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HEU-LEU CORE CONVERSION AT BUDAPEST RESEARCH REACTOR

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Abstract
The core of the Budapest research reactor WWRS-M10 has been converted to low-enriched nuclear fuel. The conversion program has recently been completed successfully. The content and sequence of the implementation of this program are presented. The considerations for the optimal fuel selection are discussed. The licensing process is described. The results of necessary physical calculations and performed measurements are presented. The gained experience is summarized.

Keywords
WWR reactor, low-enriched Uranium fuel, core conversion, mixed core

1. INTRODUCTION

The USA Department of Energy (DOE) began the Global Threat Reduction Initiative (GTRI) in 2002. One of GTRI's programs was the core conversion from high enrichment fuel to the low enrichment fuel (< 20% U-235). From 129 Russian designed reactors, 51 reactors made the conversion; the deadline for the remaining 78 reactors is 2018. Hungary – in the framework of the trilateral international agreement – began the GTRI 2 program in 2005. In the framework of the Reduced Enrichment for Research and Test Reactors (RERTR) program, the core conversion from HEU fuel to LEU fuel was performed for the Budapest research reactor (BRR) WWRS-M10. The reactor physical calculations and the safety analyses have been performed by the Energy Research Centre laboratories in Budapest and the Argonne National Laboratory jointly and/or in parallel.The JSC TVEL provided the technical database for the LEU fuels, the BRR got similar conversion reports from the IAEA, the BRR Reactor Safety Committee evaluated the conversion steps elaborated the safety report and the Hungarian Atomic Energy Authority (HAEA) issued a regulatory permit after each of the conversion milestones. The first LEU fuel was introduced in the core in 2009. The purely low-enriched uranium fuel core was achieved throughout 4 mixed cores in 2013. The present paper describes the prerequisites and milestones of the core conversion performed at the Budapest research reactor.

2. FACILITY DESCRIPTION

The WWRS-M10 research reactor is a Soviet designed [1], tank type, water cooled and water moderated, thermal neutron reactor. The initial power was 2 MW_{th}. It turned critical in 1959. The main applications are neutron physics experiments and radioisotope production. The reactor equipment include the Iodine, Iridium and Molybdenum isotopes production facilities and the cold neutron source, the neutron radiography device, the prompt gamma activation and the time-of-flight spectrometry ports. The general views of the reactor are shown on Figures 1-4.

Over the years the reactor was modernized twice: in 1967 and in 1986-92. During the first upgrade, the original fuels (EK-10) were changed to 36% enriched fuels, the beryllium reflector around the core was built up and the reactor power was increased from 2 MW_{th} to 5 MW_{th}. In the second upgrade, each reactor system, subsystem and component (SSCs) was replaced and the reactor power was increased

Figure 1. Reactor site.

Figure 2. General view of reactor.

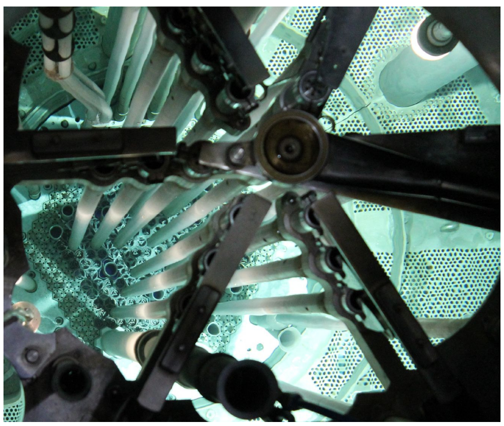

Figure 3. View (from above) of the reactor core.

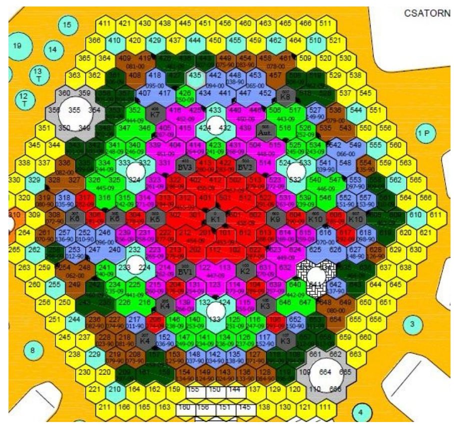

Figure 4. Core map with the different burn-up fuel groups.

replaced and the reactor power was increased from 5 MW_{th} to 10 MW_{th} [2]. The upgraded 10 MW_{th} Reactor received an operating license in November 1993, which will be valid until 2023. Since that time, the reactor has been operating an average ≈3500 hours/year without any significant problems. The main operational parameters of the reactor are presented in Table 1.

