Hebert 1993). The aim is to preserve the reaction rates from the transport equation also in the diffusion approximation.
- The pin-by-pin code **HEX3DP** calculates the fuel rod and fuel pin power and burn-up distribution in the reactor core.
- The other characteristics: criticality parameters, reactivity coefficients, control group worth, total control rods worth, assembly and nodal power and burn-up distribution are calculating with the nodal code **HEX3DA**.
- Actually, **HEX3DA** is running simultaneously with **HEX3DP**, so that the main results from both codes are available for visualization module **HEX3VI**.

5. CORE DESIGN U5/C31

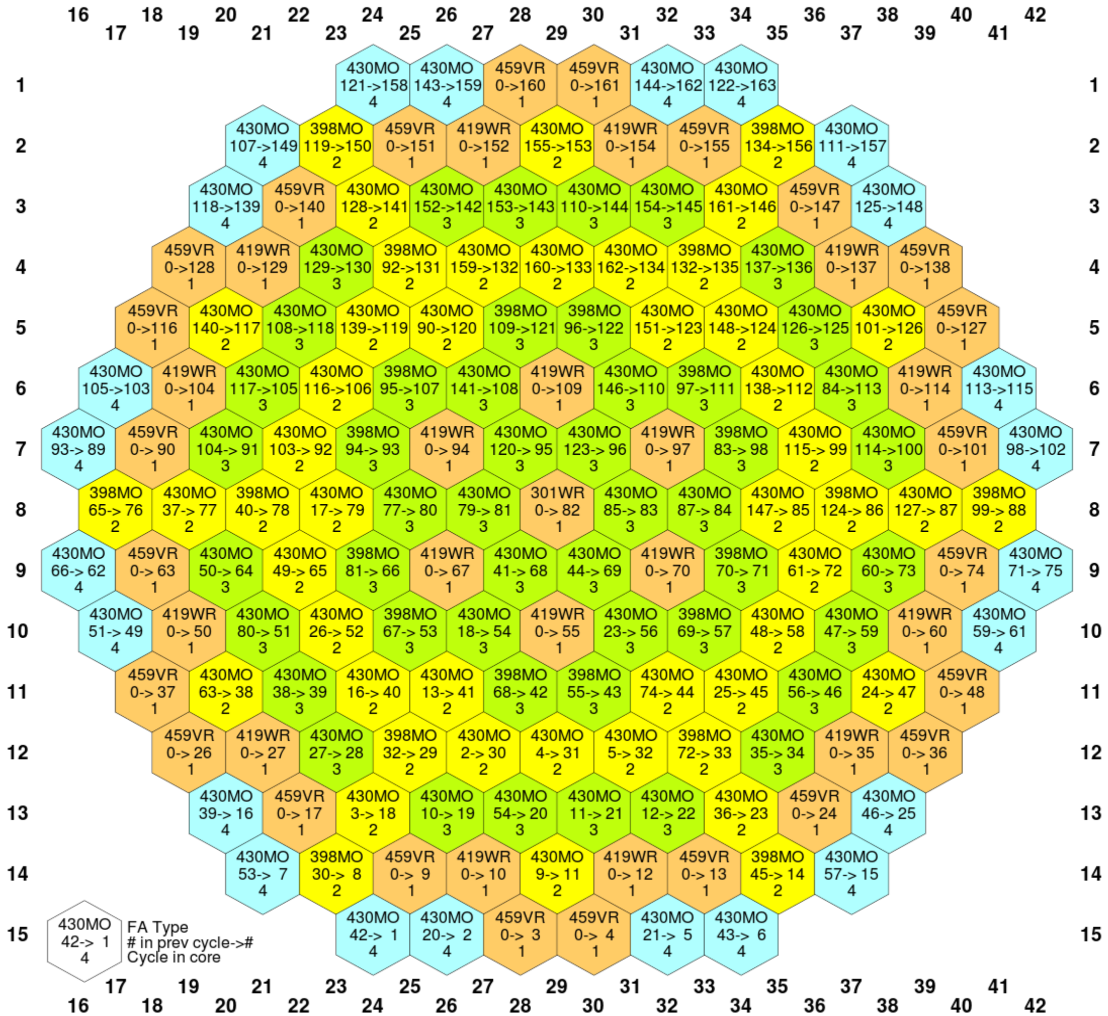


Fig. 6. FA types in cycle 31 (APA-H)

5. CORE DESIGN U5/C31

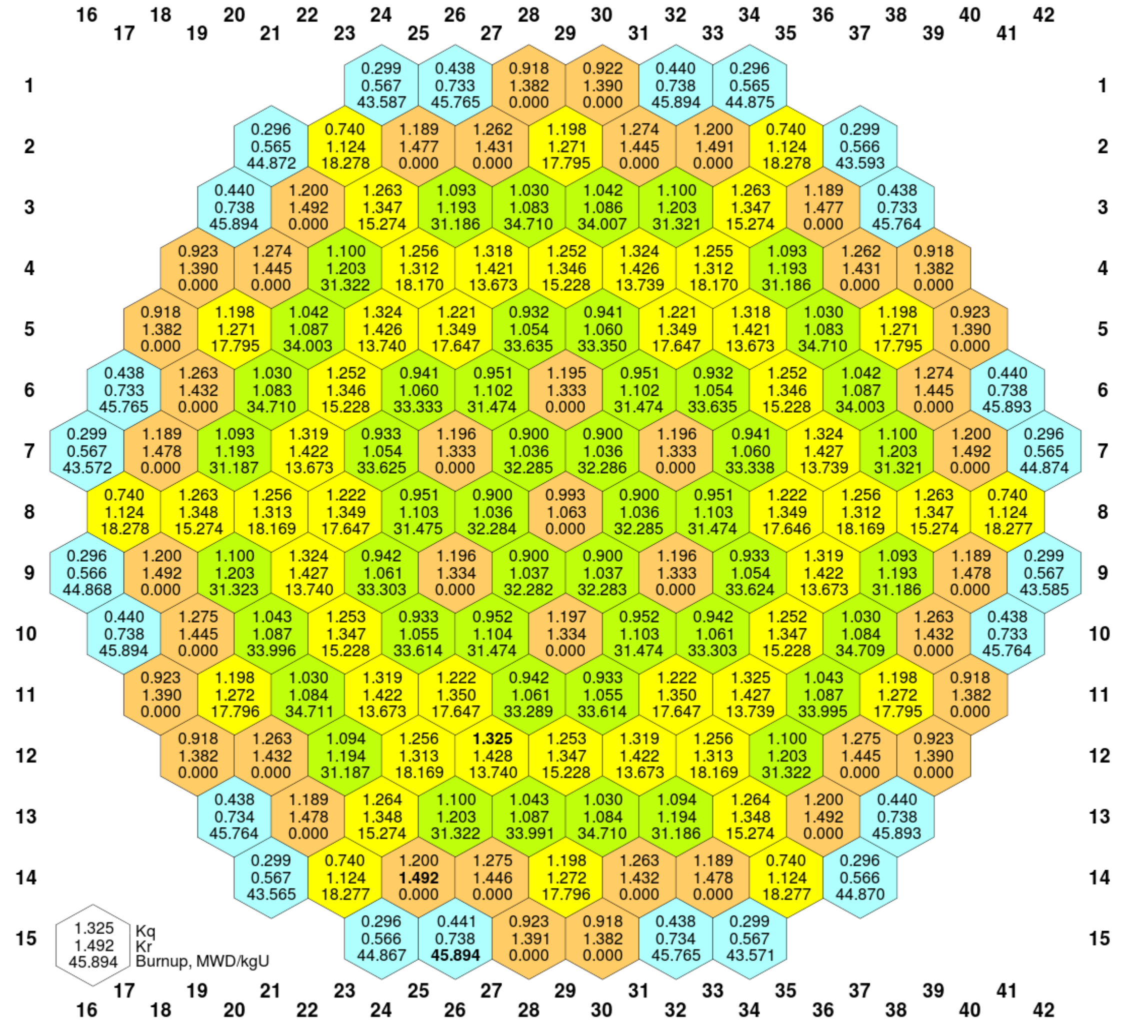
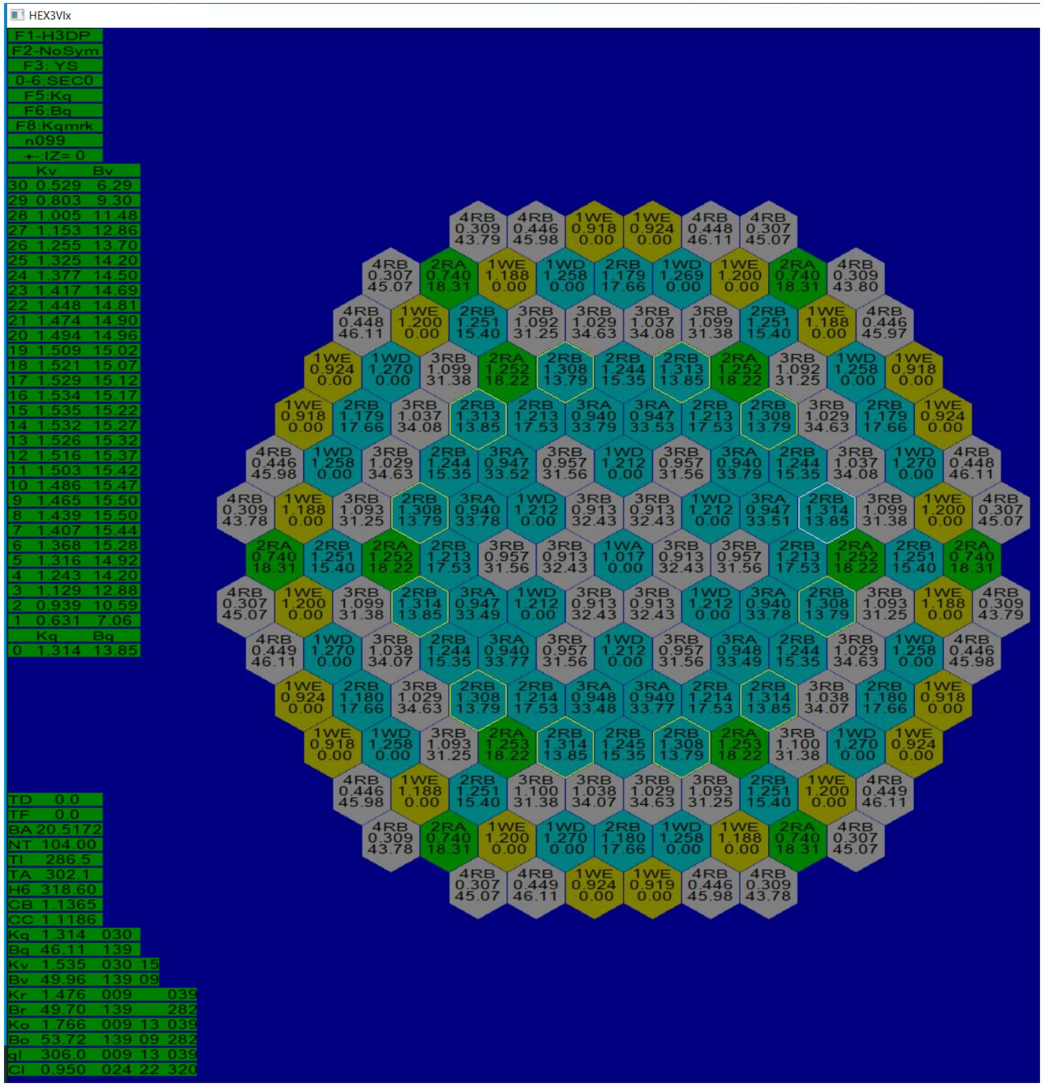


Fig. 7a. FA PPF Kq_i, FR PPF Kr_{ik} and FA Burn-up at the BOC (APA-H)

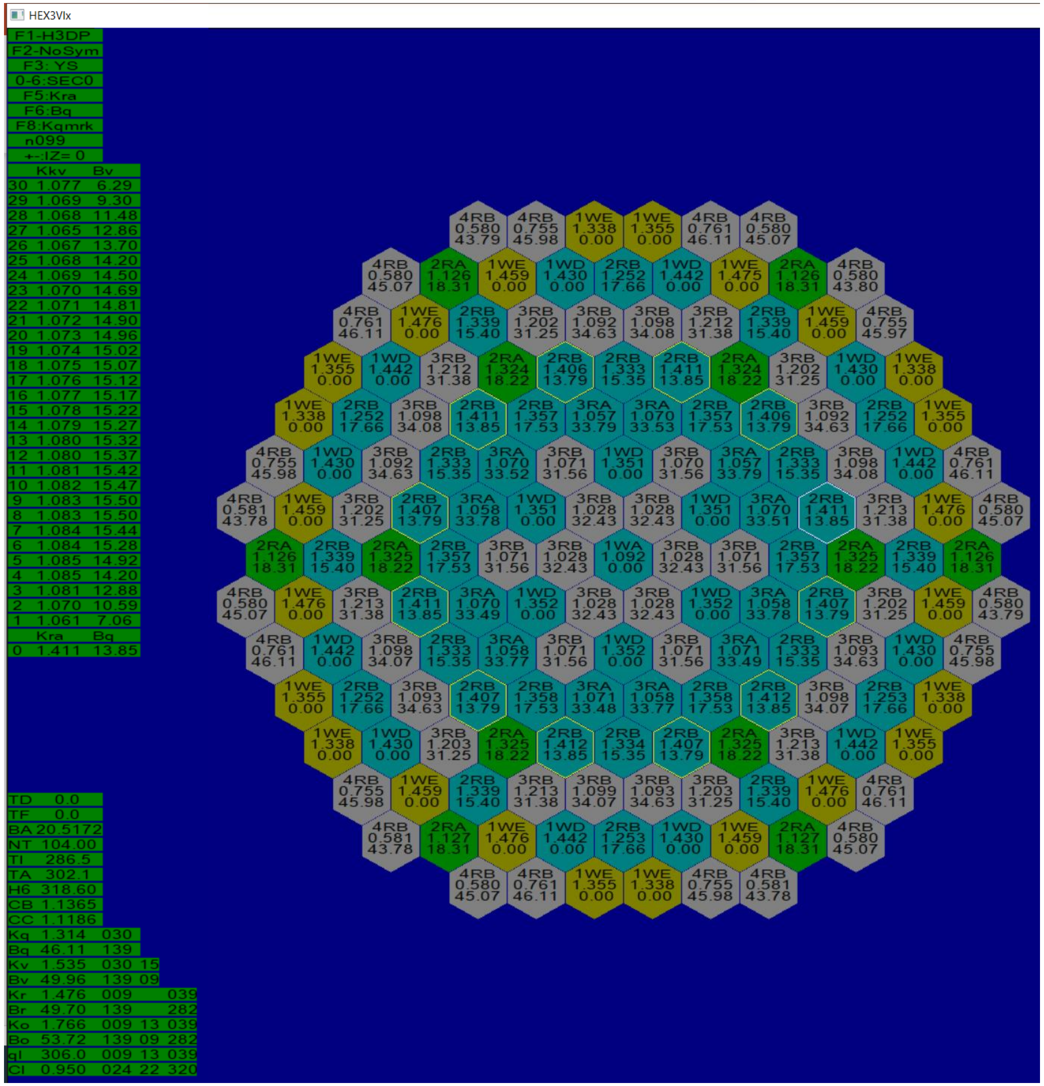
5. CORE DESIGN U5/C31



The difference between the APA-H and HELHEX calculated assembly relative power Kq_i is usually less than 0.02, for single assemblies can reach up to 0.03, but for the assemblies with maximum Kq_i is about 0.01.

