REACTIVITY EFFECTS OF A RESEARCH REACTOR (HOR) DURING THE TRANSITION OF A HEU TO LEU CORE

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ABSTRACT

The HOR is a pool-type research reactor at the Interfaculty Reactor Institute (IRI) of the Delft University of Technology and contains MTR-type fuel elements. Since the beginning of 1998, the high-enriched uranium (HEU) fuel elements are replaced step by step by low-enriched uranium (LEU) fuel elements while the core size is simultaneously reduced by replacing fuel elements by beryllium reflector elements. At present about 75% of the HEU fuel elements are replaced by LEU fuel elements. In this paper, an overview is given of the calculational methods used for the transition from HEU to LEU fuel. The three-dimensional Monte-Carlo code KENO-Va and the three-dimensional nodal diffusion code system OSCAR-3 are used. Special attention is given in this paper to the modelling of the control rods with the focus on the reactivity effects. Different calculated effective multiplication factors (k-effective) for a number of cycles are shown and compared with measured results. Then a detailed comparison is made between measured and calculated reactivity values for different cycles. The integral reactivity results (s-curve) are given for the four control rods in two different cycles. Taking into account the accuracy that can be achieved for such small critical cores using Monte-Carlo and nodal diffusion methods, the results are useful. Work to improve the results in this transition phase and the final LEU core is still in progress.

1. INTRODUCTION

In support of the transition from a HEU to a LEU core reactor calculations and reactor physics calculations and measurements[1,2] are continuously performed and evaluated to ensure safe and optimal operation of the HOR. Special attention is given to the modelling of the control rods with the focus on the reactivity effects. Integral reactivity results (s-curve) are given for the four control rods in different cycles. Calculated and measured results are compared.

The HOR (Hoger Onderwijs Reactor) is a pool-type research reactor at the Interfaculty Reactor Institute (IRI) of the Delft University of Technology and has been in operation since 1963. It is the one and only university research facility of its type in the Netherlands. Its main purpose is to serve as a scientific facility for material research using neutrons and other types of radiation, physical aspects of nuclear reactors as well as research in radiation physics, radiochemistry, and environmental research. The maximum licensed power is 3 MWth. For most of the time, the reactor is operated at a steady state power of 2 MWth. It contains MTR-type (Material Test Reactor) fuel elements. Until the end of 1997 the reactor was operated using HEU (High Enriched Uranium, 93 w/o ^{235}U) fuel. In the beginning of 1998 the first two LEU (Low Enriched Uranium, 19.75 w/o ^{235}U) fuel elements were introduced in the HOR reactor. It is anticipated that after about a total of 17 core reload operations the HOR will be fully converted from HEU to LEU fuel. During this conversion process the core will also be reduced from 30 fuel elements to 20 fuel elements and 21 beryllium reflector elements (compact core). A central irradiation facility (CIF) was recently placed in the centre of the core. In the transition phase the mixed core will consist of HEU and LEU fuel elements. In Figure 1 horizontal cross sections of a standard fuel element (19 plates) and a control-rod fuel element (10 plates) are given. Characteristics of the HEU and LEU fuel are given in Table I. The control rod is introduced into the control-rod fuel element (between the two inner aluminium plates). The control rod consists of an aluminium outer structure filled with B_4C. The rod is 5.72 cm in width and 2.25 cm thick. Its axial height is about 71.5 cm with an active (B_4C) height of 65.5 cm.

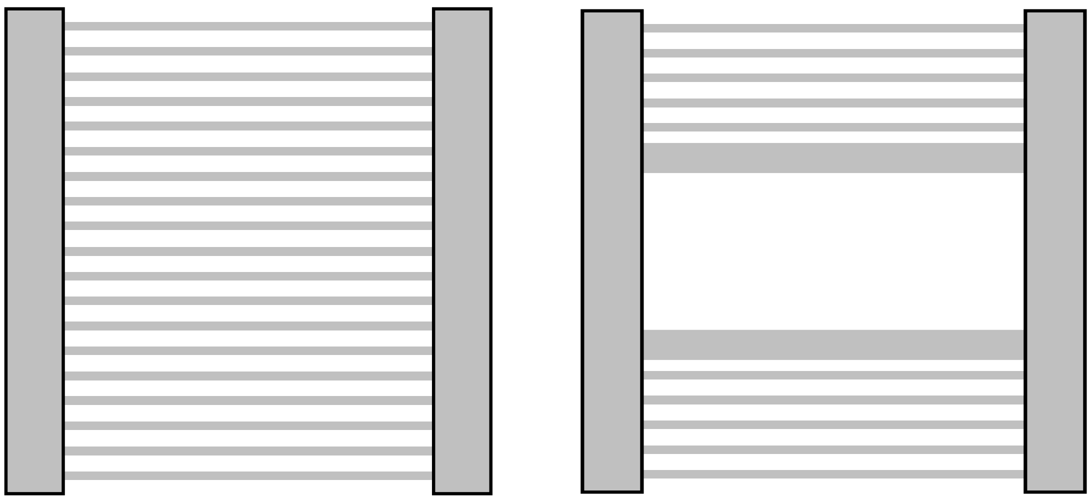


Figure 1. Fuel elements: standard and control-rod (~8x8 cm).

