# Neutronics validation during conversion to LEU

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## Abstract

From October 2005 to May 2006 the High Flux Reactor at Petten, the Netherlands, was progressively converted to low-enriched uranium. The core calculations were performed with two code systems, one being Rebus/MCNP, the other being Oscar-3. These systems were chosen because Rebus (for fuel burn-up) and MCNP (for flux, power, and activation reaction rates) have a long and good track record, whereas Oscar-3 is a newer code, with more user-friendly interfaces that facilitate day to day and cycle to cycle variable input generation.

The following measurements have been used for validation of the neutronics calculations: control rod settings at begin and end of cycle, reactivity of control rods, Cu-wire activation during low power runs of the reactor, activation monitor sets present during part of the full power cycle, and isotope production measurements.

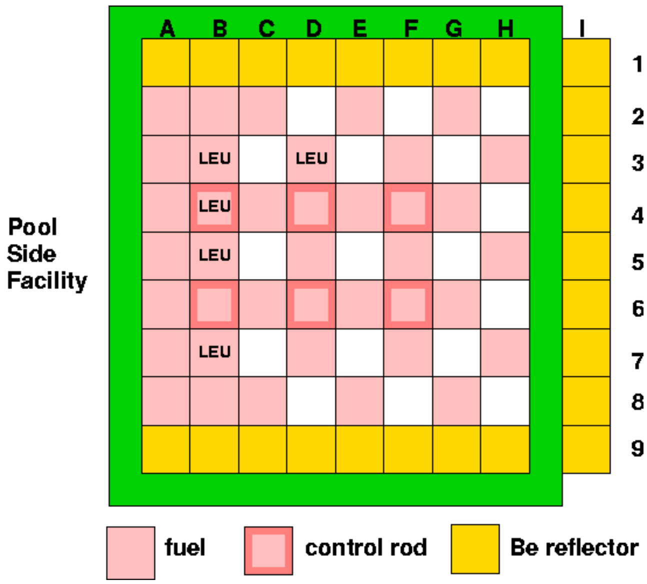
We report on a comparison of measurements and calculational results for the control rod settings, Cu-wire activation and monitor set data. The Cu-wire activation results are mostly within 10% of experimental values, the monitor set activation results are easily within 5%, based on absolute predictions from the calculations.

***KEYWORDS: core calculations, conversion, LEU, materials test reactor***

## 1. Introduction

From October 2005 to May 2006 the High Flux Reactor at Petten, the Netherlands, was progressively converted to low-enriched uranium (LEU) [1]. In the course of seven cycles, more and more LEU fuel elements were placed in the reactor, and for each these core configurations neutronics calculations had to prove that operations were safe and that the license requirements were adhered to. These calculations were therefore scrutinised closely for each of the seven conversion cores: six cores with mixed high-enriched uranium (HEU) and LEU fuel, and finally the first core containing only LEU fuel. All calculations were performed with two code systems, one being Rebus [2] / MCNP [3], the other being Oscar-3 [4]. These systems were chosen because Rebus (for fuel burn-up) and MCNP (for flux, power, and activation reaction rates) have a long and good track record, whereas Oscar-3 is a newer code, with more user-friendly interfaces that facilitate day to day and cycle to cycle variable input generation.

**Figure 1 The fuel configuration for HFR cycle 0510, the first cycle with both HEU and LEU fuel elements**




There were several factor contributing to the complexity of the core calculations. The reactor is a 45 MWth water moderated and water cooled, metallic fuel plate reactor of the type tank-in-pool. The core has a checkerboard pattern, see Fig. 1, of 33 fuel positions, 6 control rod positions, and 17 experiment positions, which creates steep gradients in the thermal flux in the core. The presence of strongly absorbing materials and of flux traps for medical isotope production ($^{99}$Mo, $^{192}$Ir, etc.) exacerbates this problem. The fuel assemblies contain burnable poison ($^{10}$B for HEU, $^{113}$Cd for LEU) in side-plates. Since this burnable poison is located outside the fuel plates, it 'sees' a different thermal flux from the fuel, making its burn-up calculation difficult for a nodal code like Oscar-3. Finally, the loading pattern of the fuel was to be optimised during the conversion, to minimize the expected flux degradation due to the extra capture on $^{238}$U.

