COMPARISONS OF DIFFUSION THEORY AND MONTE CARLO BURNUP

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ABSTRACT

Burnup analyses for research reactors have mostly been performed using diffusion theory codes. Lately, with the increase in computing power, the Monte Carlo method is being used more frequently. The Monte Carlo method provides a more precise way to perform burnup analyses for nuclear reactors. However, the method is very computer and time intensive. The purpose of this paper is to show that burnup analyses using diffusion theory with appropriate cross sections can provide results for different reactors, fuel enrichments, and fuel assembly types that are essentially the same as the Monte Carlo results.

This paper compares the results of diffusion theory and Monte Carlo burnup analyses for four different reactors (HFR-Petten in the Netherlands, WWR-SM in Uzbekistan, WWR-M in Ukraine, and TRR-II in Taiwan); different types of fuel assemblies (MTR, IRT-3M, IRT-MR, WWR-M2, and WWR-MR) were studied for these reactors. The performance parameters selected for these comparisons were: a) K-effective during the cycle; b) power produced in the fuel assemblies; and c) burnup-dependent isotopic compositions of the different fuel assemblies (^{235}U, ^{238}U, ^{135}Xe, and ^{239}Pu). The results show that for all parameters considered both the diffusion theory and the Monte Carlo burnup yield essentially identical results.

INTRODUCTION

Burnup analyses for research reactors have mostly been performed using two- and three-dimensional diffusion theory methods using a small number of energy groups (two to fifteen groups). These methods have always been considered to provide good results for the safety and operation of these reactors. Lately, because of the rapid increase in computing power, the Monte Carlo method using continuous energy cross sections has been used at many institutions. However, even with the increase in computing power, burnup analyses using Monte Carlo methods are still very computer and time intensive.

The RERTR program at Argonne National Laboratory (ANL) has been using diffusion theory for burnup analyses for many years. A few years ago the RERTR program developed a relatively easy way to perform Monte Carlo burnup analyses.

In this paper, burnup analyses for four different reactors that use very different types of fuel assemblies and enrichments are performed using both diffusion theory and Monte Carlo methods to provide a direct comparison of the results. In the following sections, the methods and codes are discussed first, and then the results for the different reactors are presented.

METHODS AND CODES

The methods and codes used for the diffusion and Monte Carlo analyses are presented below.

The Monte Carlo burnup analyses were performed using the MC/REBUS[1] code. This code uses the MCNP[2] code for the calculation of K-effective, neutron fluxes, and cross-sections. These one-group neutron fluxes and cross sections (capture, fission, n-2n, n-α, n-p) are then supplied to the REBUS[3] code for the power normalization and calculation of the burnup-buildup of the relevant isotopes. The REBUS code then supplies the "burned" compositions for the MCNP code for the next step in the analysis.

The diffusion theory burnup analyses were performed as follows. First seven-group cross-sections are generated using the WIMS-ANL[4] code. These cross-sections are then used in the REBUS/PC[5] code. This code uses the DIF3D[6] code for the calculation of K-effective and neutron fluxes, which are provided to the REBUS code for the calculation of the burnup-buildup of the relevant isotopes. The REBUS code then supplies the "burned" compositions for the DIF3D code for the next step in the analysis.

In both, the diffusion theory and the Monte Carlo analyses, ENDF/B-VI cross sections generated from the same source were used.

RESULTS

Four reactors with very different designs (two using MTR-type fuel assemblies and two using Russian-designed fuel assemblies) and different ^{235}U enrichments were used to compare the results of burnup analyses using MCNP/REBUS and DIF3D/REBUS. The results are presented below, and for the sake of succinctness only a short description of the reactors are included here.

The HFR-Petten Reactor[7]

The HFR-Petten reactor is a 45 MW reactor that presently uses HEU (93%) MTR-type fuel assemblies (FA), but is in the process of performing required analyses for conversion to LEU fuel. This reactor normally uses 39 fuel assemblies (33 standard and 6 control FA), and allocates 17 positions inside the core for isotope production and other experiments; there are seven neutron beam tubes facing three sides of the core. In these analyses aluminum plugs that are used in the safety analyses of HFR, replaced the experiments.

Two configurations were analyzed for this reactor. The first uses the present HEU fuel with boron as the burnable poison in the side plates, and the second uses the LEU fuel with twenty 0.5 mm diameter Cd wires as the burnable poison in each side plate. The latter fuel has been selected by Petten for LEU conversion.

