NUMERICAL BENCHMARKS FOR MTR FUEL ASSEMBLIES WITH BURNABLE POISON

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ABSTRACT

This work presents a preliminary version of a set of burn-up dependent numerical benchmarks of MTR fuel assemblies using burnable poisons.

The numerical benchmark calculations were carried out using two different types of calculation methodologies: Montecarlo methodology using MCNP-ORIGEN coupled codes and deterministic methodology using CONDOR collision probabilities code.

The main purpose of this work is to provide a numerical benchmark for several geometries, for example number and diameter of the Cadmium wires. The numerical benchmark provides meat and Cadmium numerical density information and the geometry and material data of the calculated systems. These benchmarks provide information for the validation of MTR FA cell codes.

This paper is the preliminary work of a 3 dimensional numerical benchmark for research reactors using MTR fuel assemblies with burnable poisons.

A short description of the MCNP and ORIGEN coupling method and the CONDOR code are given in the present paper.

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INTRODUCTION

This paper defines a set of numerical bechmarks for MTR Fuel Assemblies using Cd wires as burnable poisons. Two different systems are defined:

- ✓ a fuel plate (FP) with different Cd wire diameter, and
- ✓ a fuel assembly (FA) with different number of Cd wires.

The main calculated parameter presented is the infinite multiplication factor, but for a specific case the Cd and U_{235} numerical densities are also presented.
The geometrical and material data of the system is given to allow a comparison of the calculated parameters. Two different calculation codes were used and their results are presented.
A general description of those codes are also given, making enphasis in their differences.

BENCHMAR DESCRIPTION

Fuel Plate

A simplified U_3Si_2 MTR FA type is used for these benchmark, the main geometrical and material data is given in the following table and figure. The specific power used for burning is 500 MW/Tn.

Zone	Thickness (cm)	Width (cm)	Material	Comment
Meat	0.061	3.2	U_{235} 2.435E-03 at/cm-barn U_{238} 9.740E-03 at/cm-barn Al 2.974E-02 at/cm-barn Si 8.10E-03 at/cm-barn	Divided in 4 equal volume regions
Plate	0.135	3.5	Density: 2.7 g/cm^3 100%Al	
Coolant	0.380	3.5	Density 0.99837 11.191% H & 88.809% O	
Frame	0.380	0.5	Density: 2.7 g/cm^3 100%Al	
Water gap	0.380	0.05	Density 0.99837 11.191% H & 88.809% O	
Cd wire	Center x=3.75	Diameter Variable	Cd_{113} 5.640E-03 at/cm-barn	Divided in 4 equal volume regions

Different Cd wires diameter were used: None, 0.04, 0.05 and 0.06 cm.

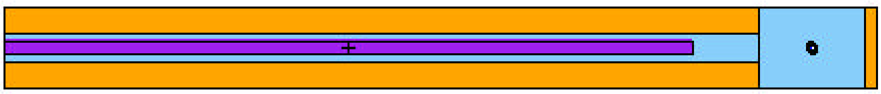


Figure 1: Geometrical model of the Fuel Plate.

Fuel Assembly

The FA is a set of 21 Fuel Plates. The external dimensions fo the whole FA is 8.1 cm * 8.1 cm.

Different number of Cd 0.05 cm wires were used: None, 42, 22 and 14.

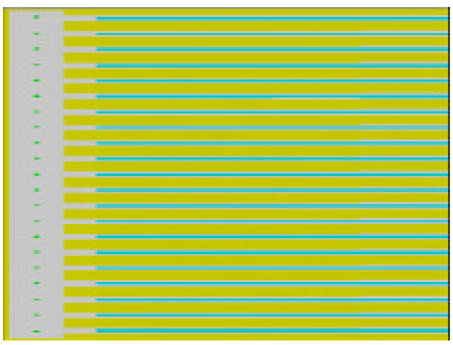


Figure 2: Geometrical model of the Fuel Assembly with 42 Cd wires.

