SWAP EXPERIMENTS ON CONTROL RODS AND BERYLIUM REFLECTOR ELEMENTS AT HOR.

A.WINKELMAN
Reactor development, Reactor Institute Delft
Mekelweg 15. 2629JB Delft –The Netherlands

ABSTRACT

To improve the calculation model of the 2MW pool reactor HOR an experiment was performed to estimate reactivity effect of Be poisoning of the central irradiation facility. In a second experiment a swap of control rods was performed in order to confirm control rod burn-up. The experiments are described and evaluated. In both cases the well documented long term irradiation history enabled calculation of the measured effects.

1. Introduction

The Higher Education Reactor (HOR) of the Reactor Institute Delft (Delft) is a medium power open pool type nuclear research reactor operated at 2MW for almost 50 years. Compacting the core from 30 to 20 fuel assemblies was combined with LEU conversion and completed in 2005. A slight divergence of the calculated multiplication factor started after LEU conversion and accumulated to unrealistic k_{eff} values. This k_{eff} was unacceptable in the modeling for safety analyses and model validation. This made HOR look into possible improvements of modeling.
In this work two experiments performed recently are reported both confirming long term irradiation effects.
Section 2 describes the HOR core configuration. Section 3 reports the swap experiment performed on control rods and the comparison to calculation.
Section 4 describes a swap experiment performed on the high fluency central Beryllium reflector and compares it to the predicted reactivity effect.
Conclusions drawn in section 5 complete this report.

2. Core configuration

The current LEU compact HOR core configuration (existing from 2005) consists of a 6 by 7 grid filled with 16 standard fuel elements, 4 control fuel elements, 18 Be metal reflector elements, 3 hollow Be metal reflector elements and 1 BeO reflector element. The control type fuel elements contain only 10 fuel plates as opposed to the 19 plates of a standard element. The open central free space in control type fuel elements is taken up by aluminum guide plates guiding a control rod traveling form above fuel into the core.
Reflector elements kept their position and orientation in the compact core from 2004 on.

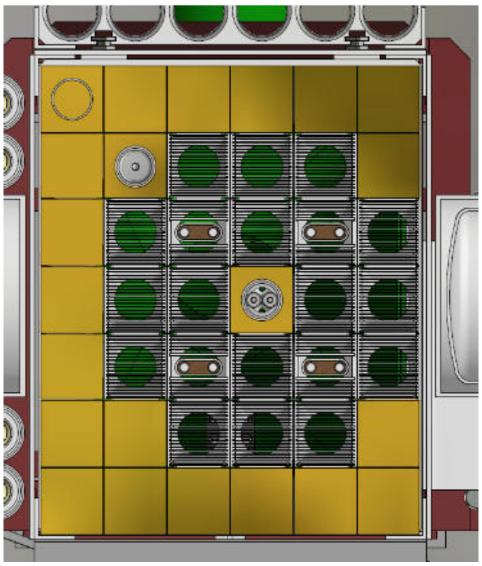
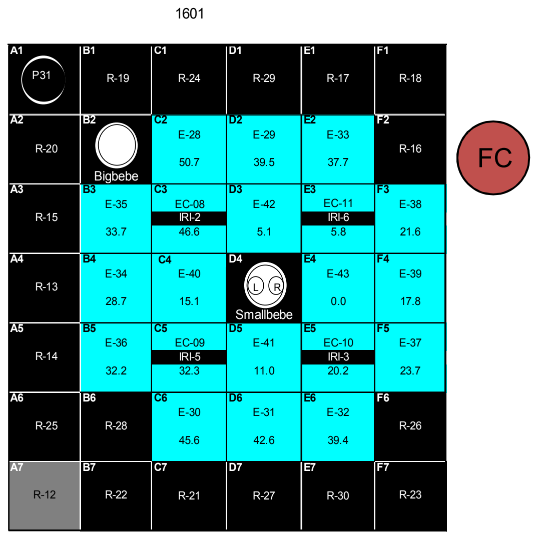


Figure 1 a. CAD cross section of the HOR core



b. schematic numbering of elements in the HOR core

The control rods consist of flattened and relatively thick-walled aluminum tubing, with aluminum welded caps. The space inside contains B4C in a mixture of grain size with a density of about 1.5 g/cm3 and two loosely mounted, thin walled, empty aluminum tubes figure 3.
Control rods are numbered IRI-2, IRI-5, IRI-3 and IRI-6 in figure 1b and table 1.

