FUEL CONVERSION (HEU/LEU) OF A RESEARCH REACTOR (HOR)

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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. It contains MTR-type fuel assemblies with both high-enriched uranium (HEU) fuel and low-enriched uranium (LEU) fuel. Since the beginning of 1998, the HEU fuel assemblies are replaced step by step by LEU fuel assemblies. The size of the core is also reduced by replacing fuel assemblies by beryllium reflector elements. In this paper an overview is given of the calculational methods used for the transition from HEU to LEU fuel. The code package (different methods) is tested using design cores. At present about 35% of the HEU fuel assemblies are replaced by LEU fuel assemblies. Different calculational results about criticality and power distributions are shown and compared with measured results. Taking into account the accuracy that can be reached for such small critical cores the results are useful. Work to improve the results in this transition phase is still in progress.

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 12 to 14 core-reload operations the HOR will be fully converted from HEU to LEU fuel. During this conversion process the core size will also be reduced from 30 fuel assemblies to 20 fuel assemblies and as many beryllium reflector elements (compact core). A central irradiation facility (CIF) 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, mixed core no. 4, and the compact LEU working core are shown in figure 1, 2, and 3, respectively.

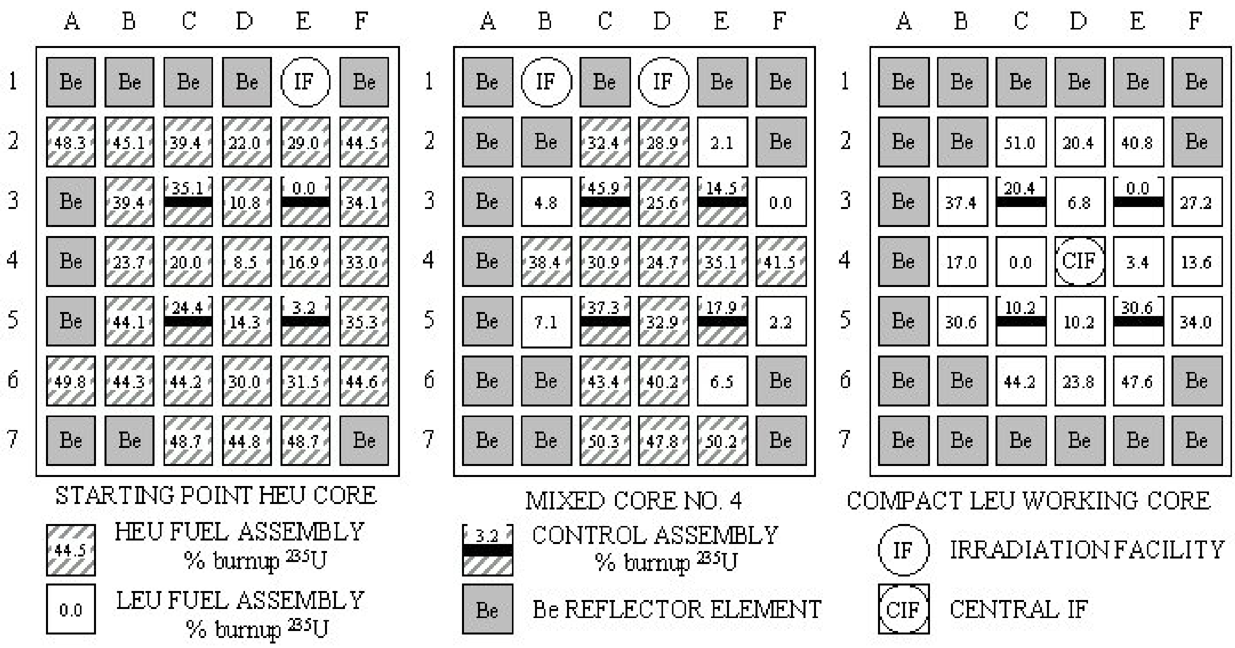

Figure 1. Figure 2. Figure 3.

