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HOR: TRANSITION (HEU-LEU) CORE FOLLOW COMPARISONS BETWEEN DIFFERENT COMPUTER CODES AND PLANT DATA

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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 assemblies. Since the beginning of 1998, the high-enriched uranium (HEU) fuel assemblies are replaced step by step by low-enriched uranium (LEU) fuel assemblies while the core size is simultaneously reduced by replacing fuel assemblies by beryllium reflector elements. At present about 50% of the HEU fuel assemblies are replaced by LEU fuel assemblies. 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 to the modelling of the beam tubes with the focus on the reactivity effect allowing for a comparison between measured and calculated reactivity values for different cores. Different calculated effective multiplication factors (k-effective) for a number of cycles with different beam tube configurations are shown and compared with measured results. 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.

1. INTRODUCTION

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 in a continuous shift of 100 hours a week, 40 weeks a year. It contains MTR-type (Material Test Reactor) fuel assemblies consisting of 19 fuel plates. Until the end of 1997, the reactor used 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 assemblies were introduced in the HOR reactor. It is anticipated that after 15 to 17 core-reload operations the HOR will be fully converted from HEU-LEU fuel. During this conversion process the core size will also be reduced from 30 fuel assemblies to 20 fuel assemblies with beryllium reflector elements replacing the removed fuel elements (compact core). A central irradiation facility will be put in the centre of the core[1]. In the transition phase the mixed core will consist of HEU and LEU fuel assemblies. Maps of the starting point HEU core, a mixed core (no. 4), and the compact LEU working core are shown in Fig. 1, 2, and 3 respectively.

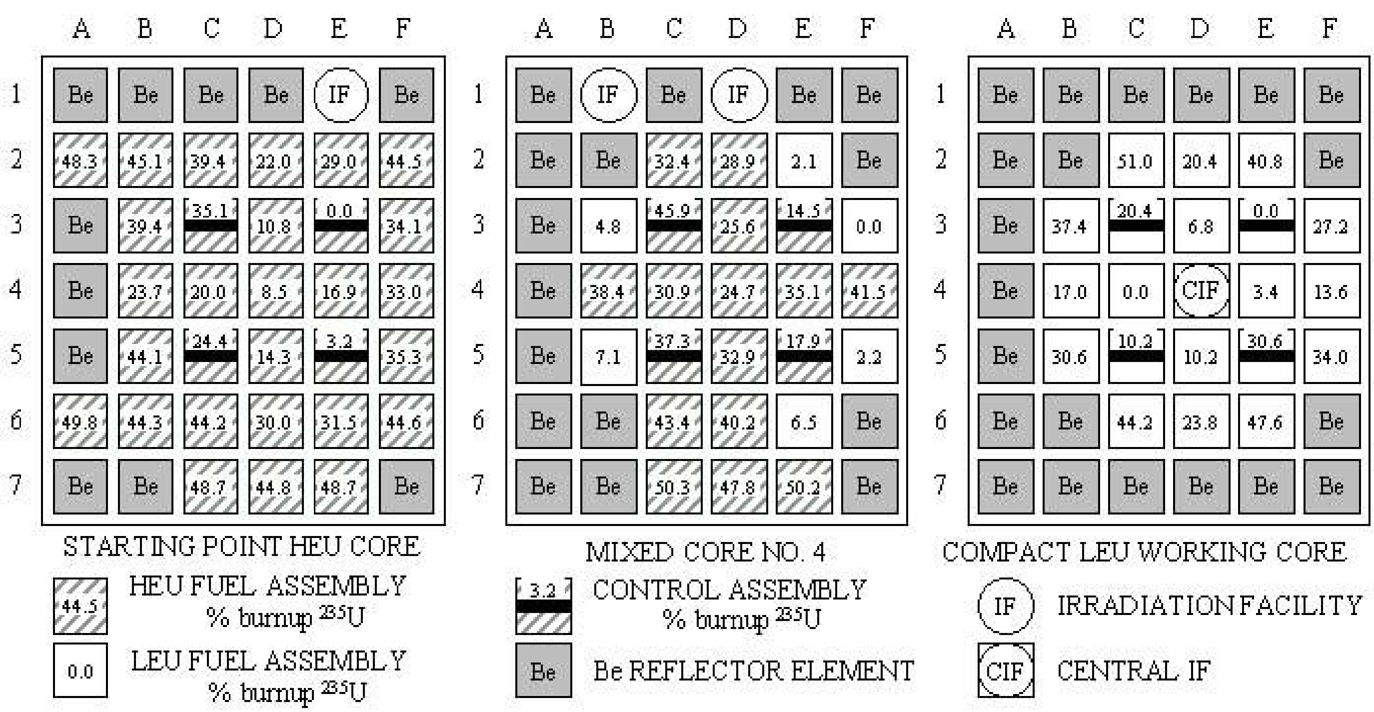

Figure 1. Figure 2. Figure 3.