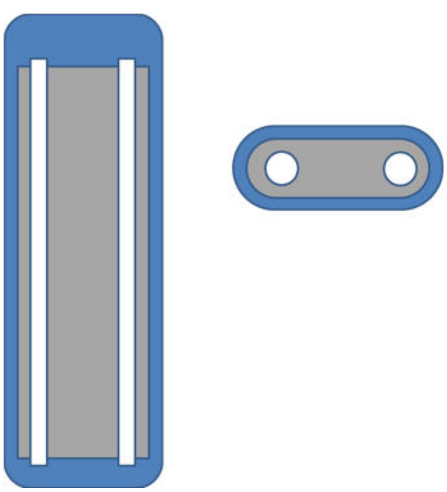


Figure 2.schematic drawing of HOR control rods, showing axial and radial cross sections. Empty thin-walled Aluminum tubes are surrounded by B_4C in a thick-walled Aluminum housing. Axial and radial dimensions are not to scale.

The control rods are driven by 8 m long aluminum tubes suspended from electro magnets. Electro magnets and aluminum driving tubes are in 8 m long stainless steel guide tubes. At the lower side these guide tubes are fixed to the control element and at the upper end they are fixed at the drive mechanism while maintaining 2 cm of freedom in height (in case of thermal expansion). In order to swap control rods (or control elements), the drive mechanism must be demounted and put aside from the guide tube. It also means re-adjusting control rod drive zero position and control rod span. In all it is a time consuming exercise.

The central hollow Beryllium reflector consists of a Beryllium mid piece of 76x80x650 mm, an aluminum foot and top handle, all with a central hole of 50 mm. In the compact core the water-filled space within the central reflector is filled with an irradiation facility. Since its introduction, the central reflector element has been at the position indicated in fig.1b. It is at the maximum flux position.

3. Control rod swap experiment

Current control rods in HOR (2017) are up to 40 years in operation. Their identification is indicated in table 1.

Table 1. Control rod identification at the start of control rod swap experiment.

Control Rod Drive	Manufacturing number of Control Rod	Date of introduction into core	Grid position from 1985-now
1	IRI-2	10-8-1977	C3
2	IRI-5	27-6-2006	C5
3	IRI-3	16-10-1978	E5
4	IRI-6	2-8-2011	E3

To asses the impact of depletion of the B_4C inside the older control rods on control rod worth, two control rods have been swapped (and swapped back).

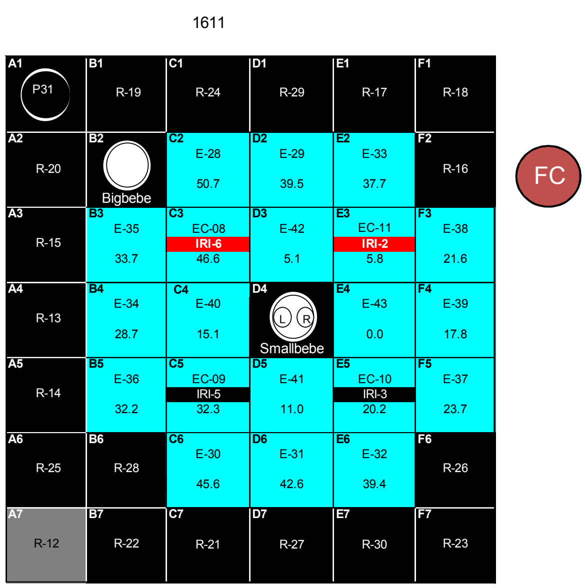


Figure 3. Configuration ‘1611’ after swapping control rod IRI-2 and IRI-6 (compare to fig. 1b)

Control rod IRI-2 was swapped with control rod IRI-6, i.e. the rods with the longest and the shortest residence time and maximum and minimum neutron fluency (table 3). A schematic picture of the core lay-out of this measurement core, designated 1611, with the two swapped control rods is shown in Figure 3. Note that control fuel elements EC-08 and EC-11 remained on grid positions C3 and E3 during the control rod swap.

