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Projekt Schneller Brüter

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Abstract

A few preliminary results about the influence of fission neutron spectra on important integral quantities of fast critical assemblies were reported in preceding papers [1-3]. The scope of those studies was limited for two reasons:

i) only a small number of integral quantities for a few assemblies had been studied,
ii) the different forms used previously for the energy dependence of the fission spectrum were of limited accuracy.

In the present work the forms of the fission spectra are taken from the KEDAK and ENDF/B library respectively. The different forms are compared with each other and with our "standard" fission spectrum generally used in our calculations which belongs to ν=2.8 of the Russian ABN-set of group constants [4]. The influence of the different forms on calculated integral quantities for fast critical assemblies and on important characteristics of large fast power reactors is investigated. Some implications for the programs used to calculate flux distributions are outlined. Important conclusions of the present study are summarized at the end of the paper.

Zusammenfassung

In früheren Berichten [1-3] haben wir bereits einige vorläufige Resultate über den Einfluß des Spaltneutronenspektrums auf wichtige integrale Kenngrößen schneller kritischer Anordnungen veröffentlicht. Der Umfang dieser Arbeiten und der darin enthaltenen Ergebnisse war beschränkt, da

i) nur wenige Kenngrößen für eine kleine Anzahl von Anordnungen untersucht wurden,
ii) die Genauigkeit der verschiedenen Darstellungen, die für die Energieabhängigkeit des Spaltneutronenspektrums verwendet wurden, nicht ausreichend war.

In der vorliegenden Arbeit werden die Spaltspektren der beiden Kerndatenbibliotheken KEDAK und ENDF/B benutzt. Sie werden untereinander, sowie mit dem von uns üblicherweise benutzten "Standard"-Spaltspektrum verglichen, das aus dem russischen ABN-Gruppenkonstanten-Satz [4] übernommen wurde.

Der Einfluß der verschiedenartigen Energieabhängigkeit des Spaltspektrums auf berechnete integrale Parameter schneller kritischer Anordnungen und auf wichtige, charakteristische Kenngrößen großer schneller Leistungsreaktoren wird ermittelt. Einige mögliche Auswirkungen auf Programme zur Berechnung der Neutronenflußverteilungen werden angedeutet. Die wichtigsten Schlußfolgerungen sind am Ende der Arbeit zusammengefaßt.

Content

I) Comparison of different fission-neutron spectra

The different forms of the fission spectra have been taken from two evaluated nuclear data files, the KEDAK- and ENDF/B-library respectively.

The KEDAK-fission spectra are described by a "Watt"-type expression:

$$\chi(E) = c \cdot \exp(-aE) \cdot \sinh \sqrt{bE}$$

with the normalization constant c given by

$$c = 2a \sqrt{a/\pi b} \cdot \exp(-b/4a)$$

(see also [5]).

The parameters on the library are for U235 and Pu239 respectively:

Material	1/a	a	b
U235	0.965	1.036269	2.29
Pu239	1.0	1.0	2.0

(see [5] p. 16, [6] p. H40 for U235, [5] p. 20 and [6] p. J.42 for Pu239)

The ENDF/B-fission spectra are described by a Maxwellian

$$\chi(E) = (2/\theta \sqrt{\pi\theta}) \cdot \sqrt{E} \cdot \exp(-E/\theta)$$

The parameter θ depends on the energy E' of the neutron which induces the fission, but for our purposes we may use the parameters given for thermal fission because for all cases considered here the median energy of the fission inducing neutrons is below about 0.5 MeV and the increase in θ with increasing energy $\Delta\theta/\Delta E'$ is only about 1%/1MeV (see [6] p. H41). The following values have been used:

for U235: θ = 1.30 MeV, for Pu239: θ = 1.41 MeV

For U238 we have used a value of Θ = 1.35 MeV. This value has been deduced from the measurements of BARNARD et al. [7] who determined the Θ-values at incident neutron energies of 2.086 and 4.908 MeV respectively. As in the work of BARNARD we assumed a linear dependence of Θ on $\bar{\nu}$, the average number of neutrons per fission. We applied our values of $\bar{\nu}$, taken from KEDAK. For most of the assemblies considered in this study the average value of $\bar{\nu}$(U238) $\approx$ 2.85. An interpolation of BARNARD's results [7] gives Θ(U238) $\approx$ 1.35 MeV. From TERRELL's formula for Θ(given in the report of BARNARD [7])

$$\Theta \approx 0.50+0.43\sqrt{\bar{\nu}+1}$$

one would obtain Θ = 1.344. The good agreement with the value which we have chosen may be fortuitous.