2. METHODS

Regarding reactor operations: criticality, flux distributions, power distributions, and burnup were measured and calculated using old approximate codes. Until the end of 1997, when the last full HEU core was used, there was a good agreement between this method and more advanced reactor-physics codes. However, increasing discrepancies were found using few-group cross-section sets in diffusion calculations for the mixed (HEU-LEU) cores. These cross sections were generated with a one-dimensional cell transport code. In this code, the effect of different neighbours (HEU-LEU) cannot be taken into account. This has made it necessary to employ more advanced methods and code systems to support the continual safe operation of the HOR. In this paper, criticality results are presented using two different code systems.

At IRI the INAS (IRI-NJOY-AMPX-SCALE) code system is used. At NECSA the OSCAR-3[2] code system is available. The two code systems are described below. The criticality is calculated at the begin of cycle (BOC) with all the control rods withdrawn, no xenon poisoning, and room temperature of 20^0C. The effect of the radial beam tubes on the criticality is also taken into account. There are seven beam tubes, three on the left side of the core (L1, L2, and L3), three on the right side (R1, R2, and R3), and one tangential tube at the back of the core. Depending on the experiments, the seven beam tubes can be ‘full’ (H_2O) or ‘empty’ (in use by an experiment). The calculations are done with all the beam tubes full (highest reactivity) and with some of the beam tubes empty (measured reactivity) depending on the experiments used during a particular cycle.

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. 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 assembly, 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.

2.2 The OSCAR-3 core calculational system

OSCAR-3 is an acronym for an “Overall System for the Calculation of Reactors”. The code system has been developed by NECSA over many years and is used in the day-to-day reload and support calculations of the SAFARI-1 reactor[7]. The user is assisted by the graphical user interface called MAESTRO to perform core reloads, cycle depletion calculations and to view results.

At the heart of the code system is MGRAC, a modern multi-group nodal diffusion code. Since MTR’s are small (and the final HOR LEU core will be even more compact) the modelling of core leakage is important. In order to take the different leakage spectra into account, the HOR core calculations were performed in five broad-energy groups.

For a more detailed description of all the codes and features in OSCAR-3 the reader is referred to the References [2, 8, and 9].

3. THE MODELS EMPLOYED

3.1 The OSCAR-3 assembly calculations

The HEU and LEU fuel and control assembly depletion calculations were performed by HEADE, a two-dimensional transport code based on a low-order interface current method[10]. The code makes use of the 172-group OSCAR-3 library based on the WIMS7 cross-section library[11] with the same group structure. The WIMS library is based on the same basic evaluated data file (JEF-2.2) as used in the INAS code system. A detailed 2D model with the fuel, cladding, and assembly structure modelled explicitly was used to generate multi-group homogenised assembly cross sections, discontinuity factors, and cross section rehomogenisation moments as a function of exposure, fuel temperature, moderator density and temperature. In Fig. 4a the model for the 300 gram LEU assembly is shown.

Another code in OSCAR-3, called EQUIVA can be used to calculate reflector cross sections. It applies advanced reflector homogenisation methods[12] in an attempt to conserve all transport and anisotropic behaviour of the reflector in the core diffusion calculation. However, in this work, simplified models of all the reflector elements, ex-core reflector regions and in particular the beam tubes, were also defined in HEADE which applied straight forward flux-volume-weighting in order to get the homogenised multi-group cross sections. An example of one of these simplified models are shown in Fig. 4b.

