32.23 STUDIEN ZUR AKTINIDENUMWANDLUNG

32.23.01 Transmutation mit Leichtwasserreaktoren und mit Beschleunigern.

Calculations for the IAEA coordinated ADS NEUTRONIC BENCHMARK

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Abstract:

Since several years the transmutation of nuclear waste (actinides and fission products) in accelerator driven subcritical systems (ADS) is investigated in many countries. In a recent publication, C. Rubbia and coworkers at CERN proposed a so-called Energy Amplifier (EA) which may be used as power generator and for the transmutation of actinides and fission products. This Energy Amplifier has been chosen as the base for the IAEA-coordinated ADS-neutronic benchmark. The aim of the benchmark is to obtain a better understanding of the neutron physics of accelerator driven subcritical reactors, and international comparison of the codes and data used for the calculation of these systems.

Some of the results obtained from the benchmark calculations at FZK will be presented.

Introduction:

The ADS - Neutronic Benchmark coordinated by the IAEA is based on the Energy Amplifier (EA) proposed by C. Rubbia and coworkers [1],[2]. This energy amplifier uses thorium as basic fuel and liquid lead coolant. A proton beam of 1 GeV hits a liquid lead target and produces spallation neutrons. The constant power of $1500 MW_{th}$ is controlled by the proton current of the accelerator. The necessary proton current depends on the reactivity eigenvalue of the system and is about 11 mA for the fresh reactor with $k_{eff} = 0.98$. A larger proton current is needed for lower values of k_{eff}.

Specification of the ADS-Neutronic Benchmark

Figure 1 shows the longitudinal cut through the cylindrical reactor. The reactor is symmetric around core midplane, only the upper half of the reactor is shown in the figure.

The fuel of the reactor is Th^{232}/U^{233}, coolant and moderator is liquid lead. The neutron source is produced by a 1 GeV proton beam of 20 cm diameter and parabolic profile. The particle beam hits the liquid lead target 25 cm above the axial symmetry line. The target is positioned within a liquid lead zone the radius of which is 32.5 cm.

The total radius of the reactor is 320 cm, its height is 640 cm. The Th^{232}/U^{233} fuelled annular core is 150 cm high and consists of two zones both having the same U^{233} enrichment, but different volume fractions. In the inner core region the volume fractions of fuel/coolant(moderator)/structural material are about 0.31/0.58/0.11, in the outer core region about 0.37/0.51/0.12, which means a relatively low volume fraction of structural material when comparing with conventional LMFR designs. The radial extent of the inner core region is from 32.5 cm to 82.5 cm, the outer radius of core region 2 is 147.5cm, the outer boundary of the radial blanket is 162.5 cm. An axial reflector (90 cm high) composed mainly of lead and iron is positioned above and below the core and blanket zones

The weight of heavy metal (HM) in the inner core region at begin of life is 6.63 t, in the outer core region it is 20.23 t, the weight of Th^{232} in the radial blanket is 6.29 t.

In the present stage 1 of the benchmark the neutron source has been provided in the benchmark specification. The energy dependent neutron source is given in a 25 energy group structure. The neutron source is assumed to be spatially homogeneous in the cylindrical region of 10 cm radius and 25 cm height above and below the axial symmetry line. For our calculations we have converted the neutron source from the 25 energy group structure into the 69 group structure that is used in the KARBUS system [6]. The calculation of the source using codes like HETC [3] or LAHET [4] will be part of a further stage of the benchmark.

Calculations for the reactor at begin of life

The calculations for the reactor at begin of life have been carried out with the S_N code TWODANT [5] in S_4/P_1 approximation with multigroup cross sections of our 69 energy group constant library. The group constants for the isotopes in the fresh reactor are based on JEF-2.2 except U^{233} which is calculated from ENDF/B-VI. In our calculations the temperature of the fuel was 1200K and the temperature of structural materials and coolant was 900K. The 25 energy group neutron source provided with the benchmark has been transformed to the 69 group structure of our group constant set in such a way that for each of the original 25 energy groups the average number of source neutrons per eV was conserved. For the power normalization the energy release per fission has been set equal to 210 MeV (default value used in TWODANT), which might a bit too large for a realistic design. The U^{233} enrichment (same enrichment in the two core zones) had to be adjusted to three different values of k_{eff} at begin of life, namely $k_{eff} = 0.98$, 0.96 and 0.94.