With these parameters the various fission spectra have been calculated For the application in multigroup calculations the group values

$$\chi_i = \int_{E_i}^{E_{i-1}} \chi(E)dE \qquad i=1,11$$

have been determined. They are given in Table 1 together with our normally used "standard" fission spectrum which belongs to ν = 2.8 of the Russian ABN-set [4]. In our calculations of group values χ_i the neutrons emitted with energies above 10.5 MeV have been included in group 1 and those with energies below 10 keV in group 11 for the sake of simplicity.

In Fig. 1 the ENDF/B fission spectrum for U235 is shown. A comparison with the corresponding KEDAK fission spectrum is also given. In the lower part of this figure the group values χ_i determined from the ENDF/B- and KEDAK-data are compared with those of our ABN-"standard" fission spectrum belonging to ν = 2.8. Fig. 2 shows the analogous figures for Pu239.

From Fig. 1 it can be seen that except for the region of very high energies the KEDAK-spectrum for U235 is somewhat "harder" than the corresponding ENDF/B-spectrum and both are softer than our "standard" fission spectrum. Fig. 2 shows that for Pu239 the KEDAK-spectrum is generally "softer" than the "standard"fission spectrum whereas the ENDF/B-spectrum is definitely "harder". Thus, for the most interesting energy range from 0.2 to 5.0 MeV,

the ENDF/B spectra show the largest deviations compared to our standard fission spectrum, that for U235 being the softest one and that for Pu239 being the hardest one of the fission spectra studied here.

The differential fission neutron spectra measurements of WERLE [8] for thermal-neutron induced fission of U235 and Pu239 support the ENDF/B description. Therefore, the ENDF/B fission spectra are considered by us to be representative for the real difference between the U235- and Pu239-fission spectra. The ratio of both fission spectra is shown in the upper part of Fig. 3.

In the Russian ABN-set the fission spectrum is given for different values of ν, the average number of fission neutrons per fission. For fast criticals and fast power reactors the averge ν is generally somewhat below 3.0 for Pu239 and somewhat higher than 2.4 for U235 (probably even above 2.5). The lower part of Fig. 3 gives the ratio of the ABN-fission spectra belonging to $\nu = 2.4$ and $\nu = 3.0$ respectively. From a comparison with the upper part of the same figure it can be concluded that the difference between the U235- and Pu239 fission spectra is not sufficiently well represented by the ν-dependence as assumed in the ABN-set.

IIA) Influence of different fission-neutron spectra on calculated integral quantities of fast critical assemblies

a) Influence on criticality

Table 2 gives the criticality differences obtained by using instead of the "standard" fission spectrum the KEDAK- and the ENDF/B-fission spectra respectively. The results have been determined by fundamental mode homogeneous diffusion calculations. As nuclear data basis we have used the group constants of the MOXTOT-set [17]. (Some few test calculations have shown that the influence of the fission spectrum on the criticality is even somewhat more pronounced in two-dimensional calculations probably because the resulting change of the leakage probability or the space dependence of the flux shape is not accounted for by a corresponding change of the buckling in the fundamental mode calculations.) The fission spectrum used corresponds in every case to the main fissionable isotope of the special assembly considered. With the ENDF/B data, the maximum criticality decrease is about 0.009, the maximum criticality increase about 0.006. The criticality difference observed in Table 2 are generally of the same order of magnitude as other corrections, e.g. heterogeneity- or transport corrections, which are applied in order to determine best theoretical criticality values. Thus the criticality correction caused by the deviation of the appropriate fission spectrum from the "standard" fission spectrum is of the same importance as other commonly applied corrections.

From Table 2 it can be noted that replacing the "standard" fission spectrum by the KEDAK fission spectrum gives for plutonium assemblies an opposite sign of the criticality differences than that obtained upon a replacement by the ENDF/B fission spectrum. This is due to the fact mentioned before that for Pu239 the KEDAK fission spectrum is "softer" whereas the ENDF/B fission spectrum is "harder" than our "standard" fission spectrum. The most pronounced difference occurs for the k_∞-experiment ZPR III-55 where the criticality difference obtained when using the ENDF/B- instead of the KEDAK-data amounts to about 0.01 in k_{eff}.

