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HEU/LEU-Conversion of BER II successfully finished

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Abstract

The BER II (**B**erliner **E**xperimental **R**eactor) research reactor is a swimming pool type reactor located in Berlin, Germany. The reactor operates with a thermal power of 10 MW and is primarily used to produce neutrons for neutron scattering experiments.

The conversion from HEU- to LEU-fuel elements began in August, 1997. At the last RERTR-Meeting 1999 in Budapest, Hungary, Hahn-Meitner-Institut (HMI) presented a "Status Report" on the conversion of 10 HEU/LEU mixed cores. In February 2000, HMI finished the HEU/LEU-conversion. Hereby, the first pure LEU-standard-core went into operation.

Our second LEU-core just ends its operation at the end of July. The third LEU-core will be built up in the beginning of August. The average burn-up rate was improved from 50 - 55% (HEU) to 60 - 65% (LEU). Therefore, only 14 elements/year are now used instead of 28/year.

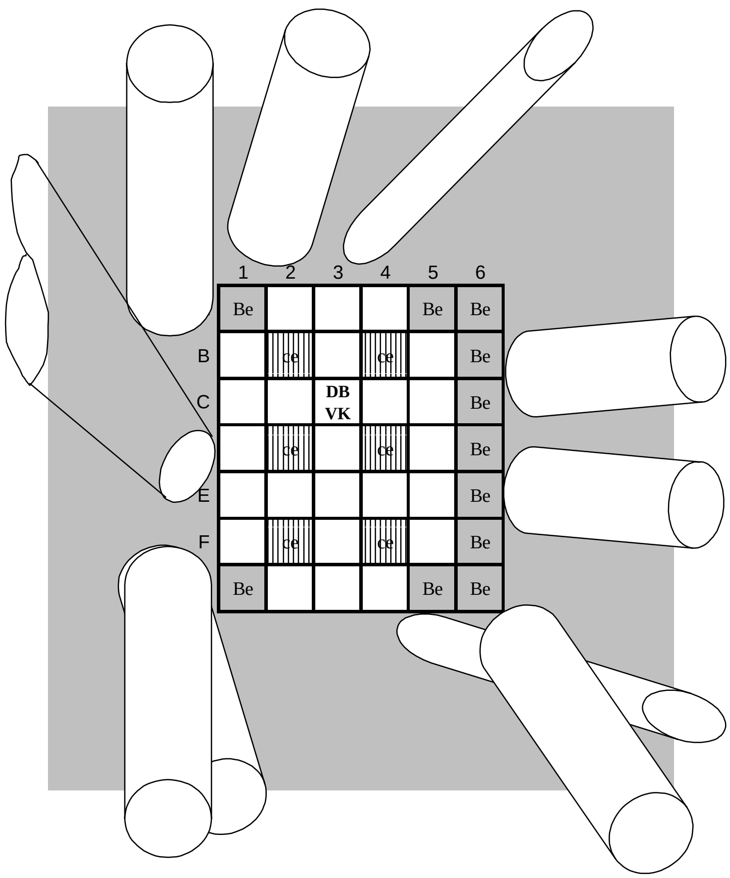
The following report describes our first steps in building pure LEU-cores from mixed HEU/LEU-cores, as well as our initial experience using the pure LEU-cores.

DESCRIPTION OF BER II

The BER II is equipped with a Cold Neutron Source. There are 9 experiments at 9 beam tubes working with thermal neutrons and 15 experiments at 6 neutron guides providing cold neutrons as well as 3 irradiation devices inside the core and the beryllium reflector respectively. Two irradiation devices in core as well as in reflector position are equipped with a rotating and oscillating sample carrier. Furthermore, there are one dry irradiation device and one fast pneumatic transfer system. One irradiation device is used for neutron-autoradiography of paintings.

The core lattice is a 6x7 array containing 24 standard fuel assemblies with 23 fuel plates and a fissile loading of 322 g U-235, 6 control fuel assemblies with 17 plates and 238 g U-235, 11 beryllium reflector elements and one irradiation device. The core lattice is surrounded by a beryllium reflector block. Core and beryllium reflector block with the beam tubes, the Cold Neutron Source and the in-core irradiation device are shown in figure 1.

The reactor is among other equipped with four neutron detectors recording the flux density by power operation. They are located at every edge of the core, respectively. So one can detect flux variations in the core, which can occur by different control rod positions, for example.



ce: control fuel element
Be: Beryllium reflector element
DBVK: in-core irradiation device

Figure 1: LEU standard core with beryllium reflector block, beam tubes, Cold Neutron Source and in-core irradiation device

HISTORY OF CONVERSION AND THE ACTUAL SITUATION

The transitional period with mixed cores of HEU and LEU lasted 2.5 years. The reactor has been safely operated with ten mixed cores composed of different number of fuel elements and different absorber materials. Currently, the 3rd LEU standard core is in routine operation.