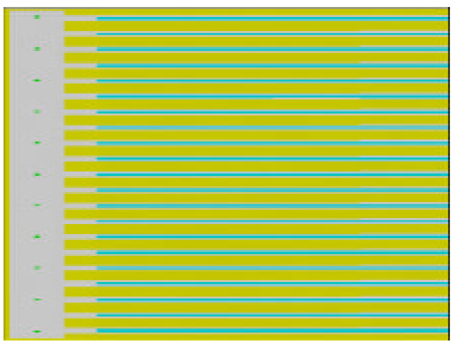


Figure 3: Geometrical model of the Fuel Assembly with 22 Cd wires.

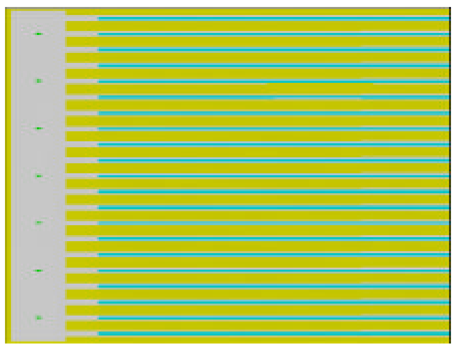


Figure 4: Geometrical model of the Fuel Assembly with 14 Cd wires.

CODES DESCRIPTION

MCNP-Origen coupled codes

A method (MCQ) [1] has been developed by introducing a microscopic burnup scheme which uses the MCNP calculated fluxes and microscopic reaction rates as a basis for solving nuclide material balance equations for each spatial region.

The resulting predictions for the system at successive burnup time steps are thus based on a calculation route where both geometry and cross sections are accurately represented with continuous energy data, providing an independent approach for benchmarking other methods.

Basically, the method includes four tasks for each burnup step:

1) MCNP [2] calculation of the full system (criticality or fixed source options) tallying fluxes and nuclide reaction rates for each spatial region (cell) of interest integrated over energy;
2) Preparation of ORIGEN [3] input and cross section libraries from MCNP output, including normalized power density of each spatial zone (MCOR auxiliary program);
3) ORIGEN calculations of isotope concentrations on the input burnup time-step; and
4) Preparation of MCNP input with the new isotope concentrations output of ORIGEN (ORMC auxiliary program).

This sequence is implemented in an automatic way by means of a batch file for MS-DOS version (or script file for UNIX version), including a predictor-corrector scheme.

There are no limitations on the number of isotopes and materials, but a selection of the most important fission products and actinides has been made, lumping other on a pseudo fission product on MCNP-ACES format.

The system MCQ is on its first stage of development. The main features that need improvements are related with the management of fission products (quantity and quality of explicit included and lumped isotopes and nuclear data) and the update of decay and fission yield data.

Condor code

The code CONDOR[4] and the CONDOR-CITVAP[5] calculation line were validated against different experimental benchmarks.
CONDOR code has the capability to calculate FA (with fuel rods or plates) with full geometrical detail (without homogenization). A two dimensional Heterogeneous Response Method with angular dependent coupling current is used to calculate the neutron flux. The whole FA is divided in elements, which are coupled by interface currents, and the elements are internally calculated by the collision probability method. The code uses, in the resonant energy range, the subgroup method to calculate effective cross sections. This method takes into account the heterogeneous character of the fuel element.

Differences between codes

There are several differences between both calculation methodologies, The are summarized in the following items:

- ✓ Different cross section.
    - ✓ Multigroup Library vs Energy dependent Library.
    - ✓ Condor codes uses HELIOS 190 groups libraries.
- ✓ Different Transport Method
    - ✓ Condor uses Collision Probabilities method. It means flat flux approximation on each region, flat current on each external segment. Cosine current (isotropic flux) on each external segment.
    - ✓ MCNP MonteCarlo method. White reflection (isotropic flux) was used to minimize the difference between both codes.
- ✓ Different Models
    - ✓ Condor needs to subdivide the system in regions and the external boundary in segments. The following figure shows the region and surface discretization.