Table I. Fuel element design parameters

	LEU	HEU
Number of Plates per Fuel Element	19	19
Number of Plates per Control Element	10	10
^{235}U Loading per Fuel Element [g]	300	190
Uranium Content per Fuel Element [g]	1519	204
^{235}U Loading per Control Element [g]	158	100
Uranium Content per Control Element [g]	800	108
Enrichment [%]	19.75	93

Meat Material	U_3Si_2-Al	UAl_x-Al
Uranium Density in Meat [g/cm^3]	4.3	0.58
Meat Thickness [mm]	0.5	0.5
Cladding Thickness [mm]	0.35	0.3
Coolant Gap [mm]	3.0	3.1
Fuel Height [cm]	60	60
Effective radial dimensions [cm]	7.71 cm x 8.1 cm	7.71 cm x 8.1 cm

A horizontal map of the mixed HEU-LEU cycle 0201 is given in Figure 2. The grid has six columns (A-F) and seven rows (1-7). This compact core has 20 fuel elements. In detail: three standard HEU fuel elements (D), two control-rod HEU fuel elements (DC), two control-rod LEU fuel elements (EC), and 13 standard LEU fuel elements (E). The average burnup is displayed in the fuel elements as well. Two irradiation facilities, Bigbebe and Smallbebe, are available. The core is surrounded by about 19 beryllium reflector elements (R) and a single beryllium-oxide reflector element in position A7.

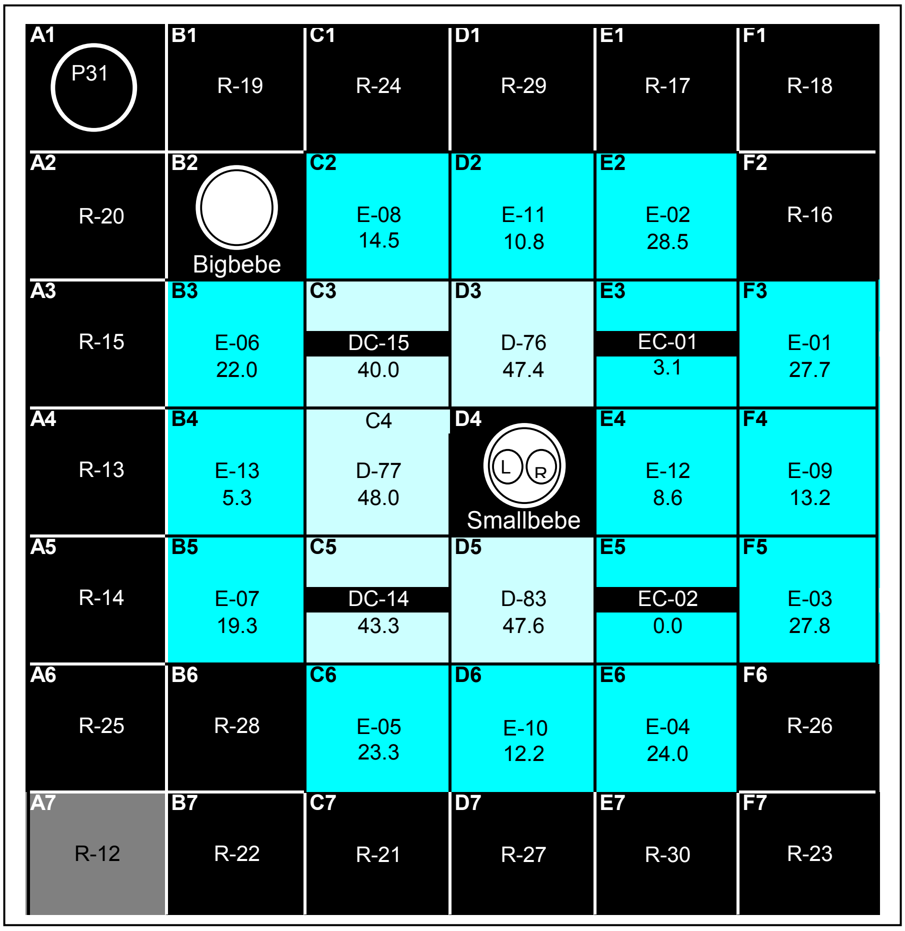


Figure 2. Horizontal map of HOR cycle 0201.

2. METHODS

2.1 THE INAS CODE SYSTEM

At IRI a comprehensive reactor-physics code system and evaluated nuclear data are implemented for detailed (mixed) core calculations called INAS (IRI-NJOY-AMPX-SCALE). This reactor-physics code system is based on the JEF-2.2[3] evaluated nuclear data file, the cross-section processing code NJOY[4], and the SCALE[5] code system. The three-dimensional Monte Carlo code KENO-Va[5] is used as a reference. Detailed geometry description of the core, control rods, and beam tubes are possible and used. Each fuel element, including the fuel slabs, is exactly described. A 172 fine-group neutron cross-section library based on JEF-2.2 in the AMPX[6] master format is used. The unresolved and resolved resonance treatment are done by the BONAMI[5] and NITAWL[5] modules of the SCALE code system respectively. The KENO-Va results are not affected by one-dimensional cell-weighted cross sections. The burnup of the fuel is calculated with SAS6 a modified SAS2H sequence of the SCALE (XSDRNPM module replaced by WIMSD4) code system. Axial burnup profiles are determined making use of a burnup-shape correlation calculated with the nodal diffusion code SILWER[7]. These axial profiles will be improved by the nodal code OSCAR-3[8].