Extensive measurement series were performed for the 'un-swapped' core (designated 1601) and the 'swapped' core (1611). These measurements, consist of the following:

1) Average critical control rod positions with cold and (approximately) xenon-free conditions for 'swapped' (1611) and 'un-swapped' core (1601).
2) Individual control rod curves and worth, measured in three trajectories for 'swapped' (1611) and 'un-swapped' core (1601) and associated critical control rod positions.
3) Shutdown margin measurements, and associated critical control rod positions at the start of the shutdown margin measurement, for 'swapped' (1611) and 'un-swapped' core (1601).

Most interesting in this context are the measured control rod worth and control rod curves build of three trajectories covering the total way of each control rod 100% down to 0% out of core.

Table 2 Comparison of individual control rod worth measurement trajectories for swapped control rods IRI-2 and IRI-6 at positions C3 and E3.

Grid pos.	Trajectory	Rod IRI-2 Worth [%Δk/k]	Rod IRI-6 Worth [%Δk/k]	Abs. diff [%Δk/k]	Rel. diff [%]
C3	100%-60%	0.689	0.782	+0.093	+13.45
	60%-30%	1.295	1.355	+0.060	+4.62
	30%-0%	0.819	0.744	-0.075	-9.11
	Total	2.803	2.881	+0.078	+2.78
E3	100%-60%	0.841	0.918	+0.077	+8.42
	60%-30%	1.562	1.604	+0.041	+2.58
	30%-0%	0.787	0.756	-0.031	-4.09
	Total	3.190	3.278	+0.088	+2.68

While the relative differences for un-swapped control rod trajectories were less than 2%, table 2 shows clear differences up to 13.45% in case of swapping. Total worth changed less than 0.7% for the un-swapped control rods, while in case of swap the total control rod worth relative change was about 2.5%.
The control rod curves shed some light on why total worth is not affected as much as individual trajectories:

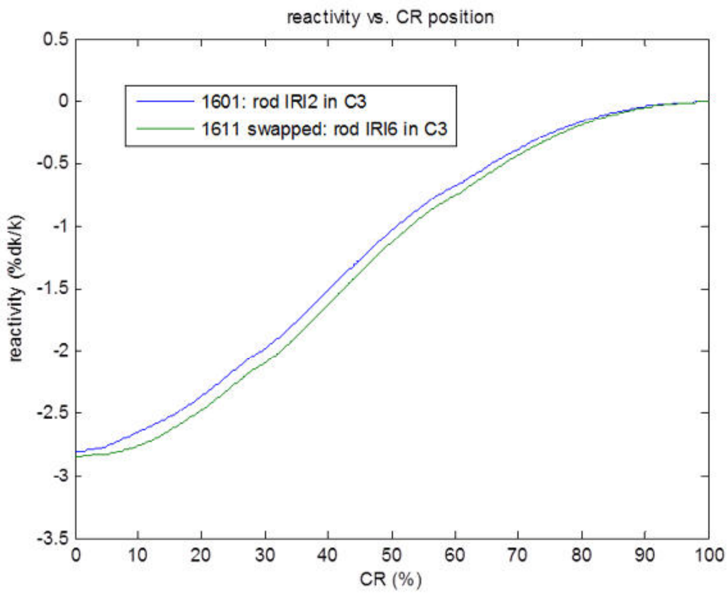


Figure 4. Control rod curve of IRI-2 and IRI-6 at grid position C3.

At grid position C3, the negative reactivity of the swapped older control rod IRI2 lags behind that of the newer control rod IRI6. However, already at 10% the worth of the newer rod flattens while the lagging reactivity of the older rod runs down further. The net total worth ends up pretty close.

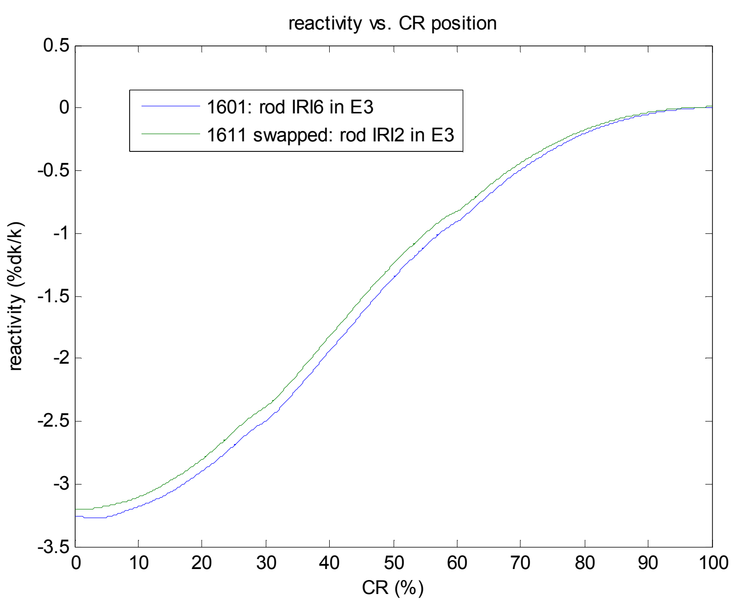


Figure 5. Control rod curve of IRI-2 and IRI-6 at grid position E3.