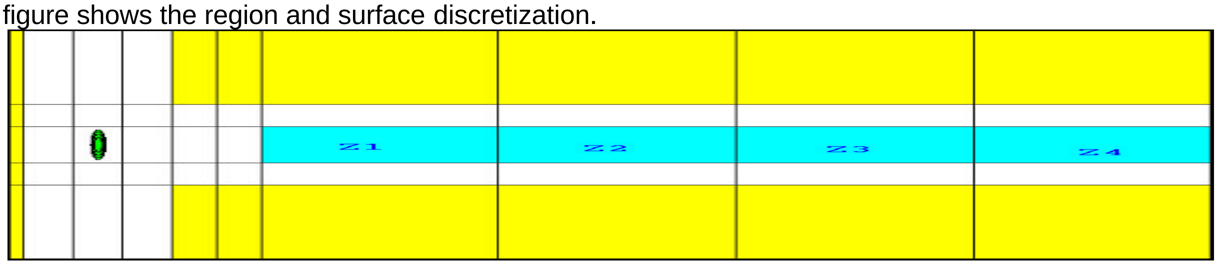


Figure 5: Fuel Plate CONDOR discretization (not in scale)

- ✓ Different burnup chains were considered in the meat depletion. The Helios library has not a lumped fission product, and the MCNP calculation includes one.

RESULTS

Infinite multiplication factors

The following Fuel Plate cases were run.

Case	Cd wire diameter	Label
Fuel Plate without Cd wire.	None	FP00x
Fuel Plate with 0.4 mm Cd wire.	0.4 mm	FP04x
Fuel Plate with 0.5 mm Cd wire.	0.5 mm	FP05x
Fuel Plate with 0.6 mm Cd wire.	0.6 mm	FP06x

x: C/M for CONDOR/MCNP code

The following Fuel Assembly cases were run.

Case	Cd wire diameter	Label
Fuel Assembly without Cd wire.	None	FA00x
Fuel Assembly with 42 0.5 mm Cd wires.	42 Cd wires	FA42x
Fuel Assembly with 22 0.5 mm Cd wires.	22 Cd wires	FA22x
Fuel Assembly with 14 0.5 mm Cd wires.	14 Cd wires	FA14x

x: C/M for CONDOR/MCNP code

The next tables and figures show the infinite multiplication factor

Burnup	FP00C	FP04C	FP05C	FP06C	FP00M	FP04M	FP05M	FP06M
0	1.66526	1.51718	1.49278	1.47180	1.66460	1.51870	1.49720	1.47530
0	1.59539	1.45753	1.43465	1.41495				
500	1.59263	1.45518	1.43223	1.41249	1.59900	1.46050	1.44130	1.42200
1000	1.58994	1.45301	1.42998	1.41020	1.59260	1.45560	1.43320	1.41860
1500	1.58714	1.45078	1.42766	1.40786				
2000	1.58441	1.44864	1.42544	1.40558				
2500	1.58184	1.44666	1.42336	1.40345	1.58310	1.44770	1.42310	1.40550
3000	1.57946	1.44487	1.42146	1.40149				
3500	1.57727	1.44329	1.41974	1.39970				
4000	1.57527	1.44189	1.41819	1.39808				
4500	1.57343	1.44066	1.41679	1.39660				
5000	1.57174	1.43958	1.41553	1.39524	1.57360	1.44300	1.42060	1.39430
5500	1.57016	1.43864	1.41439	1.39399				
6000	1.56867	1.43782	1.41335	1.39283				
6500	1.56726	1.43710	1.41239	1.39174				
7000	1.56591	1.43648	1.41150	1.39072				
7500	1.56461	1.43594	1.41068	1.38975				
8000	1.56335	1.43549	1.40991	1.38882				
8500	1.56211	1.43510	1.40919	1.38793				
9000	1.56089	1.43479	1.40851	1.38707				
9500	1.55969	1.43454	1.40787	1.38623				
10000	1.55850	1.43436	1.40727	1.38542	1.56130	1.43610	1.41010	1.38900
12500	1.55234	1.43378	1.40437	1.38138				
15000	1.54636	1.43573	1.40267	1.37809	1.55140	1.43640	1.40760	1.37590
17500	1.54029	1.44047	1.40211	1.37535				
20000	1.53411	1.44916	1.40300	1.37327	1.54150	1.45130	1.40490	1.38280
22500	1.52783	1.46283	1.40591	1.37197				
25000	1.52144	1.48028	1.41175	1.37174	1.52820	1.48360	1.41320	1.37860
27500	1.51495	1.49514	1.42187	1.37284				
30000	1.50838	1.50102	1.43758	1.37585	1.51698	1.50500	1.43890	1.38930
32500	1.50171	1.49933	1.45762	1.38169				