2. CONVERSION PROGRAM

Regarding reactor operations: criticality, flux distributions, power distributions, and burnup distributions were measured and calculated using simple 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. At IRI –for the conversion process in particular- a comprehensive reactor code system and evaluated nuclear data is implemented for detailed (mixed) core calculations called INAS (IRI-NJOY-AMPX-SCALE). This reactor-physics code system is based on the JEF-2.2[2] evaluated nuclear data file, the cross-section processing code NJOY[3], and the SCALE[4] code system. The diffusion code BOLD VENTURE[5] is used in a two-dimensional geometry. Depletion schemes are improved using dynamically generated pseudo fissioners and pseudo absorbers[6]. These schemes are included in the code package for fuel management CONHOR[7], which is based on the BOLD VENTURE code. Former schemes for determining the burnup can no longer be used for mixed cores containing HEU and LEU fuel assemblies, because of the production and fissioning of plutonium in the LEU fuel. For the burnup calculations performed, CONHOR takes into account the changing power distributions during the cycle due to the xenon-effect. Until recently, only the cold, clean (xenon free) power distributions were used in the burnup calculations. Further, CONHOR has been improved taking into account the flux measurements allowing comparison of the measurements and the calculations regarding the flux and the power distributions. In addition, the three-dimensional nodal diffusion code SILWER from the ELCOS[8] code package is used to calculate the criticality, the power distribution, and the burnup. The three-dimensional Monte Carlo code KENO-Va[4] is used as a reference. Besides reactor physics a thermal-hydraulics core model has been developed for the HOR. The model is applied in the thermal-hydraulics computer code SHORT[9] (Steady-state HOR Thermal hydraulics), which is presently in use for the design of the core configurations and for in-core fuel management. Based on good validation results and experiences so far, the code SHORT is considered a valuable asset as a design tool for in-core fuel management serving proper guidance during the HOR conversion process. However, from 1998, when the first LEU fuel assemblies were used, increasing discrepancies were found between the calculated and the measured reactor-physics characteristics of the mixed cores with a gradual increasing number of LEU fuel assemblies.

2.1 CRITICALITY RESULTS FOR DESIGN CORES

Design and safety analyses of the HOR for HEU, LEU, and mixed-fuel operation were performed in the late eighties and begin nineties. A specific conversion strategy was analysed, starting the process with the so-called HEU compact core containing 20 fuel assemblies and as many beryllium reflector elements. A central irradiation facility (CIF) is placed in the centre of the core. An example of one of the mixed cores is shown in figure 4.

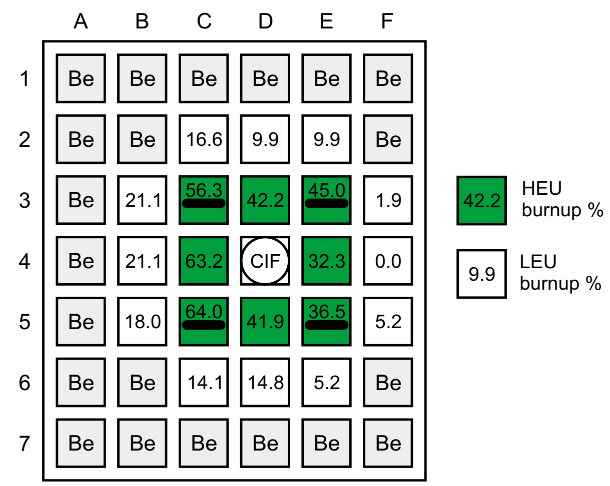

Figure 4. HOR: mixed HEU/LEU compact core.