Fig. 7b. FA type, FA PPF Kq_i and FA Burn-up at the BOC (HELHEX)

5. CORE DESIGN U5/C31



The difference between the APA-H and HELHEX calculated relative rod power Kr_{ik}, is in the frame of 0.03, but for the assemblies with maximum Kr_{ik} is less than 0.02.

The difference between APA-H and HELHEX calculated assembly burn-up Bu_i is about 0.1-0.2MWd/kgU.

Fig. 7c. FA type, FR PPF Kr_{ik} and FA Burn-up at the BOC (HELHEX)

5. CORE DESIGN U5/C31

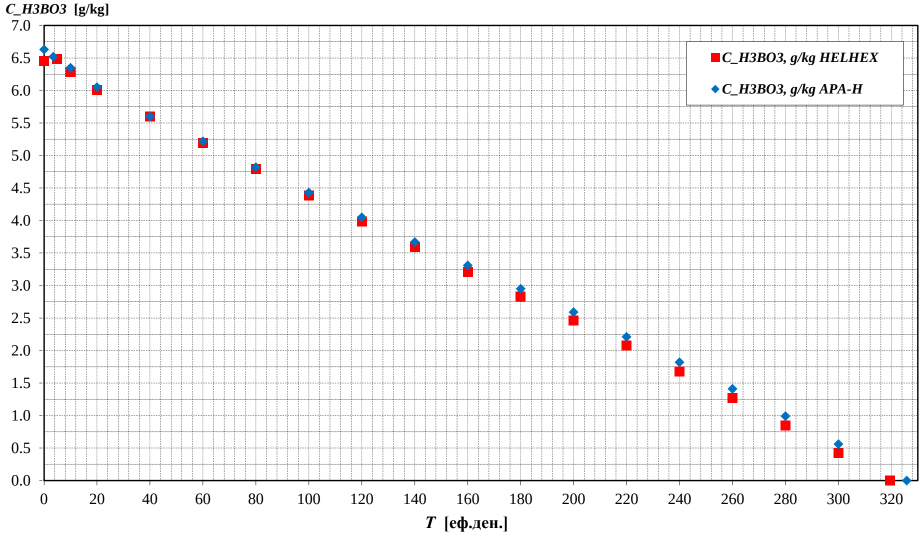
T, fpd	t_{in}, °C	N_T, MW	C_{H3BO3}, g/kg		Kq	Nas	Kq	Nas	Kv	Nas	Nlv	Kv	Na	Nlv	Kr	Nas	Kr	Nas
			A	H	A		H		A			H			A		H	
0	286.5	3120	6.63	6.46	1.33	30	1.32	30	1.53	30	12	1.53	30	17	1.49	9	1.47	9
5.00/3.52	286.5	3120	6.52	6.49	1.34	30	1.33	30	1.54	30	12	1.54	30	17	1.48	9	1.46	24
10	286.5	3120	6.35	6.28	1.34	30	1.33	30	1.52	30	12	1.52	30	17	1.48	9	1.46	24
20	286.5	3120	6.05	6.01	1.33	30	1.32	30	1.50	30	11	1.50	30	17	1.48	9	1.45	24
40	286.5	3120	5.60	5.60	1.31	30	1.30	30	1.49	10	9	1.47	10	14	1.49	9	1.46	24
60	286.5	3120	5.22	5.20	1.29	10	1.28	10	1.50	10	8	1.47	10	13	1.49	9	1.46	24
80	286.5	3120	4.82	4.79	1.30	10	1.29	10	1.51	10	8	1.48	10	11	1.49	9	1.46	24
100	286.5	3120	4.43	4.38	1.31	10	1.30	10	1.52	10	7	1.48	10	10	1.49	24	1.45	24
120	286.5	3120	4.05	3.98	1.32	10	1.31	10	1.53	10	7	1.49	10	10	1.49	9	1.46	10
140	286.5	3120	3.67	3.59	1.34	10	1.32	10	1.55	10	6	1.51	10	9	1.50	9	1.46	10
160	286.5	3120	3.31	3.21	1.35	10	1.33	10	1.57	10	6	1.52	10	9	1.50	9	1.47	10
180	286.5	3120	2.95	2.84	1.36	35	1.35	10	1.58	10	6	1.54	10	8	1.50	9	1.48	10
200	286.5	3120	2.59	2.46	1.37	10	1.35	10	1.58	10	6	1.54	35	8	1.50	10	1.49	10
220	286.5	3120	2.21	2.08	1.37	114	1.36	10	1.58	10	5	1.55	154	7	1.50	114	1.49	35
240	286.5	3120	1.82	1.68	1.37	114	1.36	154	1.57	10	5	1.54	154	6	1.50	114	1.49	114
260	286.5	3120	1.41	1.27	1.37	114	1.36	154	1.55	50	5	1.54	154	6	1.49	114	1.48	154
280	286.5	3120	0.99	0.85	1.36	154	1.35	154	1.54	10	4	1.52	154	6	1.48	154	1.47	154
300	286.5	3120	0.56	0.42	1.36	129	1.35	154	1.52	129	4	1.51	154	5	1.47	129	1.47	154
325.8/319.5	286.5	3120	0.00	0.00	1.35	154	1.34	154	1.51	10	4	1.50	154	5	1.46	101	1.46	154

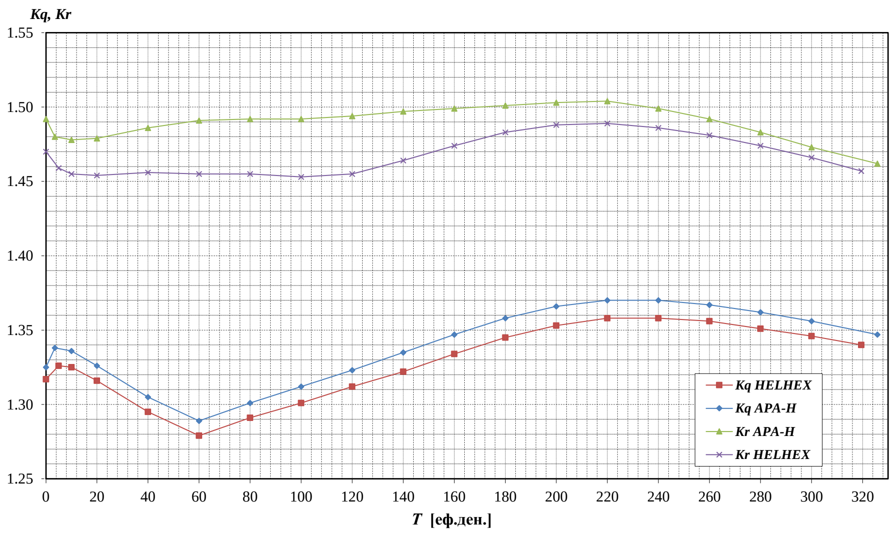
T, fpd	Ko	Nas	Nlv	Ko	Nas	Nlv	Km	Nas	Nlv	Km	Nas	Nlv	AO, %		BU, MWd/kgU	
	A			H			A			H			A	H	A	H
0	1.77	9	11	1.75	9	14	0.86	33	12	0.96	24	22	-1.28	-0.95	20.42	20.43
5.00/3.52	1.74	9	11	1.72	9	14	0.87	29	12	0.96	24	22	-1.20	-0.99	20.63	20.58
10	1.72	9	10	1.70	9	14	0.86	29	12	0.96	24	25	-1.32	-0.85	20.83	20.84
20	1.71	9	10	1.69	9	14	0.84	41	11	0.96	24	25	-1.66	-0.59	21.25	21.25
40	1.72	9	9	1.68	9	13	0.84	9	20	0.96	24	25	-2.43	-0.20	22.06	22.07
60	1.71	9	8	1.67	9	12	0.84	9	20	0.96	24	25	-2.76	0.21	22.88	22.89
80	1.71	9	8	1.66	9	11	0.84	9	20	0.96	24	25	-2.96	0.57	23.70	23.72
100	1.71	9	7	1.66	10	10	0.84	9	20	0.96	24	25	-3.14	0.90	24.52	24.54
120	1.71	9	7	1.66	10	9	0.84	9	20	0.96	24	25	-3.41	1.21	25.34	25.36
140	1.72	10	6	1.67	10	9	0.84	9	20	0.95	24	25	-3.64	1.48	26.16	26.18
160	1.74	10	6	1.69	10	8	0.84	9	20	0.95	9	25	-3.80	1.75	26.98	27.00
180	1.75	10	6	1.70	10	8	0.84	11	6	0.95	9	25	-3.92	1.99	27.80	27.82
200	1.74	10	5	1.71	35	7	0.84	11	5	0.95	9	25	-3.77	2.15	28.62	28.64
220	1.74	10	5	1.71	154	7	0.85	9	21	0.95	9	25	-3.47	2.17	29.44	29.46
240	1.72	10	5	1.70	154	6	0.86	9	21	0.95	9	25	-3.02	2.07	30.26	30.28
260	1.69	10	4	1.69	154	6	0.87	9	21	0.96	9	25	-2.52	1.90	31.08	31.10
280	1.68	10	4	1.67	154	6	0.88	9	21	0.96	101	25	-2.13	1.67	31.90	31.93
300	1.66	129	4	1.66	154	5	0.88	9	21	0.96	101	25	-1.89	1.46	32.72	32.75
325.8/319.5	1.64	10	4	1.64	154	5	0.88	9	22	0.95	101	25	-1.73	1.30	33.78	33.55

<0.02
<0.05
<0.04
<0.05
0.14g/kg
~6 fpd

Table 2. FA and FR maximum PPFs for 31st cycle (APA-H and HELHEX)

5. CORE DESIGN U5/C31





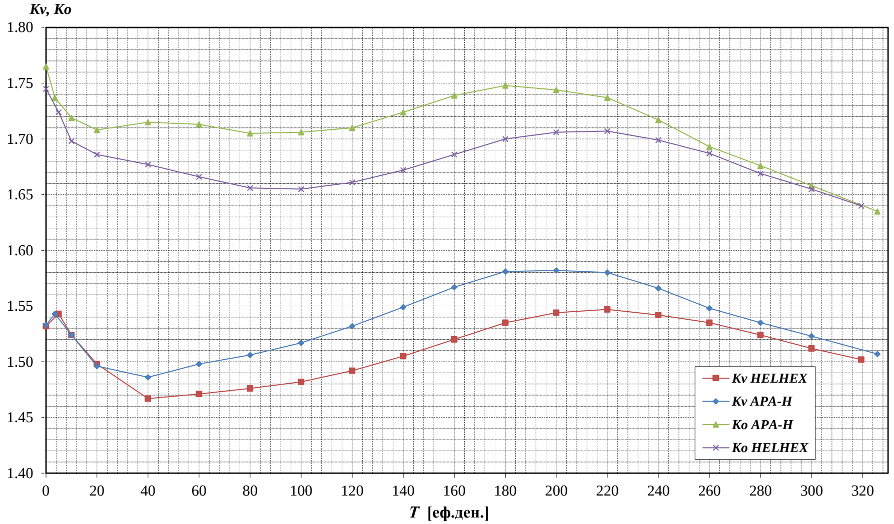
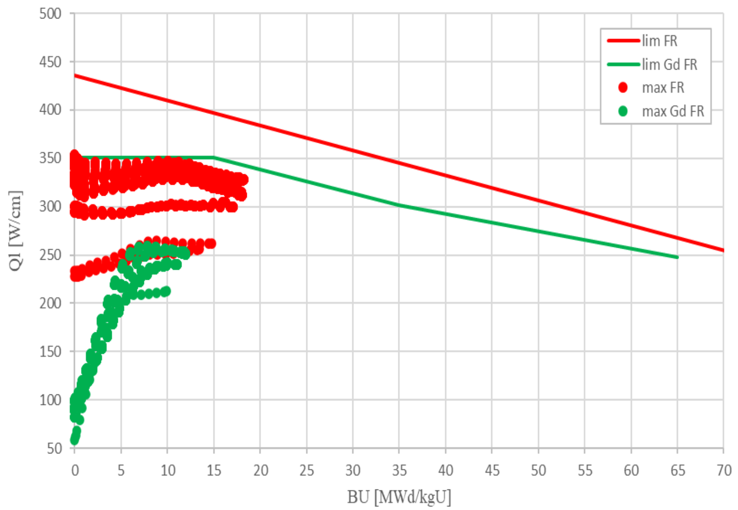
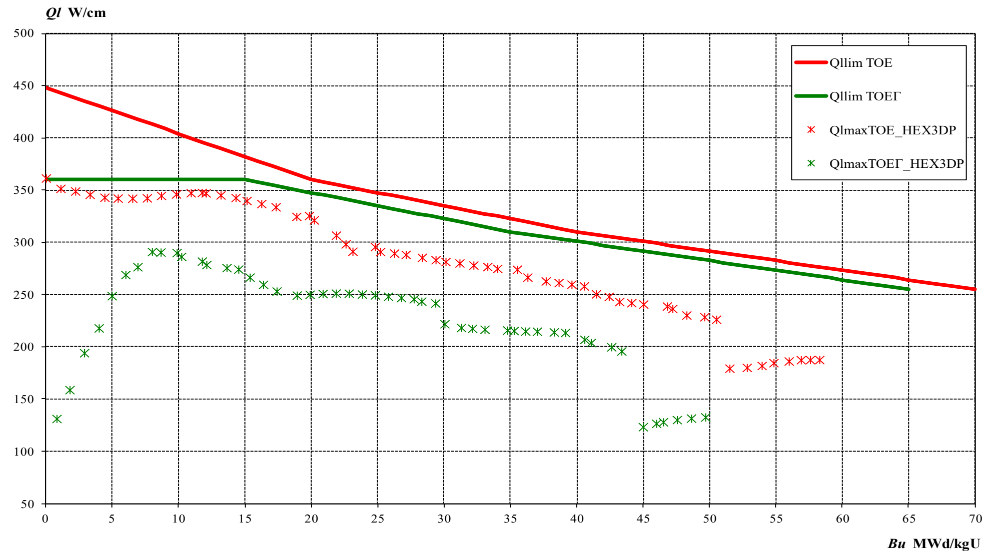


Fig. 8. C_{H3BO3}, FA and FR maximum PPFs for 31st cycle (APA-H and HELHEX)

5. CORE DESIGN U5/C31



According to the refueling methodology, the most important safety parameter is the linear power in the fuel rods Ql_{ijk} *[W/cm]*.