Since the restart, the reactor performed 64.000 hours and 26 GW days. The beginning of the HEU-LEU core conversion was during the 27th reactor campaign. One reactor campaign consists of 8-10 reactor cycles. One reactor cycle means 234 operational hours.

The BRR is located in the western part of Budapest, in the middle of a big research campus named KFKI (Central Research Institute for Physics). It hosts the radioisotopes laboratories, the particular accelerator, laser laboratory and nowadays the CERN computer network centre. The campus receives the new industrial technologies and wants to be a physical research centre in the future. This scientific background and the research reactor are necessary for the new Hungarian NPP units.

Table 1. Main reactor parameters

Parameter	Value
Thermal neutron flux (n/cm^2s): - maximal - average in the core - on the core edge	 2×10^{14} 6×10^{13} 2×10^{13}
Fuel: - HEU core: - LEU core:	 VVR-SM (36%); VVR-M2 (36%); VVR-M2 (19,7%)
Fuel number (pc) - HEU core: - LEU core:	 228 190
Power (MW_{th})	10
Maximum coolability (MW_{th})	20
Coolant agent/moderator:	ion changed light water
Reflector:	Beryllium; ion changed light water
Primary water outlet temperature (°C):	50
ΔT (°C):	5
Horizontal channels	8 radial, 2 tangential
Irradiation channels	~40 pc

3. CONVERSION PROJECT PRE-REQUISITES

As a result of a trilateral discussion between the USA, the Russian Federation and the IAEA, a project to repatriate the research reactor fuel of Russian origin was launched in 2004. The project, named the Russian Research Reactor Fuel Return Programme (RRRFRP) was supported and coordinated by the US Department of Energy. The AEKI (Atomic Energy Research Institute) signed a contract for site preparation at the end of 2005. After signing this contract, two projects were started in the same year. The first contract was for the site preparation for the transfer of Russian origin HEU SNF (spent nuclear fuel) from the reactor, while the second contract was for the preliminary analysis for core conversion from HEU to LEU.

Hungary accepted and implemented these international requirements although there has never been any defect, corrosion or any kind of incident with the 36% of enrichment fuel and every core parameter (neutron flux, fuel burn up, length of cycles and campaigns) was optimal..

There have been three Hungarian organizations participating in this project: the Hungarian Academy of Sciences as the owner; the Centre for Energy Research[1] as the operating organization and the Hungarian Atomic Energy Authority - the regulatory body. The Battelle Energy Alliance (USA) provided the funding and the JSC TVEL (Russian Federation) offered the possible fuel options.

The necessary amendments to the safety documentation and to the reactor physics calculations had to be determined.. A preliminary time schedule had to be determined in order to limit the HEU fuel burn-up and the time spent in the active core. Moreover, the minimal cooling-off time for the spent fuel before transhipment back to the Russian Federation had to be determined. The reactor time schedule had to be adjusted taking account of the isotopes production needs and the research projects in progress . Last but not least, the operational staff had to enough time for the maintenance.

4. FUEL TYPE SELECTION

The first step was the choice of the ideal fuel type. On the basis of operational experience, as well as of international practice, the requirements for the possible fuel types aimed for further reactor operation were formulated. The basic criteria [3-4] were the following:

- adequate geometry;
- suitable nuclear parameters;
- high burn-up (60%);
- 900 MW days performed energy pro campaign;
- 5 years in the core.

The drawing of the WWR-M5 assembly is shown on Figure 5 and the parameters for the two suitable candidate fuel types identified are presented in Tables 2 and 3. Both LEU fuel types satisfy the neutron physics demands and finally the BRR decided on the VVR-M2 type because the fuel cladding thickness is greater.

Further advantages of the VVR-M2 fuel include [5]:

- Suitable for 100 kW – 30 MW reactors fuel;
- Used in 30 reactors in the Russian Federation, Asia and East-Europe;
- Tolerates well the water flow rates and the pressure drops;
- Can build up high flexibility and variety cores;Suitable neutron fluxes (T_{mod}= 50 °C) in the beryllium reflector and the active core for the isotope production, the silicon doping and the material testing.