Configuration A: HEU Fuel with Boron Burnable Poison

For the HEU configuration a reactivity rundown starting with fresh fuel was performed. Figure 1 presents the K-effective results for the burn time considered. The agreement between the diffusion theory and Monte Carlo results is excellent. Note that in the K-effective results presented throughout this paper the bias between the Monte Carlo and diffusion K-effective at the beginning of the cycle is added (subtracted) from the diffusion results.

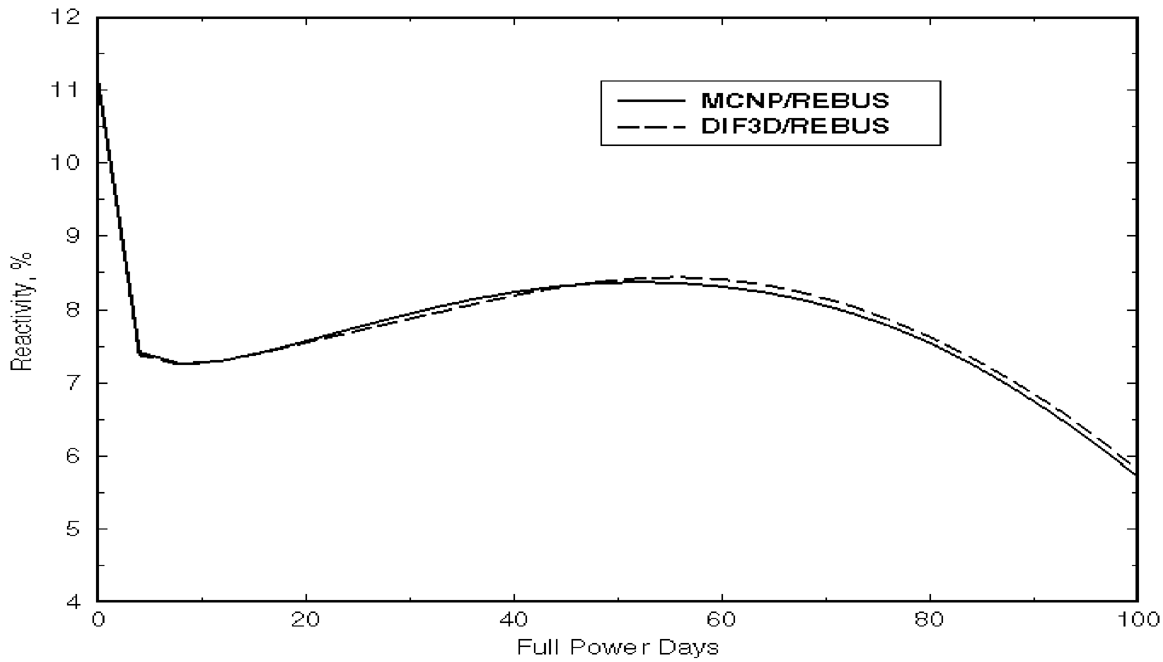


Figure 1. HFR with HEU MTR Fuel: Reactivity Rundown

Table I compares the power produced per FA, and Table II shows the ^{235}U burnup at 40 days. The results show very good agreement for both power produced per FA and ^{235}U burnup; differences of less than 3% are present. The same good agreement exists for the important fission products and actinides. The agreement is not as good for the higher actinides and for the burnable poison (differences of about 9% in a few side plates are present), but most of these differences can be explained by the uncertainty in the MCNP generated cross-sections for these isotopes (about 2%). These differences have almost no impact on the important results of a burnup analysis.

Configuration B: LEU Fuel with Cd Burnable Poison

For the LEU case a cycle-by-cycle burnup analysis was performed following the fuel shuffling pattern presently used in the HFR reactor. Figure 2 presents the reactivity traces for cycles 5 and 7; the analysis started with a fresh core. The results in Figure 2 show a good agreement between diffusion and Monte Carlo results. Differences do exist, as expected, because of the complex nature of modeling the burnup of thin Cd wires with diffusion theory; however, these differences are small (less than 0.2% at the end of the cycle).