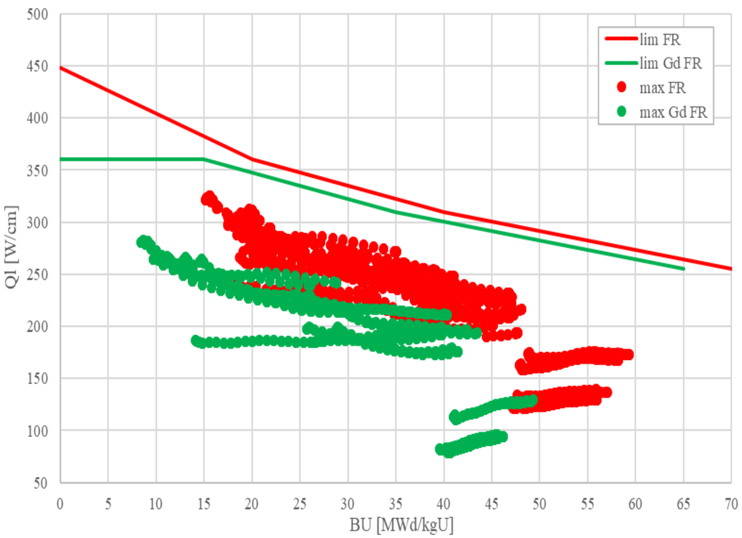
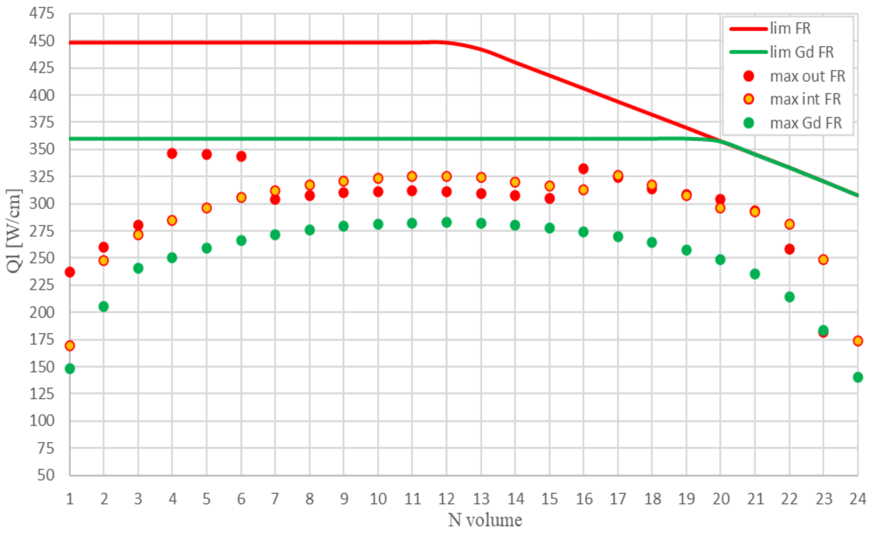


Fig. 9. LHR (Ql_{ijk} *[W/cm]*) vs *FR Burn-up* (APA-H and HELHEX)

5. CORE DESIGN U5/C31



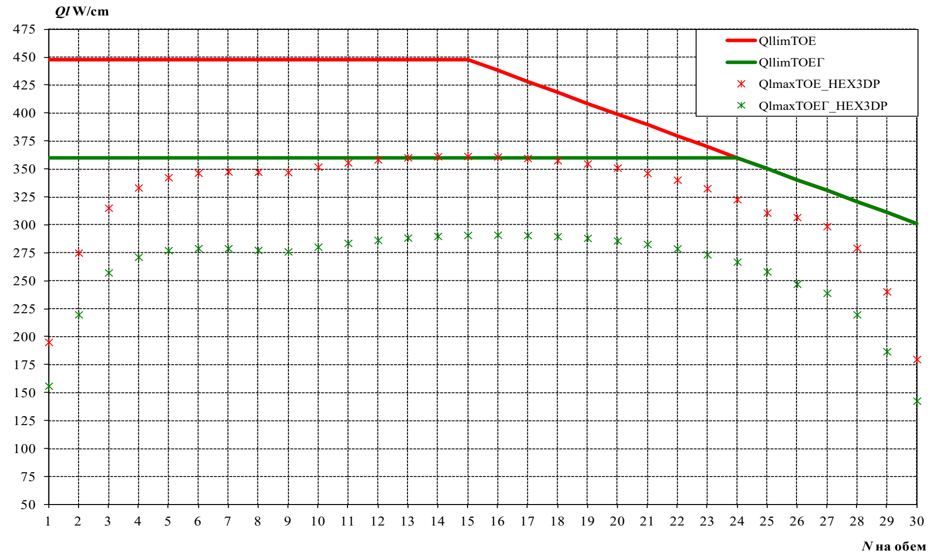


Fig. 10. LHR (Ql_{ijk} *[W/cm]*) vs *Hcore* (APA-H and HELHEX)

6. HZP START-UP TESTS U5/C31

- Hot Zero Power physics tests at the BOC are the first opportunity to compare the core design calculations with the measurements.
- The aim of HZP physics tests is to confirm experimentally the predicted neutron-physics characteristics and to prove that the reactor core is designed according to the safety requirements.
- Usually there are 4 tests performed at Kozloduy NPP at HZP:
  - critical boric acid concentration at HZP: test criterion: ±0.5g/kg;
  - isothermal reactivity coefficient (ITRC): test criterion: ±4pcm/°C;
  - 10^{th} (working) group worth: test criterion: ±15%;
  - total control rods worth: test criterion: ±20%.
- All acceptance criteria have been met at the beginning of cycle 31.

6. HZP START-UP TESTS U5/C31

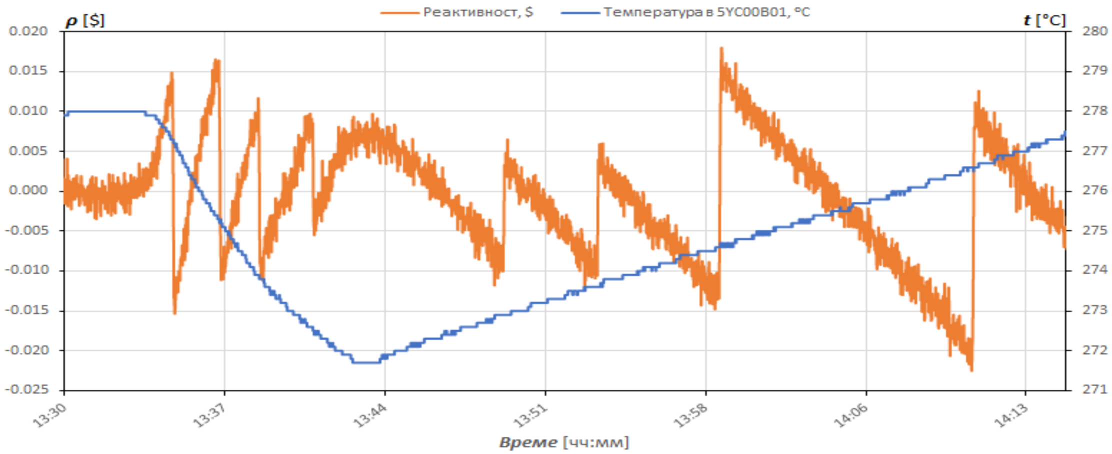
№	T [fpd]	t_{in} [°C]	$P_{1к.}$ [kgf/cm²]	H_{10} [cm]	$C^{крит.}_{H_3BO_3}$ [g/kg] Exp.	$C^{крит.}_{H_3BO_3}$ [g/kg] APA-H	APA-H – Exp [g/kg]
1	0.00	276.7	159.9	136	9.39	9.72	0.33
2	0.00	277.9	159.6	154	9.58	9.74	0.16
3	0.00	272.1	159.9	128	9.58	9.73	0.15
4	0.00	277.0	157.4	152	9.58	9.74	0.16
5	0.00	277.6	159.2	312	10.07	10.09	0.02
6	0.00	272.6	157.9	300	10.07	10.08	0.01
7	0.00	278.4	158.1	318	10.07	10.10	0.03
8	0.00	276.6	159.5	312	10.07	10.09	0.02
9	0.00	276.3	159.3	116	9.46	9.69	0.23
10	0.00	278.2	159.2	150	9.58	9.73	0.15
11	0.00	276.3	160.7	51	9.52	9.64	0.12

Test criterion: ±0.5g/kg

№	T [fpd]	t_{in} [°C]	$P_{1к.}$ [kgf/cm²]	H_{10} [cm]	$C^{крит.}_{H_3BO_3}$ [g/kg] Exp.	$C^{крит.}_{H_3BO_3}$ [g/kg] HELHEX	HELHEX – Exp [g/kg]
1	0.00	276.7	159.9	136	9.39	9.74	0.35
2	0.00	277.9	159.6	154	9.58	9.75	0.17
3	0.00	272.1	159.9	128	9.58	9.76	0.18
4	0.00	277.0	157.4	152	9.58	9.76	0.18
5	0.00	277.6	159.2	312	10.07	10.12	0.05
6	0.00	272.6	157.9	300	10.07	10.12	0.05
7	0.00	278.4	158.1	318	10.07	10.14	0.07
8	0.00	276.6	159.5	312	10.07	10.13	0.06
9	0.00	276.3	159.3	116	9.46	9.70	0.24
10	0.00	278.2	159.2	150	9.58	9.75	0.17
11	0.00	276.3	160.7	51	9.52	9.65	0.13

Table 3. Critical boric acid concentration at HZP tests – U5/C31 (APA-H and HELHEX)

6. HZP START-UP TESTS U5/C31



Test criterion: ±4pcm/°C

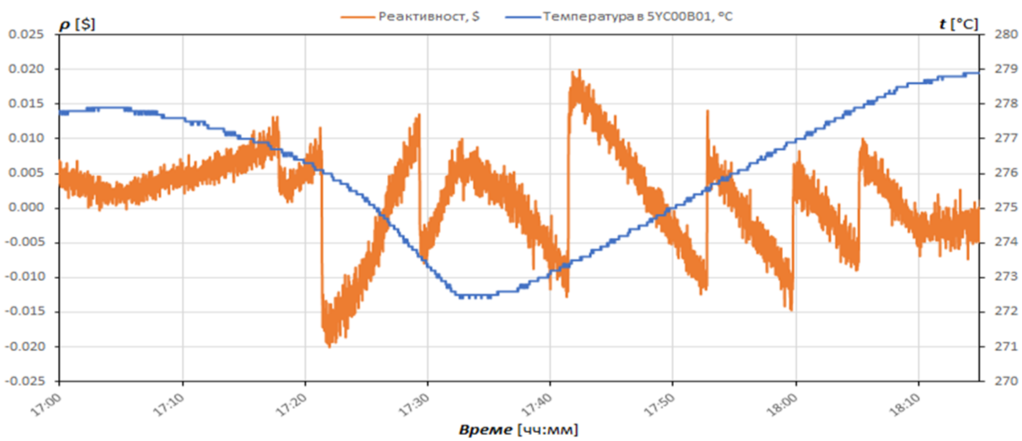
Fig. 11. Temperature and reactivity change at H_{10} ~37% - U5/C31

№	$P_{1к}$ [kgf/cm^2]	t_{in} [°C]		Δt_{in} [°C]	$H_{1\div9}$ [cm]	H_{10} [cm]		$\Delta\rho$ [$\times10^{-2}$ %]	$\partial\rho/\partial t_{H_2O} + \partial\rho/\partial t_U$ [$\times10^{-3}$ % / °C]		Exp.- APAH [$\times10^{-3}$ % / °C]
		beg.	end			beg.	end		Exp.	APA-H	
1	159.9	272.1	272.8	0.7	354	128	132	-0.61	-8.53	-8.56	0.03
2	159.6	272.8	273.6	0.8	354	132	136	-0.73			
3	159.2	273.6	275.2	1.6	354	136	144	-1.37			
4	158.4	275.2	277.0	1.8	354	144	152	-1.47			

№	$P_{1к}$ [kgf/cm^2]	t_{in} [°C]		Δt_{in} [°C]	$H_{1\div9}$ [cm]	H_{10} [cm]		$\Delta\rho$ [$\times10^{-2}$ %]	$\partial\rho/\partial t_{H_2O} + \partial\rho/\partial t_U$ [$\times10^{-3}$ % / °C]		Exp.- HELH [$\times10^{-3}$ % / °C]
		beg.	end			beg.	end		Exp.	HELHEX	
1	159.9	272.1	272.8	0.7	354	128	132	-0.61	-8.53	-10.58	2.05
2	159.6	272.8	273.6	0.8	354	132	136	-0.73			
3	159.2	273.6	275.2	1.6	354	136	144	-1.37			
4	158.4	275.2	277.0	1.8	354	144	152	-1.47			

Table 4. ITRC at HZP tests – U5/C31 (APA-H and HELHEX)

6. HZP START-UP TESTS U5/C31



Test criterion: ±4pcm/°C

Fig. 12. Temperature and reactivity change at H_{10} ~85% - U5/C31

№	$P_{1к}$ [kgf/cm²]	t_{in} [°C]		Δt_{in} [°C]	$H_{1÷9}$ [cm]	H_{10} [cm]		$\Delta\rho$ [×10⁻² %]	$\partial\rho/\partial t_{H_2O} + \partial\rho/\partial t_U$ [×10⁻³ % / °C]		Exp.- APAH [×10⁻³ % / °C]
		beg.	end			beg.	end		Exp.	APA-H	
1	157.9	272.6	274.6	2.0	354	300	306	-1.30	-6.24	-6.33	0.09
2	157.7	274.6	275.9	1.3	354	306	310	-0.83			
3	157.4	275.9	277.3	1.4	354	310	314	-0.75			
4	157.5	277.3	278.4	1.1	354	314	318	-0.74			

№	$P_{1к}$ [kgf/cm²]	$t_{вх.}$ [°C]		$\Delta t_{вх.}$ [°C]	$H_{1÷9}$ [cm]	H_{10} [cm]		$\Delta\rho$ [×10⁻² %]	$\partial\rho/\partial t_{H_2O} + \partial\rho/\partial t_U$ [×10⁻³ % / °C]		Exp.- HELH [×10⁻³ % / °C]
		beg.	end			beg.	end		Exp.	HELHEX	
1	157.9	272.6	274.6	2.0	354	300	306	-1.30	-6.24	-8.11	1.87
2	157.7	274.6	275.9	1.3	354	306	310	-0.83			
3	157.4	275.9	277.3	1.4	354	310	314	-0.75			
4	157.5	277.3	278.4	1.1	354	314	318	-0.74			

Table 5. ITRC at HZP tests – U5/C31 (APA-H and HELHEX)