35000	1.49495	1.49424	1.47447	1.39189	1.50550	1.50650	1.48190	1.40540
37500	1.48812	1.48791	1.48088	1.40838				
40000	1.48119	1.48114	1.47900	1.43072	1.49470	1.49370	1.48630	1.45110
42500	1.47418	1.47416	1.47359	1.45083				
45000	1.46708	1.46708	1.46697	1.45919	1.48155	1.48150	1.48290	1.46550
47500	1.45988	1.45990	1.45992	1.45772				
50000	1.45260	1.45263	1.45268	1.45216	1.46800	1.46840	1.46861	1.46420

Burnup	FA00C	FA14C	FA22C	FA42C	FA00M	FA14M	FA22M	FA42M
0	1.66541	1.58440	1.55084	1.49160	1.66460	1.58280	1.54990	1.49720
0	1.59558	1.52024	1.48893	1.43355				
500	1.59283	1.51773	1.48649	1.43116	1.59900	1.52370	1.49150	1.44130
1000	1.59015	1.51532	1.48416	1.42892	1.59260	1.51480	1.47920	1.43320
1500	1.58735	1.51283	1.48175	1.42661				
2000	1.58462	1.51043	1.47944	1.42439				
2500	1.58205	1.50819	1.47728	1.42232	1.58310	1.51060	1.47620	1.42310
3000	1.57967	1.50614	1.47531	1.42042				
3500	1.57749	1.50429	1.47354	1.41871				
4000	1.57549	1.50264	1.47195	1.41717				
4500	1.57365	1.50116	1.47053	1.41579				
5000	1.57196	1.49983	1.46927	1.41454	1.57360	1.50090	1.46970	1.42060
5500	1.57038	1.49863	1.46813	1.41341				
6000	1.56890	1.49754	1.46710	1.41238				
6500	1.56750	1.49656	1.46617	1.41143				
7000	1.56615	1.49566	1.46533	1.41056				
7500	1.56486	1.49483	1.46456	1.40975				
8000	1.56359	1.49407	1.46385	1.40900				
8500	1.56236	1.49337	1.46321	1.40830				
9000	1.56115	1.49272	1.46262	1.40764				
9500	1.55995	1.49212	1.46208	1.40702				
10000	1.55876	1.49157	1.46158	1.40645	1.56130	1.49390	1.46700	1.41010
12500	1.55262	1.48887	1.45924	1.40363				
15000	1.54667	1.48770	1.45855	1.40213	1.55140	1.49400	1.46170	1.40760
17500	1.54062	1.48790	1.45938	1.40180				
20000	1.53447	1.48985	1.46222	1.40303	1.54150	1.49840	1.47140	1.40490
22500	1.52821	1.49397	1.46785	1.40642				
25000	1.52184	1.49980	1.47687	1.41295	1.52820	1.50510	1.48490	1.41320
27500	1.51538	1.50448	1.48802	1.42401				
30000	1.50882	1.50470	1.49631	1.44075	1.51698	1.51610	1.50600	1.43890
32500	1.50218	1.50085	1.49774	1.46109				
35000	1.49544	1.49504	1.49407	1.47694	1.50550	1.50780	1.50850	1.48190
37500	1.48862	1.48850	1.48822	1.48221				
40000	1.48170	1.48168	1.48161	1.47981	1.49470	1.49750	1.49710	1.48630
42500	1.47470	1.47471	1.47471	1.47422				
45000	1.46761	1.46763	1.46764	1.46755	1.48155	1.48640	1.48310	1.48290
47500	1.46042	1.46045	1.46046	1.46049				
50000	1.45314	1.45317	1.45319	1.45325	1.46800	1.47313	1.47228	1.46861