The schedule of HEU / LEU conversion activities are described in detail in our previous paper reported in Jackson Hole [1]. Status reports after seven respectively ten mixed cores were presented in São Paulo [2] and in Budapest [3].

The gradual conversion to LEU started in August 1997 and ended after 2.5 years in February 2000. Hereby, the core size was reduced from 31 to 24 standard fuel elements by replacing the fuel elements with beryllium reflector elements. At this way, we shifted the neutron flux density to our Cold Neutron Source. The number of 6 control fuel elements retained unchanged, only the positions of 3 control elements were changed from B5, D5 and F5 to B4, D4 and F4. The absorber material changed within the sixth mixed core from AgInCd to Hafnium.

The time necessary for doing the measurements of the conversion work was all together 4.5 months. After doing the measurements, one week of maintenance was scheduled. Within this week, the measurements were evaluated and the licensing authority released for power up.

The operating schedule consists of 12 cycles of 3 weeks, followed by one week maintenance. Operating with HEU, the fuel consumption was about 28 elements per year. Now, operating with LEU, the consumption is due to a higher burn-up reduced by 50% to about 14 elements per year.

The average burn-up from the whole core increased from about 30% (HEU standard core, EOC) to about 40% (LEU standard core, EOC).

The licensing manual is now shortened compared with building up a new HEU/LEU mixed core. For building up a new LEU standard core, it is no more necessary to determine the coolant flow, the underpressure for the primary coolant circuit as well as the changing reactivity by pouring the beam tubes and by driving in the in-core irradiation device.

The most important points are calibration of the control rods and thereby determination of shut down safety and maximum changing reactivity and determination of flux mapping for balanced and distorted control rod positions with location of the hot channel and proof of burn-out safety.

Time necessary for reloading the LEU core now takes one week.

Tab.1 shows the timetable for all mixed cores and the three LEU cores. The different core numbers are founded on fact that, every time a core went critical, it was given a unique core number, even when loading the core continued.

Tab.1: Period of Time each Mixed Core as well as each LEU Core was in Operation, changed Elements and produced Power in MWd

	1st mixed core	2nd mixed core	3rd mixed core	4th mixed core	5th mixed core	6th mixed core	7th mixed core	8th mixed core	9th mixed core	10th mixed core	1st LEU core	2nd LEU core	3rd LEU core
core no.	39	40	41	42 / 43	44	45 / 46	47 - 49	50 / 51	52 - 57	58 - 61	62 - 64	65 / 66	67 / 68
fresh LEU st.el.	3	3	-----	4	-----	2	4	1	3	2	2	4	4
fresh LEU c.el.	-----	-----	-----	-----	-----	4	-----	-----	-----	2	-----	-----	2
fresh HEU c.el.	-----	-----	2	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
new Be refl. el.	2	-----	-----	3	-----	-----	2	-----	-----	-----	-----	-----	-----
conver-sion and mainte-nance	97-08-04 until 97-08-26	97-10-24 until 97-11-10	97-11-24 until 97-12-08	98-01-12 until 98-01-26	98-02-23	98-04-01 until 98-06-30	98-08-31 until 98-09-21	98-12-14 until 99-01-18	99-04-06 until 99-04-27	99-08-23 until 99-09-13	00-01-24 until 00-02-06	00-04-27 until 00-05-05	00-07-31 until 00-08-06
running from	97-08-26 until 97-10-19	97-11-10 until 97-11-23	97-12-08 until 98-01-10	98-01-26 until 98-02-15	98-02-23 until 98-03-15	98-06-30 until 98-08-30	98-09-21 until 98-12-12	99-01-18 until 99-04-01	99-04-27 until 99-08-22	99-09-13 until 00-01-22	00-02-07 until 00-04-20	00-05-08 until 00-07-30	00-07-08 up to now
EOC in MWd	398.2	113.7	163.8	184.6	201.3	314.5	556.1	570.9	786.4	855.7	550.0	574.3	

REACTOR PHYSICS

Changing the absorber material from AgInCd to Hafnium within the 6th mixed core resulted in a significant increase of the control rod worths.