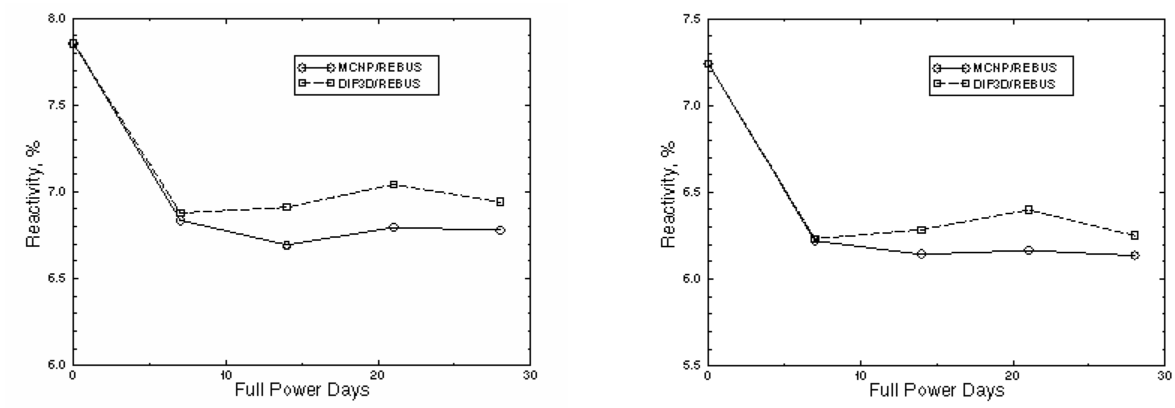
The results for the power produced per FA, the ^{235}U burnup, and the concentration of important fission products and other actinides are also in very good agreement, with most differences between diffusion theory and Monte Carlo of less than 2%; a few FA show difference of 5% in power produced. Again, as for the HEU case, differences in the burnup of the Cd burnable poison are larger in some side plates, but these differences have little impact on the important results.

Table I. HFR HEU Power Comparison at 40 Days

Fuel Assembly	MCNP/REBUS POWER (%) A	DIF3D/REBUS POWER (%) B	RATIO B/A
A2	1.627	1.600	0.983
A3	1.908	1.910	1.001
A4	2.290	2.267	0.990
A5	2.325	2.307	0.992
A6	2.324	2.267	0.975
A7	1.941	1.910	0.984
A8	1.631	1.600	0.981
B2	2.181	2.164	0.992
B3	2.694	2.703	1.003
B5	3.307	3.349	1.013
B7	2.708	2.704	0.999
B8	2.219	2.165	0.976
C2	2.703	2.690	0.995
C4	3.618	3.678	1.017
C6	3.638	3.678	1.011
C8	2.745	2.691	0.980
D3	3.181	3.210	1.009
D5	3.923	3.953	1.008
D7	3.205	3.210	1.002
E2	2.698	2.639	0.978
E4	3.467	3.527	1.017
E6	3.481	3.527	1.013
E8	2.695	2.640	0.980
F3	2.594	2.593	1.000
F5	3.183	3.209	1.008
F7	2.589	2.593	1.002
G2	1.832	1.797	0.975
G4	2.292	2.317	1.011
G6	2.305	2.317	1.005
G8	1.843	1.798	0.976
H3	1.584	1.572	0.992
H5	1.920	1.867	0.972
H7	1.591	1.573	0.989
B4	2.388	2.429	1.017
B6	2.418	2.429	1.005
D4	2.775	2.800	1.009
D6	2.734	2.800	1.024
F4	2.258	2.279	1.009
F6	2.248	2.279	1.014

Table II. HFR HEU ^{235}U Burnup Comparison at 40 Days

Fuel Assembly	MCNP/REBUS % BU A	DIF3D/REBUS %BU B	RATIO B/A
A2	8.436	8.278	0.981
A3	10.012	9.918	0.991
A4	11.932	11.760	0.986
A5	12.090	11.971	0.990
A6	11.910	11.761	0.988
A7	9.985	9.919	0.993
A8	8.416	8.281	0.984
B2	11.465	11.212	0.978
B3	14.004	14.011	1.001
B5	17.170	17.334	1.010
B7	13.973	14.011	1.003
B8	11.429	11.214	0.981
C2	14.004	13.709	0.979
C4	18.540	18.805	1.014
C6	18.488	18.806	1.017
C8	13.975	13.710	0.981
D3	16.290	16.378	1.005
D5	20.109	20.326	1.011
D7	16.298	16.379	1.005
E2	13.557	13.318	0.982
E4	17.699	17.957	1.015
E6	17.658	17.958	1.017
E8	13.581	13.320	0.981
F3	13.196	13.212	1.001
F7	13.196	13.213	1.001
G2	9.277	9.084	0.979
G4	11.782	11.828	1.004
G6	11.785	11.828	1.004
G8	9.277	9.086	0.979
H3	8.125	7.982	0.982
H5	9.668	9.498	0.982
H7	8.139	7.983	0.981
B4	18.277	18.465	1.010
B6	18.233	18.465	1.013
D4	20.846	21.164	1.015
D6	20.895	21.164	1.013
F4	16.959	17.153	1.011
F6	17.002	17.154	1.009