**Table 1 The main characteristics of the HEU and LEU fuel for the HFR. The numbers in brackets are for the cvontrol rods.**

| | HEU | LEU |
|---|---|---|
| Enrichment | 91% | 19.75% |
| U-235 | 450 g (310 g) | 550 g (440 g) |
| Number of plates | 23 (19) | 20 (17) |
| Burnable poison (in side plate) | 1000 mg $^{10}$B | 40 Cd wires (Ø 0.5 mm) |
| Cycle length in days | 25.7 | 28.3 |

It was realised a priori that this amounted to a sizable challenge, also in view of the role the HFR plays in medical isotope production in Europe, for which the operational schedule needs to be dependable, and the isotope production predictable. The reactor is operated around 290 full power days per year, which means that the neutronics were boxed into a tight schedule. Therefore a scheme was put in place to perform all calculations by two independent code systems, enabling code to code verification, and to perform measurements during the conversion, opening the way for a validation of the calculational results on a cycle by cycle basis. In this way, before starting any cycle, the calculations for the previous cycle have already been validated using experiments, and the calculations for the cycle to be started have already been verified by code to code comparison. In this paper we report on the results of the validation for REBUS/MCNP. The modelling in OSCAR-3 is currently in progress. the results of which will be presented in Ref. [5].

## 2. Neutronics codes used

Because of the introduction of LEU fuel into the HFR, a new code or code system for core calculations was necessary. The code used until mid-2005, HFR-TEDDI, was developed many years ago without taking into account possibilities for other types of fuel. The code was not flexible in coding, nor user friendly. Therefore it was decided to start using the OSCAR-3 code system for the core calculations in the new situation. However, in view of the many changes that were foreseen for the reactor, and because OSCAR-3 was new for us, we deemed it necessary to back OSCAR-3 up by another set of codes, for which we chose REBUS for the burn-up calculations and MCNP for the flux, power, and activation rate calculations.

In both OSCAR-3 and REBUS we used seven energy groups, three thermal groups up to 0.625 eV, one group until 4 eV as the maximum energy for upscattering, two epithermal groups, and one fast group above 0.83 MeV. The fuel height was divided in 16 zones in OSCAR-3, and in 8 zones in REBUS. For the REBUS and MCNP codes a tool was developed to read the fuel inventory from the REBUS output, and import it into the existing MCNP model of the reactor. The modelling of the experimental positions posed a significant challenge, because there were (and still are) experiments and irradiation facilities with large amounts of moderation, absorption, and even fission (for molybdenum production). These rigs were difficult to model in both OSCAR-3 and REBUS, but MCNP models were already available. Therefore we used a tool, “El Ninjo” [6], to create homogenized macroscopic group cross sections, based on MCNP calculations, for all the experiments that could have a sizable influence on the core calculations. These cross sections were also in seven energy groups and 16 axial zones (for OSCAR-3, in HEADE format) or 5 axial zones (for REBUS in ISOTXS format). Apart from these homogenized group cross sections, the OSCAR-3 code worked fully independent from the REBUS/MCNP codes, so that comparison of results between the codes was a valuable test.

## 3. Validation results

The following measurements have been used for validation: control rod settings at begin and end of cycle, reactivity of control rods, Cu-wire activation during low power runs of the reactor, activation monitor sets present during part of the full power cycle, and isotope production measurements. The Cu-wire measurements provide us with a thermal flux profile in several fuel assemblies from top to bottom of the fuel height. This serves as a powerful check on the burnup calculations for those assemblies. Also, because this thermal flux profile is closely related to the power profile, the comparison with this measurement justifies the uncertainty margins that are used for the thermal hydraulics safety considerations. The control rod setting and control rod reactivity give us feedback on the overall reactivity of the core, and on the control rod worth. The activation monitors were placed in experimental positions and thus serve as a check on our flux predictions in these positions, and hence on the isotope production (rate) predictions.