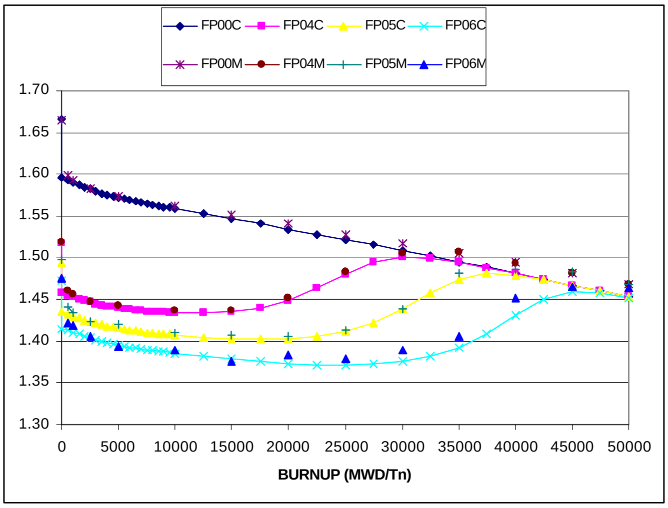


Figure 6: Infinite multiplication factor for the Fuel Plate.

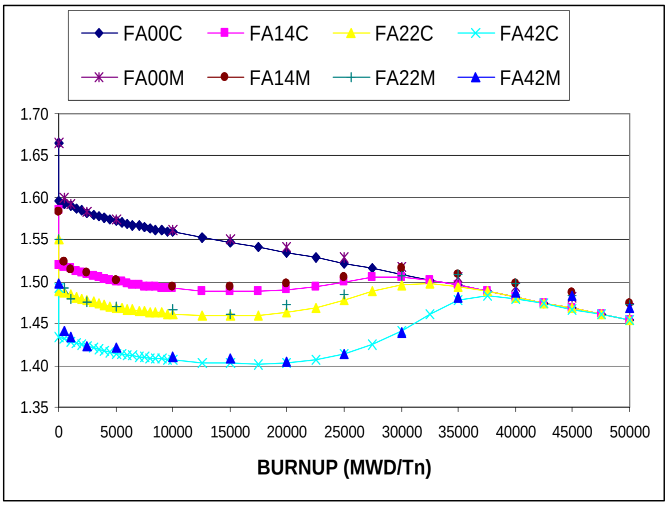


Figure 7: Infinite multiplication factor for the Fuel Assembly.

Numerical densities

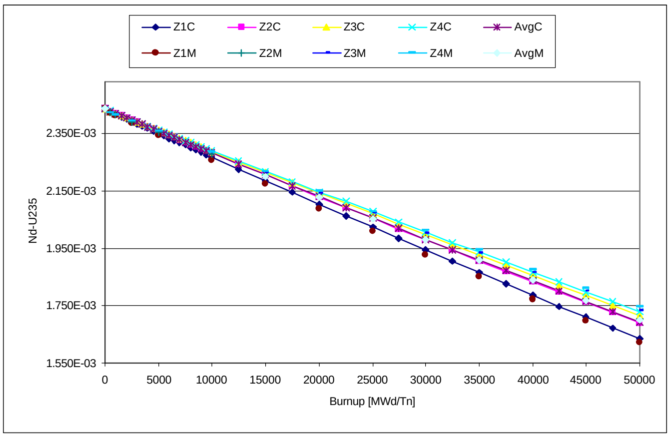
<u>U_{235} Numerical Densities:</u> The FP00 case was used to present the U_{235} numerical densities. The numerical density per region and it average. The zone numbering is shown in the figure 5.