A B

Figure 2. HFR LEU: Cycle 5 (A) and Cycle 7 (B)

The TRR-II Reactor[8]

The TRR-II is a 20 MW reactor design planned to be built in Taiwan to replace the decommissioned TRR-I reactor. This multipurpose reactor design uses MTR LEU fuel assemblies without burnable poison. The core design consists of 21 standard and 4 control FA.

For this reactor design a reactivity rundown starting from fresh fuel was performed. The reactivity trace for this burnup is shown in Figure 3, where the excellent agreement between diffusion theory and Monte Carlo results is seen. Results for the other performance parameters used in this paper (power produced per FA, and concentration for the important fission products and actinides for the different FA) also show very good agreement with differences smaller than 3% between diffusion theory and Monte Carlo methods. As in the HFR case, the differences in isotopic compositions for the higher actinides are larger than 3% (smaller than 8%), but these differences have no impact on the important results of a burnup analysis performed for operational purposes.

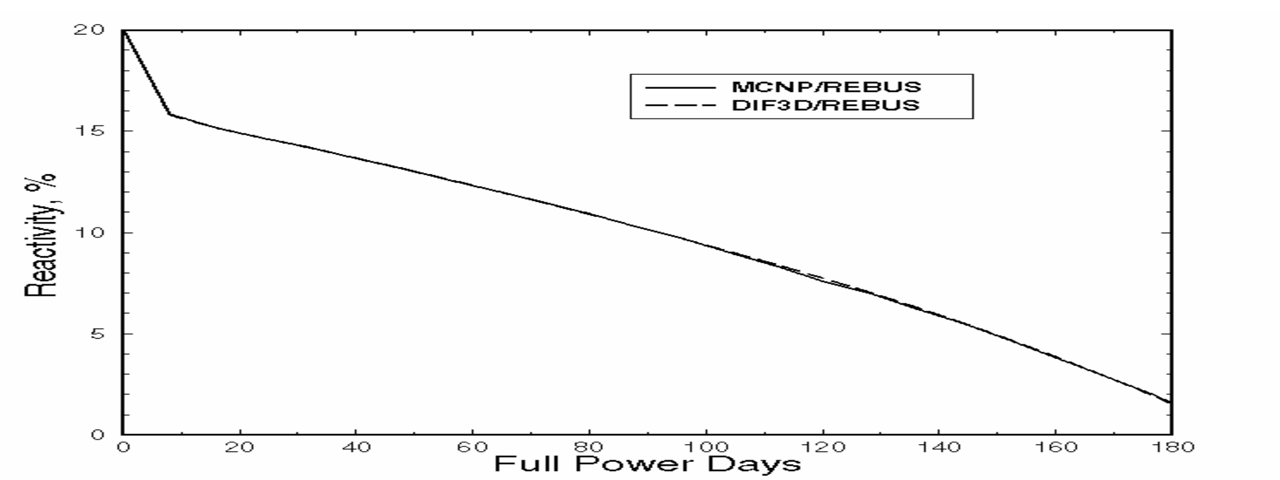


Figure 3. TRR-II with LEU MTR Fuel: Reactivity Rundown

The WWR-SM Reactor[9]

The WWR-SM reactor, located in Uzbekistan, is a 10 MW reactor presently being operated at 8 MW using IRT-3M HEU (36%) FA. The core used in these analyses uses 16 FA, and is surrounded by a Be reflector. The RERTR Program at ANL in cooperation with the Institute of Nuclear Physics in Ulugbek (Uzbekistan), is presently performing a study[9] for conversion of this reactor to LEU fuel using pin-type IRT-MR FA. In this paper, comparisons were performed for cores using both HEU (36%) tube-type IRT-3M fuel and LEU IRT-MR pin-type fuel. The IRT-3M FA consists of six concentric square tubes (with round corners), with space in the center for control rods or experiments. The IRT-MR FA used in this paper consists of 164 square pins (with fins for better heat transfer) with space in the center of the FA for control rods or experiments. For both FA types the core configuration is exactly the same.