2.2 THE OSCAR-3 CORE CALCULATIONAL SYSTEM

OSCAR-3[8] is an acronym for an "Overall System for the Calculation of Reactors". The code system has been developed by NECSA over many years with the recent focus on including features and tools to support the calculation of plate type research reactors. The code is used in the daily support of the SAFARI-1 reactor in supporting cycle analyses, reload planning, new product development (rig design, viability studies), and licensing calculations[9].

All the five group assembly homogenised cross sections were prepared with the HEADE two-dimensional transport code. The code uses the collision probability method within a cell while a low-order interface current method[10] is used to connect these cells in the total assembly calculation. Calculations are performed with a 172 fine-group neutron cross-section library[11] based on JEF-2.2. Some detail of the models employed can be found in reference[2]. During the process of generating control-rod fuel element and control rod cross sections, it was found that the input model had to be adjusted in order to get acceptable control rod reactivity results. In the HEADE model multiple fuel plates and the absorber rod were modelled within a single cell (where collision probabilities are applied). This is in contrast with the typical model normally used where each plate and the absorber rod would be modelled as separate cells and where the interaction between cells are calculated with the low order interface current method. This will be further evaluated including the use of other methods.

For the HOR core calculations a detailed 3D core model was defined in the MGRAC multi-group nodal diffusion code. A single node per assembly in the radial direction and 4 cm meshes axially within the active core height (60 cm) was used. The reactor multi-cycle operation history was simulated in detail with the actual control rod positions, beam line status (experiment / flooded with water) and plant temperatures utilized. In the MGRAC calculations the control rod axial positions are not limited to the axial calculational mesh boundaries with the benefit that the actual distance inserted can be specified. In the axial calculational mesh where the control rod bottom tip is positioned, the so-called partially "rodded" mesh, volume weighting is employed to calculate the representative homogenised cross sections. Since a simple volume weighting scheme is used, the absorption of the control rod will be over-estimated when smeared out over the whole volume and therefore the k–eff results will display the cusping effect[12]. However, since the axial meshes is quite small (4 cm), the effect should be quite small. In an auxiliary calculation (cycle 9802) the effect was shown to be less than 80 pcm for the four control rods being moved as a single bank. The presence of the control above and below the core (active height) is also taken into account and has an effect of about 400-500 pcm.

2.3 MEASUREMENTS

After each core reload operation the (differential) reactivity worth of all four rods is measured separately by using an inverse kinetics calculation method for a point core model. At the beginning of a measurement, the reactor is critical with one rod fully withdrawn (100%) and the other three rods in equal bank position (partially inserted). Once a specific power level is reached, the single rod is inserted into the core at its nominal driving speed until it reaches a position of 60%. This process is repeated for the trajectories from 60% to 30% and 30% to 0% each time by making the reactor critical again with the three-rod compensating bank. An integral reactivity curve for each rod is constructed after deducing the reactivity from the time history of a detector n-flux signal for these trajectories. The used point kinetics model includes kinetics parameters such as neutron lifetime, fractions of delayed neutrons, decay constants of precursors of delayed neutrons, etc and a source term. The greater part of this source is caused by γ,n-reactions in the beryllium reflector of the core and is therefore strongly dependent of the operating history of the reactor. Only after each measurement (trajectory) the source strength is evaluated by running the inverse kinetics program with different source terms followed by selecting the optimum value of the source term.

The observed critical bank position at begin of cycle or startup is recorded for each cycle together with the coolant temperature at the time of the measurement. This critical position corresponds to a situation with all four rods in equal bank position. The excess reactivity can then be calculated by adding the integral rod worth for all rods between a rod position of 100% and the observed overall critical position. Note that the excess reactivity is corrected for the actual pool temperature and the reactivity effect of samarium build-up after shutdown. The samarium effect is assumed to be 0.20% for all the cores.

3. RESULTS

3.1 BOC CRITICALITY AND CALCULATED k-eff

Until the end of 1997 when the last full HEU core was used, there was a good agreement between the measurements and the reactor physics codes used at that time. However, from 1998, when the first LEU fuel elements were used, increasing discrepancies were found[13] between the calculated and the measured reactor physics characteristics of the mixed cores with a gradual increasing number of LEU fuel elements and beryllium reflector elements. To improve the full mixed HEU/LEU core reactor physics calculations several changes in the use of the different codes are being analysed and changes are still in progress. For example, special attention was already given to the modelling of the beam tubes[2] with the focus on the reactivity effects of the beam tubes when emptied (utilized in experiments) or full (flooded with water).

The calculated begin of cycle (BOC) k-eff for the given critical (k-eff=1.0) control rod positions and temperature conditions are shown in Figure 3 for different cycles. The KENO-Va results, although calculated at 20^0C were adjusted to the actual plant conditions by correcting the k-eff at 20^0C by -22 pcm/^{0}C. The OSCAR-3 calculations were performed at the actual plant conditions since the cross-section library prepared includes cross sections at so-called off-base temperatures and water densities. First of all it can be noticed that in all cases the KENO-Va results are generally closer to the experiment than the OSCAR-3 results. It is also interesting to note the increasing and consistent discrepancy in reactivity for the KENO-Va calculations and to a lesser extent the OSCAR-3 calculations until cycle 0103. The reactivity is decreasing after including more and more LEU fuel elements and by replacing HEU control-rod fuel elements by LEU control-rod fuel elements where the axial burnup does not yet affect the calculated results.