Burnup	Z1C	Z2C	Z3C	Z4C	AvgC	Z1M	Z2M	Z3M	Z4M	AvgM
0	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03
0	2.435E-03	2.435E-03	2.435E-03	2.435E-03	2.435E-03					
500	2.427E-03	2.427E-03	2.428E-03	2.428E-03	2.427E-03	2.421E-03	2.422E-03	2.423E-03	2.423E-03	2.422E+02
1000	2.418E-03	2.420E-03	2.420E-03	2.420E-03	2.420E-03	2.412E-03	2.415E-03	2.415E-03	2.416E-03	2.414E+02
1500	2.410E-03	2.412E-03	2.413E-03	2.413E-03	2.412E-03					
2000	2.401E-03	2.404E-03	2.405E-03	2.406E-03	2.404E-03					
2500	2.393E-03	2.396E-03	2.398E-03	2.399E-03	2.396E-03	2.386E-03	2.391E-03	2.393E-03	2.394E-03	2.391E+02
3000	2.385E-03	2.389E-03	2.391E-03	2.391E-03	2.389E-03					
3500	2.376E-03	2.381E-03	2.383E-03	2.384E-03	2.381E-03					
4000	2.368E-03	2.373E-03	2.376E-03	2.377E-03	2.373E-03					
4500	2.359E-03	2.366E-03	2.368E-03	2.370E-03	2.366E-03					
5000	2.351E-03	2.358E-03	2.361E-03	2.363E-03	2.358E-03	2.343E-03	2.353E-03	2.357E-03	2.358E-03	2.353E+02
5500	2.343E-03	2.350E-03	2.354E-03	2.355E-03	2.350E-03					
6000	2.334E-03	2.342E-03	2.346E-03	2.348E-03	2.343E-03					
6500	2.326E-03	2.335E-03	2.339E-03	2.341E-03	2.335E-03					
7000	2.318E-03	2.327E-03	2.331E-03	2.334E-03	2.327E-03					
7500	2.309E-03	2.319E-03	2.324E-03	2.326E-03	2.320E-03					
8000	2.301E-03	2.312E-03	2.317E-03	2.319E-03	2.312E-03					
8500	2.293E-03	2.304E-03	2.309E-03	2.312E-03	2.305E-03					
9000	2.284E-03	2.297E-03	2.302E-03	2.305E-03	2.297E-03					
9500	2.276E-03	2.289E-03	2.295E-03	2.298E-03	2.289E-03					
10000	2.268E-03	2.281E-03	2.287E-03	2.291E-03	2.282E-03	2.257E-03	2.278E-03	2.285E-03	2.287E-03	2.277E+02
12500	2.227E-03	2.243E-03	2.251E-03	2.255E-03	2.244E-03					
15000	2.185E-03	2.205E-03	2.214E-03	2.219E-03	2.206E-03	2.174E-03	2.202E-03	2.213E-03	2.217E-03	2.201E-03
17500	2.145E-03	2.167E-03	2.178E-03	2.183E-03	2.168E-03					
20000	2.104E-03	2.130E-03	2.142E-03	2.148E-03	2.131E-03	2.089E-03	2.129E-03	2.143E-03	2.149E-03	2.127E-03
22500	2.064E-03	2.092E-03	2.105E-03	2.112E-03	2.093E-03					
25000	2.024E-03	2.055E-03	2.069E-03	2.077E-03	2.056E-03	2.009E-03	2.055E-03	2.072E-03	2.079E-03	2.054E-03
27500	1.984E-03	2.018E-03	2.034E-03	2.042E-03	2.019E-03					
30000	1.944E-03	1.980E-03	1.998E-03	2.007E-03	1.982E-03	1.928E-03	1.984E-03	2.004E-03	2.012E-03	1.982E-03
32500	1.905E-03	1.944E-03	1.962E-03	1.972E-03	1.945E-03					