For this reactor a reactivity rundown starting with fresh fuel was performed for both the HEU and the LEU cores. The results presented in Figures 4 and 5 show excellent agreement between diffusion theory and Monte Carlo for reactivity as function of burnup. The results for power produced per FA, ^{235}U burnup, and for the concentration of fission products and other actinides is also very good (differences smaller than 3%).

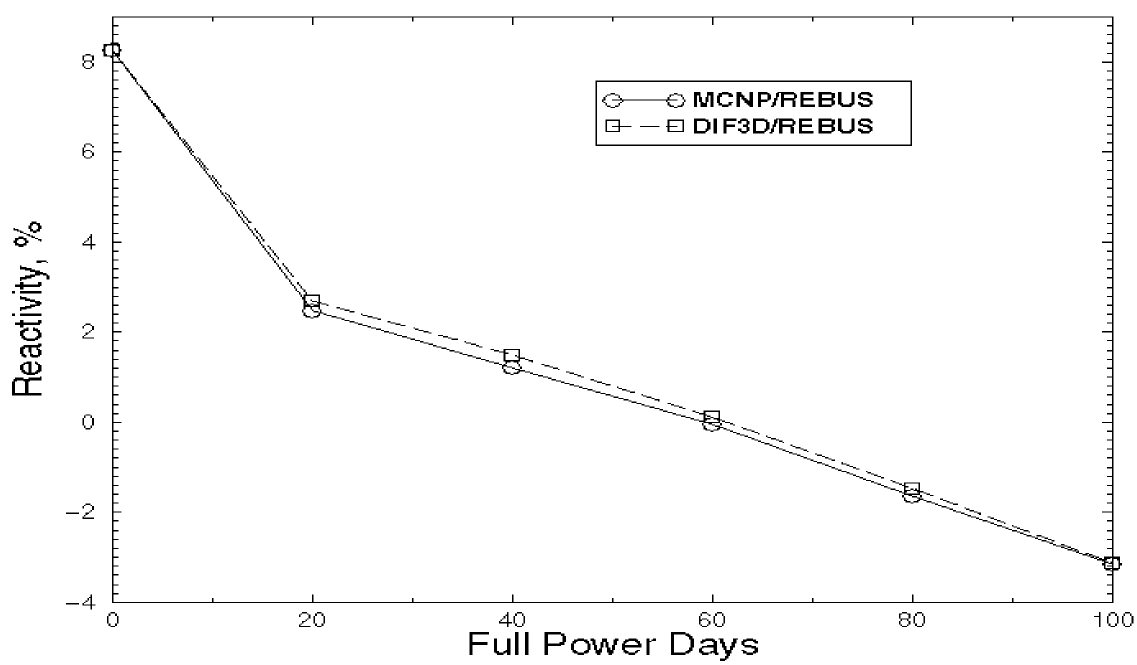


Figure 4. WWR-SM with IRT-3M Fuel Assemblies

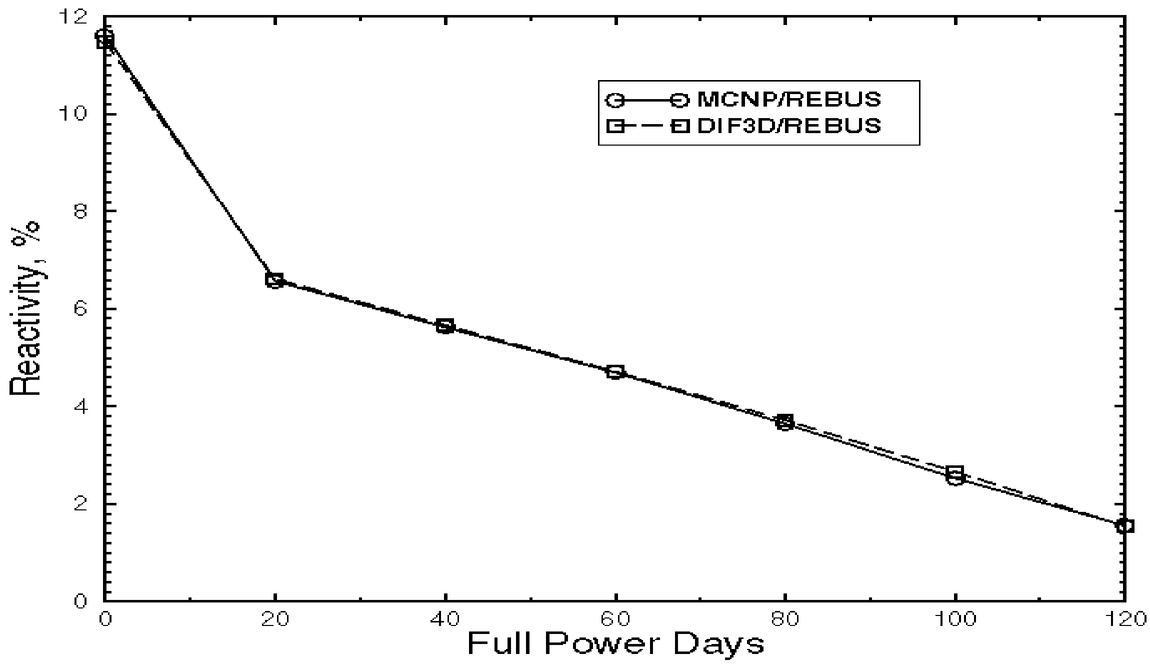


Figure 5. WWR-SM with IRT-MR Fuel Assemblies

The WWR-M Reactor[10]

The WWR-M reactor, located in Ukraine, is a 10 MW reactor presently using WWR-M2 HEU (36%) FA. The core used in these analyses had 216 FA, and is surrounded by a Be reflector. The RERTR Program at ANL in cooperation with the Kiev Institute for Nuclear Research is presently performing a study[10] for conversion of this reactor to either LEU WWR-M2 tube-type FA or LEU WWR-MR pin-type FA. In this paper, comparisons were performed for cores with HEU (36%) tube-type FA and with LEU WWR-MR pin-type fuel assembly. The WWR-M2 FA consists of three concentric fuel elements (two cylindrical and one hexagonal). The WWR-MR FA consists of 37 square pins with the same geometric cross-section as those used in the IRT-MR FA. For both FA the core configuration is exactly the same.

For this reactor the equilibrium cycle burnup analysis was performed for both the HEU and the LEU cores. The results presented in Figures 6 and 7 show the reactivity agreement between diffusion theory and Monte Carlo is excellent. The results for power produced per FA, ^{235}U burnup, and for the concentration of fission products other actinides is also very good (differences smaller than 3%).