Shut down safety is demanded for at least 1% $\Delta k/k$ (taking into account experiments) and is defined as follows:

reactivity worth of all control rods
minus the reactivity worth from the most effective control rod
minus excess reactivity

Fulfilling this demand is no problem. With an excess reactivity of 10%, the reactor can go in operation for about 1000 MWd corresponding to 4-5 cycles with 3 weeks operation time each.

The maximal changing reactivity velocity may not exceed 0.0292 % $\Delta k/k$ / s. With the hafnium absorber, the greatest values amounted 0.019 % $\Delta k/k$ / s which is far away from the limit.

Control rod calibration at BOC as well as EOC was done within the 1st LEU core. The critical position of the control rods was 329 mm at BOC and 536 mm at EOC. The whole length in end position amounts 600 mm. The percentage decrease of control rods reactivity worths extends from minus 2.2% for rod no. 1, which is the most ineffective rod, to minus 7.0% for the most effective rod no.4. The worth for all control rods is lowered from 16.65 % $\Delta k/k$ to 15.88 % $\Delta k/k$ which corespondents to a percentage decrease of minus 4.6%.

Table 2 shows the reactivity worths for the mixed cores with exception of the 5th mixed core as well as for the LEU cores. In the 5th mixed core just 2 HEU standard fuel elements with a high burn-up were replaced by 2 HEU standard elements with a low burn-up. All LEU elements remained in their positions. With permission from licensing authority and TÜV, the licensing manual was reduced to consideration of the reactivity balance.

THERMOHYDRAULICS

The procedure for detecting the hot channel and burn-out safety was presented in our last report held at the RERTR-Meeting in Budapest [3]. The demanded minimum burn-out safety is 1.42. Up to now, copper wire measurements for balanced and distorted control rod positions were done for every new core. The activation of the copper wires is carried out at 1.5 kW with about 50 wires per core. With the determined neutron flux distribution and the mass of fissile material, the hot channel can be located.

Burn-out safety is calculated for three cases. In the first two cases it is supposed, that one of the three primary cooling pumps fails which is immediately followed by reactor scram. The power will reach 113 % of the maximum power. The calculations are performed with the coolant flow and coolant velocity reached by two pumps. Furthermore, this case is divided into operation with balanced rod position and with distorted rod positions. In the last case, the most effective control rod is completely driven out and the opposite rod is fully driven in.

Tab.2: reactivity of the control rods, excess reactivity and shut-down safety

control rods worths [% $\Delta k/k$]	1st m.c. core 39	2nd m.c. core 40	3rd m.c. core 41	4th m.c. core 43	6th m.c. core 46	7th m.c. core 49	8th m.c. core 51	9th m.c. core 57	10th m.c. core 61	1st LEU-core 64 BOC	1st LEU-core 64 EOC	2nd LEU-core 66	3rd LEU-core 68
rod no. 1	2.20	1.79	1.19	1.91	2.50	2.09	2.66	1.98	2.35	2.27	2.22	2.21	2.46
rod no. 2	1.33	2.49	2.04	1.82	2.79	2.35	2.78	2.45	2.92	2.70	2.57	2.84	2.02
rod no. 3	2.47	1.74	1.53	2.19	2.54	2.61	2.74	2.42	2.79	2.75	2.68	2.49	2.82
rod no. 4	1.73	2.52	2.66	2.29	2.77	2.77	2.83	2.87	3.41	3.44	3.20	3.39	2.05
rod no. 5	2.84	1.95	2.10	2.62	2.96	3.46	2.72	2.96	2.80	2.63	2.51	2.56	3.21
rod no. 6	1.92	2.19	3.13	2.69	2.98	3.47	2.92	3.30	3.22	2.86	2.70	2.74	2.69
worth of all control rods [% $\Delta k/k$]	12.49	12.68	12.65	13.52	16.54	16.75	16.65	15.98	17.49	16.65	15.88	16.23	15.25
excess reac-tivity [% $\Delta k/k$]	6.59	4.28	5.95	5.96	7.77	11.18	8.50	8.88	10.47	7.56		7.66	8.76
shut down safety [% $\Delta k/k$] required: > 1 % $\Delta k/k$	3.05	5.88	3.56	4.87	5.79	2.11	5.23	3.80	3.60	5.64		5.17	3.30

For all mixed cores as well as for the three pure LEU cores, the distorted control rod position is limited. The most effective rod is not fully drawn out but only 100 mm above the four remaining rods. The opposite rod is fully driven in.

The third case assumes power-trip to 125 % of the maximum power as a result of start-up accident. Hereby, according to single mistake criteria, operation with three pumps is the basis for the calculations.

With respect to burn-out safety, the limiting case is always the second one.