5. LEGAL BACKGROUND AND LICENSING PROCESS

The first step was the HAEA's decision-in principle permit for 2000 pc VVR-M2 LEU fuel purchase in 2007. The trilateral contract between the Battelle Energy Alliance (USA); the MTA KFKI AEKI and the JSC TVEL (Russian Federation) on 396 pc LEU fuel purchase followed this permit [6-7]. The contract included the Factory Acceptance Test (FAT) and the Site Acceptance Test (SAT) according to BRR quality assurance (QA) programme [8]. An important milestone was the HAEA core conversion permit in 2009. The permit comprised of 15 proceeding steps, 3 hold points and 4 authority intervention points. For obtaining permission to proceed beyond the hold points and the intervention point, approval was needed from the Reactor Safety Committee and from the HAEA.

[1] Earlier name is Atomic Energy Research Institute /AEKI/

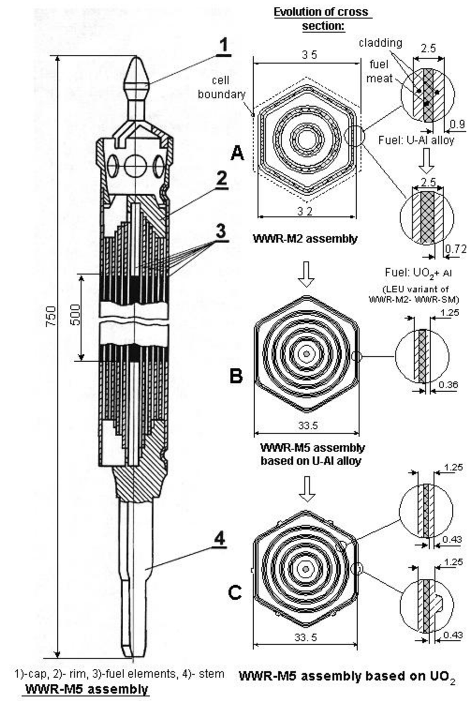

Fig. 5 Fuel drawing and cross sections

Table 2. Possible fuel parameters

Parameters	Fuel type	
	VVR-M2	VVR-M5
Enrichment (%)	19.75	90*
^{235}U average mass in the fuel (g)	41.7	66
Fuel element thickness (mm)	2.5	1.25
Uranium density in the fuel (g/cm^3)	2.5	1.21
Cladding thickness (mm)	0.72	0.43
Fuel	UO_2+Al	UO_2+Al
Unit heat convection surface/unit value (cm^2/cm^3)	3.55	6.6
Average hydraulic diameter (mm)	6	3.1
Density ^{235}U (g/l)	79	125

*Planned 20% enrichment UMo fuel type in the 2007.

Table 3. Comparison the HEU and LEU fuels

Parameter	Fuel		
	VVR-SM	VVR-M2	VVR-M2
Enrichment (%)	36	36	19,75
Cladding material	Al (SAV-1)	Al (SAV-1)	Al (SAV-1)
Cladding thickness (mm)	0,9	0,75	0,75
Fuel element thickness (mm)	2,5	2,5	2,5
Fissionable material composition	UAl_4 eutectic	UO_2+Al	UO_2+Al
Fissionable material thickness in the fuel element (mm)	0,7	1	>0,7
Number of elements in the fuel assembly	3	3	3
Nominal active length (mm)	600	600	600^{+20}_{-30}
Heat convection surface (m^2)	0,232	0,232	0,232
Average ^{235}U mass (g)	38,9	44	50,0±2,5
H/U ratio in the cell	235	208	183

The conversion was performed in accordance with the BRR QA programme. The programme main chapters included:

- The BRR QA work programme;
- The conversion phases and steps;
- Contents of repeated tasks;
- Time schedule;
- The staff education and training programme.

The conversion hold points and intervention points were:

- LEU fuel Site Acceptance Test;
- Conversion process from HL1 to HL4 campaigns;
- Test campaign;
- Obtaining the operating license.

The operators had to keep a record of every observation, every uncommon event in the operational diary and established a summarizing database. This database included the reactor physics, dosimetry, water chemistry data and the events. The Reactor Safety Committee evaluated every first cycle of HL and LEU campaigns.
The Reactor Safety Committee also made a general evaluation after the end of campaigns and send a report to the HAEA.
The HAEA evaluated the report, approved it and gave the permit for the next phase.