The first comparison between measured and calculated values is for the control rod settings at begin and end of cycle. In Table 1 these values are listed for five of the mixed cores during conversion. The values represent the control rod position in height above their minimal setting. The control rods consist of a cadmium section on top, and a fuel follower below. A low control rod setting therefore means that more of the cadmium section is in the core, and less of the fuel follower. The measured values in Table 1 are given as a range, because in reality the setting fluctuates due to handlings that are taking place in the reactor (loading and unloading of irradiation facilities etc.).

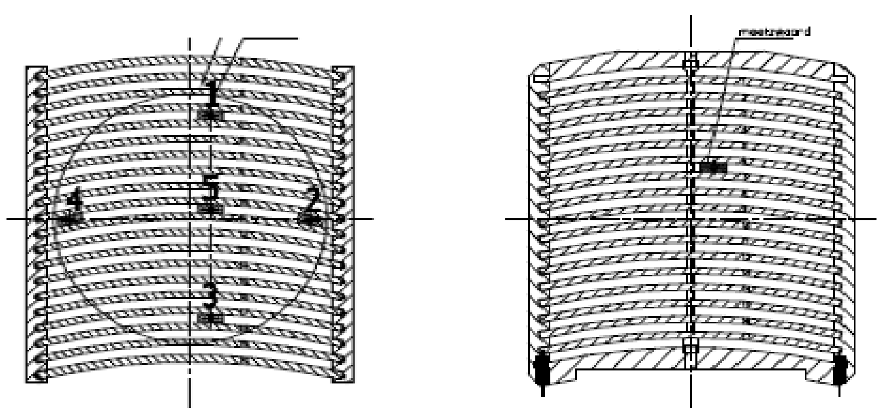
Moreover, the value at BoC is an estimate of the value when Xe-equilibrium has been reached. Table 1 shows that the MCNP calculations consistently predict a slightly higher control rod setting than is realised in the reactor. This implies that the reactivity of the MCNP model is a bit on the low side, which can be compensated for by a higher control rod setting. For most of the values the discrepancy between calculation and measurement is of the order of 1–2 cm (around 500 pcm in reactivity), but for cycle 06-02 there is a 3–4 cm difference both at BoC and EoC. These deviations are presently not well understood. The consistent mismatch of 1–2 cm was not as good as hoped for, but nevertheless acceptable for the present purposes.

**Table 2 Actual and calculated control rod positions (in cm) at begin of cycle (BoC) and end of cylce (EoC)**

| | Actual | | Calculated (MCNP) | |
|---|---|---|---|---|
| Cycle | BoC | EoC | BoC | EoC |
| 05-10 | 56 | 56–57 | 56 | 58 |
| 05-11 | 55–56 | 57–58 | 55 | 58.5 |
| 05-12 | 56–57 | 63–65 | 58.5 | 66 |
| 06-01 | 57–58 | 61–62 | 57 | 63 |
| 06-02 | 50 | 53 | 53 | 57.5 |

There are three mixed core configurations for which Cu-wire activation measurements have been performed. These measurements were done during low-power runs of the reactor, shortly before starting the full-power cycle. Inside certain fuel elements Cu-wires were placed: one central wire only for the HEU elements and the control rods, and five wires for the LEU elements, see Fig. 2.