6. HZP START-UP TESTS U5/C31

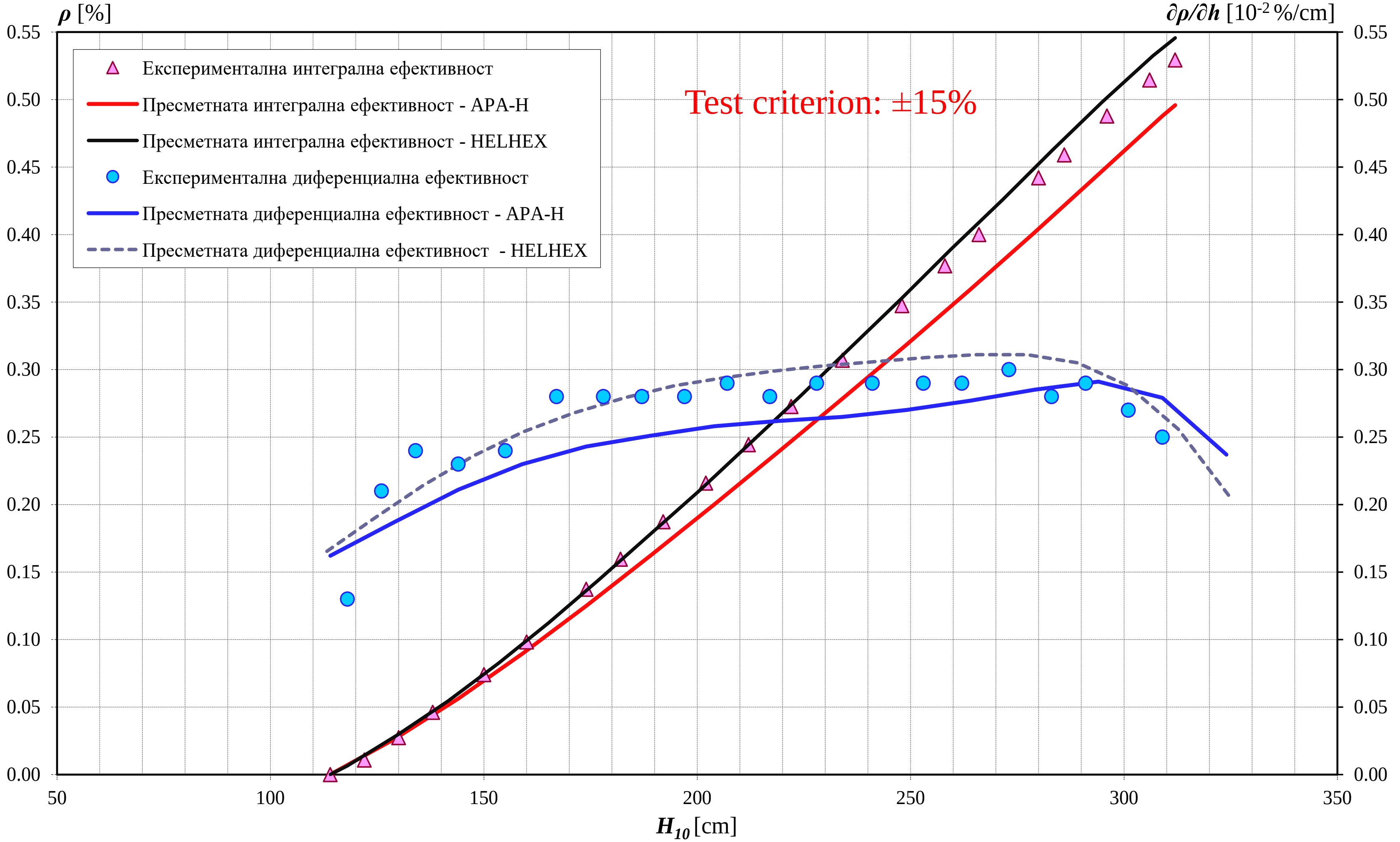


Fig. 13. Working group worth at HZP tests – U5/C31

6. HZP START-UP TESTS U5/C31

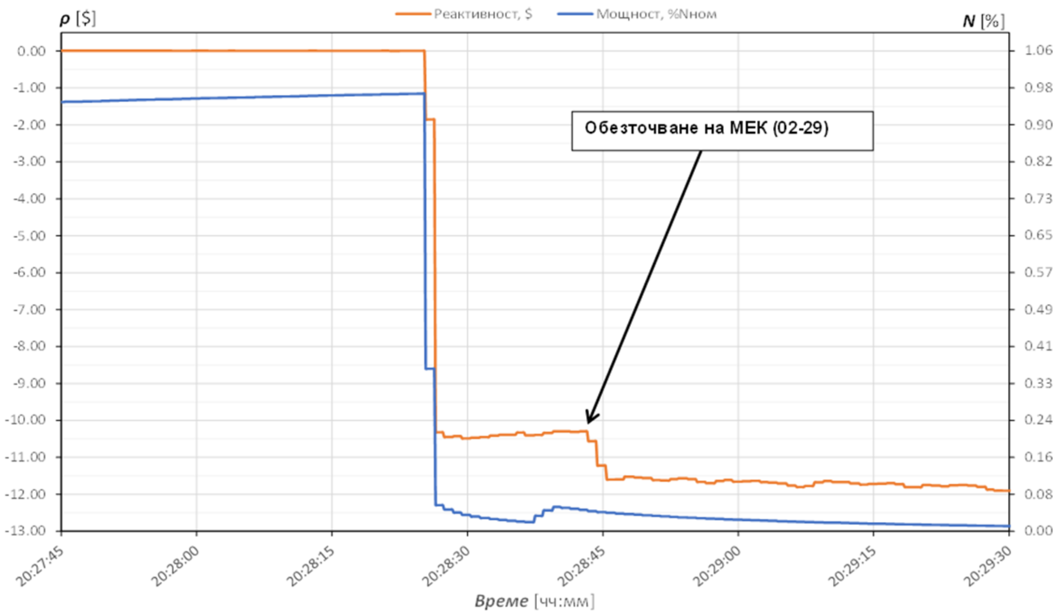


Fig. 14. Total control rod worth at HZP tests – U5/C31

Test criterion: ±20%

№		$t_{in.}$ [°C]	$P_{1к}$ [kgf/cm²]	H_{MEC} (02-29) [cm]	Hgr [cm]		$C^{изм.}_{H_3BO_3}$ [g/kg]	Δρ [%]		$\frac{изм. - пресм.}{изм.} \times 100$ [%]	Code
					$H_{1÷9}$	H_{10}		Exp.	Calc.		
1	Begin	278.2	159.2	354	354	150	9.58	-6.28	-6.67	-6.21	HELHEX
	End	278.2	159.2	354	0	0			-6.41	-2.07	APA-H

Table 6. Total control rod worth at HZP test – U5/C31 (APA-H and HELHEX)

7. CRITICAL C_{H3BO3} U5/C31

- Critical boric acid concentration: test criterion: ±0.3g/kg.

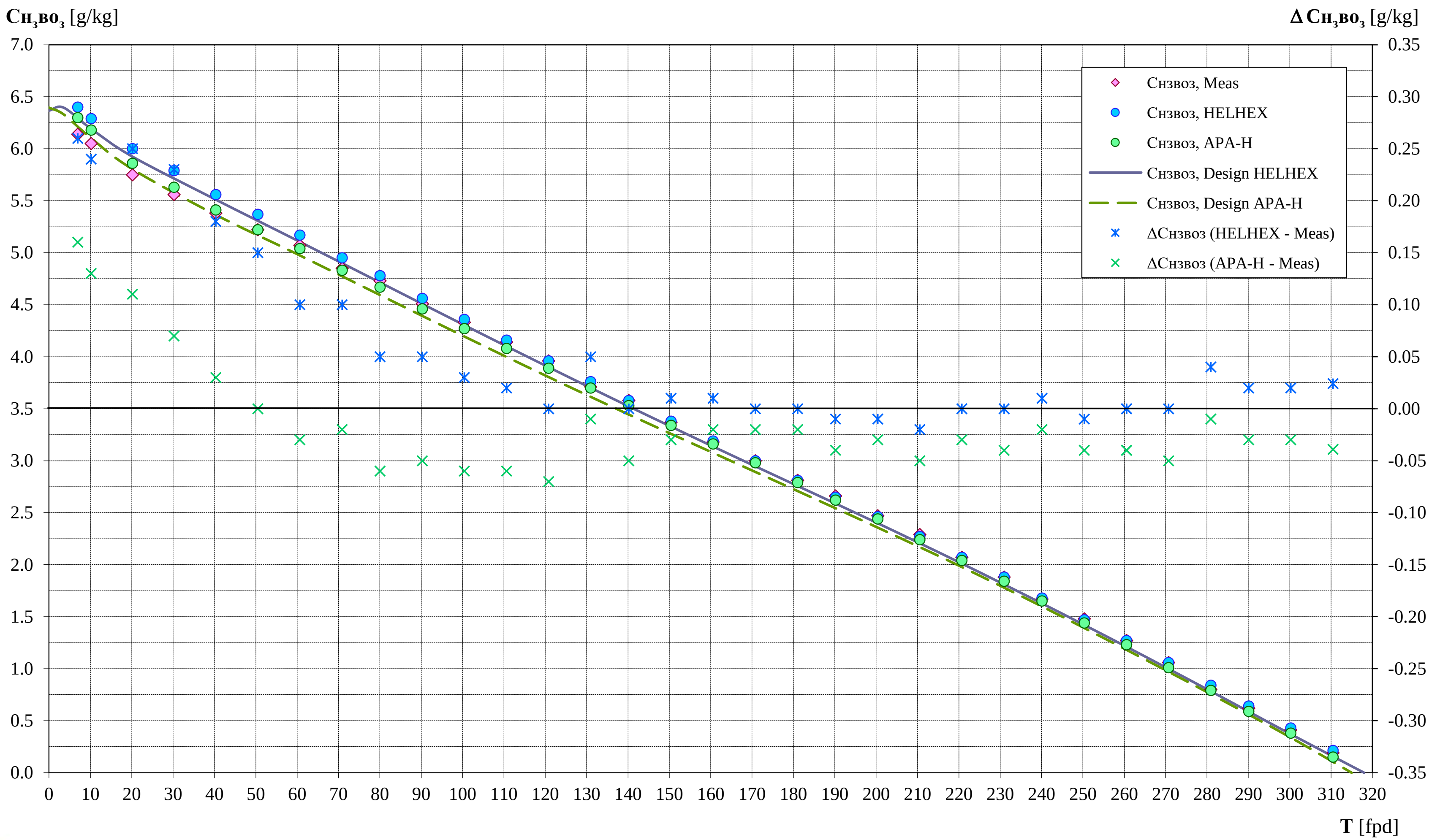
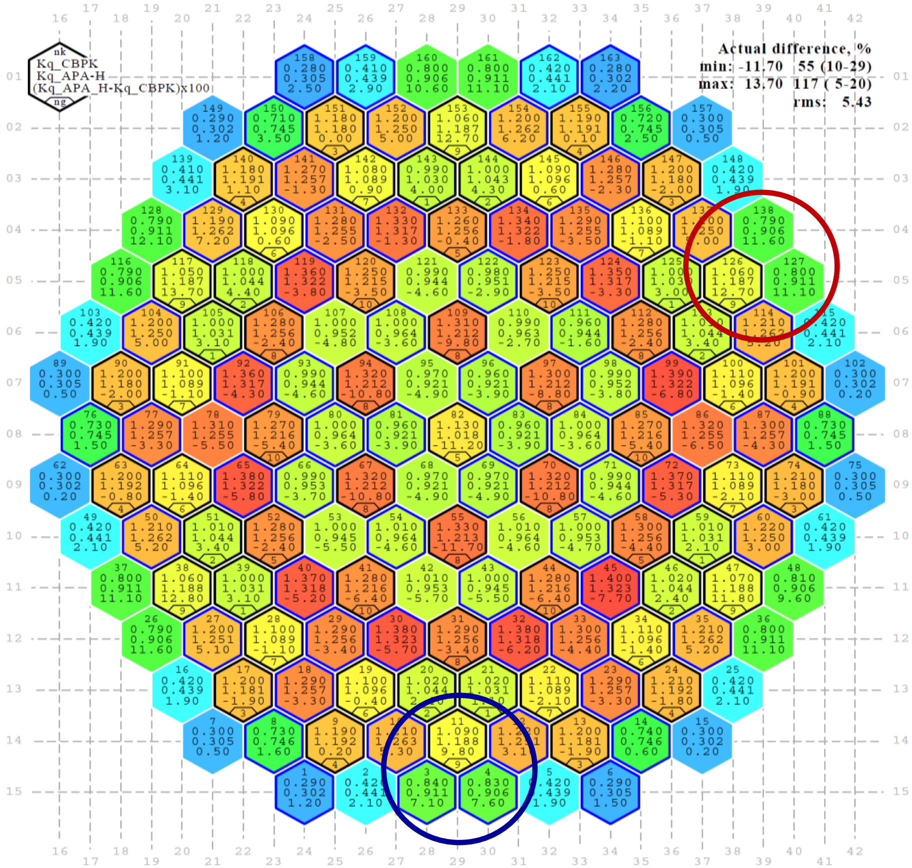


Fig. 15. Critical boric acid concentrations and difference (calc-exp) vs. fuel cycle length – U5/C31

8. ASSEMBLY AND NODAL POWER DISTRIBUTION

- A comparison between the ICMS (СВРК) and BEACON measured/reconstructed and APA-H and HELHEX calculated assembly power peaking factors (Kq_i) at full power for 20.21fpd and 230.97fpd of 31[st] cycle of unit 5 is presented in Figs. 16÷18 and 20÷22.
- The differences between ICMS (СВРК) and APA-H and HELHEX are less than 6-7%, except for the 18 FAs next to the reflector – see Figs. 16 and 20. The differences between BEACON reconstructed and APA-H and HELHEX calculated Kq_i are less than 4-5% – see Fig. 17 and 21. If compare the APA-H and HELHEX calculated assembly relative power, the relative difference is less than 3.4%, except for the central FA – see Fig. 18 and 22.
- Concerning the nodal power peaking factors Kv_{ij}, the relative deviation between the measured and APA-H and HELHEX calculated data is less than 10% (Fig. 19 and 23).

8. ASSEMBLY AND NODAL POWER DISTRIBUTION



The differences between ICMS (CBPK) and APA-H and HELHEX are less than 6-7%, except for the 18 FAs next to the reflector.