It was ensured that the project steps are transparent and clear for every participant: for the operators, for the researchers and for the management.

6. DOCUMENTATION AMENDMENT AND THE REACTOR PHYSICS CALCULATIONS

The Final Safety Report [9] with the Safety Analyses Report (SAR) of the mixed and the LEU cores had to be completed. The following task was the changing of the technological parameters of response matrixes (subroutines). The reactor physical calculations were made with the KIKO3D programme [7] and were validated by ANL DIF3D programme [6]. The KIKO3D reactor dynamic programme was used for the safety analyses of reactivity transients. Applying this programme was acceptable for the type of reactivity incident/anomaly when the power distribution change on both radial and axial directions . During the calculation the time dependent diffusion equation was solved by nodal method in 3D [5].

In parallel with the KIKO3D, the ATHLET thermo hydraulic programme was run which determined the coolant agent density and temperatures. The MULTICELL programme gave the nuclear particle’s parameters (nuclear group factors) for the KIKO3D. The ANL used for this purpose the WIMS software. The final step was the completion of the Operational Limits and Conditions (OLCs) [7] revised with the LEU fuel parameters. The changing and the supplementation of the fuel handling procedures was also performed.

7. THE CONVERSION BOUNDARY CONDTIONS

Requirements for the core build-up strategy were determined as following:

- Shutdown reactivity not less than 2 % (2,5 $);
- The reserve reactivity on the beginning of a campaign will be enough for the operation and the isotope production;
- Fuel burn-up maximum of 70% and the time spent in the core of maximum 5 years;
- Operation within the OLCs ;
- Aim for the maximum fuel burn-up;
- Aim for the maximum neutron flux in the irradiation channels;
- The fine rod reactivity worth should be of 0,7$ - 1$;
- Aim for the equilibrium core.

The final results of the calculations and the iterations performed satisfied the requirements; they are within the OLC and suitable for the operators and the beam users. The length of cycles and the reactor time table is the same as it was earlier.

<u>Campaigns and cycles for the conversion:</u>

- 4 mixed core (HL) and the 5th LEU core as the test campaign,
- The mixed cores contents was of 228 fuel elements and the LEU core contents was of 190 fuel elements,
- The mixed cores contained 6 different burn-up fuel age groups (6 x 38 = 228) and the LEU cores contenained 5 different burn-up fuel age groups (5 x 38 = 190).

Table 4. Campaigns main data

No	Fuel composition			Reactor operation			Fuel campaign	
	NF	*HEU*	*LEU*	*cycles*	*hours*	*energy (MW×day)*	*begin*	*end*
28	228	190	38	8	1871	783	December 2009	June 2010
29	228	152	76	11	2574	1072	October 2010	May 2011
30	228	114	114	12	2809	1173	June 2011	March 2012
31	228	76	152	10	2310	968	April 2012	November 2012
32	189	0	189	10	2419	978	February 2013	September 2013