**Figure 2. The positions of the Cu-wires in an LEU fuel element (left) and an LEU control rod (right).**

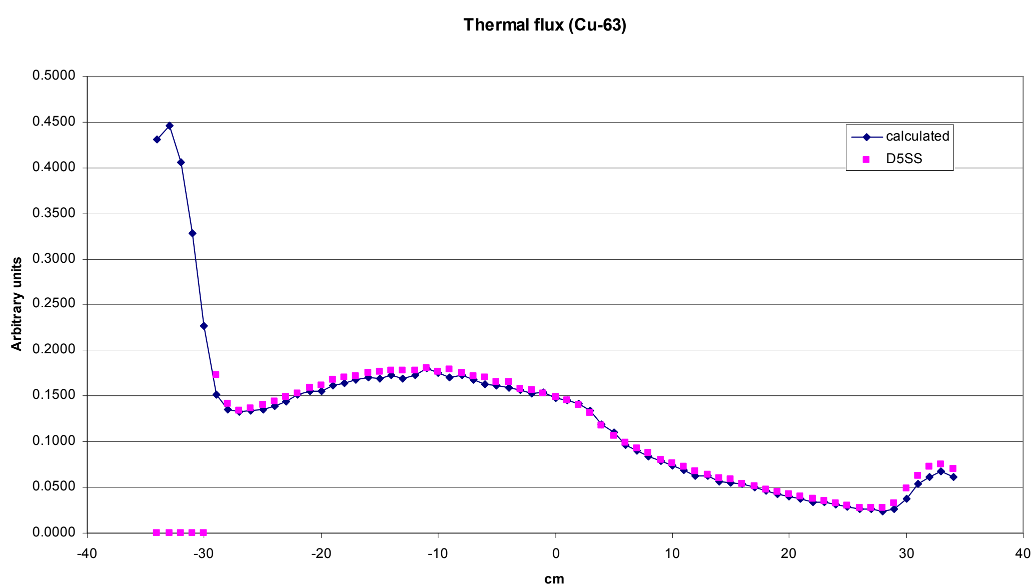


The reactor power for these low-power runs could not be established with sufficient accuracy. Therefore the results of the Cu-wire measurements can only be used for a relative comparison against calculations; not for an absolute comparison. There is one normalization constant that should be fixed. We have done this by summing all the measured values and equating that to the sum of the calculated values. Since there were more than ten Cu-wires measured, and for each wire the were tens of measurements along the wire, the comparison between this experiment and calculation tests the axial profile that is calculated and also the distribution of the thermal flux over the fuel positions.

The calculation of the wire activation was done both by MCNP and by OSCAR-3. In MCNP a volume flux tally with a 2×2×1 $cm^3$ volume was defined, even though the wires are clearly much thinner. The results based on this tally definition were satisfactory, as is shown below, so that there was no need to go to smaller tally volumes, or even to point tallies. In OSCAR-3 we used the intra-nodal flux reconstruction within the fuel elements, and convoluted that with the relevant activation cross section. This was done in 69 energy groups, which were subsequently condensed into seven, dependent on the burn-up of the fuel element.

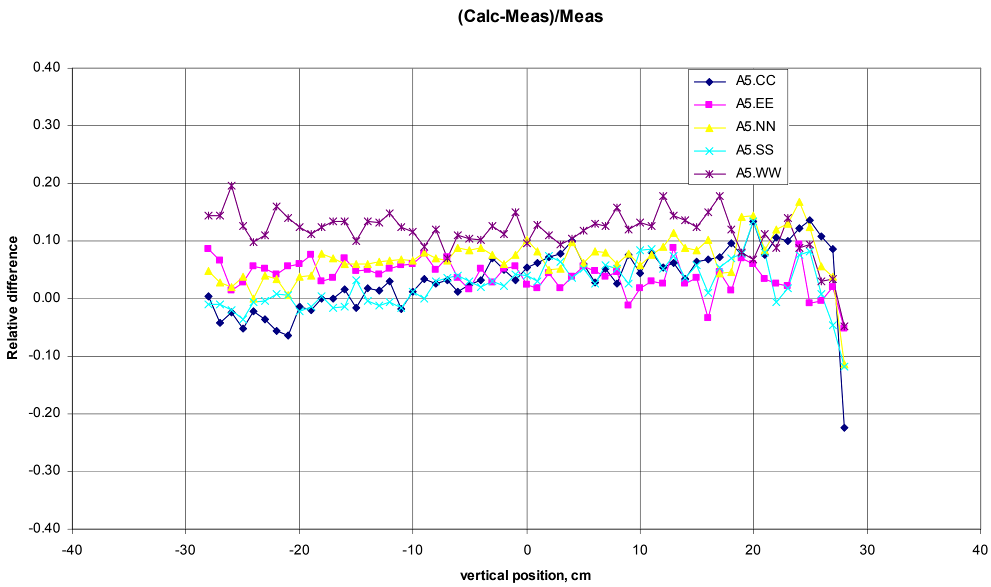
A selection of the data for the measurements preceeding cycle 06-03 is shown in Figs. 3–5. In Fig. 3 the experimental curve is shown for D5 from bottom ($z$=–30 cm) to top ($z$=30 cm) of the reactor, next to the calculational results from MCNP. The position D5 is in the centre of the reactor, so it is not surprising that we get good agreement between measured and calculated values, even though the south wire is quite close to the control rod at D6. In fact, the influence of that control rod can be seen by the bend in the curve around 4 cm above centreline core: above that bend the influence of the cadmium section of the control rod at D6 lowers the thermal flux (and hence the Cu activation) in the south part of fuel element D5.