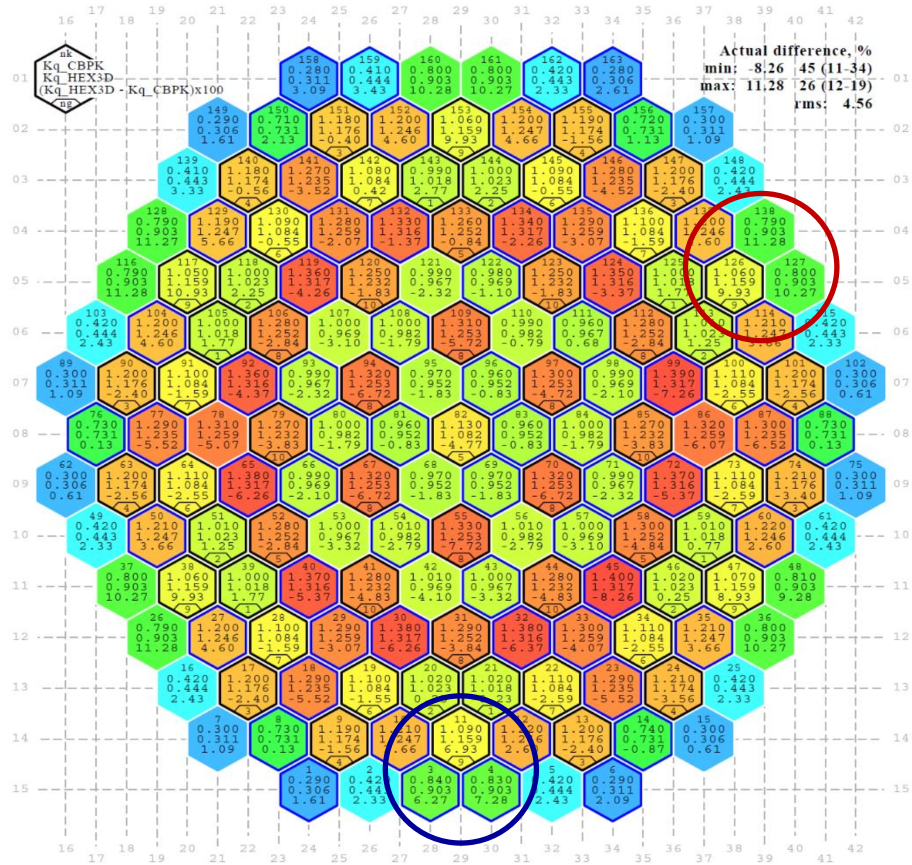
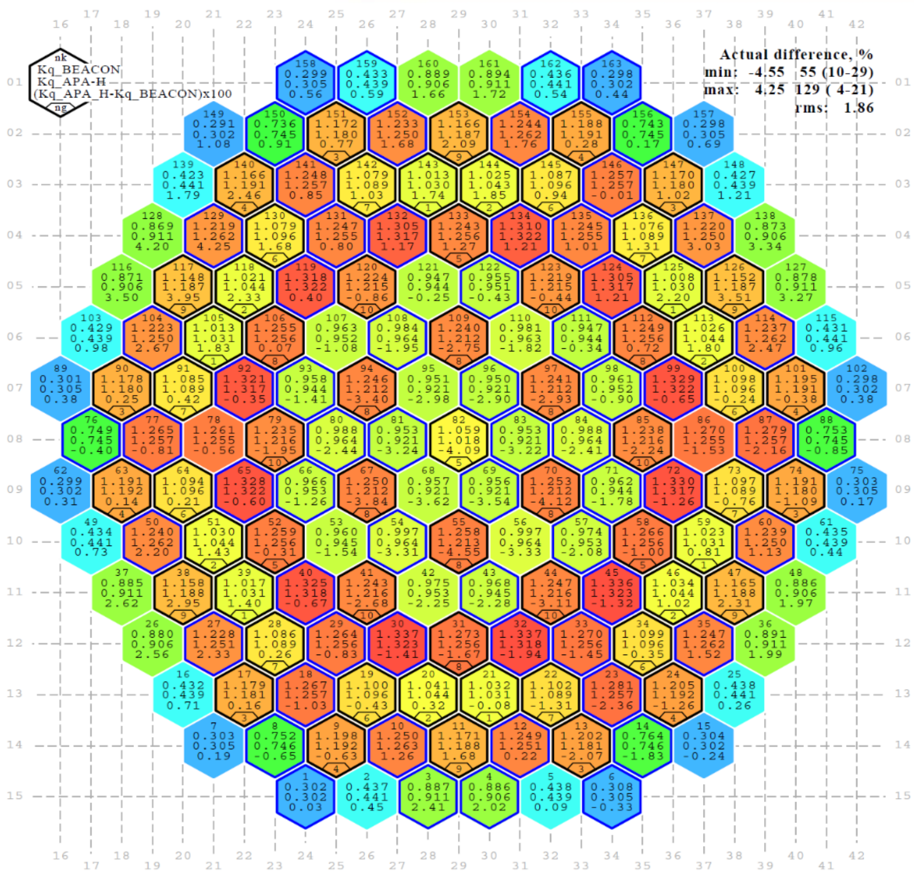


Fig. 16. Assembly power distribution at 20.21fpd – U5/C31 (ICMS/APA-H/HEX3DA)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION



The differences between BEACON reconstructed and APA-H and HELHEX calculated Kq_i are less than 4-5%.

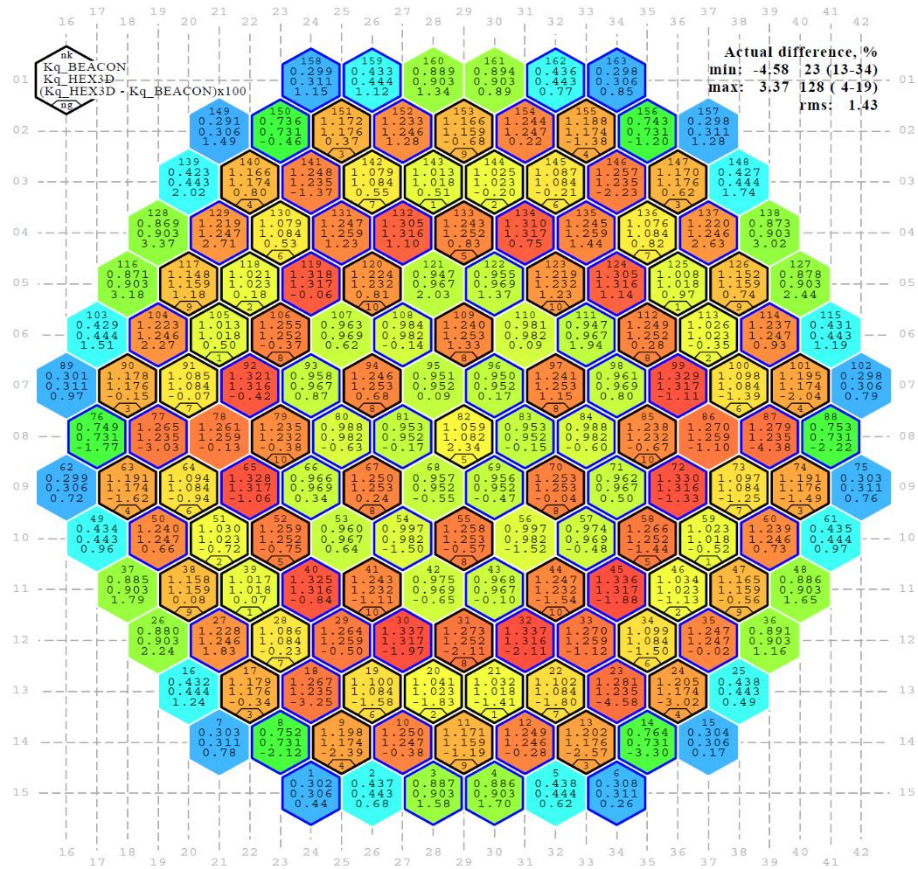
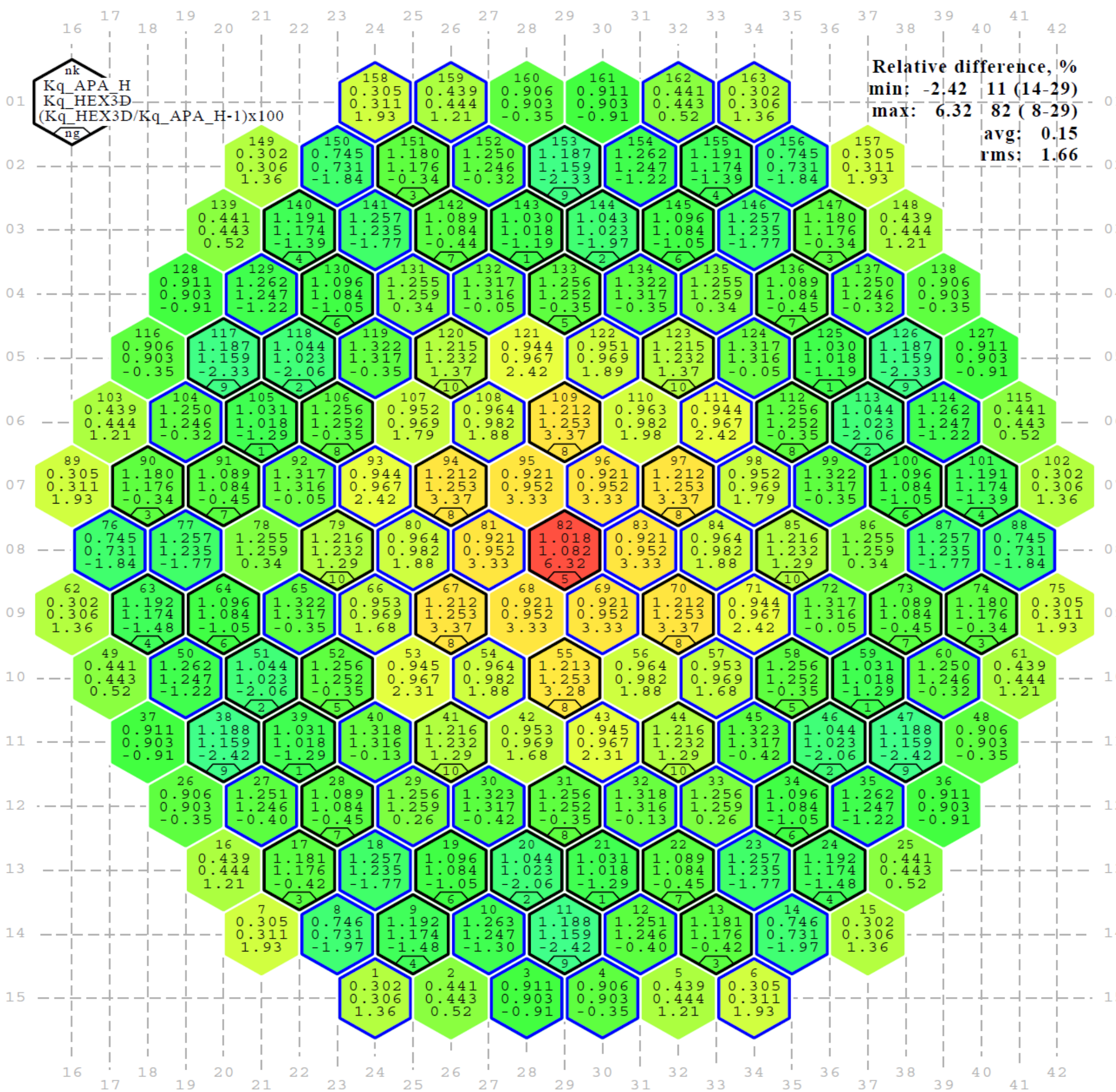


Fig. 17. Assembly power distribution at 20.21fpd – U5/C31 (BEACON/APA-H/HEX3DA)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION



The relative differences between APA-H and HELHEX calculated assembly relative power, are less than 3.4% except for the central FA.

Fig. 18. Assembly power distribution at 20.21fpd – U5/C31 (APA-H/HEX3DA)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION

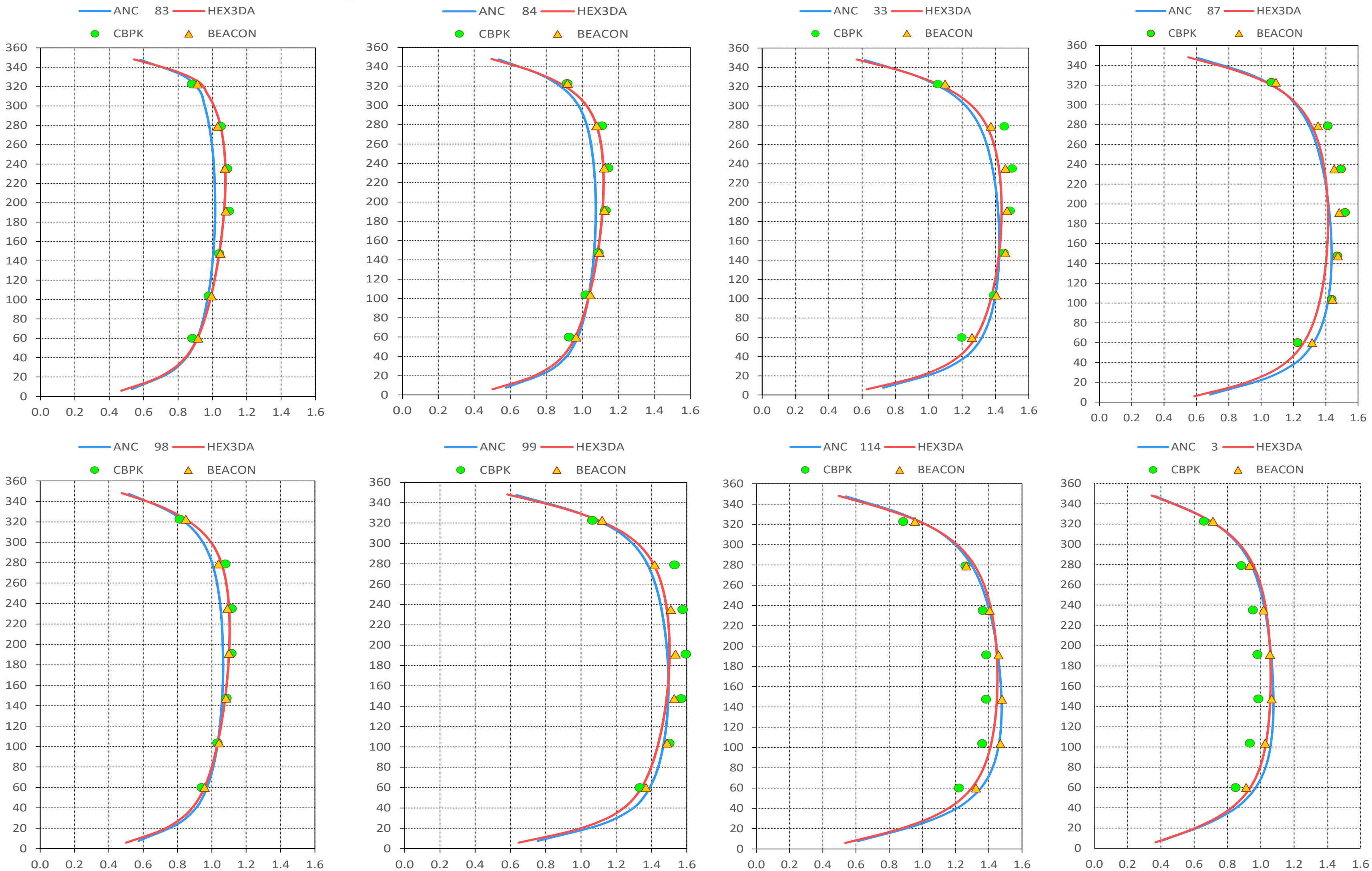
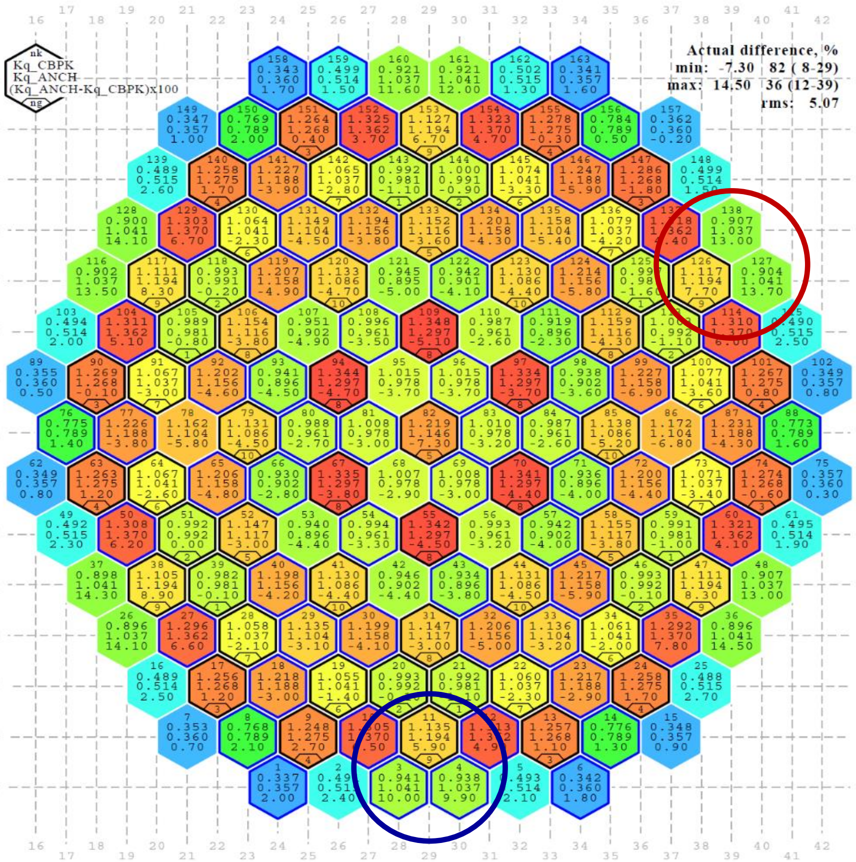


Fig. 19. Assembly nodal power distribution at 20.21fpd – U5/C31 (EXP/CALC)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION



The differences between ICMS (CBPK) and APA-H and HELHEX are less than 6-7%, except for the 18 FAs next to the reflector.