In table 2 are the location of the hot channel, the power peaking factors, the values for η, the flux skew factor and the maximum power for all mixed as well as LEU cores stated.

The critical value for η amounts to $\eta_c = 32.83\ cm^3.K.J^{-1}$.

When loading fresh control elements, the hot channel is located there like in the 6th and 10th mixed core and the 3rd LEU core. In the other cases, one finds the hot channel towards the beryllium reflector elements.

When changing fuel elements, spent fuel elements are discharged from the center, highly burned-up elements are moved towards the core center and fresh fuel elements are inserted outwards. Fresh fuel elements as well as elements with little burn-up should not be placed directly to the reflector elements because the hot channel is then located towards the reflector elements and the criteria burn-out safety will be fulfilled only with reduced power.

Within the 1st pure LEU core, 4 fresh standard elements were loaded in the positions A3, C1, E1 and G3. The same procedure happened by building up the 2nd and the 3rd LEU core, respectively. In the case of the last one, two fresh control elements were furthermore put in B4 and F2.

Flux measurements were done for the first LEU core at BOC and at EOC for the case of balanced rod positions. Concerning the axial form factors, no changes occurred.

With two exceptions, the radial neutron flux density didn't change, too. In the case of element A4, the radial flux form factor was lowered from 0.92 to 0.89 and in the case of element G3, the maximum increase was from 0.79 to 0.82 in the middle fuel plate 14. Whereas, according to burn-up, the radial power peaking form factors changed from BOC towards EOC.

The values for the mean radial power peaking form factors BOC and EOC for core no. 64 are shown in figure 2. In the high burned-up elements (burn-up > 45 %), the factor increased up to 7.3%, whereas in the fresh elements and in the less burned-up elements, the factor decreased up to 6.2%.

Figure 3 shows the burn-out safety for balanced rod positions at BOC and EOC as well as for distorted rod positions at BOC. It is evident, that the limiting case is the one with distorted rod positions.

Tab.3: Thermohydraulics of all Mixed Cores and LEU standard cores

	1st mixed core	2nd mixed core	3rd mixed core	4th mixed core	5th mixed core	6th mixed core	7th mixed core
no. of fuel plates	769	769	769	700	700	700	654
hot channel	G2-1	D6-22	D6-22	G2-1, F1-21	-----	F4-1 (F3-22)	F5-22
power peaking form factors radial – axial *	2.05 – 1.36 2.55 – 1.32	2.09 – 1.23 2.43 – 1.28	----- 2.25 – 1.33	1.99 – 1.74 2.20 – 1.47	-----	2.26 – 1.91 3.04 – 1.68	1.71 – 2.05 1.94 – 1.70
burn-out safety (hot spot)* required: > 1.42	2.09 1.56	2.15 1.55	----- 1.87	1.65 1.62	-----	2.11 1.43	1.78 1.74
flux skew factor due to distorted control rods	15.0% no. 5 and 2	14.4% no. 4 and 5	14.6% no.6 and 1	16.2% no.5 and 2	-----	15.3% no.6 and 1	14.9% no.6 and 1
max. power [MW]	9.5	10	10	10	10	7	10

	8th mixed core	9th mixed core	10th mixed core	1st LEU core BOC	1st LEU core EOC	2nd LEU core	3rd LEU core
no. of fuel plates	654	654	654	654	654	654	654
hot channel	B5-23, G4-23	F5-23, G4-23	F4-4	B5-23	B5-23	B5-23	F2-20
power peaking form factors radial – axial *	1.67 - 1.77 2.03 - 1.41	1.84 – 1.84 2.45 – 1.37	1.59 – 1.86 2.12 – 1.81	1.71 – 1.76 1.97 – 1.70	1.66 – 1.76 -------	1.79 – 1.71 2.14 – 1.83	1.57 – 1.98 2.18 – 1.69
burn-out safety (hot spot)* required: > 1.42	2.09 1.82	1.86 1.46	2.24- 1.43	2.07 1.64	2.17 -------	1.98 1.44	2.21 1.47
flux skew factor due to distorted control rods	18.9% no. 6 and 1	15.3% no. 6 and 1	14.4% no.6 and 1	14.8 no. 4 and 5		12.9% no. 4 and 5	14.5% no. 5 and 2
max. power [MW]	10	9.7	9.9	10		9.6	9.8