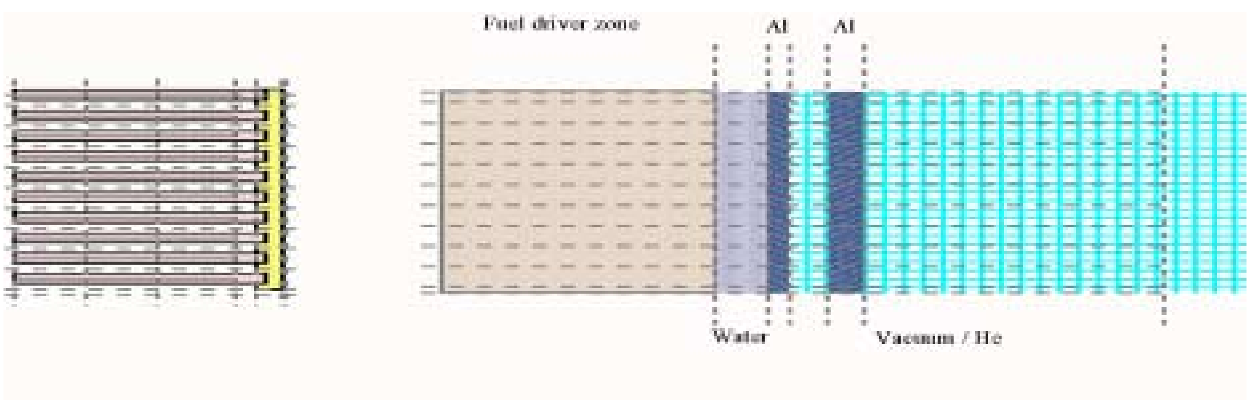

Fig. 4 Examples of the HEADE models employed for the (a) LEU fuel assembly and (b) for the Neutron Guide System (SF) in beam tube L2 with the shielding tank filled with He.

In all cases, the models were defined to try and to conserve both the physical distances and material properties (volume ratios) of the region of interest. Since the core is presented as a Cartesian array of rectangular channels, the size of an assembly (7.71 x 8.1 cm), the angle of incidence of some of the beam tubes (R1, R3, L1, and L3) were ignored.

3.2 The OSCAR-3 core calculations

The reactor reload and burnup studies were performed in OSCAR-3. The neutronic calculations at BOC were performed by MGRAC while the core reloads, both for the core-follow-calculations with the empty beam tubes present as well as the definition of the reference (beam tubes full) environment, were performed by the code called SHUFFLE. In the MGRAC model the core is divided into 4 cm meshes axially within the active core height (60 cm) and a 12 cm mesh for the top and bottom reflector regions. The side reflector is represented by a 15 cm mesh followed by black boundary conditions. The representation of cycle 0004 as displayed in MAESTRO is shown below (Fig. 5).