The sharp increase in the k-eff of OSCAR-3 for cycle 0103 could be due to the re-introduction of HEU fuel elements from previous cycles. Two HEU fuel elements from cycle 9802 were reintroduced in cycles 0103 and 0104 while three HEU fuel elements were introduced from more recent cycles (9903, 0002, 0003) in cycle 0201. The OSCAR-3 results for cycle 0103 display the same increase discrepancy in k-eff seen for 9801 and 9802 where the two HEU fuel elements last reside in the core. The discrepancies in k-eff for cycles 9801 and 9802 were also noticed in the BOC, all rods out cases studied in reference [2]. The OSCAR-3 core follow calculations only started from cycle 9703 and it is thus highly likely that the effect is caused by incorrect initial conditions (element exposures). The decreasing discrepancy between OSCAR-3 and KENO-Va up to cycle 0102 also confirms this.
The increase in the differences between the KENO-Va results at begin of cycle and the measured results could be due to a few reasons. The initial conditions for a KENO-Va calculation are the isotopic distribution as determined from the INAS system where 2D cycle power distributions are still employed. The three-dimensional burnup shapes in KENO-Va are then introduced from burnup-shape correlations. In the radial direction, no burnup shape (over the 19 plates) is included. The accuracy of the KENO-Va calculations is therefore dependent on the appropriateness of the input data.
Other factors that are still investigated and which, in most cases, would lead to an overall reduction in the discrepancies are the impurities in the different core structures and the buildup of the poisons ^{6}Li and ^{3}He in the beryllium reflectors. The equilibrium effect of ^{6}Li and ^{3}He should be small for such a low power reactor, even for the compact core. The importance of the ^{3}He buildup from ^{3}H ($T_{½}$ = 12.4 years) after shutdown (or removal from the core) and the reintroduction of these elements in the compact core could however be important and will be evaluated in future work.

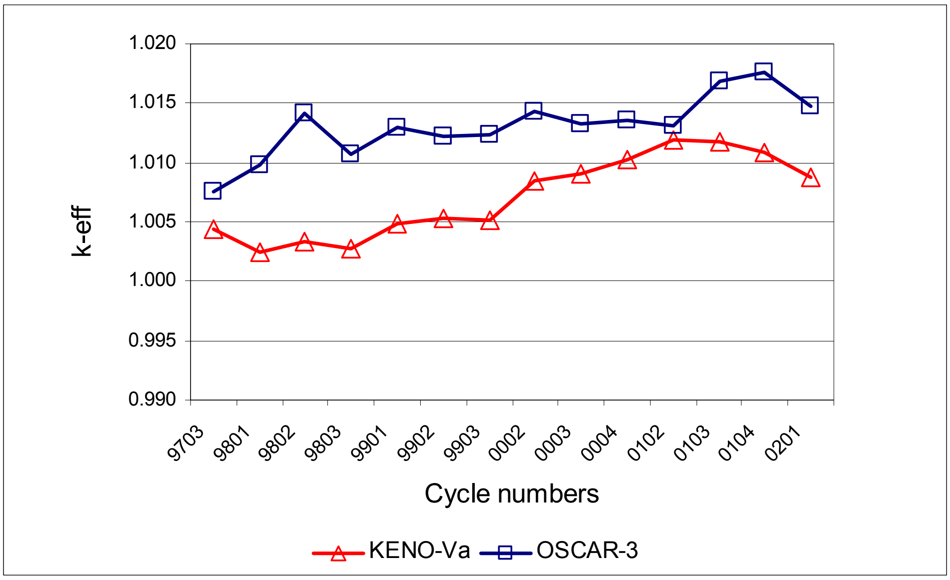


Figure 3. BOC calculated k-effective compared with start-up critical conditions.

3.2 CONTROL ROD REACTIVITY

As a next step the reactivity worth of individual control rods were investigated. A change in the control rod reactivity worth during the HEU to LEU transition could also introduce some discrepancies and could help explain the behaviour seen in Figure 3. The prediction of control rod reactivity worths is important not only for safety studies but also for reactor operations in predicting cycle lengths and critical bank positions. The incremental control rod worths (s-curves) were therefore calculated with KENO-Va and OSCAR-3 and compared with measurements. In the calculations the exact control rod configuration of the measurement were followed with one rod moving from 100% to 60% extracted, 60% to 30% and then 30% to 0%, in each case with the other three rods at the insertion depth that kept the core critical. The calculated (KENO-Va and OSCAR-3) and measured results for the s-curve for core 0103 and 0201 are shown in Figure 4 and 5 respectively. The results are shown individually for each of the four control rods.

The s-curves show a favourable correspondence between the measurement and the calculated values. The tendency is for the calculations to slightly over-predict the measured value. This is clear from the data provided in Tables II and III. In these tables the total reactivities are provided but also the contribution from the three individual "measurements" (100%-60%, 60%-30%, and 30%-0%). The maximum difference between measured and calculated is just over 10% and is for the OSCAR-3 value of Rod 1, cycle 0103. For both cycles considered the smallest differences were obtained for Rods 3 and 4. This can, however, not be attributed to the control-rod fuel elements in these positions. Incidentally the two HEU control-rod fuel elements in positions E5 and E3 (rod positions 3 & 4) in cycle 0103 ended up in positions C5 and C3 (rod positions 2 & 1) in cycle 0201. In cycle 0103 the differences between calculated and measured incremental reactivity for both these rods were less than 1% for KENO-Va as well as OSCAR-3 while the differences for cycle 0201 lie between 2.1% and 8.3%.