At grid position E3, we see the same effect. The negative reactivity of the swapped older control rod IRI2 clearly lags behind that of the newer control rod IRI6. However the net total worth ends up close because the differential worth of the new rod reaches zero while it does not for the old rod.

The un-swapped control rod curves in both cores were practically equal as expected.

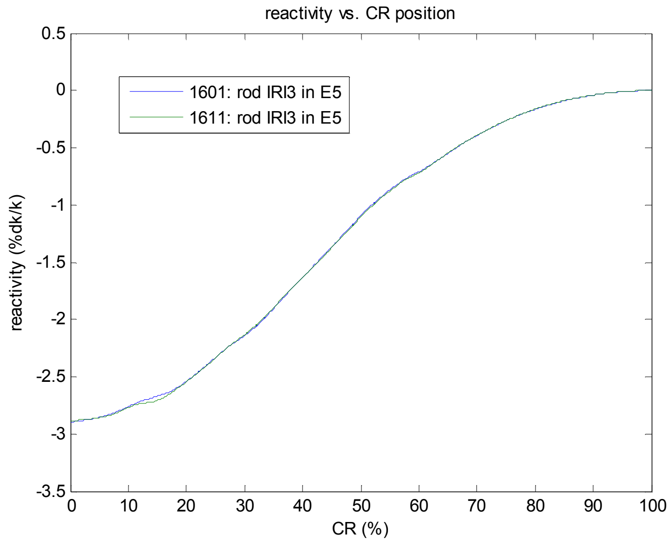


Figure 6. Control rod curve of IRI-3 that stayed at grid position E5 in the original and swapped core..

The power distribution and history of HOR was used to estimate thermal neutron fluency in the control elements indicated in table 3.

Table 3. Estimated fluency for the control rod grid positions

Control Rod Position	**Thermal neutron fluency (n/(cm^2)) in the assembly**
C3	7.35E+21
C5	2.00E+21
E5	5.32E+21
E3	8.58E+20

MCNP6 [1] was used to burn B_4C in axial zones in the control rod by imposing 2 MW constant power and at a fixed time averaged control rod position 78% out of core. The total estimated depletion of ^{10}B was 10% for the oldest rod IRI2 at position C3.

The effect of 10% depletion of ^{10}B was evaluated by calculating the control rod curve in mcnp in three cases: un-depleted B_4C (rho(ref), 10% homogeneously depleted B_4C (rho(dep) and a case where 10% depletion is concentrated in the lower 10 cm of the control rod rho(tipdepl).

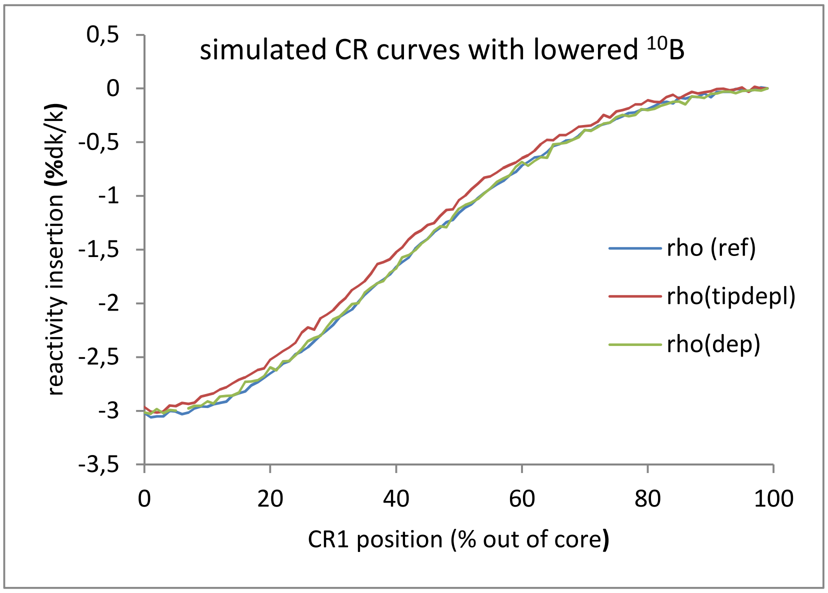


Figure 7.MCNP simulated control rod cureves with and without ^{10}B depletion.