In order to avoid complications from the definition of k_{eff} for external source driven subcritical systems, the benchmark specification required the k_{eff} determination from the well defined eigenvalue calculation of the system.

The following U^{233} enrichments have been calculated:

10.0 at% U^{233} for $k_{eff} = 0.98$

9.68 at% U^{233} for $k_{eff} = 0.96$

9.36 at% U^{233} for $k_{eff} = 0.94$

The radial power density distribution at core midplane at begin of life is shown in Figure 2. The power is zero in the inner lead region (power production due to (n,γ)- and (n,n')- reactions has been neglected here) and jumps to its maximum value at the inner core boundary. From there it decreases rapidly in radial direction. The power jumps to another peak value at the boundary between core region 1 and core region 2 corresponding to the higher fuel volume fraction in core region 2, in the radial blanket the power is close to zero (in the graph the jumps are simulated by steep slopes).

Figure 3 presents the radial distribution of the neutron flux density at core midplane at begin of life for the three values of k_{eff} investigated in the benchmark.

Finally Figure 4 shows the radial dependence of the spectral indices: $\sigma_{fiss}(Th^{232})/\sigma_{fiss}(U^{233})$. The ratio of the two fission cross sections is large in the target region because of the high energy of the spallation neutrons. The neutrons are slowed down in the buffer lead region between 10cm and the inner core boundary at 32.5cm and the spectral indices are decreasing correspondingly. The slight increase of $\sigma_{fiss}(Th^{232})/\sigma_{fiss}(U^{233})$ at the inner edge of core region 2 is due to a noticeable spectrum hardening effect resulting from the lower coolant volume fraction in the outer zone. The spectral indices are rapidly decreasing in the radial blanket caused by the strong attenuation of high energy neutrons and the piling up of low energy neutrons (see Figures 4a and 4b showing the group fluxes fo four coarse energy groups).

For two of the cores ($k_{eff} = 0.98$ and $k_{eff} = 0.94$) the void reactivity effect has been determined for begin of life (BOL) from eigenvalue calculations with TWODANT. In both cases k_{eff} increases if only core region 1 is voided. If both core regions are voided, k_{eff} decreases. The results are shown in more detail in Table 1.

If we make the conservative assumption that on the average 25 spallation neutrons are produced per source proton, the proton current required to obtain the power of $1500 MW_{th}$ at begin of life is 11.1 mA for $k_{eff} = 0.98$. For the fresh reactor with $k_{eff} = 0.96$ a proton current of 22.8 mA is needed to obtain $1500 MW_{th}$. For the case $k_{eff} = 0.94$ the proton currrent necessary for $1500 MW_{th}$ is 35.7 mA.

According to the change of k_{eff} during burnup a variation of the proton current is required to obtain constant power. For constant power, the correlation between proton current and k_{eff} is approximately proportional to $(1 - k_{eff})$ [8]

Behaviour of k_{eff} as a function of burnup

The main goal of the benchmark was to study the behaviour of the eigenvalue k_{eff} during burnup. Our burnup calculations have been carried out with the program chain TWODANT/KARBUS [6] [7]. Neutron flux densities for the burnup calculations have been obtained from **source** calculations with TWODANT, the k_{eff} values at begin of life and after each burnup step are obtained from **eigenvalue** calculations with TWODANT. KARBUS has been applied for the burnup calculations.

Figure 5 shows our results for k_{eff} as a function of burnup from 0 days to 2250 full power days in time steps of 150 days. After 2250 days a burnup of about 115 $GW_{th}d/t(HM)$ is reached. The main reasons for the strong decrease of k_{eff} during the first 150 days is the buildup of Pa^{233} , which has a large capture cross section (about 1 barn in the core regions, about 4 barn in the radial blanket at begin of life). Pa^{233} is built up by $Th^{232}(n,\gamma)Th^{233}$ and subsequent β^- - decay of Th^{233} into Pa^{233}. The half life of Th^{232} is 22.3 m and that of Pa^{233} (β^--decay) is 27 d.