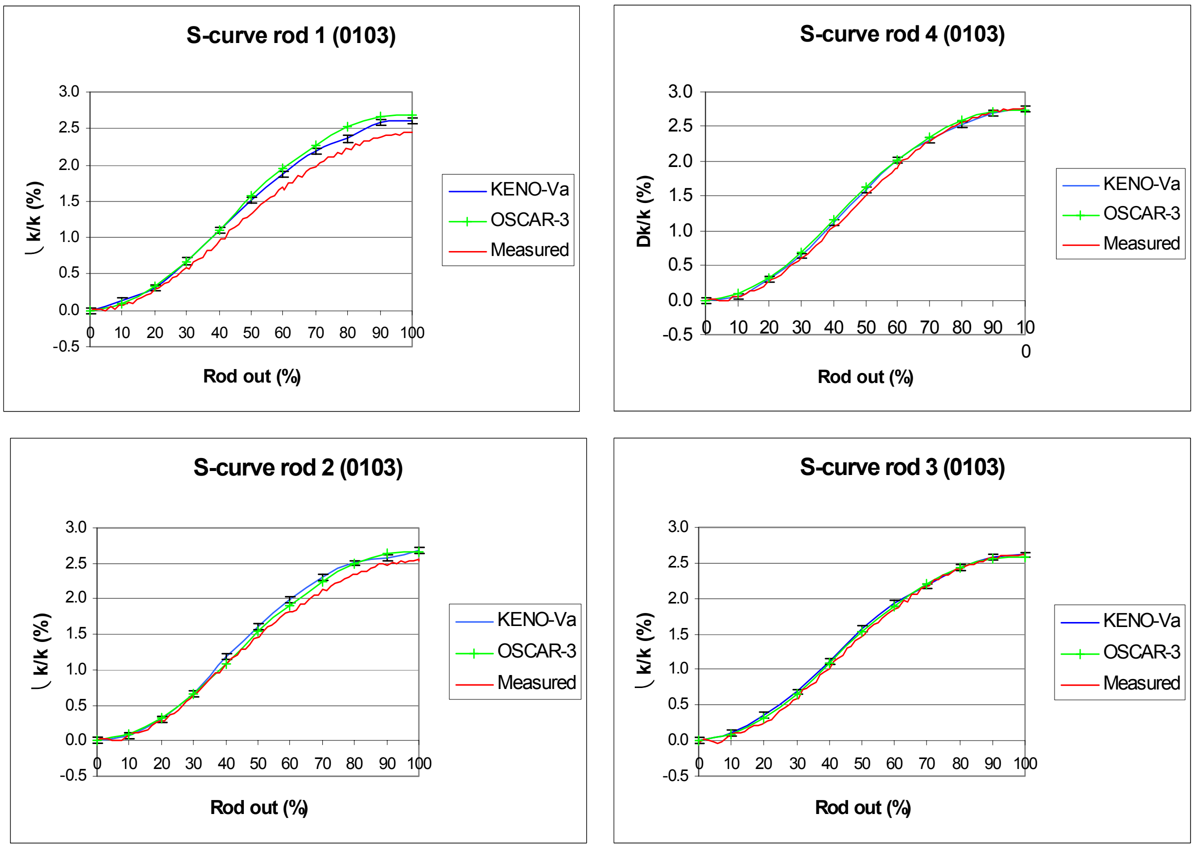


Figure 4. S-curves rod 1-4, cycle 0103.