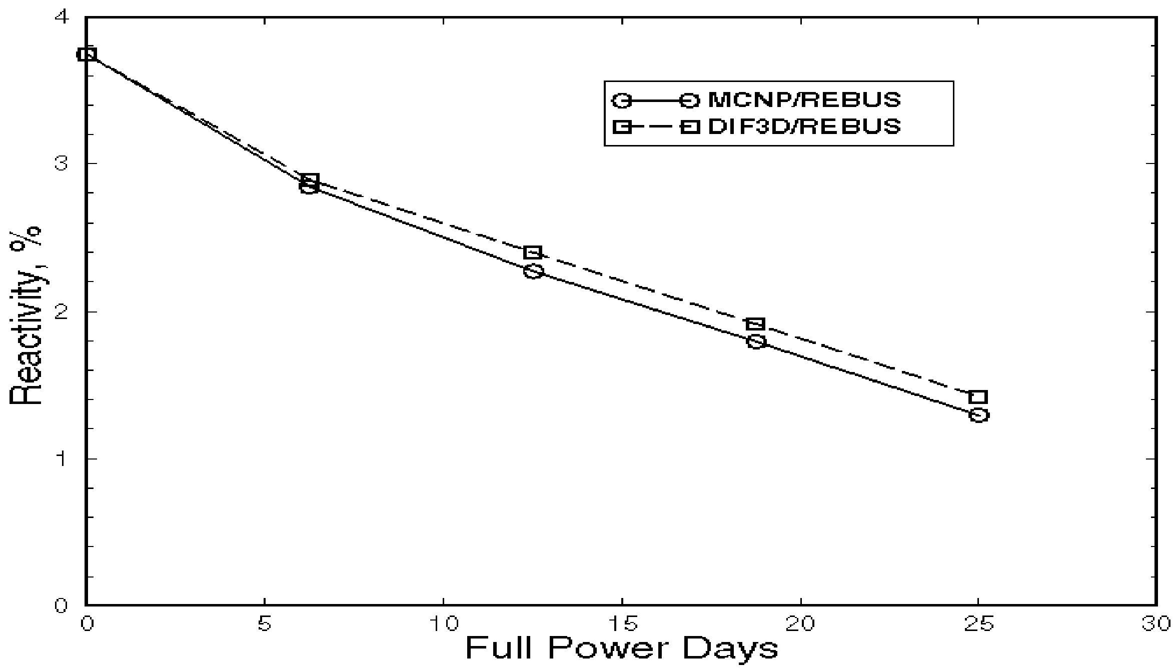


Figure 6. WWR-M with WWR-M2 (36%) Fuel Assemblies: Equilibrium Cycle

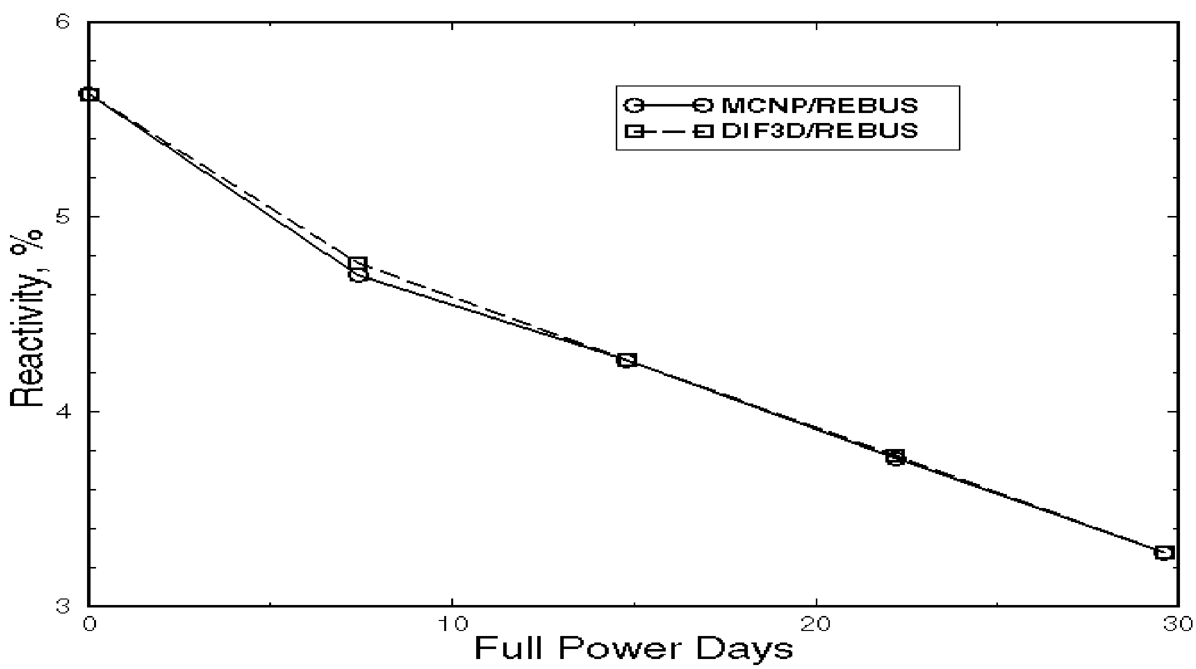


Figure 7. WWR-M with WWR-MR (19.75%) Fuel Assemblies: Equilibrium Cycle

SUMMARY AND CONCLUSIONS

Burnup analyses using both diffusion theory and Monte Carlo methods were performed for four different reactors (HFR-Petten in the Netherlands, TRR-II in Taiwan, WWR-SM in Uzbekistan, and WWR-M in Ukraine) to compare the results obtained with both calculational methods. The different reactors also use different fuel assembly designs (MTR, IRT-3M, IRT-MR, WWR-M2, and WWR-MR), and different enrichments [HEU (93%), HEU (36%), and LEU (19.75%)].

It is common knowledge that Monte Carlo codes allow for a more realistic geometrical representation of the reactor and as such should provide more appropriate results. However, the results presented in this paper show that burnup analysis using diffusion theory (with appropriate cross-sections) can provide excellent agreement with Monte Carlo methods for the parameters analyzed here. The differences in reactivity during the entire operating cycle are negligible to very small (less than 0.2%), and the differences in power produced per FA, ^{235}U burnup, and concentration for the important fission products and actinides are also small (in general less than 3%).

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