For a few test cases the influence of the fission spectrum of U238 has also been studied. We have chosen such critical assemblies where the

fission in U238 is of relatively large importance: for the uranium assembly ZPRIII-25 about 27% of the neutron production stems from U238 and 73% from U235; for the plutonium assembly ZPR III-55 more than 20% of the neutron production stems from U238, about 75% from Pu239, the rest from U235 and the higher plutonium isotopes. The criticality values of the assemblies studied are known to be sensitive to the form of the fission spectrum. As a modified fission spectrum we have used a weighted average of the corresponding fission spectra: for ZPRIII-25 U235 (73%) and U238 (27%) and for ZPRIII-55 PU239 (75%) and U238 (25%) (the contributions of U235 and the higher plutonium isotopes have been neglected in this case). The criticality differences Δk obtained with these modified fission spectra compared to the results obtained with the corresponding pure fission spectra of the appropriate main fissionable isotope are $\Delta k = +0{,}0023$ for ZPRIII-25 and $\Delta k = -0{,}0021$ for ZPRIII-55. Even these criticality differences are of the order of other more familiar criticality corrections. Thus for some particular assemblies even the effect of the U238 fission spectrum has to be taken into account for a precise criticality determination. This statement holds at least as long as the differences in the temperatures for the Maxwell distributions are as large as assumed at present: $\Theta(U235) = 1{,}30$ MeV, $\Theta(U238) = 1{,}35$ MeV, $\Theta(Pu239) = 1{,}41$ MeV.

b) Influence on reaction rate ratios

Besides the criticality one is also interested in the reaction rate ratios for fast zero power assemblies because these quantities provide additional possibilities for testing the quality of the basic neutron cross sections. Of course, one is mainly interested in those reaction rates which are relevant for the neutron balance, i.e. for neutron production- or loss-processes. It is evident that a change in the fission spectrum will cause the largest effect for those reactions which have a threshold in the MeV-region. Here the fission process in U238 is the most important one. Replacing our "standard" ABN-fission spectrum by the ENDF/B representations the fission rate ratio R_f^8/R_f^5 decreased by about 5-6% for U-fuelled and increased by about

2.5-3.5% for Pu-fuelled assemblies. Moreover, noticeable variations of this ratio are even observed if the U238 contribution to the fission spectrum is taken into account appropriately.
For ZPRIII-25, a mixed fission spectrum composed of U235 (73%) and U238 (27%) leads to a 1% increase of the ration R_f^8/R_f^5 as compared to the result obtained for a pure U235 fission spectrum. For ZPRIII-55 we used a mixed fission spectrum composed of Pu239 (75%) and U238 (25%) instead of a pure Pu239 fission spectrum and obtained a decrease of 1% for the R_f^8/R_f^5 ratio.
All other important reaction rate ratios remain nearly unchanged for the presently considered changes of the fission spectrum. Especially for the important ratios $\alpha^5 = R_c^5/R_f^5$, R_c^8/R_f^5, R_f^9/R_f^5, $\alpha^9 = R_c^9/R_f^9$, R_c^8/R_f^9, R_f^o/R_f^9, R_c^o/R_f^9 the changes are smaller than 1% for the assemblies considered here. This change is much smaller than that caused by the uncertainties in the corresponding basic nuclear data. Only if those errors in the above mentioned reaction rate ratios which are caused by basic cross section uncertainties can be reduced below 1% the influence of the fission spectra on these reaction rate ratios must be taken into account.

c) Influence on material worth- and substitution-experiments

For two assemblies (ZPRIII-25 and ZPRIII-48) we have studied the influence of the different forms of the fission neutron spectrum on the central material worth. Such an effect may be important if the reactivity of a plutonium (Pu239) sample in a uranium (U235) core has to be determined or vice versa that of a U235 sample within a Pu239 core. In both cases the fission spectrum of the sample is different from that of the surrounding medium, an effect which usually has been neglected up to now and cannot be taken into account in most of the existing perturbation codes. The net perturbation effect for the central material worth is composed of three terms: production, absorption and degradation.
Our test calculations have shown that the production term is changed by about 2% for ZPRIII-25 and by about 1% for ZPRIII-48 if we used the fission spectrum for Pu239 instead of that for U235 (both taken from ENDF/B). For the assembly ZPRIII-48 the production term is larger than

the net perturbation effect by a factor of about 1.5 for Pu239 and about 2.0 for U235. Therefore we have to expect that errors of the order of a few per cent (probably up to 5%) may arise by neglecting the difference between the fission spectrum of the sample and that of the surrounding core material .