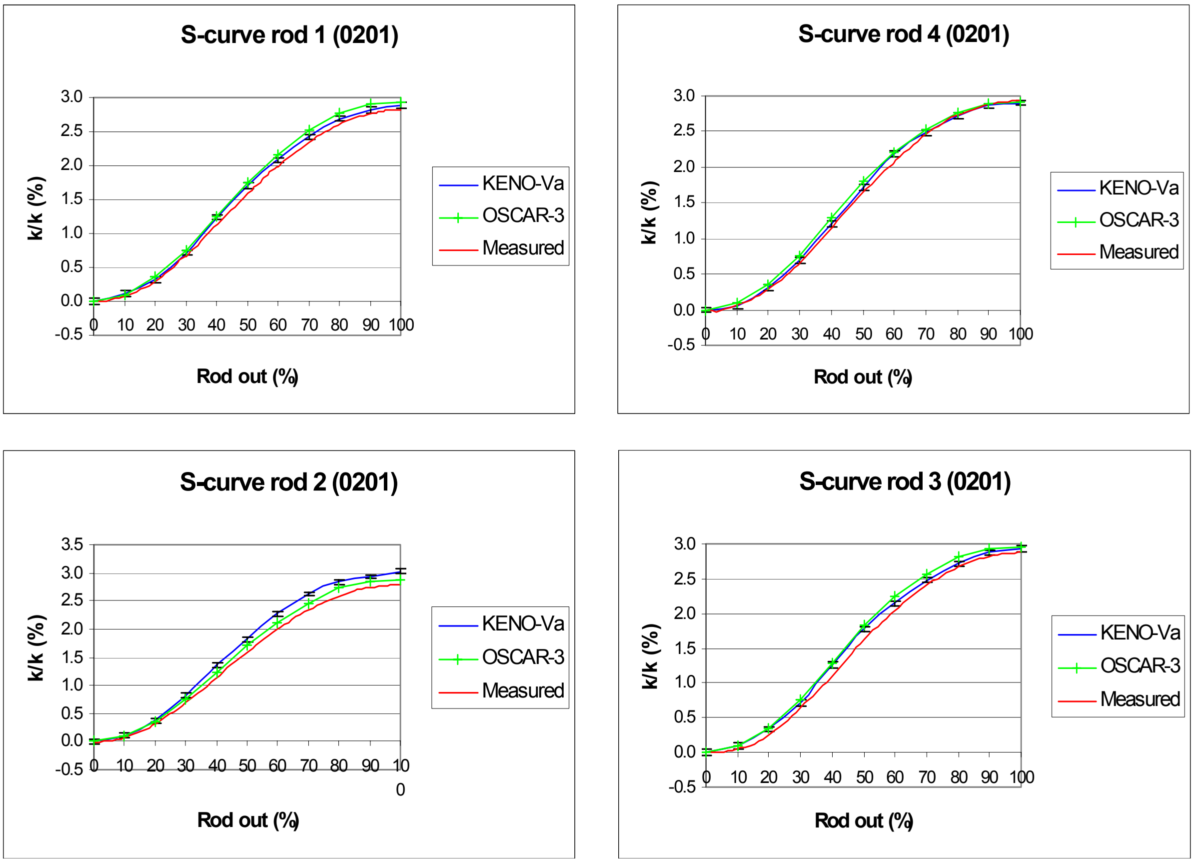


Figure 5. S-curves rods 1-4, cycle 0201.

Table II. Cycle 0103 individual control rod reactivities [in %]

Case		100%-60%	60% - 30%	30% - 0%	Total	Delta
Rod 1	KENO-Va	0.725	1.200	0.676	2.601	0.158
	OSCAR-3	0.748	1.273	0.671	2.691	0.249
	Measured	0.751	1.106	0.586	2.443	
Rod 2	KENO-Va	0.706	1.320	0.666	2.692	0.149
	OSCAR-3	0.755	1.258	0.653	2.665	0.122
	Measured	0.719	1.195	0.628	2.543	
Rod 3	KENO-Va	0.686	1.242	0.685	2.613	0.025
	OSCAR-3	0.686	1.251	0.646	2.583	-0.005
	Measured	0.736	1.255	0.597	2.588	
Rod 4	KENO-Va	0.725	1.389	0.636	2.751	-0.014
	OSCAR-3	0.725	1.333	0.683	2.740	-0.024
	Measured	0.865	1.288	0.612	2.765	

Table III. Cycle 0201 individual control rod reactivities [in %]

Case		100%-60%	60% - 30%	30% - 0%	Total	Delta
Rod 1	KENO-Va	0.800	1.373	0.712	2.884	0.059
	OSCAR-3	0.775	1.419	0.749	2.943	0.117
	Measured	0.841	1.320	0.665	2.826	
Rod 2	KENO-Va	0.750	1.461	0.810	3.022	0.234
	OSCAR-3	0.762	1.388	0.735	2.885	0.097
	Measured	0.797	1.304	0.687	2.788	
Rod 3	KENO-Va	0.791	1.433	0.711	2.935	0.054
	OSCAR-3	0.717	1.478	0.763	2.959	0.078
	Measured	0.836	1.412	0.633	2.881	
Rod 4	KENO-Va	0.711	1.490	0.701	2.902	-0.032
	OSCAR-3	0.700	1.450	0.761	2.911	-0.023
	Measured	0.868	1.413	0.654	2.934	

It can be concluded that the calculated and measured incremental reactivity worth of the individual rods is in good agreement and presents a valuable tool in support of safe reactor operations.

3.3 KENO-Va AXIAL BURNUP SHAPE ASSUMPTION

The assumptions made for the axial burnup shape of the fuel and control-rod fuel elements in the reference KENO-Va calculations were evaluated further. The use of the correlation to relate the fuel element average burnup with the axial burnup shape was compared with OSCAR-3 results. Whereas the correlation was calculated for a HEU core (using SILWER) with the control bank at its critical position throughout the cycle, the OSCAR-3 axial burnup profiles are the result of core follow calculations of actual operating cycles (starting cycle 9703) with the control bank at its critical position throughout the cycle. The KENO-Va correlation for HEU is used for both fuel and control-rod fuel elements, and also for LEU elements.

When evaluated the OSCAR-3 and KENO-Va axial burnup shapes compared favourable for the HEU and LEU fuel elements. A comparison between a HEU fuel element and control-rod fuel element did however show a considerable difference in the axial burnup shape as a function of time. This can clearly be seen in Figure 6. In this figure a correction factor, defined relative to the element axially average burnup is given for each axial mesh. The profiles for a standard HEU fuel element (H) and a HEU control-rod fuel element (HC) are shown. The H profile corresponds to the correlation used for control elements in KENO-Va. In the graph the profiles for 44% and 47% burned in mass ^{235}U are shown. The non-symmetric control-rod fuel element burnup shape is to be expected due to the presence of the B_4C absorber rods. The profile will of course also be dependent on the typical begin and end of cycle control bank positions. Since LEU control-rod fuel elements were only introduced in cycle 0104, its axial burnup profile will only be constructed with time.