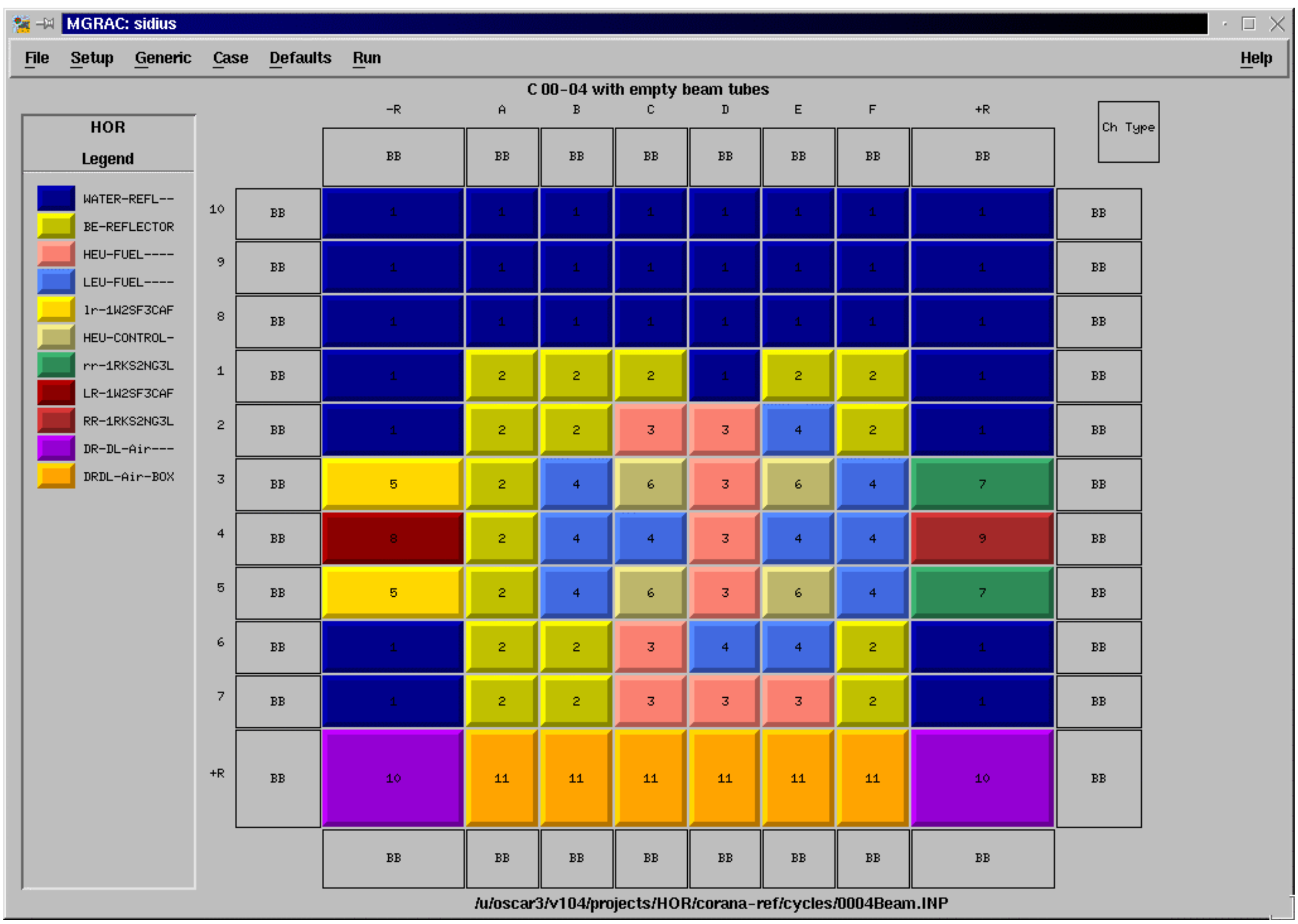

Fig. 5 Cycle 0004 core load map as represented in MAESTRO. The reflector areas where beam tubes are modelled can clearly be distinguished from the water regions.

Since the last fully HEU core (9703) was taken as the starting point in this work the assembly ^{235}U masses and the axial burnup profiles were taken from the plant data and the old 2D / 3D corrected diffusion codes respectively. The plant data was also used to perform core follow depletion calculations for each cycle with the correct environment (empty beam tubes) and control rod positions being taken into account. A convergence criterion of $5x10^{-6}$ for the k-effective (eigenvalue) and 10^{-5} for the assembly powers was used.

4. MEASUREMENTS

After each core reload operation the excess reactivity of the new core is measured by using an inverse kinetics calculation method for a point core model. The measurements consist of determining the differential control rod worth of all four rods separately. 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. A differential 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 excess reactivity is then calculated by adding the integral rod worth for all rods between a rod position of 100% and the observed overall critical position. This critical position corresponds to a situation with all four rods in equal bank position. Finally, the excess reactivity is corrected for the actual pool temperature and the reactivity effect of samarium build-up after shutdown. The corrected excess reactivity corresponds to room temperature (20^0C) in accordance with the conditions in the KENO-Va and OSCAR-3 calculations. The samarium effect is assumed to be 0.20% for all cores. Fig. 6 shows the measured excess reactivity for the cores 9703 through 0004 as well as the calculated values using detailed modelling of the beam tubes.

5. RESULTS

The results of all the k-effective calculations with KENO-Va and OSCAR-3 for the different cycles are shown in Fig. 6. The MGRAC CPU time for a single k-effective calculation is 20 seconds on a PENTIUM III 600 MHz laptop running LINUX. A Monte Carlo run with KENO-Va for a single k-effective calculation using 1000 generations is about four hours on a COMPAQ AXP 667 MHz workstation running OPEN VMS. In all the calculations, the control rods were fully out, no xenon poisoning, and room temperature (20^0C) was used. The simulation is done with nuclide densities at the begin of cycle (BOC). The results for the reference cores (beam tubes full) and with detailed beam tubes (in use by an experiment) are displayed. The results of the measurements are displayed in the same figure as well.