From the preceding discussion it is evident that in the case of substitution experiments errors of the same order as for the material worth may arise when the effect of differences in the fission spectra is neglected. In these experiments e.g. a uranium zone is successively replaced by a plutonium zone [9]. From the results of successive substitution steps one tries to extrapolate to the results which would correspond to a full core with the composition of the substituted zone. Direct numerical calculations to determine the reactivity effect caused by the differences in the fission spectra of the substituted and the surrounding zone could not be performed up to now because the appropriate codes were not available. However, from the criticality calculations mentioned in section IIAa) one may conclude that for the extrapolated results of a fully substituted core criticality errors of up to 0.01 may arise if the differences in the fission spectra of the substituted and the original core zone are neglected.

d) Influence on reaction rate traverses

In [2] it has been shown that the form of the fission spectrum has some influence on the shape of reaction rate traverses too, apart from the influence on the absolute magnitude of central reaction rates or central reaction rate ratios discussed in section IIAb). The result of the earlier work for the assembly SNEAK 3A2 [2] is redrawn here in Fig. 4. The FABRY-fission spectrum used for Fig. 4 is based on results of integral measurements for the temperature of the U235 thermal neutron fission spectrum [10]. This fission spectrum is "harder" than our "standard" fission spectrum and therefore considerably harder than the ENDF/B U235 fission spectrum which in the present work is considered to be the most realistic representation of the differential measurements. The ENDF/B U235 fission spectrum has been used to obtain the results of Fig. 5.

With the "harder" spectrum used for Fig. 4 all the three reaction rate traverses studied (R_c(U238), R_f(U235), R_f(U238)) show an increase of

0.7% in the outer part of the core region (all traverses are normalized at the core center). In the blanket region R_c(U238) and R_f(U235) are increased by about 2% and R_f(U238) by about 4%.

In Fig. 5 the corresponding results with the "softer" ENDF/B U235 fission spectrum are shown. In the outer part of the core the three reaction rate traverses studied are lower by about 0.7% than those calculated with the "standard" fission spectrum. In the blanket region the traverses for R_c(U238) and R_f(U235) are decreased by about 2.5% and for R_f(U238) by about 4%.

It is probably interesting to mention that even the discrepancies between the shape of the traverses determined with the U235 ENDF/B- and U235 KEDAK-fission spectrum, respectively, are not too small: for the case studied here the traverses with the KEDAK-spectrum are in the outer part of the core region about 0.5% and in the blanket region up to 1.5% higher than those calculated with the ENDF/B-spectrum.

The present results indicate that for the precise determination of the reaction rate traverses including the power traverse it will be necessary to take into account the appropriate form of the fission spectrum if discrepancies in the shape between theory and experiment of the order of 1% in the core region and/or several per cents in the blanket region become relevant. The possible effect of using different fission spectra in the core (U235) and blanket region (U238), respectively, could not be studied because an appropriate code is not available at the moment.

IIB) Influence of other nuclear data uncertainties on the criticality of of fast critical assemblies

The importance of a precise knowledge of the appropriate fission spectrum must be judged in the context of the presently existing other uncertainties in the nuclear data. We will discuss here only two examples of uncertainties namely the fission- and the inelastic scattering cross sections of U238.

The following results will show the sensitivity of the criticality on certain changes in the nuclear data. As a first change (CI) of Table 3 we study an increase of the U238 fission cross section by 5%. Then the inelastic scattering cross section of U238 is changed from the values used in the MOXTOT-set [1] to the ABN-values. In the first step (CII) for the energy range from 1.4-10.5 MeV (groups 1-4) and in the second step (CIII) from 0.05-1.4 MeV (groups 5-9). In addition to the change of the inelastic scattering cross section of U238 we considered also a change of the corresponding scattering probabilities, i.e. of the energy distribution of the neutrons scattered inelastically by U238. Instead of the probabilities determined for the MOXTOT-set [1] we use those of the ABN-set for the next two changes: Change CIV concerns the energy range between 1.4-6.5 MeV (groups 2-4) and CV the energy range between 0.05-1.4MeV (groups 5-9). For case CVI the changes CII and CIII are applied simultaneously, i.e. the cross section for inelastic scattering by U238 is changed in the whole energy range from the MOXTOT- to the ABN-values. The same is done for the inelastic scattering probabilities in case CVIIwhich is a combination of CIV and CV. For case CVIII, finally, all data for the inelastic scattering on U238 are changed from the MOXTOT- to the ABN-values.