The different axial burnup profile in OSCAR-3 and KENO-Va could perhaps explain some of the discrepancies seen between KENO-Va and OSCAR-3. In the future the OSCAR-3 axial burnup shapes will be used to update the correlations used and the possibility to generate the KENO-Va fuel element burnup and axial shape data directly will be investigated.

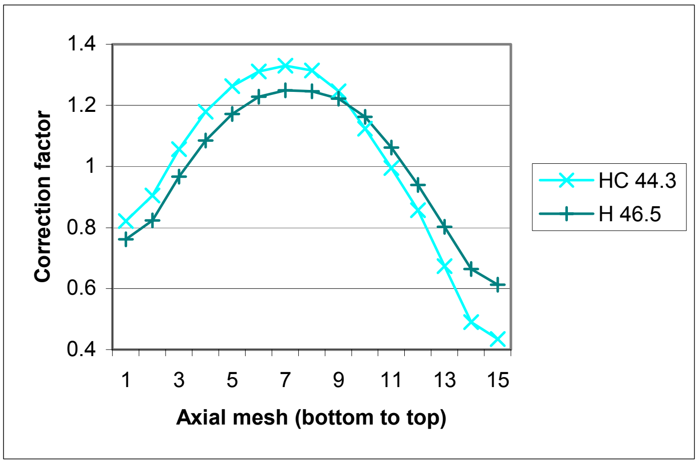
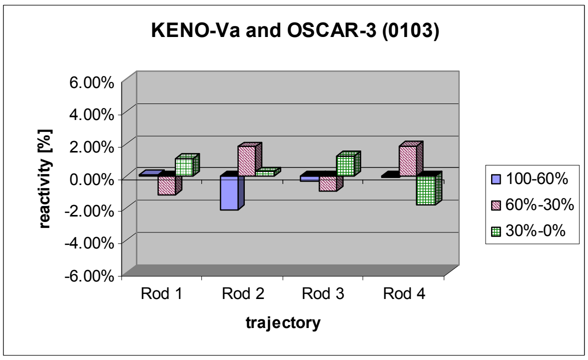


Figure 6. Axial burnup profiles, HEU control (HC) and standard (H) element.

From the incremental reactivity worth measurements and calculational results the reactivity values for the three control rod axial extraction heights are available (Tables II and III). The relative contribution of each part of control insertion (% extraction) to the total rod reactivity worth were calculated and compared. The KENO-Va and OSCAR-3 results are compared in Figure 7. No general trend can be seen for the four rods in the two cycles considered. The differences seen are most probably due to differences in the axial (and radial) burnup profiles and of course effects introduced by the solution methods, such as the cusping effect in the case of OSCAR-3.



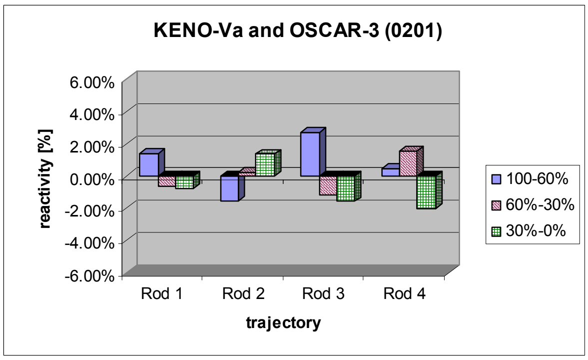
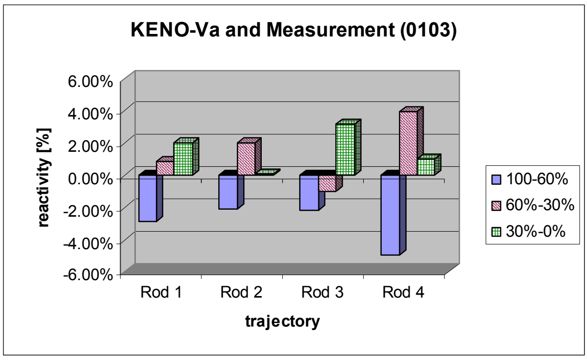


Figure 7. Difference integral trajectory reactivity between KENO-Va and OSCAR-3.

In Figure 8 the relative contributions of the control rod sections extracted (100%-60%; 60%-30%, 30%-0%) are compared between KENO-Va and the measured values. In this case a trend can clearly be seen. In all cases KENO-Va underestimates the 100%-60% extracted reactivity worth (as a percentage of the total worth). This is then balanced by the larger fraction of the total worth contributed by the extraction axial regions 60%-30% and 30%-0%. The behaviour could perhaps be explained by the control-rod fuel element axial burnup shape assumed in KENO-Va. In Figure 6 it was already shown and explained that the profile for a control-rod fuel element is different from a standard fuel element profile assumed in the correlation. Since the burnup of the upper part of the elements are over predicted in the correlation, the control rod worth of a rod inserted into this upper region of the control-rod fuel element will be under predicted in the KENO-Va calculation (due to the downward shifted flux profile). The effect should therefore disappear when fresh control-rod fuel elements are introduced. This is not the case since the control-rod fuel elements into which rods 3 and 4 were introduced in cycle 0201 are relatively fresh (3% and 0% ^{235}U depleted) but the effect of under prediction of the 100%-60% cases are still evident. What must however be kept in mind is that the reactivity behaviour is not only dependent on the burnup shape of the element position where the rod is inserted but also on the general axial flux profile. The core axial flux profile also depends on the burnup profile of the other three control rods (used to kept the reactor critical) where the "incorrect" burnup profile is still assumed (for two of the three positions). These arguments are not totally convincing and will have to be verified after updating the fuel element axial profiles in KENO-Va with the OSCAR-3 data as suggested. Comparative KENO-Va calculations and comparisons with the measured values will then once again be performed. This was left for future work.