The analysis started with the so-called HEU compact core. HEU fuel assemblies were replaced with an increasing number of LEU fuel assemblies (mix 1, mix 2, etc. core). The final compact core contains 20 LEU fuel assemblies. A comparison was made with several codes. The diffusion code BOLD VENTURE was used in a two-dimensional geometry and with five-neutron energy groups. The nodal code SILWER was used in a three-dimensional geometry and with five-neutron energy groups as well. The three-dimensional Monte Carlo code KENO-Va was used as a reference with 172-neutron energy groups. In all these calculations a temperature of 20C was used, all the control rods were withdrawn, and the core was xenon free. The results of the criticality calculations are shown in figure 5. The results revealed higher discrepancies in k_{eff} for the most heterogeneous mixed cores (mix 3, mix 4, and mix 5). These discrepancies (errors) were introduced using a conventional homogenisation technique. The broad-group cross-sections were prepared (cell weighted) using the one-dimensional S_n transport code XSDRNPM[4] with a zero net current boundary condition. Conventional homogenised cross-sections preserve group-wise average reaction rates only for an infinite medium, which is never the case in real reactor analysis[10] and certainly not with strong different 'neighbours' as the HEU and LEU fuel assemblies. Of course, there is a good agreement between the calculated k_{eff} results with the different codes for full HEU and LEU cores. These full HEU and LEU design cores have the same HEU and LEU fuel assemblies as neighbours. Small discrepancies are due to slightly different burnup and reflector elements.

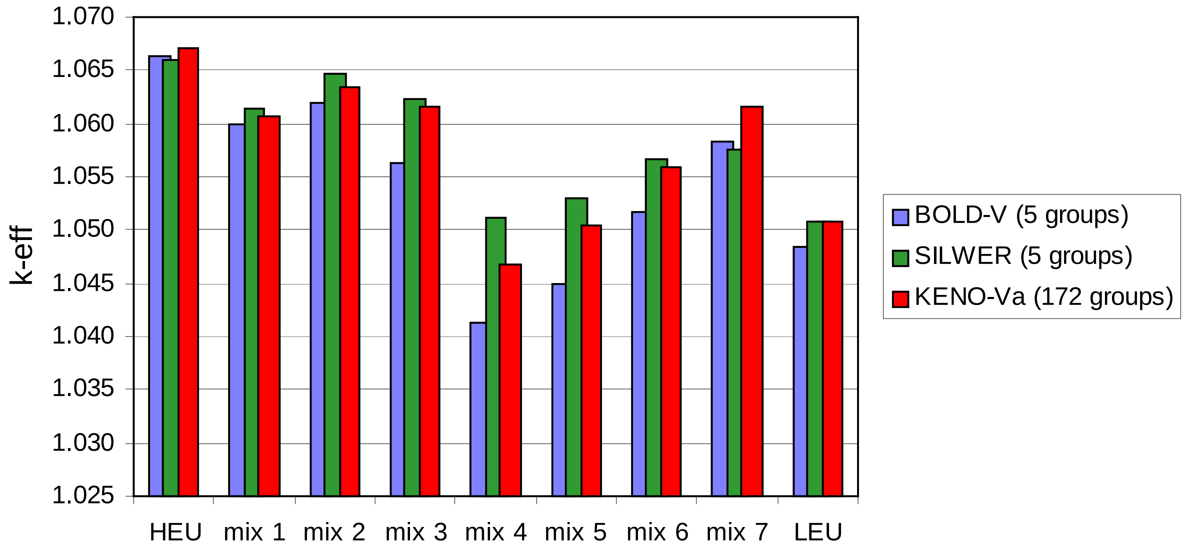

Figure 5. k-eff values for different design cores, using different codes.

2.2 CRITICALITY RESULTS FOR ACTUAL CORES

At present, six of the 12 to 14 core-reload operations of the conversion trajectory from HEU to LEU have already been performed. In total eight LEU fuel assemblies are introduced into the core while at the same time the size of the core (9703, year 1997 reload 3) was reduced from 30 to 24 fuel assemblies. A map of the actual mixed core 9903 is shown in figure 6.