Before discussing the results it is probably useful to mention that the changes considered here are reasonably realistic. PITTERLE [11] has increased the U238 fission cross section by about 6% as compared to his earlier evaluation [12] for which a reasonable agreement with the corresponding data of the MOXTOT-set exists. The modified data are similar to the ABN-data. KALLFELZ et al. [13] have shown that a possible reduction of the inelastic scattering cross section by an amount between 15% - 30% would improve the agreement

between theory and experiment for integral quantities as e.g. the criticality or the fission rate ratio R_f^8/R_f^5 for a series of fast critical assemblies. PITTERLE [12] changed the parameter γ, which via the "effective temperature" $\Theta = \sqrt{E/\gamma A}$, determines the inelastic scattering probabilities of U238, from $\gamma = 0.099\ MeV^{-1}$ [12] to the new value $\gamma = 0.0685\ MeV^{-1}$ [11]. For the MOXTOT-set $\gamma = 0.16\ MeV^{-1}$ has been used to calculate the inelastic scattering probabilities for U238 in the "continuum" range of residual nucleus levels.
The difference in the inelastic scattering probabilities between the MOXTOT-set and ABN-set data is similar to the difference which results when the parameter γ is changed from $\gamma = 0.16\ MeV^{-1}$ to $\gamma = 0.099\ MeV^{-1}$. Therefore all changes considered here are within the range of the presently existing uncertainties or within the range of suggested modifications of the nuclear data.

All criticality differences Δk given in Table 3 are based on fundamental mode homogeneous diffusion calculations using the MOXTOT-set as nuclear data basis. The results should be compared with those given in Table 2. With respect to the absolute Δk-values each of the changes CI through CV of Table 3 has about the same importance as the differences in the fission spectrum representations. From the cases CVI and CVII it can be seen that the uncertainties in the magnitude of the inelastic scattering cross section as well as that of the inelastic scattering probabilities are somewhat more important with respect to the criticality than the changes in the form of the fission spectrum. Especially case VIII demonstrates the large effect of the inelastic scattering data for U238 on the criticality of most of the fast assemblies included in our study. If the uncertainties assumed for case VII are realistic then a precise determination of the inelastic scattering data of U238 is of high priority.

IIIA) Influence of the different fission neutron spectra on important calculated quantities of large fast power reactors

a) Influence on criticality and critical mass

Besides the influence of different fission neutron spectra on the calculation of fast critical assemblies discussed before it is important to study the influence on the calculation of large fast power reactors. As test example of a large fast power reactor we have chosen the simplified model suggested by BAKER which was used for a worldwide intercomparison study. The details of the specifications may be found in the recently published report [14] on the results of this intercomparison of nuclear reactor calculations. The main features of the reactor model are as follows: spherical model with a core radius of 84,196 cm and a spherical annular blanket of 45.72 cm thickness. The fuel is mixed PuO_2-UO_2. Sodium is used as coolant and stainless steel for the structure and cladding material. Three versions have been studied with somewhat different fuel compositions:

(A) only Pu239 and U238, no fission products, no higher plutonium isotopes

(B) Pu239 plus U238 plus 10% fission product pairs, no higher plutonium isotopes

(C) Pu239, Pu240 and U238 plus 10% fission product pairs, Pu239: Pu240 = 1:0.5.

In the first column of Table 4 the criticality differences are given which arise if the fission spectra for U235 and Pu239 respectively (ENDF/B-form) are used instead of our "standard" fission spectrum. The reactor composition has been kept constant in this case. Then the fuel enrichment has been adjusted in such a manner that the original criticality value $k_{eff} = 1.0000$ is attained. The corresponding absolute changes in critical mass of fissile material (Pu239) are given in the second column. The third column shows the relative changes of the critical fissile mass which have been necessary in order to reestablish the criticality.