**Figure 3. The Cu-wire activation in D5, southern-most wire, measured vs calculated (MCNP)**




In Fig. 4 we show the deviations between measured and experimental values (C/E-1) for position A5, measured preceeding cycle 06-03. Position A5 is chosen here because it is at the edge of the reactor. Most of the points deviate less than 10% from the measured values, except for the west wire, which is close to the core box wall. This has not yet been investigated further, but it is conceivable that this is a result of the gradient in thermal flux that can be expected in the vicinity of the pool side. Possibly the gradient is not described entirely accurately, or the flux tally definition is extended over too large a volume to cope with the gradient. Also there is a tendency that the values near the top of the reactor, around 20–30 cm above centerline core, are somewhat less accurate. This may be a result of the large influence of the cadmium sections of the six control rods, which causes a significant gradient towards the top of the reactor (see e.g. Fig. 3).

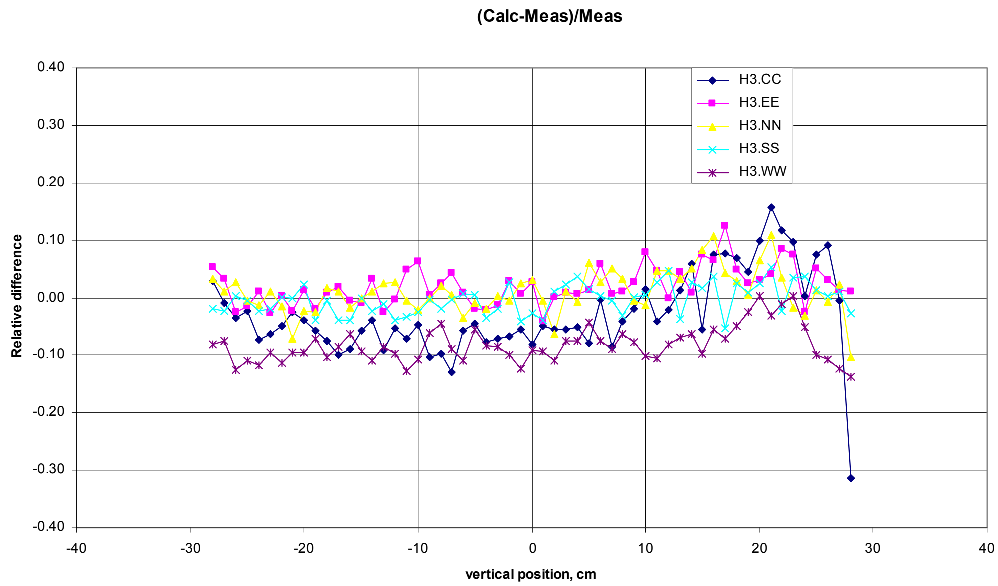
**Figure 4. C/E-1 values for the Cu-wire activation in A5 (calculations by MCNP)**




In Fig. 5 the results for H3 (measured preceeding cycle 06-03) are shown. Position H3 is chosen here because it is the outer-most position among the fuel elements. Again we see that most points deviate less than 10% from the measured values. The results for the west wire are consistently on the low side, which is not well understood at present. There is the same slight tendency for the C/E values to go up towards the top of the reactor.