During the first burnup step of 150 d the U^{233} enrichment decreases in both core regions. After 150 d the U^{233} enrichment increases steadily as a consequence of the U^{233} buildup. This leads to the increase of k_{eff} between 150 d and about 900 d which is shown in Figure 5.

The decrease of k_{eff} after about 900 days is due to the increase of fission product concentration in the core regions. The change of fuel isotope concentrations and the buildup of some actinides and of Tc^{99} during burnup are shown in Table 2 for the **inner core region** of the reactor with $k_{eff} = 0.96$. After 2250 days of burnup 72.5kg of Tc-99 are produced in the reactor: 28.7 kg in the inner core region, 42.1 kg in the outer core region and 1.7 kg in the radial blanket.

Table 1: Void reactivity effect at begin of life (BOL)

	no void	core region 1 voided	core regions 1 + 2 voided
k_{eff}	0.97969325	0.98971642	0.97843171
$(\frac{\Delta k}{k})_{void}(BOL)$		.01023	-.00129
k_{eff}	0.93996718	0.95017181	0.93966408
$(\frac{\Delta k}{k})_{void}(BOL)$		.01086	-.000322

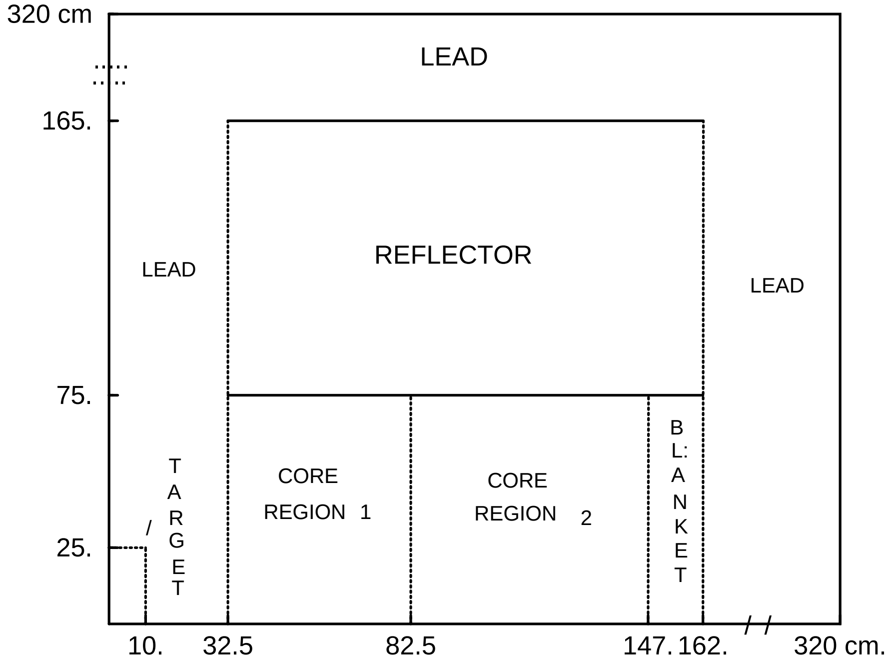
$$(\frac{\Delta k}{k})_{void}(BOL) = [k_{eff}(voided) - k_{eff}(BOL)]/k_{eff}(BOL)$$

Table 2 : weight of isotopes [kg] as a function of time

core region 1 ($k_{eff} = 0.96$)