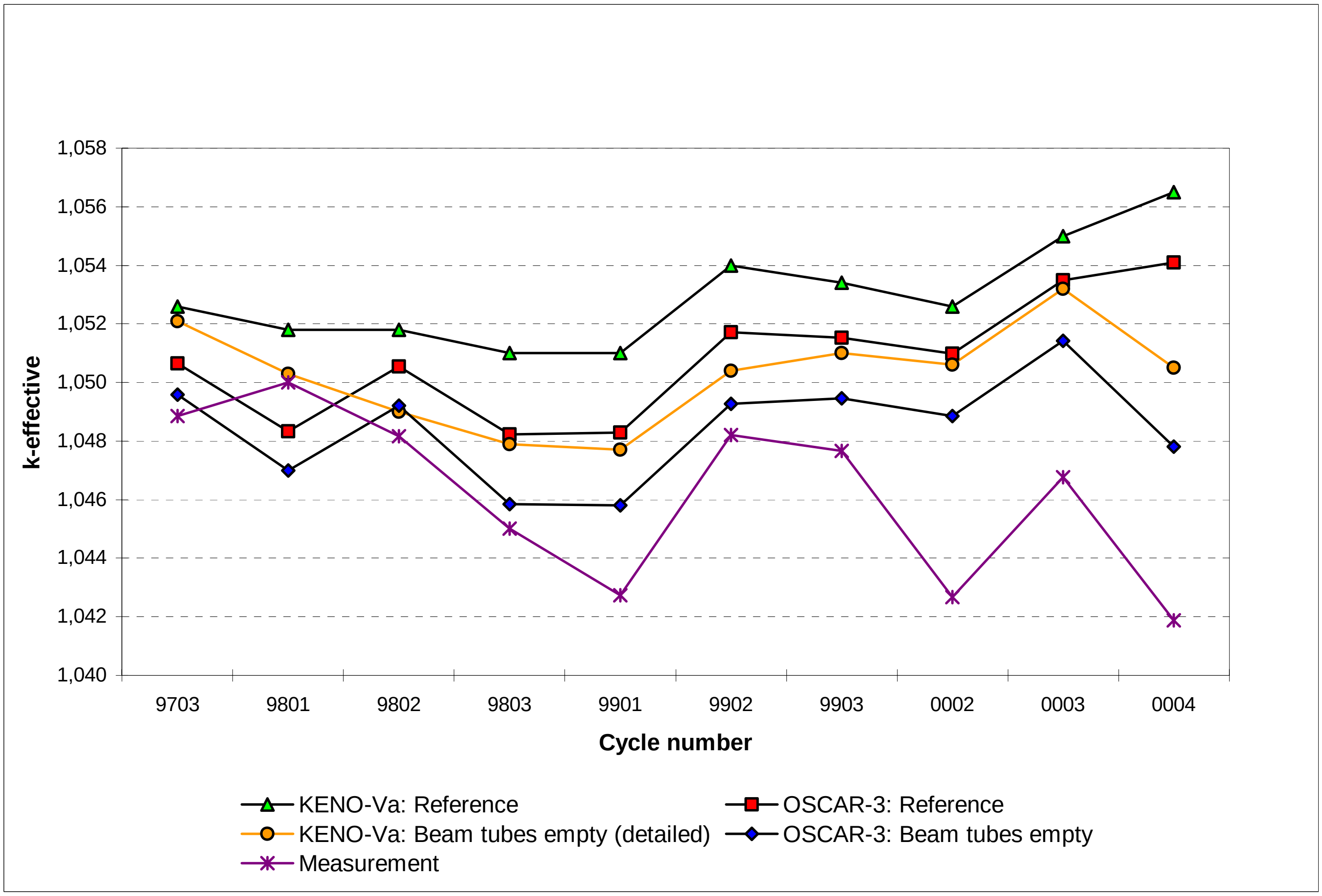

Fig. 6 k-effective for different core cycles.

The reference results for OSCAR-3 have a very similar (and consistently lower) behaviour for cycles 9803 through 0004. The same observation is true when the results for empty beam tubes are compared although it is slightly less consistent. For the first three cycles this trend is no longer true. In fact, the k-effective difference between the reference KENO-Va and OSCAR-3 results for cycle 9801 is nearly three times that of cycle 9802. No immediate explanation could be found although possible reasons are given below as part of the more detailed discussion of the beam tubes' negative reactivity effects. The experimental results, which should be compared with the empty beam tube calculations, are consistently lower than the reference KENO-Va results and only roughly follow the general trend of the calculated results.