The homogeneous depleted control rod curve coincides with the un-depleted case. The case where the lower tip is depleted qualitatively resembles the delayed behavior seen in the experiment. Further analysis are needed to quantify the depletion.

4. Beryllium reflector swap experiment

Fast neutron fluency is the initiator for the production of Be poisons, because the first step of the beryllium poisoning chain (shown below) is a neutron capture reaction in ^{9}Be with high neutron energy threshold.

$$^{9}_{4}\mathrm{Be} + n \rightarrow ^{6}_{3}\mathrm{Li} + ^{4}_{2}\mathrm{He} \text{ (assuming instantaneous decay of } ^{6}_{2}\mathrm{He})$$

$$^{6}_{3}\mathrm{Li} + n \rightarrow ^{4}_{2}\mathrm{He} + ^{3}_{1}\mathrm{H}$$

$$^{3}_{1}\mathrm{H} \xrightarrow{\beta, t_{1/2}=12.33\,yr} ^{3}_{2}\mathrm{He}$$

$$^{3}_{2}\mathrm{He} + n \rightarrow ^{3}_{1}\mathrm{H} + p$$

The fast flux (E_n>0.1 MeV) distribution was calculated for the reflector assemblies in various core configurations from 1991 up to the current compact core.
Adding all contributions the total fluency estimation in Be reflector assemblies per 1/1/2016 are as shown in fig 8. It is essential to note that the reflector assemblies remained at fixed position most of their irradiation history. In case of the three hollow Be elements (green in fig.8) the position is absolutely fixed throughout their presence in HOR core.

3.5E+20	1.1E+21	2.7E+21	2.4E+21	2.6E+21	1.5E+21
1.8E+21	3.0E+21				2.7E+21
3.2E+21					
3.7E+21			5.9E+21		
3.1E+21					
1.2E+21	3.0E+21				2.8E+21
3.6E+20	1.6E+21	2.4E+21	2.6E+21	1.9E+21	1.4E+21

Figure 8. Estimated fast (E_n > 0.1 MeV) fluency in reflector assemblies of the HOR core summed up to 1/1/2016. The values shown are average per assembly.

Perfect candidates for experimental proof of the presence of Be poisons by swapping are the central hollow Be element R32 with highest fluency and the outer hollow Be element R31 which shows lowest fluency according to calculation. They are mechanically identical so a swap test is straight forward.
Swapping the relatively low poisoned outer element to the central position will increase reactivity.
The only complicating item is a Be plug P31 filling the outer hollow Be element R31.While swapping R31 for R32 the accompanying plug P32 must be used with R32 while plug P31 is stored. This introduces a small extra reactivity boost as plug P32 was never irradiated.
The swap was executed three days after end of cycle core 1403 so that most ^{135}Xe has decayed. The reactivity effect was evaluated by checking 700 W critical bank position of the four control rods. The swap lowered critical bank position by 2.2% at constant temperature. This was converted to a positive reactivity effect of 320+/-20 pcm by measurement of control rod reactivity curves.
To simulate the effect, Beryl [1] was adapted to the flux levels of HOR and the relatively well documented power on and off history was used as input to beryl.
The poison densities calculated by Beryl were then entered in the Be elements at hand in the MCNP model for HOR and the calculated reactivity effect was 280 +/-30 pcm.

5. Conclusions

Reactor physics experiments at the Reactor Institute Delft helped in identifying a number of refinements needed in the modelling of the HOR reactor.
The B_4C control rods experience ^{10}B depletion and a resulting measureable control rod curve changet, but the total rod worth is barely affected even after 40 years of service.
Even for a medium power research reactor the Be reflector poison reactivity effect can be substantial.

6. References

Beryl, Institute of atomic energy,1999
MCNP6.1 Monte Carlo N Particle Transport Code System, ORNL, August 2013