*: first value: balanced rod positions
second value: distorted rod positions

	1	2	3	4	5	6
A	Be	0.84 0.84	1.20 1.14	0.97 0.94	Be	Be
B	0.82 0.84	1.10 1.06	0.85 0.88	0.79 0.79	1.27 1.24	Be
C	1.30 1.22	0.96 1.01	**DB** **VK**	1.06 1.10	1.41 1.37	Be
D	0.82 0.85	0.89 0.90	0.82 0.88	0.86 0.88	1.23 1.23	Be
E	1.32 1.25	0.71 0.75	0.84 0.89	0.89 0.93	1.13 1.12	Be
F	0.86 0.87	0.76 0.77	0.88 0.90	1.17 1.13	0.95 0.98	Be
G	Be	1.00 0.99	1.29 1.24	0.89 0.90	Be	Be

fresh fuel element

control element

Be — beryllium reflector element

DB VK — in-core irradiation device

Figure 2: mean radial power peaking form factors at balanced rod position for the 1st LEU standard core at BOC (first value) and EOC (second value)

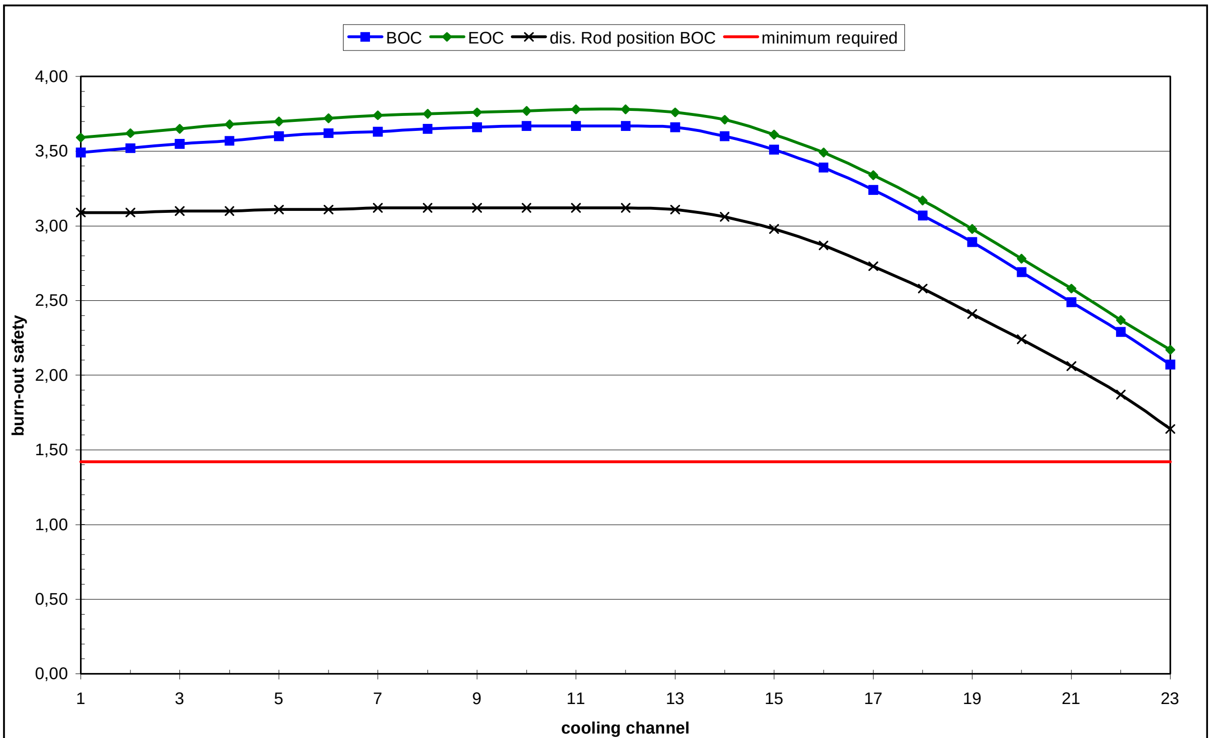


Figure 3: burn-out safety for element B5 core no. 64 - BOC and EOC balanced rod position BOC distorted rod position

SUMMARY

After 3 or 4 cycles with 3 weeks operation each, loading of fresh fuel within the LEU standard core has to be done. It is not advisable to load fresh fuel towards the reflector elements.

Up to now, the distorted control rod positions is limited. This limitation doesn't influence reactor operation.

It is scheduled, to build up the 4^{th} pure LEU core at the new year.

At the moment, it is not intended to build up LEU compact core. Hereby, the fuel elements B5, C5, D5, E5 and F5 would be replaced by beryllium reflector elements. This way, the power distribution of the core would be shifted again to the Cold Neutron Source.

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