For all the cycles considered five different beam tube configurations were identified, as shown in Table 1. This means that for several cycles the beam tube environment are identical. In the table below, these are identified and associated with a relative void percentage. This void percentage is a measure of the void volume of the beam tubes in close proximity (15 cm) of the core and was normalised so that cycle 0004 was 100%. An indication of the position of the voided areas is also given by the allocation of the void fractions to the left, back, or right beam tube areas respectively (column –R, row +R and column +R in Fig. 5). Note that the void fraction is at most a relative indication of the possible leakage due to streaming into these void areas since many other factors such as the core loading or the proximity of the beam tubes to the core should be taken into account. For example, the left side beam tubes are separated from the fuel assemblies by one row of beryllium reflector assemblies reducing the impact of the void on the left side significantly.

Table 1 Beam tubes, void fraction

Core cycle	void fraction (%)	Left	Back	Right
9703, 9801, 9802	25	14	0	11
9803	74	29	34	11
9901, 9902	84	29	34	21
9903, 0002, 0003	69	14	34	21
0004	100	14	34	52

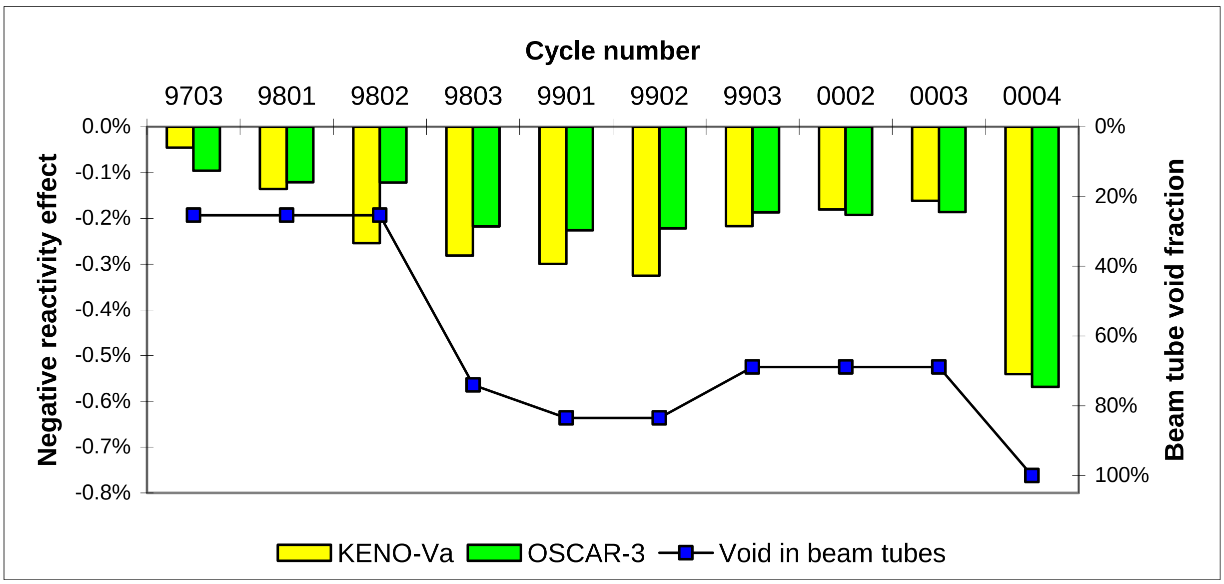

Fig. 7 Relative Reactivity Effect of Empty Beam Tubes.

In Fig. 7 the negative reactivity effect of the beam tubes are presented as calculated by KENO-Va and OSCAR-3 respectively. Also included in the graph is the relative void fraction as defined above. It is immediately apparent that there exists a relation between the void fraction and reactivity effect as could be expected.

Furthermore, the results for the last four cycles are in excellent agreement with differences of the same order than the uncertainty in the reference results. Larger differences are however observed for the earlier cycles. The results for cycles 9703 and 9802 in particular do not compare favourably. One possible explanation can be defective initial input data in OSCAR-3 (such as the assembly exposure profiles obtained from the old methods). The phenomenon of errors being “burned” away over time is often seen in reactor calculations. Another reason could be that the simplified flux-volume-weighting applied in this study may be inadequate for specific beam tube configuration used in the earlier cycles. In future work the use of the advanced homogenisation methods in EQUIVA (to represent the correct empty beam tube leakage) could resolve this uncertainty.