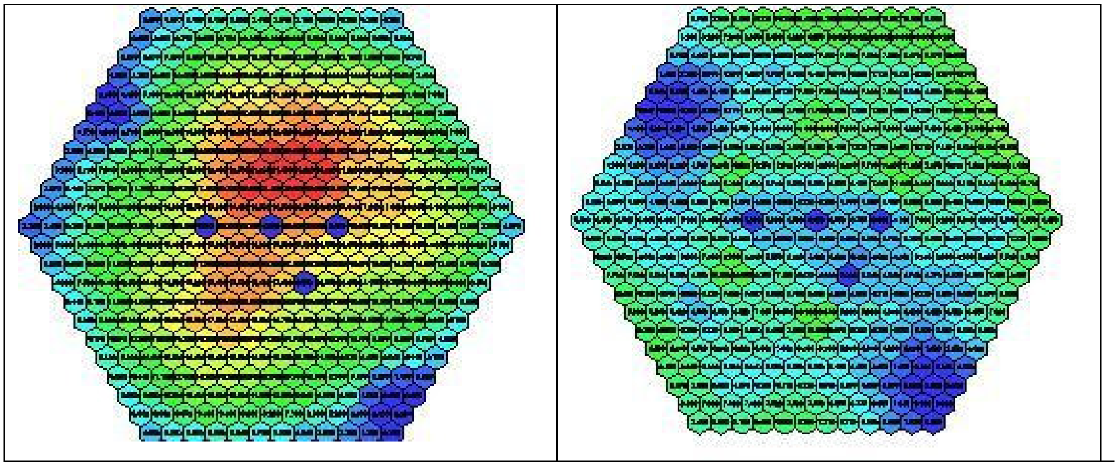

Fig. 6 Fast- and thermal neutron flux distribution at N30 campaign /HL core/

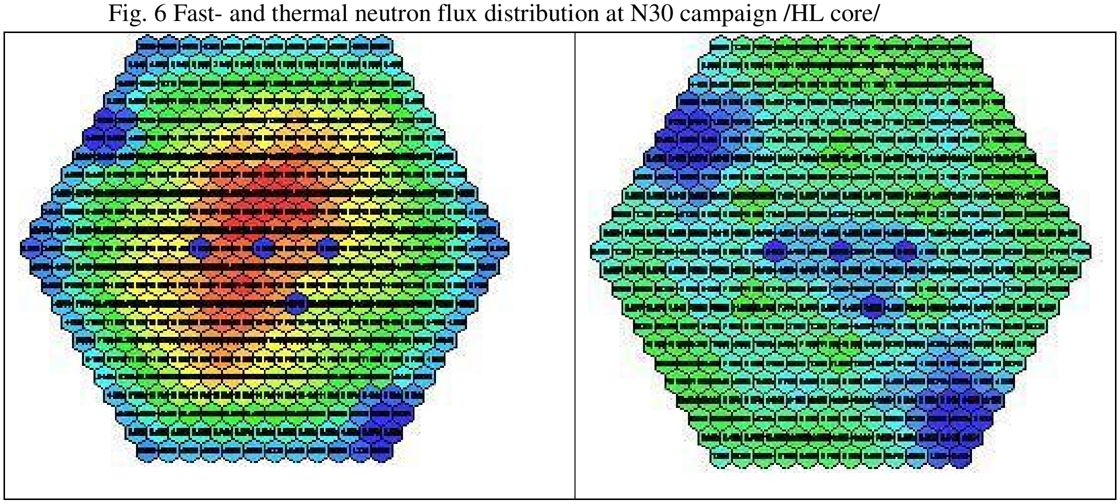

Fig. 7 Fast- and thermal neutron flux distribution at N33 campaign /LEU core/

The core shuffling, the core refuelling and the control rods moving strategy is different from the others WWRS reactors. The first cause is that the control rods number is 18. The second cause is that in the core there are two fast irradiation channels with boron filters. The core shuffling strategy main principle is the equal neutron flux and the maximum fuel burn-up, so the fresh fuels is put in the edge of core and at first the edge control rods are moved. Following are the control rods on the middle circle and last step involves moving the central rod. The fuel groups moving involves the following:

- The fresh LEU fuel group (X generation) gets on the edge of the core,
- The older HEU or LEU fuel group (X-1 generation) gets on the core centre,
- From X-2 to X-5 the fuel groups move from centre to the edge,
- In the pure LEU core, the edge of core has beryllium elements.

8. STEPS OF CONVERSION

The BRR experts made a reception inspection at Novosibirsk Chemical Concentrates Plant (NCCP) in April 2009. After this came the reception inspection in Budapest with the Russian experts.

Next step was the reactivity change measurement with one LEU fuel element in September 2009. Two reactor start-ups happened and the changes in the reactivity worth were measured. The reactor operated on automatic minimum power level (~50 kW). The reserve reactivity worth was 663% (829 ¢). The following step involved the 441-09 number LEU 3 elements fuel put into 635-636-643 core position. The second automatic power level reserve reactivity worth was 674% (843 ¢). The cause of the difference was the LEU fuel was fresh and the HEU fuel already burntup. The HEU and LEU fuel elements reactivity worth change was equal to the calculation, $\Delta k/k = 0{,}9$ ‰.

The main data for different campaigns are presented in Table 4. The reactor operation was the same during the conversion as in the previous HEU campaigns. The reactivity-moderator temperature relations and the reactor poisons (Xe, Sm) concentration (equilibrium and after shutdown) of LEU core measurements were repeated.

The steps of core shuffling and core refuelling were the same than earlier. Only the last campaign differed from the previous campaigns, because the core size was reduced and had to put extra beryllium elements in the core edge. Moreover the highest irradiation channel was moved into the core central area.

The operational staff took more often water samples and gathered the information from the reactor users. Unfortunately during this period the radioisotope production was low: only 15-20 capsules ^{60}Co and some aluminium-silicate in the fast irradiation channels. The feedback of beam users was good and they did not find any significant deviation.