The largest absolute criticality change is about 0.007 which causes a change of the critical mass of somewhat more than 1% corresponding in this case to about 11 kg of Pu239. This change occured if we use the U235 fission spectrum instead of our standard fission spectrum. Using the Pu239 fission spectrum which is more appropriate in this case because the fissionable material is plutonium and which is closer to our standard fission spectrum than the U235 fission spectrum the resulting changes are smaller in absolute magnitude although of alternate sign. For this more realistic change the criticality difference is about 0.003, the change in critical mass about 0.6%, equivalent to somewhat less than 6 kg of Pu239 for these simplified cases with about 1000 kg total fissile mass. The main reason for the criticality differences is the change of the fission- and production rate in the fertile materials U238 and Pu240 with fission thresholds in the high energy range.

b) Influence on breeding performance

The most important quantity next to the critical mass is the breeding performance of a power reactor. Column 4 of Table 4 shows that changes in the breeding ratio of up to 0.015 may be caused by changes in the form of the fission spectrum. The change of the breeding ratio is mainly caused by the adjustment of the enrichment which is necessary to bring the reactor with modified fission spectrum back to criticality. The ratio of reaction rates per atom R_c^8 / R_f^9 is changed by at most 0.5% upon changing the fission spectrum. For the corresponding fission rate ratio R_f^8/R_f^9 changes similar to that mentioned in section IIAb) for the fast critical assemblies have been observed, i.e. -5.3% for the U235 fission spectrum and +2.3% for the Pu239 fission spectrum. The adjustment of the enrichment causes very small variations in the reaction rate ratios per atom, generally one order of magnitude smaller than the variations caused by using different forms of the fission spectrum.

IIIB) Influence of other nuclear data uncertainties on criticality, critical mass and breeding performance

The influence of nuclear data uncertainties on criticality and breeding performance may be judged on the basis of the intercomparison study by BAKER and HAMMOND [14] already mentioned. Excluding those sets of group constants which still used the old KAPL-values for α (Pu239) in the resonance region we found the following maximum deviations between the most extreme cases appearing in the intercomparison. For the criticality difference: $\Delta k \approx 0.04$, for the critical mass about 7.5% equivalent to 73 kg of Pu239 and 0.10 for the physical breeding ratio. For version B of the reactor model considered here, the most extreme values for the total breeding gain are 0.160 and 0.268 (see Table 21 of [14]) if those group-constant-sets still using the old and too low KAPL-α (Pu239)-values are excluded. The corresponding average value is 0.206 for the total breeding gain of version B, which has the lowest total breeding gain of the three versions which formed the basis of the study by BAKER. The deviation from the average value of about ± 0.05 for the extreme cases is much larger than the deviation caused by changes in the fission spectrum. The amount of ± 0.05 represents about 25% of the average value for the total breeding gain and will lead to a similar deviation in the doubling time, i.e. the time which is necessary for a reactor to produce a surplus of fissile mass equal to its own inventory. It should be mentioned that similar changes of 0.12-0.15 for the breeding ratio or the breeding gain have been observed at Karlsruhe upon using the recently established MOXTOT-set instead of the formerly used SNEAK- or NAPPMB-set [15], [16].

From a comparison of the differences discussed in the preceding setion with those obtained when the fission spectrum is changed it seems to us that for the physics prediction of large fast power reactors the form of the fission spectrum is not the most important uncertainty which presently exists in the nuclear data field.

IV) Implications for the computer programs used to calculate flux distributions

Table 2 illustrates the importance of taking into account the appropriate fission spectrum for each material composition. In order to do this correctly it will be necessary to modify the diffusion and transport codes in such a way that they are able to handle at least a composition-dependent fission spectrum. Even more desirable would be an isotope-dependent fission spectrum and as ultimate refinement an isotope-dependent fission matrix which takes into account also the dependence of the fission spectrum on the energy of the fission-inducing neutron (probably most important for U238). As a good first approximation a composition-dependent fission spectrum is presumably sufficient. This may be obtained by a calculation prior to the flux claculation if reliable values for the neutron production in the various isotopes are available. Otherwise an iteration procedure has to be applied. The indicated modification of the codes calculating the flux distribution seems to be necessary because otherwise one will not be able to calculate very accurately the nuclear characteristics of e.g. an assembly like SNEAK 3B2 with an inner plutonium zone and an outer uranium driver zone in the core region.

For small cores reflected by natural or depleted uranium, i.e. mainly U238, an influence of the different fission spectra in core and blanket may be important too. It seems worthwhile to study if an effect on the reaction rate traverses, e.g. the fission traverse of U238, can be observed by using the appropriate different fission spectra for different material compositions. If a cell arrangement for a fast zero power assembly contains platelets of both U235 and Pu239 of about equal amount or of enriched fuel and natural (or depleted) uranium then also the heterogeneity codes like ZERA [17] should probably be able to take into account a composition-dependent fission spectrum.

An isotope-dependent fission spectrum may probably be desirable for the calculation of a power reactor which at the beginning may have U235 as main fissionable isotope and during the power production produces Pu239 according to its breeding properties although it may

turn out that in the burn-up calculations an approximate treatment of the variation of the form of the fission spectrum during the reactor lifetime may be sufficiently accurate.