Time $[days]$	Th^{232}	U^{233}	U^{235}	Pa^{233}	Pu^{238}	Pu^{239}	Tc^{99}
0	5.986E+03	6.443E+02	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.00E+00
150	5.876E+03	6.247E+02	2.21E-01	2.69E+01	2.4E-07	1.5E-09	2.25E+00
300	5.761E+03	6.233E+02	8.90E-01	2.88E+01	8.8E-06	1.1E-07	4.59E+00
450	5.650E+03	6.324E+02	1.90E+00	2.78E+01	6.5E-05	1.2E-06	6.84E+00
600	5.543E+03	6.339E+02	3.16E+00	2.68E+01	2.5E-04	5.9E-06	9.00E+00
750	5.439E+03	6.332E+02	4.60E+00	2.60E+01	7.0E-04	2.0E-05	1.11E+01
900	5.338E+03	6.310E+02	6.17E+00	2.53E+01	1.6E-03	5.4E-05	1.31E+01
1050	5.239E+03	6.275E+02	7.84E+00	2.47E+01	3.2E-03	1.2E-04	1.51E+01
1200	5.142E+03	6.229E+02	9.58E+00	2.42E+01	5.6E-03	2.5E-04	1.70E+01
1350	5.047E+03	6.174E+02	1.13E+01	2.38E+01	9.4E-03	4.5E-04	1.88E+01
1500	4.953E+03	6.112E+02	1.31E+01	2.34E+01	1.5E-02	7.8E-04	2.06E+01
1650	4.861E+03	6.044E+02	1.49E+01	2.31E+01	2.2E-02	1.3E-03	2.23E+01
1800	4.769E+03	5.970E+02	1.67E+01	2.29E+01	3.2E-02	2.0E-03	2.40E+01
1950	4.679E+03	5.893E+02	1.84E+01	2.27E+01	4.4E-02	3.0E-03	2.56E+01
2100	4.589E+03	5.812E+02	2.02E+01	2.25E+01	6.0E-02	4.3E-03	2.71E+01
2250	4.500E+03	5.728E+02	2.18E+01	2.23E+01	8.0E-02	6.1E-03	2.87E+01

Figure 1: ADS− NEUTRONIC BENCHMARK
GEOMETRY



References

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[8] M. Segev “Personal communication” Sommer 1995

Figure 2: radial power density distributions
at core midplane (begin of life)

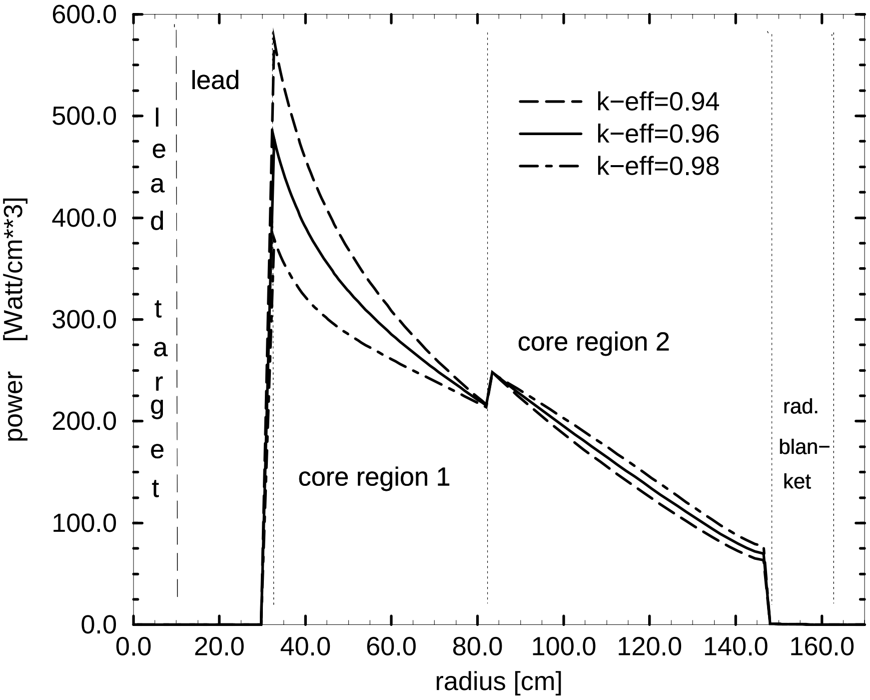

Figure 3: radial dependence of neutron flux densities
at core midplane (begin of life)