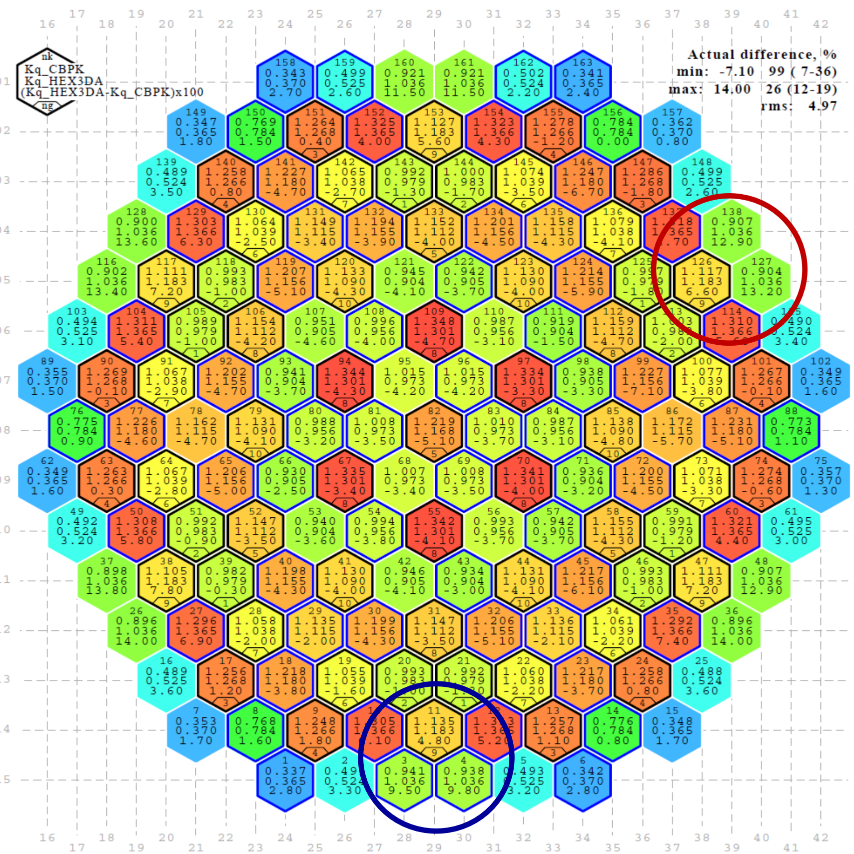
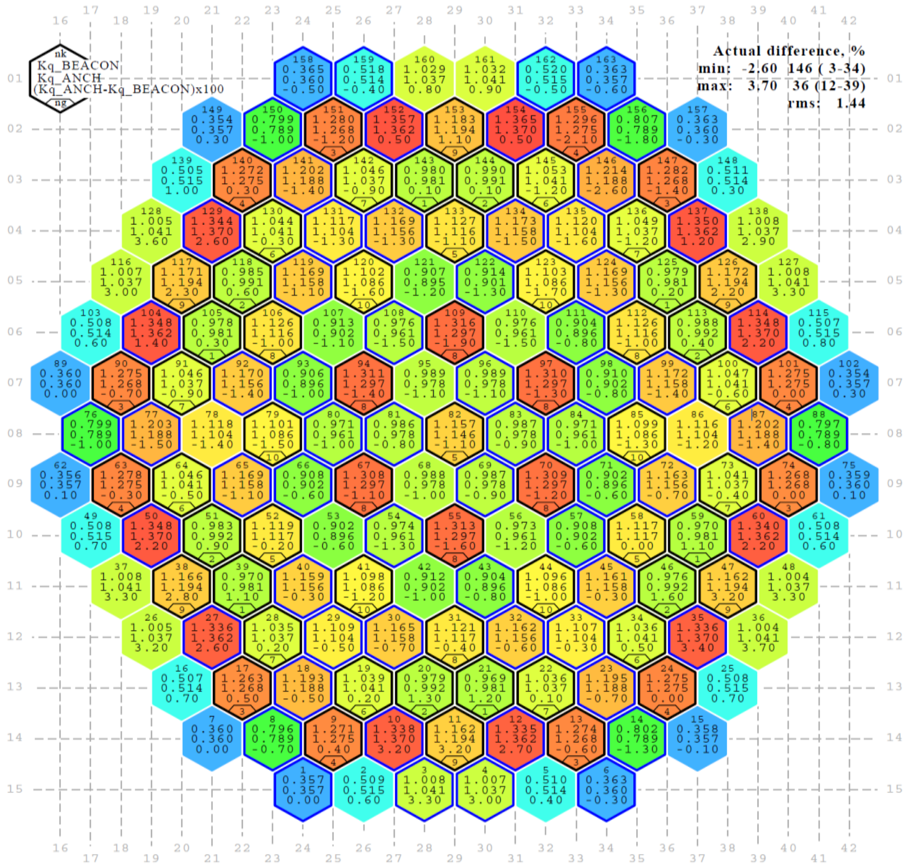


Fig. 20. Assembly power distribution at 230.97fpd – U5/C31 (ICMS/APA-H/HEX3DA)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION

The differences between BEACON reconstructed and APA-H and HELHEX calculated Kq_i are less than 4-5%.



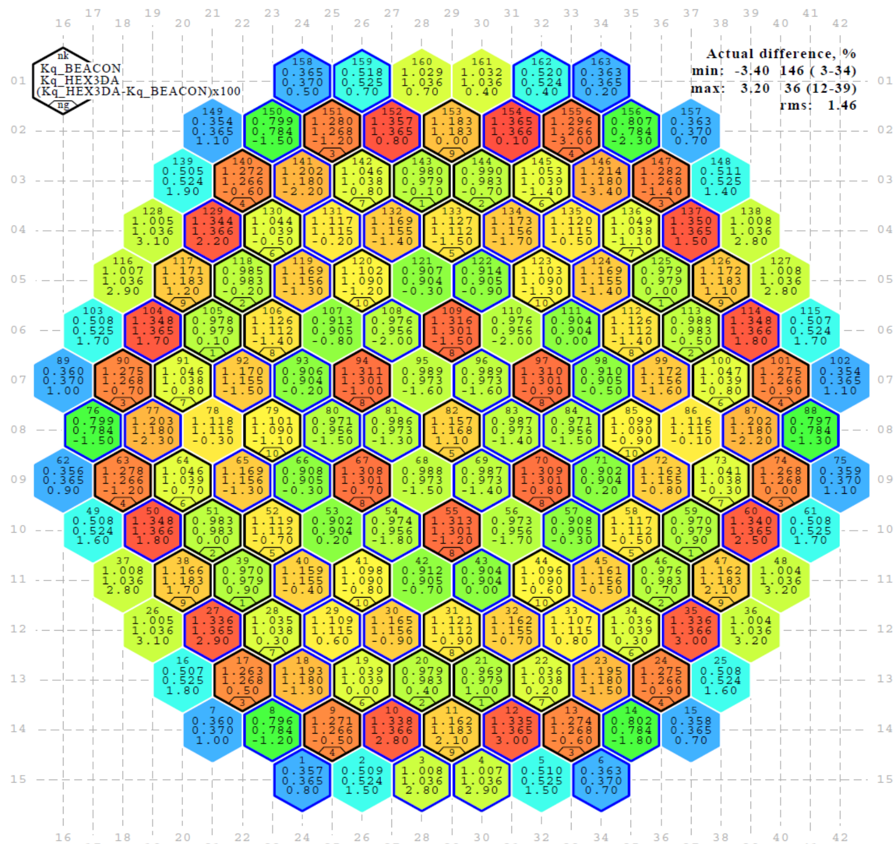
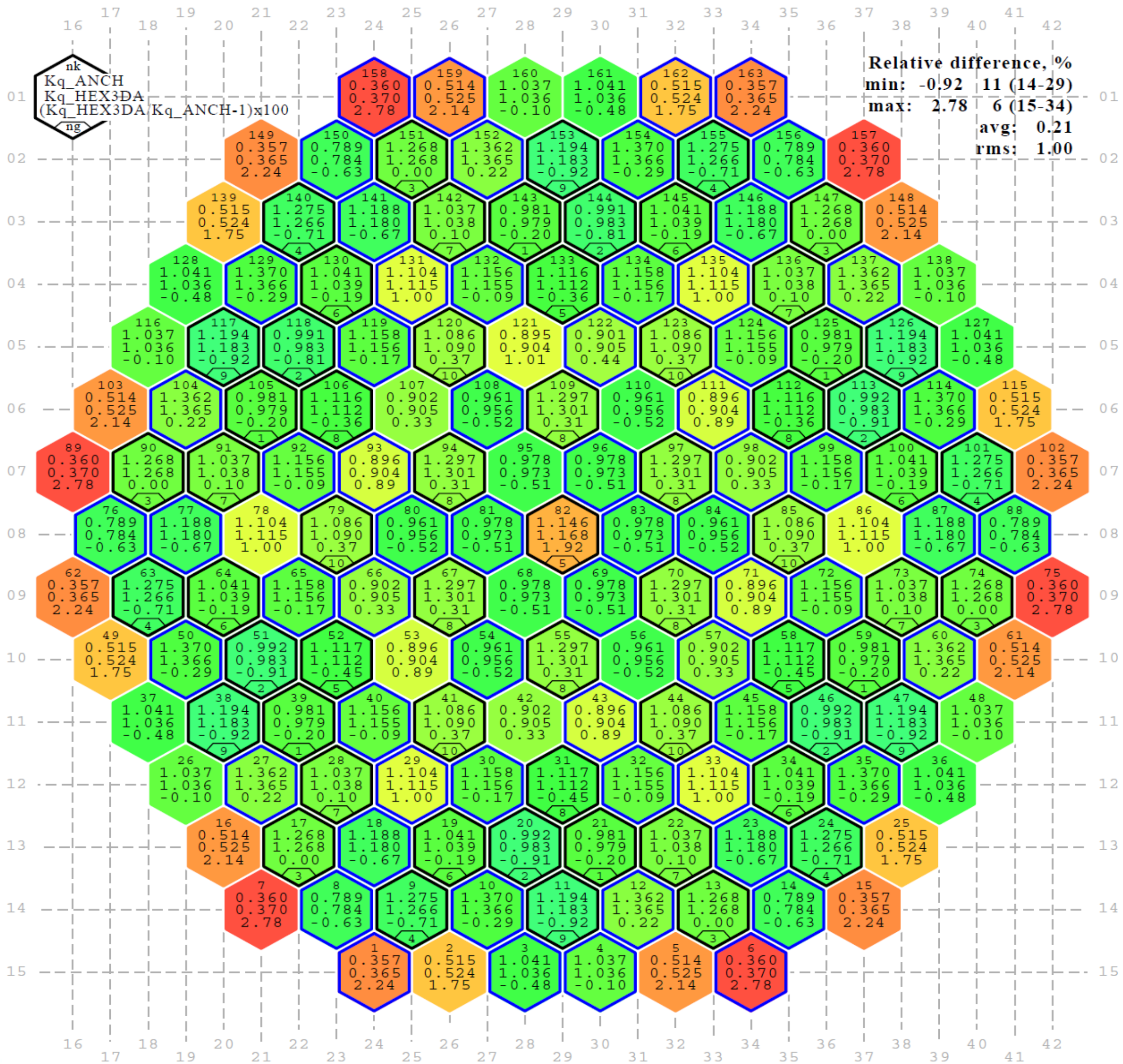


Fig. 21. Assembly power distribution at 230.97fpd – U5/C31 (BEACON/APA-H/HEX3DA)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION



The relative differences between APA-H and HELHEX calculated assembly relative power, are less than 3%.