Every beginning of new HL and LEU core measurements were performed for the gamma- and neutron dose rates around the biological shield and the reactor hall and the airborne concentration in the chimney. The frequency of the water samples measurement from the primary loop and the spent fuel store tank was increased.

There have been four mixed cores operating from December of 2009 to November of 2012. The last campaign of the conversion was a pure LEU core as a test campaign from February 2013 to September 2013.

Summing up, no abnormal events / deviations happened during the conversion and the length of cycles, the reactor parameters and the radiological data were the same as before.

The fast and the thermal neutron flux distribution are visible in the Figures 6 and 7. It can be seen that they almost coincide with each other.

9. MEASUREMENTS DURING THE CONVERSION

The methods for the failed fuel detection are the airborne concentration measurement and the primary water fission products analyses. During the conversion, the frequency of the samples was increased in comparison to the normal operation and analyses were performed according to the following programme. Water samples were taken during the reactor cycles:

- before reactor start-up;
- on the 4th day of operation;
- on the 5th day filtering by mixed ion changed resin;
- on the 9th day take the sample after filtering 4 hours by mixed ion changed resin;
- on the 10th day take a sample after reactor shutdown.

Primary water limits were as follows[10]:

- Activity: 40 MBq/l;
- Electro conductivity: 2 μS/cm;
- pH: 5.5÷6.5;
- Cl ion concentration max.: 5×10^{-5} g/kg
- Cu concentration max.: 1×10^{-5} g/kg
- Al concentration max.: 5×10^{-5} g/kg
- Fe concentration max.: 5×10^{-5} g/kg

The fission and the corrosion elements concentrations stayed under the limits; no significant difference was found. Although the primary loop has a large number of elements, the concentration is very low (Table 5). The noble gases were measured by gamma spectrometry. The Krypton or Xenon isotopes were not detec-.ted; the isotope 41-Argonne originated from the primary water and the concentration was the same as during the normal operation.

10. CONCLUSIONS

The core conversion at the BRR was completed successfully and all planed tasks have

Table 5. Corrosion products in the primary water

Corrosion product	Core composition					
	HEU		*mixed*		*LEU*	
	(mg/kg)	SD (%)	(mg/kg)	SD (%)	(mg/kg)	SD (%)
Al	8.71	4.8	3.11	5.1	3.29	5.2
Ba	1.00		1.00		1.00	
Br	0.02	9.5	0.13	8.9	1.79	6.1
Ca	6.78	9.1	7.98	6.9	1.79	6.1
Cl	8.95	11.1	13.7	8.1	9.92	5.2
Cr	1.23	8.7	0.97	8.9	< 0.1	
Cu	0.45	8.7	0.24	11.4	0.26	5.8
Fe	< 5		< 5		< 5	
K	< 10		5.11	12.9	37.7	6.9
Mg	5.00	12.7	4.56	11.7	3.90	8.2
Mn	0.68	4.8	0.19	9.1	0.41	5.8
Na	4.64	4.7	13.7	6.1	22.2	4.6
V	< 0.01		< 0.01		< 0.01	
Zn	0.98	7.5	0.78	9.6	0.92	9.6
mg_{ekv}/L	**0.76**		**0.79**		**0.42**	

been performed. This conversion will provide a safe reactor operation during next years.

The experience gained may be briefly summarized as follows:

- we did not find significant any deviation in the neutron flux distribution between HEU; HL and LEU cores;
- although they did not measure the neutron flux at the end of beam shutters, the researchers did not find deviations at their neutron physics devices;
- the control rods' reactivity worth remained the same;
- the LEU campaign with 190 pc fuel elements is not shorter than the HEU campaigns with 228 fuel elements;
- as in the Reactor Safety Committee final statement, the conversion was made according the programme without any kind of modification or alteration;
- HAEA issued the operating licence at November 2013;
- an event: the number 241-09 LEU fuel head was damaged during the core shuffling in January 2013; a beryllium element was introduced in the core instead of the damaged fuel; the N° 32 campaign operated with 189 fuels.

Summing up, the conversion of the Budapest RR to LEU fuel was an important milestone and a successful project for the reactor's 55 years lifetime. The reactor owner and the operating organization have plans for safe operation on the long term and for important material test project in the near future, as well as for a boost in the radioisotopes production.

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