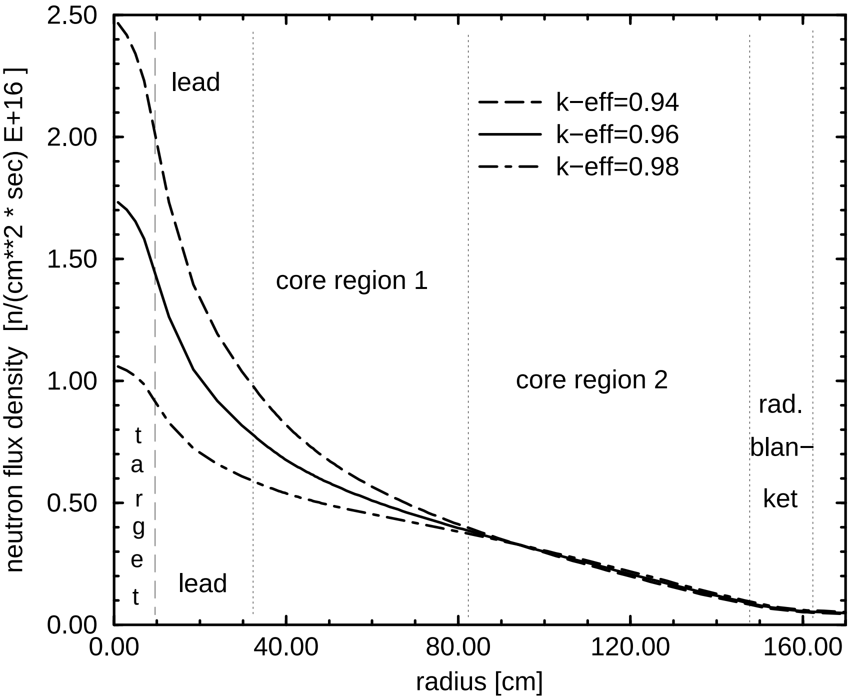

Figure 4a: radial dependence of neutron flux density in coarse groups
at core midplane (begin of life) k−eff=0.96

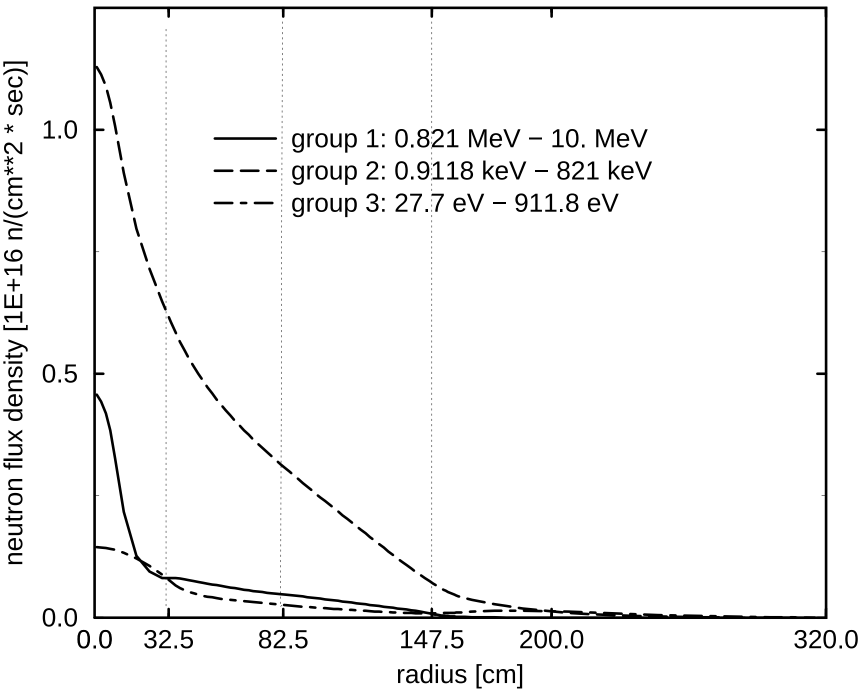

Figure 4b: radial dependence of neutron flux density in coarse groups
at core midplane (begin of life) k−eff=0.96