The implications for the codes used in perturbation calculations have already been mentioned in section IIAc.

V) Conclusions

Our studies confirm the fact that the difference in the form of the fission spectrum for U235 and Pu239 respectively, as obtained in differential spectrum measurements cannot be represented reasonably well by the ν-dependence as given e.g. in TERRELL'S formula and as e.g. assumed in the Russian ABN-set.

For the calculation of fast critical assemblies we have found criticality changes of up to 1% upon changing the form of the fission spectrum from our "standard" form to the forms which are more appropriate for the individual assemblies considered.
The reaction rate ratios which are important for the neutron balance are rather insensitive to the form of the fission spectrum with the only exception of the fission rate ratio $R_f(U238)/R_f(U235)$ or $R_f(U238)/R_f(Pu239)$. This ratio is changed by several per cents if the form of the fission spectrum is changed.
For some special assemblies it seems even important to take into account the contribution of the U238 fission spectrum to the total fission spectrum of the fuel mixture (either (U235+U238) or (Pu239+U238)). Criticality changes slightly above 0.2% and changes of the fission rate ratio $R_f(U238)/R_f(U235)$ of about 1% have been found when the U238 contribution has been taken into account properly.

Generally the criticality changes which have been obtained when the form of the fission spectrum is changed within reasonable limits are of the same order of magnitude as the criticality changes which result from various usually applied corrections: e.g. transport-(S_N)-correction, heterogeneity correction etc. This fact shows that the form of the fission spectrum is of the same importance as these corrections just mentioned which need usually rather complicated and/or time-consuming computations. Therefore the appropriate form of the fission spectrum should be taken into account for accurate and reliable nuclear calculations.

At the present state of knowledge of the nuclear data it seems impossible for us to draw definite conclusions from the analysis of fast critical assemblies on the correctness of the fission spectra used for this analysis. However, we have found that when using appropriately the ENDF/B-forms for U235 and Pu239 instead of our "standard" fission spectrum the agreement

between theory and experiment for the criticality is improved. With our "standard" form we have found in our analysis of a series of fast criticals using the MOXTOT-set [1] that U235-fuelled assemblies are generally predicted supercritical whereas Pu239-fuelled assemblies are predicted subcritical. These discrepancies are reduced by using the more reasonable ENDF/B-forms of the fission spectra.

For fast power reactors the form of the fission spectrum is in most cases less important than for fast criticals. But the test of the nuclear data and methods of calculations which should subsequently be used for the calculation of power reactors can only be performed by comparing the experimental results obtained in fast criticals with the corresponding theoretical results. The reliability of the nuclear data used for the power reactor design can therefore only be judged on the basis of checking the experimental results of a variety of different fast criticals. This fact explains why the fission spectrum is more important for the calculation of fast power reactors than one would assume from its direct influence on the nuclear characteristics of fast power reactors.

The effect of nuclear data uncertainties on the design of large fast breeder reactors has been studied by several authors (see e.g. [18] [19]). One major concern is for the design of the early-generation fast breeder power plants. Here the uncertainties in the nuclear data and the resulting uncertainties in the predicted reactor parameters as e.g. criticality or reactivity coefficients will cause economic disadvantages. The costs of the power plant will increase because of the increased flexibility of the core design which is necessary in order to counterbalance the effects of uncertainties in the predicted reactor parameters. Probably at the same time the maximum total power output can not be attained because the optimum conditions for the power production can not be reached. Futhermore an extrapolation from the early demonstration power reactors to the large size power plants with a power output of at least 1000 MWe will be affected by uncertainties in the nuclear data (even if the results derived from critical assemblies are taken into account). This leads us to the second concern: The uncertainties in the nuclear data causes uncertainties in the long-term potential of fast breeders as e.g. the doubling time or the long-term power generating costs. Usually a criticality uncertainty Δk of $\pm$ 1% caused by the combined effects of all nuclear data uncertainties is considered to be tolerable at present.