Criticality calculations are performed for the following cores, starting with a full HEU core (9703), and the following mixed cores: 9801, 9802, 9803, 9901, 9902, and 9903, respectively. The following codes are used: BOLD VENTURE in a two-dimensional geometry and with five-neutron energy groups, SILWER in a three-dimensional geometry and with five-neutron energy groups, and the Monte Carlo code KENO-Va as a reference in a three-dimensional geometry and using 172-neutron energy groups. The KENO-Va results are not affected by cell weighting. In the calculations a temperature of 20C was used, all control rods were withdrawn, and the core was xenon free. In all these calculations, the radial beam tubes (six) are filled with water and the irradiation facilities are removed. In practice, the temperature is about 25C, and some radial beam tubes are empty (air, experiment). The results of the k_{eff} are shown in figure 7. The measured results are also included and show lower values. The calculated results should be corrected for the temperature effect (–0.00022/K Δk_{eff}), and the beam tubes (–0.00125/tube Δk_{eff}). The average total correction is about –0.005 Δk_{eff}. To take into account the effect of different HEU and LEU fuel neighbours, simplified equivalence theory (SET)[10] was applied using the SILWER code. These results are flagged as SILWER* and show a lower k_{eff} value, but still no satisfactory improved power distribution. Equivalence theory[11,12] represents an extension of diffusion theory through the introduction of new parameters, with the aim to reproduce integral quantities of homogenised zones (integral reaction rates and leakage), as they would be obtained with more accurate transport codes.

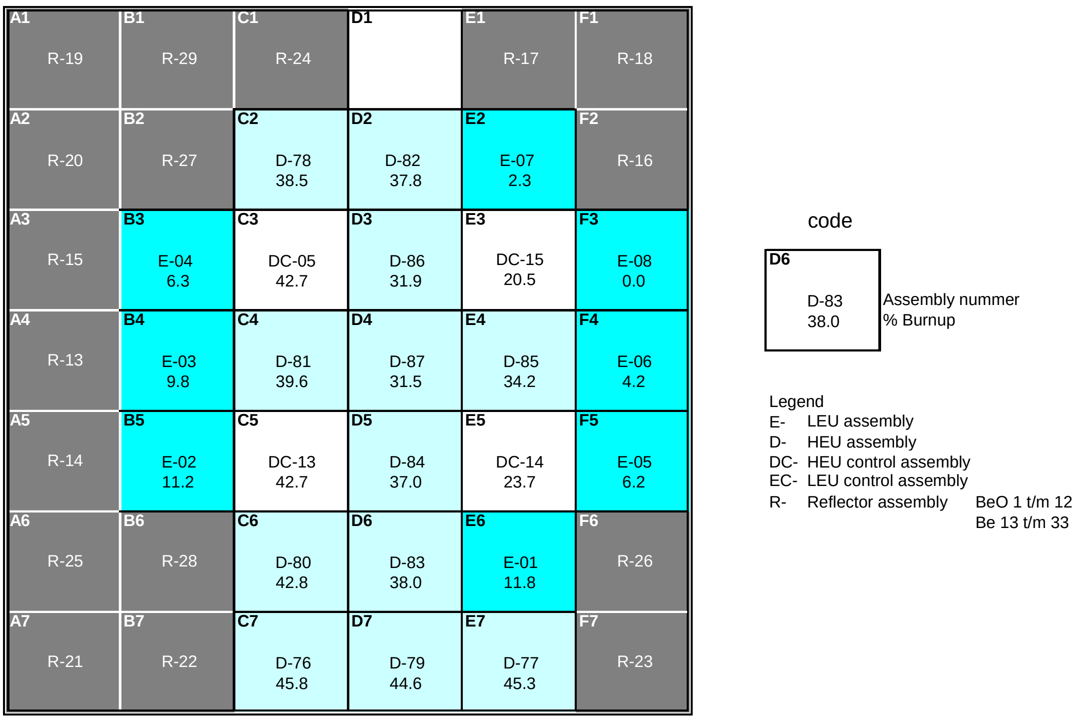

Figure 6. Map of HOR core 9903 at begin of cycle.