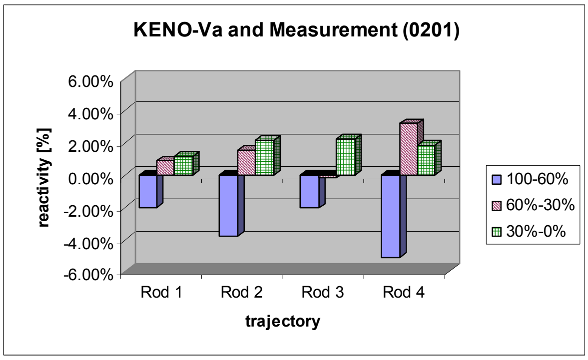


Figure 8. Difference integral trajectory reactivity between KENO-Va and the measurements.

3.4 CONTROL ROD BURNUP

The question must of course be asked if any depletion of the B_4C in the control rods takes place. In MTRs the control rods are positioned within the core throughout the cycle. In HOR the typical control bank is 53% extracted at startup and totally (100%) extracted at end of cycle several weeks later. Most of the lower half of the control rods will therefore be exposed to a very high thermal flux. The burnup of the control rods are not measured in any way. The criteria for control rod lifetime are minimum total reactivity worth (which is easily achievable) and the amount of swelling that occurs in a control rod. The current rods have all been in use for over 30 years and only one (rod 2), being in use since 1962, is now approaching its end of life (due to swelling). This aspect was not further investigated. Since the replacement of one of the absorber rods is foreseen, it will present an ideal opportunity to evaluate the control rod burnup in more detail.

CONCLUSIONS

The calculational support and evaluation of the conversion of the HOR research reactor from HEU to LEU conversion is on going. Not only the INAS code available at TU-Delft but also the OSCAR-3 calculational system available at NECSA is used. Improvements in models as well as the measuring techniques are continuously evaluated. The objective is a conversion process where calculations are performed in such a way that the new mixed core designs and the final compact LEU core designs are realised, fulfilling all the safety and operational constraints without necessary adjustments during the real reshuffling operation program.

Reasonable results with accuracies within 2% in k-eff were obtained for both KENO-Va and OSCAR-3 for the begin of cycle criticality as compared with the measured control bank at startup. The reactivity differences between calculated and measured results increase as the conversion to LEU and the compact core progress up to cycle 0103. At this point the KENO-Va results start to improve while the further increase in the OSCAR-3 k-eff results is still further investigated. It must, however be said that the results obtained can already be considered as reasonable for such a small reactor.
The incremental reactivity worth of individual control rods were compared for cycle 0103 and 0201. Excellent agreement between the calculated and measured incremental reactivity worths (the s-curves) were illustrated for both KENO-Va and OSCAR-3 for all four control rods. A maximum difference of 10% and an average difference of 3.5% were found in the calculated results. Although the uncertainties in the measured results were not quantified, they are probably similar than these differences. In most cases the calculated value slightly over predicts the measured value.
The discrepancies in the relative axial reactivity contributions of the control rods for the three axial extraction regions (100%-60%, 60%-30% and 30%-0%) when the measured and results calculated with KENO-Va are compared, can probably be attributed to the current (standard) burnup profile used in KENO-Va. Work is in progress to improve this by using a more realistic axial burnup profile, as calculated by OSCAR-3, for the control-rod fuel elements in the KENO-Va calculations. The possibility to also introduce radial or element burnup data from OSCAR-3, an improvement on the 2D cycle power distributions in the INAS system, will also be considered.
The HEADE two-dimensional assembly calculations, used to prepare the five-group homogenised HEU and LEU control-rod fuel element cross sections, were found to be sensitive to the model employed. The low order interface current method, with its assumptions of constant interface current and cosine directional current shape between cells, was shown to be inadequate for the strong directional dependence in the control assembly with the rod inserted. This will be further evaluated including the use of other methods such as the collision probability code called STYX[14] available in OSCAR-3.
Improvements to the OSCAR-3 code system are also ongoing. A generalization of the axial mesh definition in MGRAC, which separate the flux solution and the burnup or material meshes, was already implemented and is being tested[15]. Since axial homogenisation (flux weighting) can now also be applied to partially rodded meshes, the cusping effect should be largely eliminated. The detailed axial design of the rod tips (aluminium structure) can also be modelled more accurately.
The results reported in this paper have increased the confidence in the calculational methods and approach followed. In particular the control rod models were evaluated and the calculational tools were shown to be of practical value in the support of the reactor operation. As part of the further evaluation of the INAS and OSCAR-3 codes for HOR the comparison of assembly and even plate power distributions are foreseen.

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