Fig. 22. Assembly power distribution at 230.97fpd – U5/C31 (APA-H/HEX3DA)

8. ASSEMBLY AND NODAL POWER DISTRIBUTION

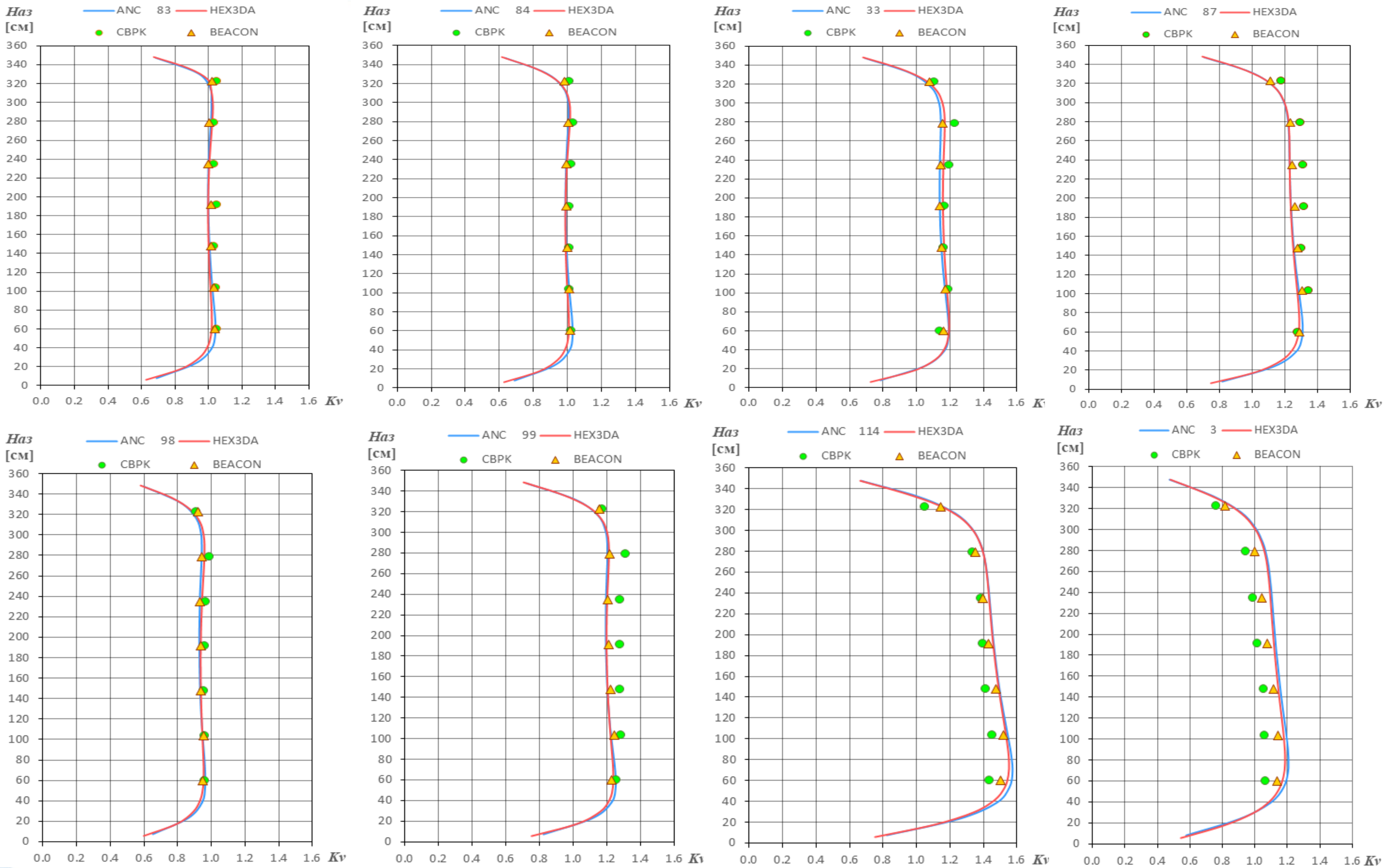


Fig. 23. Assembly nodal power distribution at 230.97fpd – U5/C31 (EXP/CALC)

9. CORE DESIGN U5/C32

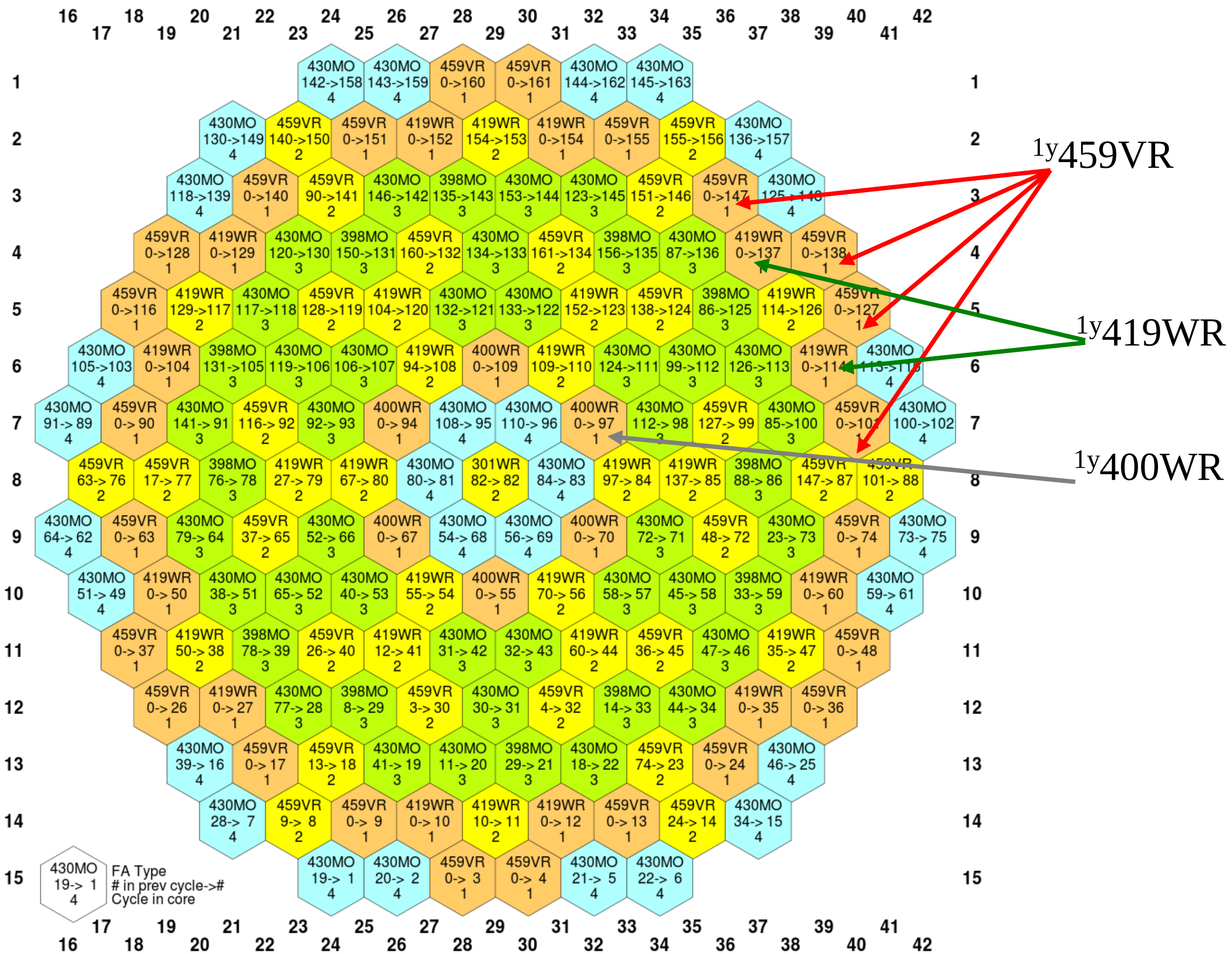
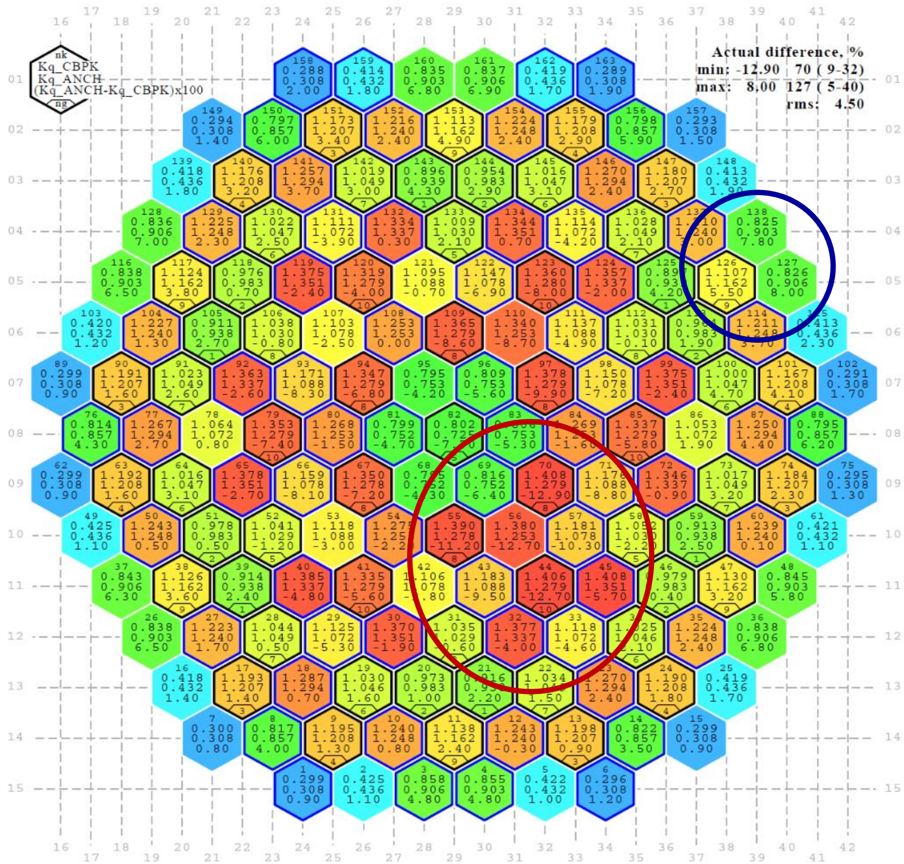


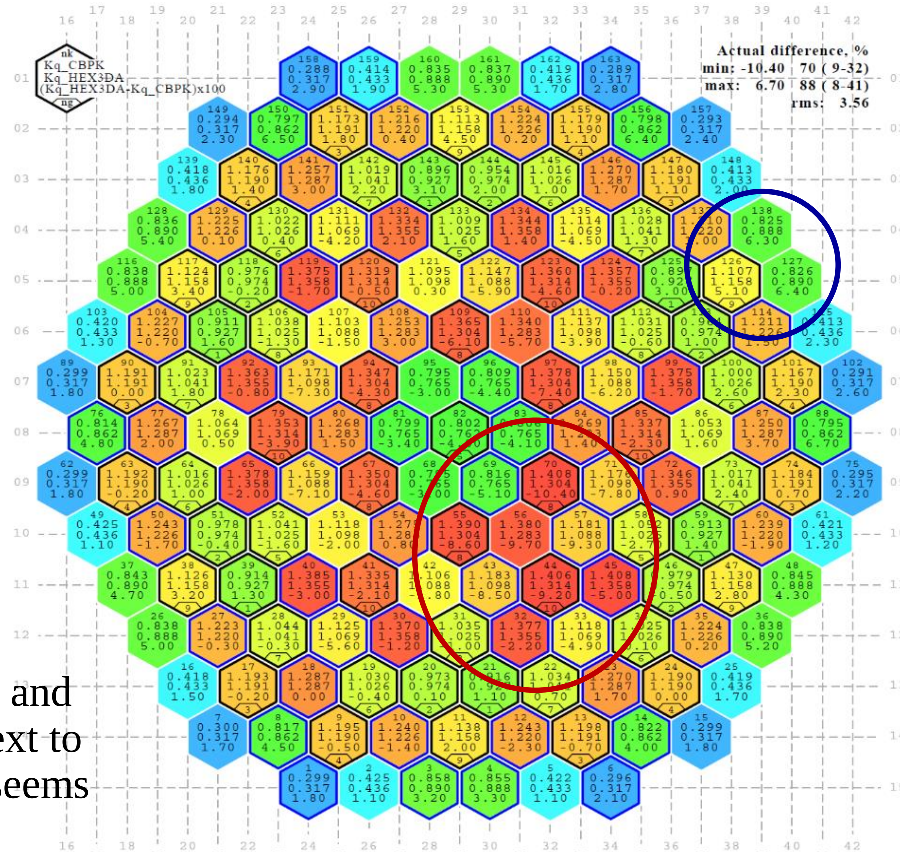
Fig. 24. Loading Pattern for Cycle 32 – the second transition cycle

10. ASSEMBLY AND NODAL POWER DISTRIBUTION

- A comparison between the ICMS (СВРК) and BEACON measured/reconstructed and APA-H and HELHEX calculated assembly power peaking factors (Kq_i) at full power for 10.68fpd of 32nd cycle of unit 5 is presented in Fig. 25 and 26.
- The differences between ICMS (СВРК) and APA-H and HELHEX are less than 7-8%, except for a couple FAs circled in Fig. 25. This effect is not observed by BEACON – not in a such scale. The actual differences between BEACON reconstructed and APA-H and HELHEX calculated Kq_i are less than 4-5%. If compare the APA-H and HELHEX calculated assembly relative power, the relative difference is less than 3.0%, except for the central FA with 5.1% – see Fig. 27.
- Concerning the nodal power peaking factors Kv_{ij}, the relative deviation between the measured with BEACON and APA-H and HELHEX calculated data is less than 10% (Fig. 28). For particular FA, the discrepancies between ICMS and BEACON are slightly bigger than 10%, nevertheless both data are measured with the same SPNDs.

10. ASSEMBLY AND NODAL POWER DISTRIBUTION

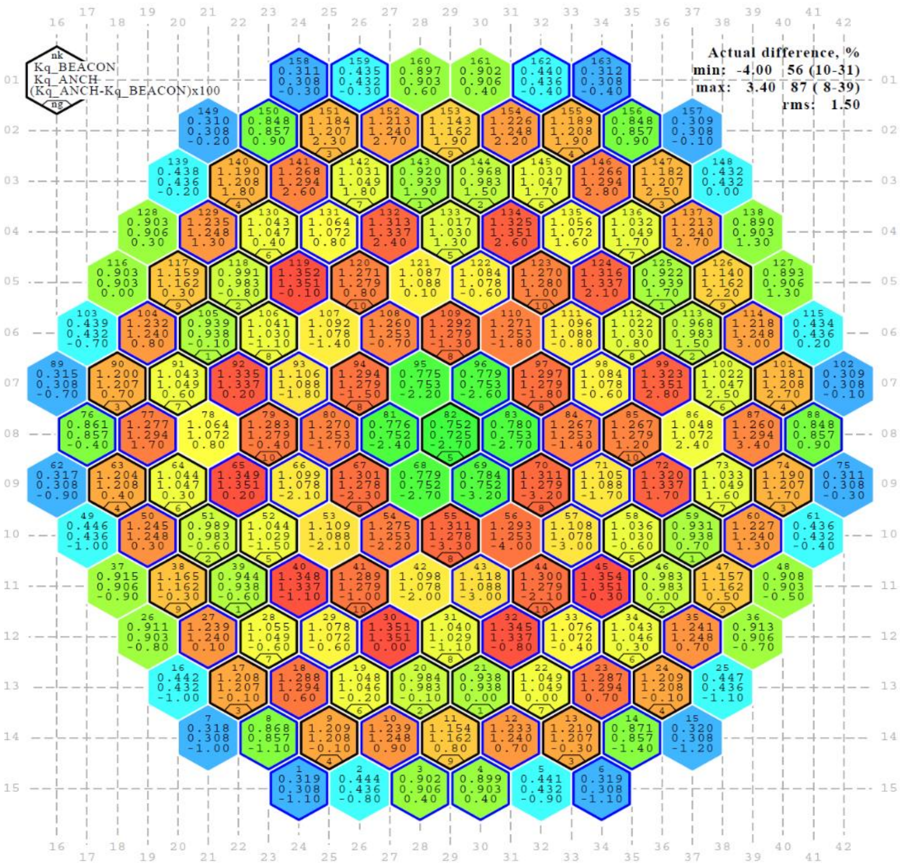




The differences between ICMS (СВРК) and APA-H and HELHEX are less than 5%, except for the 18 FAs next to the reflector, and for a couple FAs circled in red. It seems ICMS is very sensitive to the flow rate differences.

Fig. 25. Assembly power distribution at 10.68fpd – U5/C32 (ICMS/ANC-H/HEX3DA)

10. ASSEMBLY AND NODAL POWER DISTRIBUTION



The differences between BEACON reconstructed and APA-H and HELHEX calculated Kq_i are less than 4-5%.