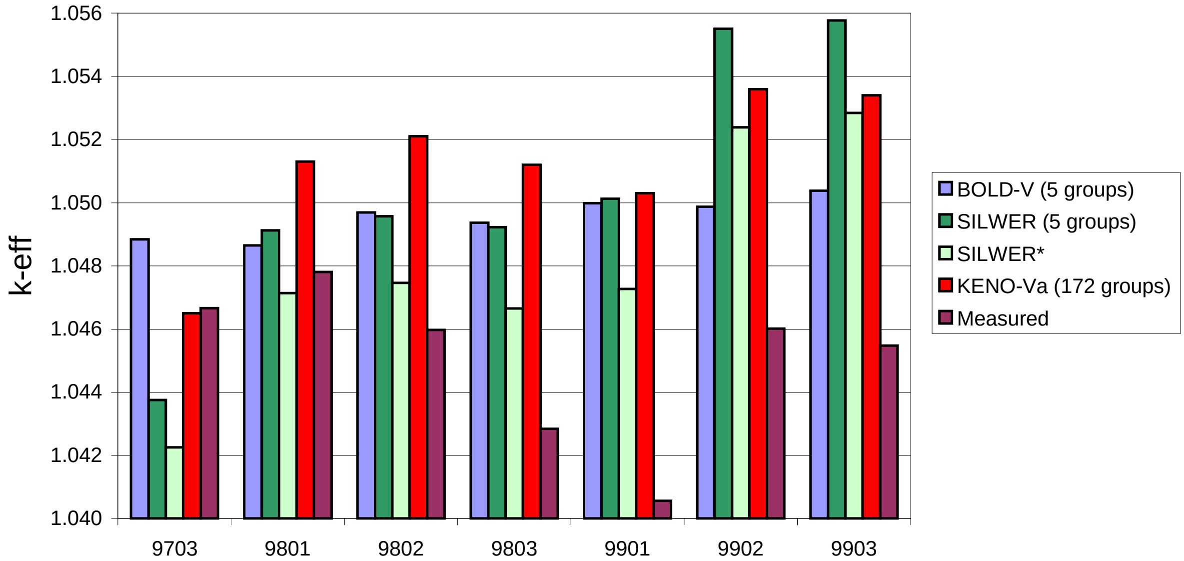

Figure 7. k-eff values for different cores, using different codes (calculated), and measured results. The calculated results should be corrected with -0.005 Δk-eff.

2.3 POWER DISTRIBUTION

The power distribution in a reactor core is another important parameter for safe operation, burnup, and fuel management. Due to the homogenisation method as used in SCALE (as mentioned earlier), the flux and power distribution in the homogenised fuel assemblies are affected by the zero net current boundary condition as well. Cell-weighted cross-sections are not used for the KENO-Va code, so the power distribution results of this code can be used as a calculated reference. Power distributions can be calculated by CONHOR (BOLD VENTURE) and the SILWER code as well. The latter code can also be used with a cross-section set including heterogeneity factors (simplified equivalence theory, SET). The results with the standard cross-section set (without heterogeneity factors) are flagged STD. The CONHOR code (based on BOLD VENTURE) can display both the measured and calculated power distribution. In this paper, the calculated and measured power distributions are displayed for HOR core 9902 at the begin of cycle (BOC). The calculations and measurements were done with the control rods in critical (k_{eff}=1) position. Calculations and measurements are also done at the end of cycle (EOC) of core 9902, but these results show the same behaviour as the BOC ones and are not shown. The calculated power distribution for core 9902 at the begin of cycle is shown in figure 8. The results of the KENO-Va code (reference) are compared with the results of the SILWER code using a standard (STD) cross-section set and a cross-section set with heterogeneity factors (SET). From the results obtained, it can be seen that the SET results show in general a slight improvement of the power distribution for the assemblies in the centre of the core and for the control rod assemblies. The largest discrepancies are shown for LEU fuel assemblies and assemblies close to

Be	Be	Be	Be	Be	Be
Be	Be	L: 6.0 -4.1 -5.4	H: 3.7 -5.0 -4.5	L: 5.6 -7.1 -8.4	Be
Be	L: 6.6 -5.3 -6.5	HC: 2.0 0.8 3.2	H: 4.8 -4.6 -4.6	HC: 2.6 -3.5 -1.2	L: 5.1 -5.6 -6.8
Be	H: 4.0 -4.8 -4.0	H: 5.0 -3.9 -3.7	H: 5.5 -4.4 -4.0	H: 4.7 -4.8 -4.6	H: 3.3 -2.8 -1.8
Be	L: 6.5 -5.1 -6.2	HC: 2.3 -0.9 1.2	H: 5.1 -4.7 -4.5	HC: 2.6 -3.0 -0.7	L: 5.3 -4.4 -5.7
Be	Be	H: 3.6 -2.8 -2.5	H: 3.8 -3.8 -3.0	L: 5.6 -7.0 -7.7	Be
Be	Be	H: 2.2 5.1 5.5	H: 2.2 4.0 4.9	H: 2.0 3.2 3.7	Be