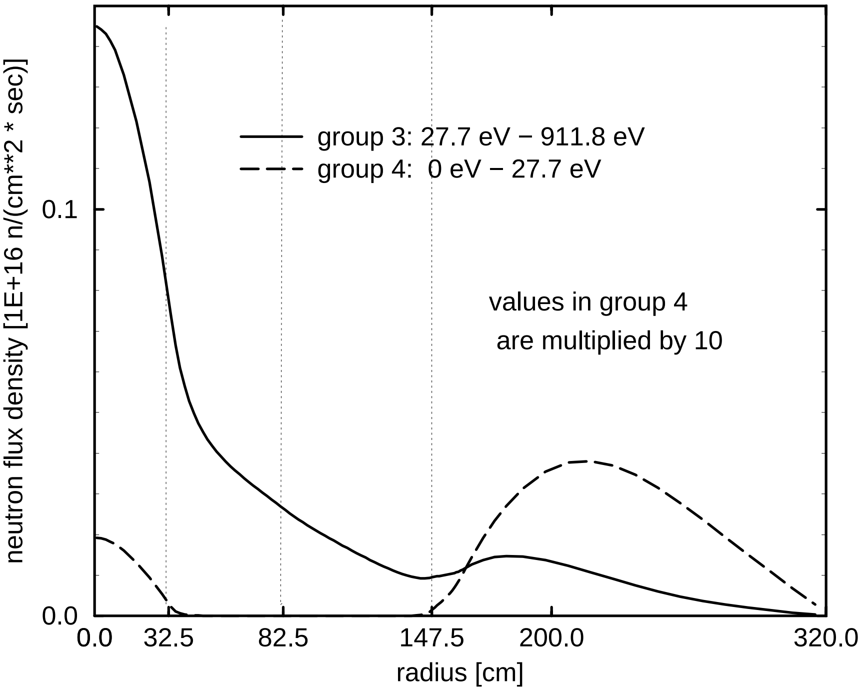

Figure 4: spectral indices

at core midplane (begin of life)

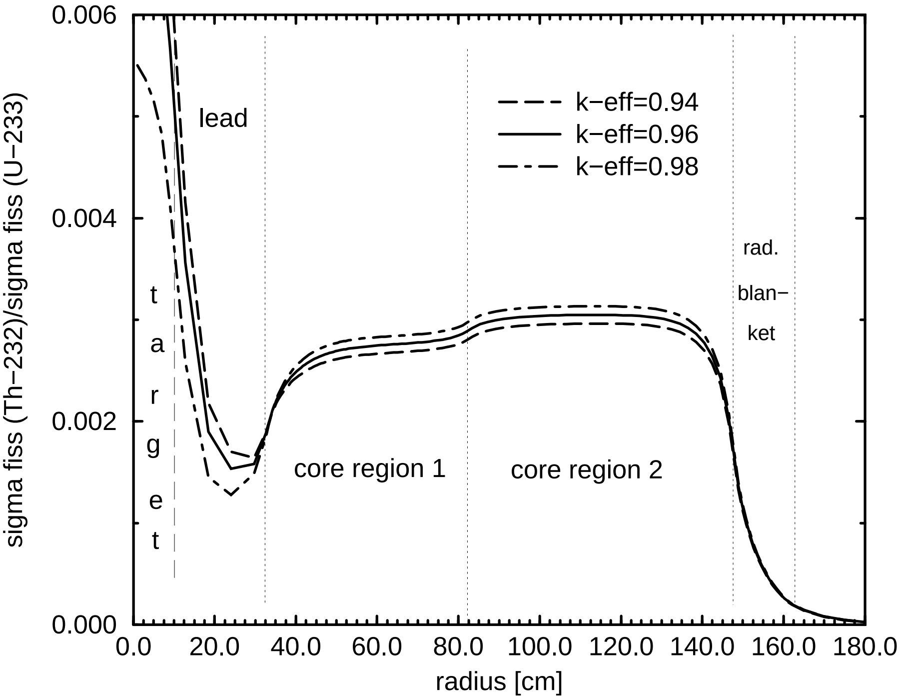

Figure 5: k−eff as function of burnup