Also of interest, when the reactivity for the same beam tube configurations are compared, is that OSCAR-3 predicts very similar values for any single beam tube configuration fairly independent of the cycle or core loading (compare cycles 9901 and 9902 or cycles 9903 through 0003). This is not so apparent for the reference KENO-Va results, especially not for cycles 9703 through 9802. The introduction of the first two LEU elements in cycle 9801 and the concurrent reduction in core size could perhaps explain this especially if it introduces large spectrum effects that may not be sufficiently represented in the current five-group leakage spectrum in OSCAR-3.

In the section describing the OSCAR-3 core calculation, it was noted that cycle depletion calculations were performed with the appropriate empty beam tube environment in place. Although the empty beam tubes have a small effect on the overall neutron economy, (about 1% increase in core radial leakage) it also affects the core relative power distribution and thus the assembly depletion or mass ^{235}U remaining. Therefore, although the initial ^{235}U masses were adjusted to match for cycle 9703, the OSCAR-3 depletion calculations predict slightly different assembly and total core ^{235}U masses in comparison to plant data (and therefore in comparison to the KENO-Va input values). For cycle 0004 this amounts to a difference of 4 grams in the total mass with larger variations (up to 6 grams) for individual assemblies. These slight differences in mass distribution (and therefore power and flux profiles) could introduce some discrepancies in the calculated beam tube reactivities being compared in this work. The reason for this is further discussed below.

An option exists in MGRAC that enables the user to define the assembly ^{235}U masses (by entering appropriate exposures). This could have been used to define ^{235}U masses in accordance with plant data and KENO-Va input values. However, this will require not only assembly cross sections but also isotopic number densities to be taken from the few-group homogenised cross-section library generated by HEADE. The only problem with this is that the fuel assembly calculations assume an infinite array of fuel assemblies and the neutron spectrum is therefore only dependent on the fuel type. During the HOR core conversion to LEU, the mixture of HEU and LEU assemblies in the core would mean that the neutron spectrum is very different from the assembly calculation. In MGRAC these spectrum effects can be taken into account when solving the microscopic depletion calculations and would therefore yield the correct isotopic compositions. For cycle 0004 it was shown that the ^{239}Pu content could differ by as much as 25% just because of this spectrum effect. This also places some doubt on the traditional approach (acceptable for HEU) to characterise the core and assembly "loading" by the ^{235}U mass alone.

6. CONCLUSIONS

The HOR transition (HEU-LEU) core follows comparison between different computer codes and plant data is described. The criticality results for the different cycles, using different codes, are in good agreement for both the reference core models and detailed beam tubes core models. Discrepancies of about 0.35% Δk-effective or less are acceptable results for such small critical systems with strong flux gradients and taking into account the more exact simulation using Monte Carlo with 172 energy groups compared to the five energy groups nodal diffusion method.

The discrepancies between the calculated and measured results can be explained by the use of an inverse-kinetics calculation method for a point-core model to determine the excess reactivity. The result is rather good for the cycles 9801 and 9802, with few LEU fuel elements and less beryllium reflector elements. It is assumed that the discrepancies are increasing due to the point-core model used, which does not take into account more power production at the boundaries of the core (LEU fuel elements at the boundary), increasing flux gradients (compact core), and the beryllium reflector elements which are not taken into account. From the experience with the cycle lengths of the HOR, the measured-excess reactivity values are too low and should be higher, depending on the increasing number of LEU fuel elements and beryllium reflector elements. Work is still in progress to improve the method to determine the excess reactivity.

The OSCAR-3 code system is fast and accurate and the results show that the system can be used for the design of mixed cores (that contains both HEU and LEU fuel elements) with high leakage. For mixed cores the microscopic depletion and multi-group features of MGRAC is essential and calculations using more than five groups should be investigated. Features such as the rehomogenisation moments could also play an important role to model such small cores, with strong leakage effects due to the beam tubes, accurately.

The Monte Carlo code KENO-Va can be used to determine a good reference result. From past experience at IRI this has proven to be important in order to illustrate that adequate shutdown margins are maintained. It also serves as a tool to validate other more approximate models to be used in other methods or codes such as in OSCAR-3.

As part of future studies the individual and combined beam tube reactivity effects could be quantified. This will provide the information required to develop and validate more exact beam tube models in OSCAR-3 using either HEADE or EQUIVA models.

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