35000	1.865E-03	1.907E-03	1.927E-03	1.937E-03	1.909E-03	1.851E-03	1.912E-03	1.935E-03	1.944E-03	1.910E-03
37500	1.826E-03	1.870E-03	1.891E-03	1.902E-03	1.872E-03					
40000	1.788E-03	1.834E-03	1.856E-03	1.867E-03	1.836E-03	1.773E-03	1.843E-03	1.867E-03	1.878E-03	1.840E-03
42500	1.749E-03	1.797E-03	1.821E-03	1.833E-03	1.800E-03					
45000	1.711E-03	1.761E-03	1.785E-03	1.798E-03	1.764E-03	1.697E-03	1.772E-03	1.801E-03	1.812E-03	1.771E-03
47500	1.673E-03	1.725E-03	1.751E-03	1.764E-03	1.728E-03					
50000	1.635E-03	1.689E-03	1.716E-03	1.730E-03	1.692E-03	1.623E-03	1.704E-03	1.735E-03	1.748E-03	1.702E-03

Cd_{113} Numerical Densities: The FP05 case was used to present the Cd_{113} numerical densities.

Burnup	R4C	R3C	R2C	R1C	AvgC	R4M	R3M	R2M	R1M	AvgM
0	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03
0	5.640E-03	5.640E-03	5.640E-03	5.640E-03	5.640E-03					
500	5.412E-03	5.540E-03	5.588E-03	5.611E-03	5.538E-03	5.403E-03	5.536E-03	5.590E-03	5.611E-03	5.535E-03
1000	5.188E-03	5.438E-03	5.535E-03	5.581E-03	5.435E-03	5.182E-03	5.435E-03	5.536E-03	5.584E-03	5.434E-03
1500	4.968E-03	5.333E-03	5.480E-03	5.550E-03	5.333E-03					
2000	4.753E-03	5.227E-03	5.423E-03	5.518E-03	5.230E-03					
2500	4.542E-03	5.119E-03	5.365E-03	5.485E-03	5.128E-03	4.539E-03	5.128E-03	5.376E-03	5.488E-03	5.133E-03
3000	4.337E-03	5.008E-03	5.305E-03	5.451E-03	5.025E-03					
3500	4.136E-03	4.896E-03	5.243E-03	5.417E-03	4.923E-03					
4000	3.940E-03	4.782E-03	5.180E-03	5.381E-03	4.820E-03					
4500	3.749E-03	4.666E-03	5.114E-03	5.344E-03	4.718E-03					
5000	3.563E-03	4.548E-03	5.047E-03	5.306E-03	4.616E-03	3.566E-03	4.579E-03	5.075E-03	5.327E-03	4.637E-03
5500	3.382E-03	4.429E-03	4.978E-03	5.266E-03	4.514E-03					
6000	3.207E-03	4.308E-03	4.906E-03	5.226E-03	4.412E-03					
6500	3.037E-03	4.186E-03	4.833E-03	5.184E-03	4.310E-03					
7000	2.872E-03	4.062E-03	4.757E-03	5.140E-03	4.208E-03					
7500	2.712E-03	3.938E-03	4.679E-03	5.096E-03	4.106E-03					
8000	2.558E-03	3.812E-03	4.599E-03	5.049E-03	4.005E-03					
8500	2.410E-03	3.686E-03	4.517E-03	5.001E-03	3.904E-03					
9000	2.267E-03	3.559E-03	4.433E-03	4.952E-03	3.803E-03					
9500	2.129E-03	3.432E-03	4.346E-03	4.901E-03	3.702E-03					
10000	1.996E-03	3.304E-03	4.257E-03	4.848E-03	3.601E-03	2.079E-03	3.479E-03	4.404E-03	4.945E-03	3.727E-03
12500	1.416E-03	2.671E-03	3.780E-03	4.553E-03	3.105E-03					
15000	9.640E-04	2.067E-03	3.254E-03	4.204E-03	2.622E-03	9.611E-04	2.140E-03	3.384E-03	4.334E-03	2.705E-03
17500	6.271E-04	1.519E-03	2.688E-03	3.788E-03	2.156E-03					
20000	3.879E-04	1.049E-03	2.105E-03	3.296E-03	1.710E-03	3.895E-04	1.116E-03	2.273E-03	3.523E-03	1.825E-03
22500	2.266E-04	6.756E-04	1.539E-03	2.726E-03	1.292E-03					
25000	1.238E-04	4.006E-04	1.030E-03	2.094E-03	9.120E-04	1.200E-04	4.237E-04	1.145E-03	2.385E-03	1.018E-03
27500	6.243E-05	2.154E-04	6.169E-04	1.442E-03	5.842E-04					
30000	2.843E-05	1.028E-04	3.211E-04	8.507E-04	3.257E-04	2.794E-05	1.114E-04	3.795E-04	1.121E-03	4.099E-04
32500	1.145E-05	4.260E-05	1.413E-04	4.102E-04	1.514E-04					
35000	4.057E-06	1.528E-05	5.246E-05	1.598E-04	5.791E-05	4.048E-06	1.697E-05	6.416E-05	2.379E-04	8.078E-05
37500	1.308E-06	4.912E-06	1.710E-05	5.291E-05	1.906E-05					
40000	5.167E-07	1.490E-06	5.194E-06	1.604E-05	5.811E-06	3.023E-07	1.310E-06	4.980E-06	1.811E-05	6.177E-06
42500	2.854E-07	5.548E-07	1.530E-06	4.679E-06	1.762E-06					
45000	1.905E-07	2.960E-07	5.604E-07	1.344E-06	5.977E-07	2.293E-08	9.681E-08	3.715E-07	1.364E-06	4.638E-07
47500	1.407E-07	1.952E-07	2.967E-07	5.133E-07	2.865E-07					
50000	1.108E-07	1.426E-07	1.950E-07	2.807E-07	1.823E-07	1.492E-09	6.432E-09	2.410E-08	8.854E-08	3.014E-08