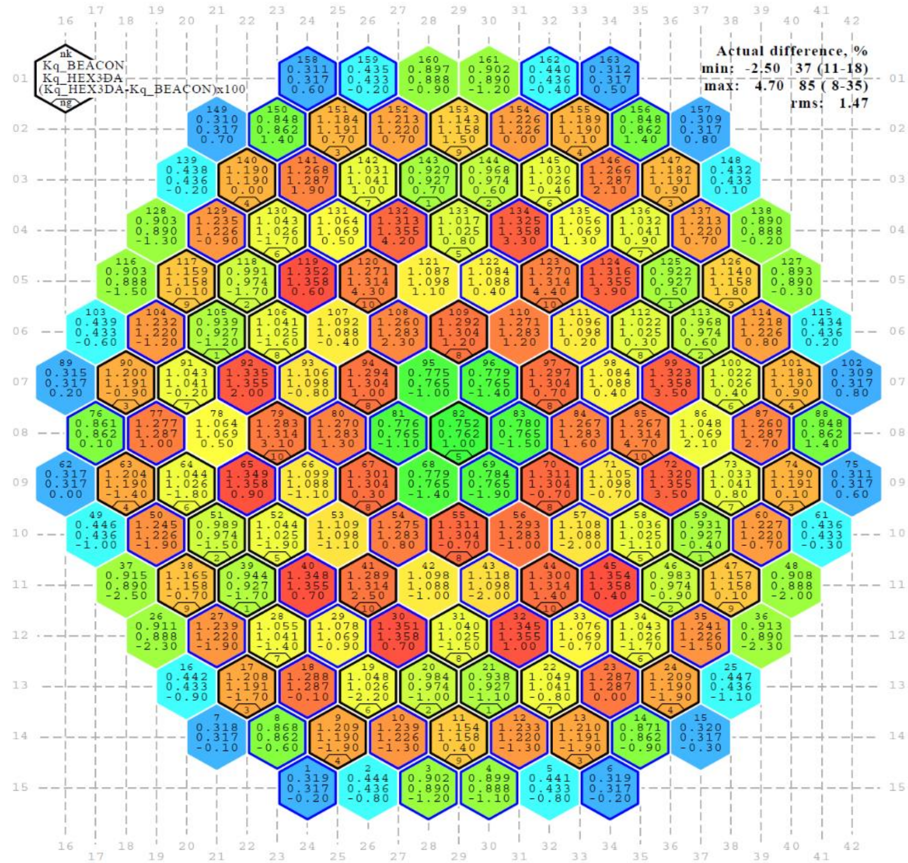
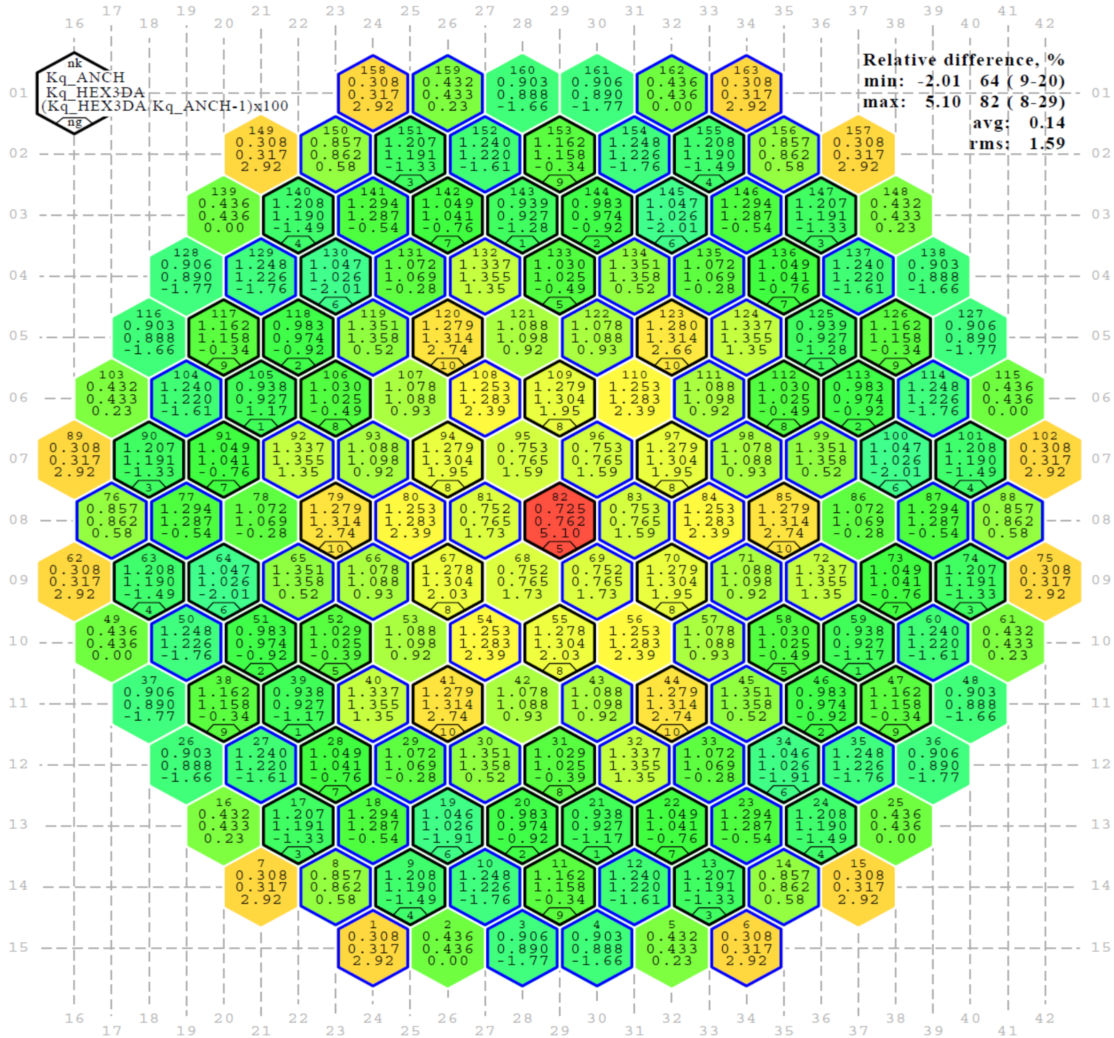


Fig. 26. Assembly power distribution at 10.68fpd – U5/C32 (BEACON/ANC-H/HEX3DA)

10. ASSEMBLY AND NODAL POWER DISTRIBUTION



The relative differences between APA-H and HELHEX calculated assembly relative power, are less than 3% except for the central FA.

Fig. 27. Assembly power distribution at 10.68fpd – U5/C32 (ANC-H/HEX3DA)

10. ASSEMBLY AND NODAL POWER DISTRIBUTION

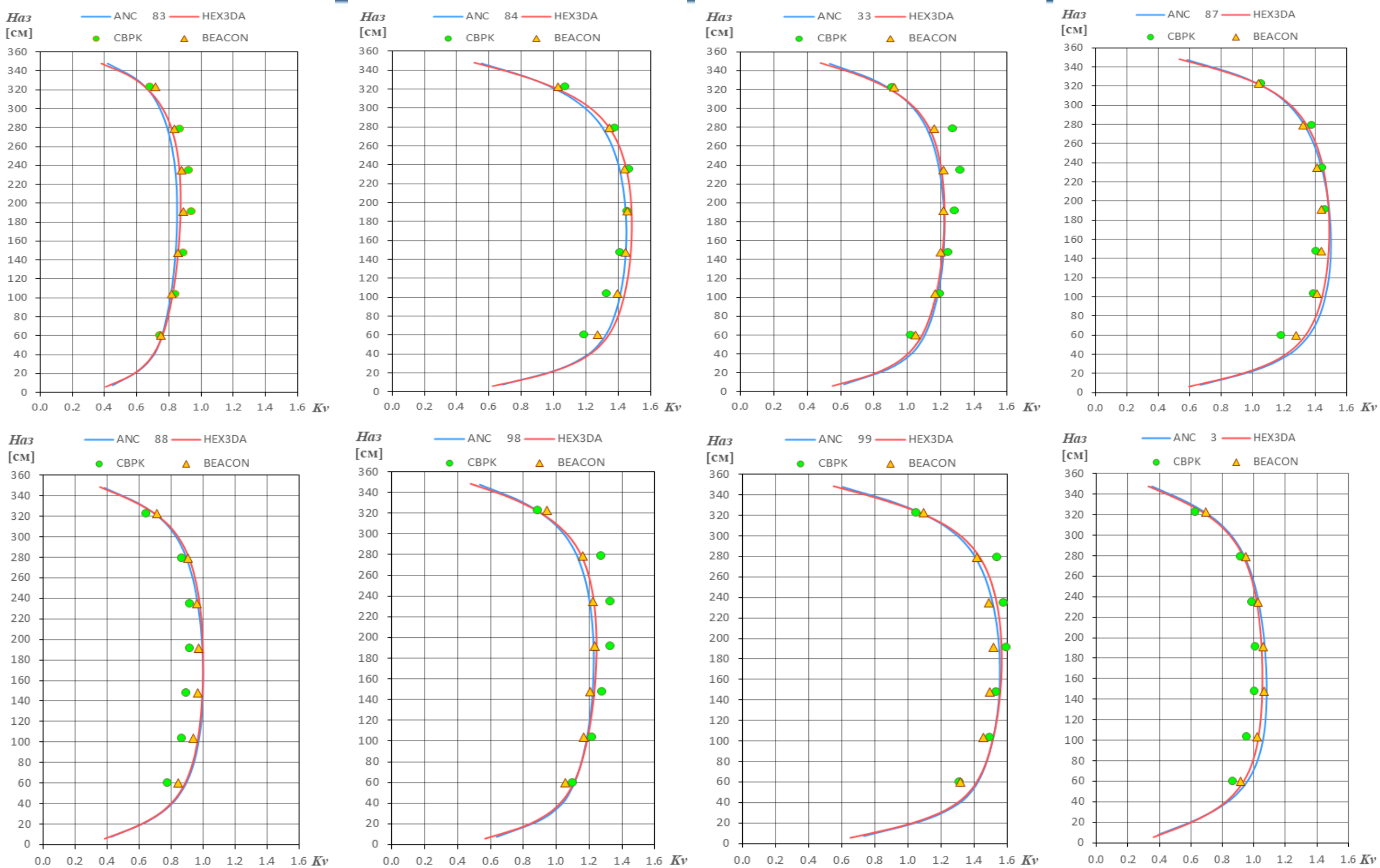


Fig. 28. Assembly nodal power distribution at 10.68fpd – U5/C32 (EXP/CALC)

11. APA-H SHELL

- APART is a standalone GUI application to quickly handle the majority of the input/output files necessary for APA-H runs.
- APART allows for parallel execution of PHOENIX-H for all user-defined regions in the core computational model.
- With APART any hot full power or cold zero power model for ANC-H can be produced by the user in just a few minutes.
- APART has an automated end of boron cycle search module and is also capable of simulating operation during coastdown until a user defined end of cycle.
- The GUI allows for an easy on-display assembly shuffle using cursor and mouse.
- The GUI can display power and burnup distributions as well as other results from the APA-H output files.

11. APA-H SHELL

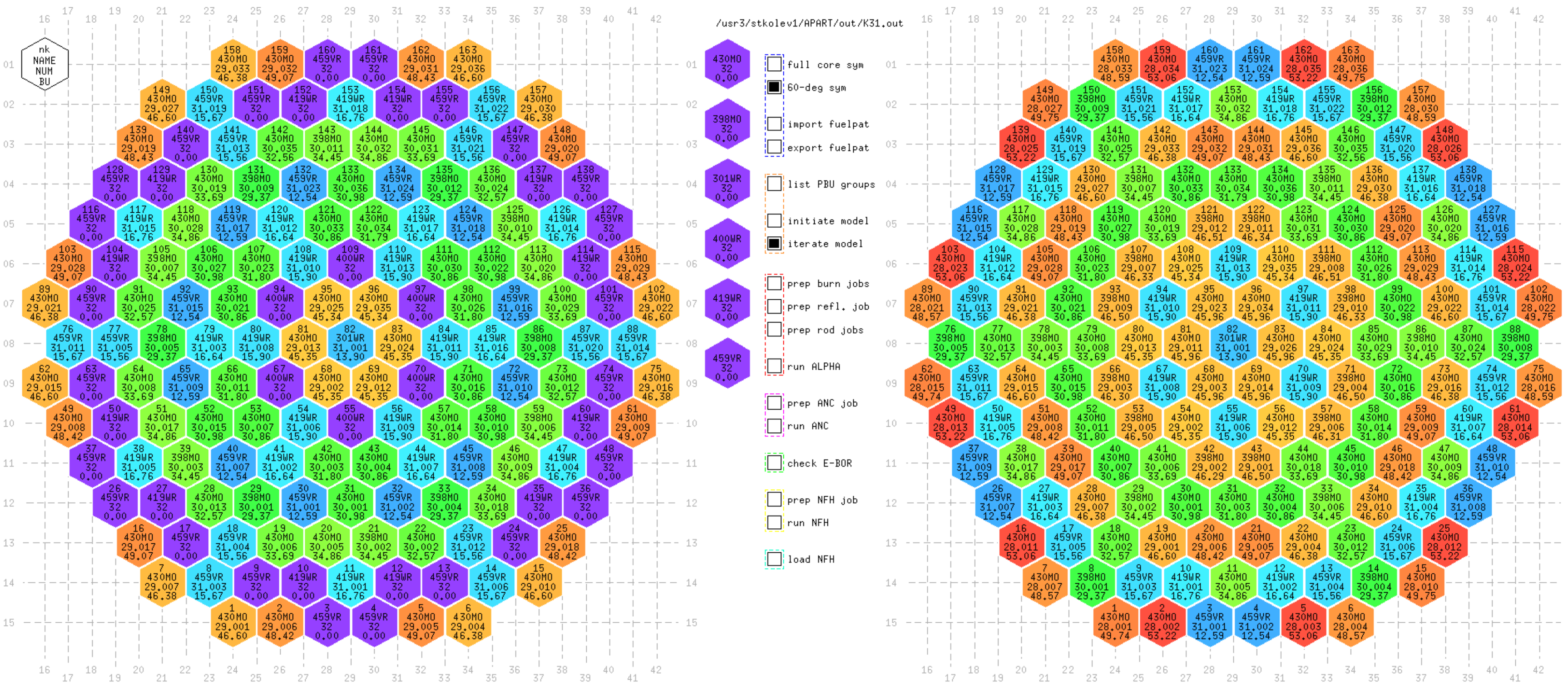


Fig. 29. APART - a shell for APA-H was developed at Kozloduy NPP by Dr. Srebrin Kolev

12. CONCLUSIONS

- Information about the experience of RWFA fuel implementation at the Kozloduy NPP Unit 5 is presented and discussed in the paper.
- The comparison between the **predicted** neutron-physics characteristics using APA-H and HELHEX – such as critical boric acid concentration; fuel assembly, fuel rod and fuel pin power distributions; fuel assembly burn-up distribution – shows a good agreement and acceptable differences of the results, all in the range of codes uncertainties.
- The comparison between the **measured/reconstructed** and APA-H and HELHEX calculated neutron-physics characteristics – critical boric acid concentration at HZP and full power; isothermal reactivity coefficient, working group worth, total control rods worth at HZP; fuel assembly and nodal relative power distribution – shows a very good agreement of the measured and calculated results using the two codes.
- **The two code packages APA-H and HELHEX can be independently used for the reactor core calculations with sufficient precision**.

THANK YOU FOR YOUR ATTENTION!