H: 1.5	KENO-Va
1.3	% error SILWER STD
-2.1	% error SILWER SET

H: HEU fuel assembly
L: LEU fuel assembly
HC: HEU control rod assembly
Be: Beryllium reflector element

Figure 8. Relative power distribution in HOR core 9902 at the begin of cycle (BOC). Comparison between KENO-Va (reference), SILWER STD, and SILWER SET results.

the reflector elements. The average discrepancy is about 5%. For the same 9902 core, the calculated KENO-Va results (as a reference) are compared with the CONHOR calculated results and the CONHOR measured results. These results are shown in figure 9. From these results obtained, it can be seen that both the CONHOR calculated and measured results show a good agreement with the KENO-Va reference. However, the calculated HEU and LEU results for assemblies close to a reflector element show the largest discrepancies. For both HEU and LEU assemblies, beryllium reflector elements are not taken into account in the one-dimensional cell calculations preparing the broad-group cross-sections for the BOLD VENTURE and SILWER code. Heterogeneity factors are not used for the beryllium cross-sections as used in SILWER.

CONCLUSIONS

The conversion from high-enriched uranium (HEU) to low-enriched uranium (LEU) fuel of the research reactor (HOR) is described. The nuclear data and different computer codes are tested for design cores from a full HEU core via mixed (HEU/LEU) cores to a full LEU core. The criticality results for the different cores using different codes are in good agreement. Discrepancies of about 0.5% Δk_{eff} are acceptable results for such small critical systems with strong flux gradients. Until now, about 35% of the reload operations have been performed. Calculated and measured results of the criticality and power distributions are shown. For both criticality and power distributions, the discrepancies are within acceptable boundaries for these types of MTR or TRIGA cores[13].

Be	Be	Be	Be	Be	Be
Be	Be	L: 6.0 1.6 1.6	H: 3.7 -1.9 -9.4	L: 5.6 0.4 1.6	Be
Be	L: 6.6 0.7 0.2	HC: 2.0 -3.7 -3.9	H: 4.8 0.9 1.6	HC: 2.6 -1.2 0.8	L: 5.1 1.5 5.1
Be	H: 4.0 -3.4 -2.1	H: 5.0 0.9 -0.1	H: 5.5 0.7 1.0	H: 4.7 1.2 3.7	H: 3.3 -0.3 -1.8
Be	L: 6.5 1.0 2.1	HC: 2.3 -1.8 -0.2	H: 5.1 0.4 2.4	HC: 2.6 -2.2 -1.3	L: 5.3 1.0 1.7
Be	Be	H: 3.6 -1.6 2.5	H: 3.8 -1.2 -0.6	L: 5.6 0.0 -1.7	Be
Be	Be	H: 2.2 -0.7 -9.4	H: 2.2 0.7 -5.8	H: 2.0 -1.9 -8.3	Be

H: 1.5	KENO-Va
1.3	% error CONHOR
-2.1	% error CONHOR measured

H: HEU fuel assembly
L: LEU fuel assembly
HC: HEU control rod assembly
Be: Beryllium reflector element

Figure 9. Relative power distribution in HOR core 9902 at the begin of cycle (BOC). Comparison between KENO-Va (reference), CONHOR calculated, and CONHOR measured results.

It can be concluded that the present data and codes can be used for the transition from a HEU to a LEU fuel core. Nevertheless, work is in progress to improve the calculated and measured criticality and power distributions. In the next version of the SCALE code package the one-dimensional S_n cell transport code XSDRNPM will be replaced by a two-dimensional version called NEWT[14]. It is expected that this new cell code will improve the cross-sections as used in the BOLD VENTURE and SILWER code.

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