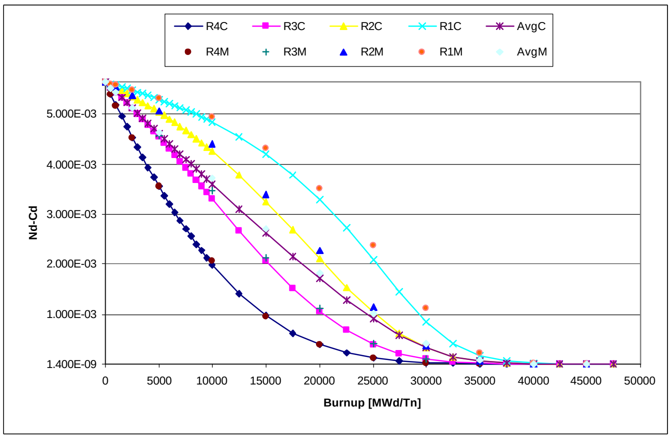


Figure 8: U_{235} numerical densities for FP00 fuel plate.

Figure 9: Cd_{113} numerical densities for FP05 fuel plate.

CONCLUSION

This preliminary numerical benchmark is a starting point to validate numerically MTR fuel assembly codes.

The Cd wire depletion in the Fuel Plate and the Fuel Assembly shows a good agreement between both methodologies.

A clear difference in the Fission Product worth is detected when the burnup increase, in both cases (with and without Cd wires). This effect must be analyzed in detail to determine the proper infinite multiplication behavior.

A more detailed Fission Product inventory must be taken into account before start a 3D numerical density to predict the MTR core behavior using this type of burnable poisons.

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