The results from the Cu wire activation comparison give a consistent picture over the whole core. Although there is an arbitrary normalization constant, its value is identical for all positions. Therefore, the fact that the results for A5 are in line with those for H3 means that thermal flux is well described over the whole reactor.

**Figure 5. C/E-1 values for the Cu-wire activation in H3 (calculations by MCNP)**

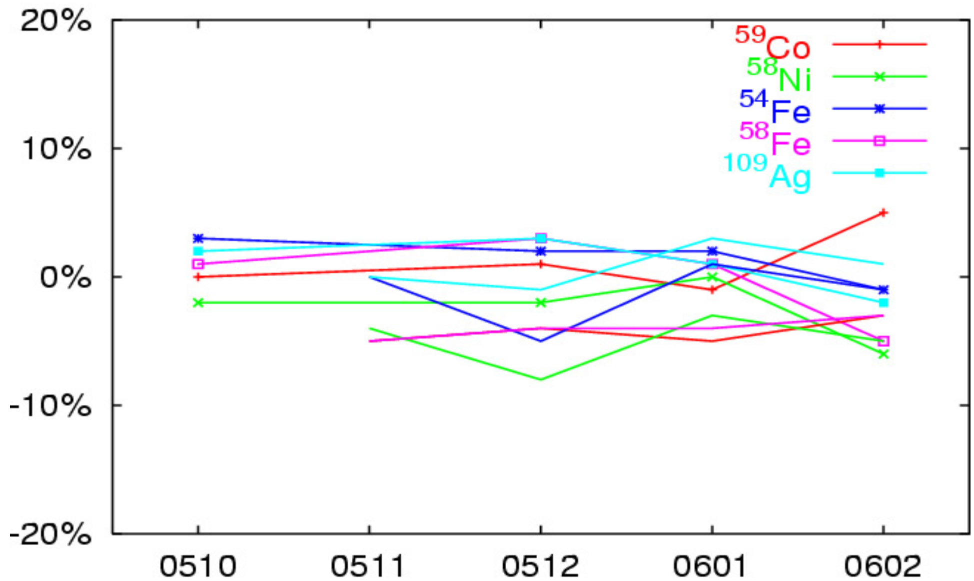



During each of the mixed cores, reaction rate measurements were performed in several experimental positions at centerline core: G5/E7, and D8. The following reactions were used.

- $^{59}Co(n,\gamma)^{60}Co$, $^{58}Fe(n,\gamma)^{59}Fe$ for the thermal part of the spectrum,
- $^{54}Fe(n,p)^{54}Mn$, $^{58}Ni(n,p)^{58}Co$ for the fast part of the spectrum,
- $^{109}Ag(n,\gamma)^{110m}Ag$ for the thermal and epi-thermal part of the spectrum.

The results of the measurements were reported in units of 'reactions per second', enabling a comparison of absolute numbers between calculation and experiment. The normalization of the calculational result from MCNP was based on the overall power generated in the reactor. The results of the comparison are given in terms of C/E-1, from cycle to cycle, for all five activation channels, see Fig. 6. Calculational results based on OSCAR-3 are unavailable at the moment, because this would require intra-nodal reconstruction of the flux in experimental positions, and activation cross sections for these particular reactions.

**Figure 6. The comparison between calculation (MCNP) and measurement for five activation channels in two different experimental positions, from cycle to cycle. Plotted is C/E-1 in percents.**




As can be seen from Fig. 6, the results of the absolute comparison of reaction rate values between calculation and measurement are well within 10% for all cases. This, in combination with the Cu wire results, justifies the use of a 10% uncertainty margin in the power values when used in the thermal hydraulics calculations. In fact, the differences between calculation and reaction rate measurements are of the order of 3% in most cases.

## 4. Conclusions

We conclude that we have successfully put in place a neutronics calculations scheme for conversion to LEU, including validation, in an operational environment of a materials test reactor with 290 days uptime per year. The application of REBUS/MCNP and OSCAR-3 to the HFR is validated along the way.

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