Table 4 shows that a criticality difference of about this magnitude is caused just by replacing the Pu239 fission spectrum by the U235 fission spectrum (ENDF/B-forms). If the uncertainty in the fission spectrum is only allowed to cause a criticaly uncertainty smaller than ± 0.2%, which seems reasonable for an accepted total criticality uncertainty of ± 1% caused by a combination of all nuclear data uncertainties, this would mean that the temperatures of the corresponding Maxwell-distributions of the fission spectra have to be determined with an absolute uncertainty smaller than ± 0.02 MeV. This fact demonstrates more drastically than Table 4 or the discussion in chapter III A) that the fission spectrum should be determined with a rather high accuracy because it is only one out of a long list of important nuclear data.
It is probably worthwhile to mention that the form of the fission spectrum is also of some importance with respect to irradiation effects on fuel elements and structural materials caused by high energy neutrons.

The studies presented in this paper have shown that the form of fission neutron spectrum plays an important role for the neutron physics calculations of fast critical assemblies and large fast power reactors.

At present, however, there exists one specific difficulty: most existing codes for nuclear calculations assume that the fission spectrum is the same for all regions or compositions of the reactor. Probably this assumption is too crude and may give rise to difficulties in the interpretation of material worth- or substitution-experiments as explained in more detail in section IIAc). It may turn out that in special cases even in heterogenity codes like ZERA [17] it will be desirable to use different fission spectra for the different fuel platelets.

In the analysis of fast critical assemblies and in the nuclear design calculations of large fast power reactors a variety of important nuclear data is involved. The fission spectrum is only one of several nuclear data which are important in the high energy range and which are still uncertain to some extent. Other uncertainties in the nuclear data field are the inelastic scattering cross section and the fission cross section of U238 for the calculation of criticality or critical mass and the capture cross section of U238 for the determination of the breeding properties of power reactors. In order to draw more definite conclusions with respect to the reliability of these other data it is highly desirable to know the form of the fission spectra of the different isotopes rather accurately.

Acknowledgement:

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Table 1 Various forms of the spectrum of fission neutrons

$$\chi_i = \int_{E_i}^{E_{i-1}} \chi(E)dE$$

Group	Energy range	"Standard" fission spectrum	U235 KEDAK	Pu239 KEDAK	U235 ENDF/B	Pu239 ENDF/B	U238
1	6.5-10.5 MeV	0.018	0.016684	0.018076	0.018609	0.026561	0.02199
2	4.0- 6.5 MeV	0.095	0.08832	0.09056	0.08579	0.1021	0.09328
3	2.5- 4.0 MeV	0.188	0.1834	0.1840	0.1742	0.1862	0.1800
4	1.4- 2.5 MeV	0.269	0.2699	0.2684	0.2625	0.2605	0.2619
5	0.8- 1.4 MeV	0.198	0.2023	0.2008	0.2045	0.1933	0.1994
6	0.4- 0.8 MeV	0.137	0.1406	0.1397	0.1473	0.1352	0.1416
7	0.2- 0.4 MeV	0.059	0.06103	0.06078	0.06567	0.05921	0.06260
8	0.1- 0.2 MeV	0.023	0.02388	0.02382	0.02610	0.02331	0.02477
9	46.5-100 keV	0.009	0.00939	0.009373	0.01035	0.009201	0.009799
10	21.5-46.5 keV	0.003	0.003069	0.003065	0.003397	0.003014	0.003213
11	10,0-21.5 keV	0.001	0.001427	0.001426	0.001584	0.001404	0.001448

Table 2 Criticality differences Δk caused by using fission spectra different from the "standard" fission spectrum.
(Results of fundamental mode diffusion calculations for homogeneous mixtures using the MOXTOT-set)

Assembly	Main fissionable isotope	k_{eff}(KEDAK) $-k_{eff}$(STANDARD)	k_{eff}(ENDF/B) $-k_{eff}$(STANDARD)
SUAK U1B	U235	-0.0033	-0.0054
SUAK UH1B	"	-0.0013	-0.0011
ZPRIII-10	"	-0.0037	-0.0062
ZPRIII-25	"	-0.0051	-0.0091
SNEAK-3A1	"	-0.0016	-0.0027
SNEAK-3A2	"	-0.0013	-0.0021
ZPRIII-48	Pu239	-0.0015	+0.0030
ZEBRA-6A	"	-0.0011	+0.0024
SNEAK-5C	"	-0.0018	+0.0034
ZPRIII-55	"	-0.0032	+0.0064

Table 3 Criticality differences Δk caused by changes in the nuclear data of U238

Assembly	CI	CII	CIII	CIV	CV	CVI	CVII	CVIII
	$\sigma_f \cdot 1.05$	σ_{inel} Gr.1-4 MOXTOT →ABN	σ_{inel} Gr.5-9 MOXTOT →ABN	P_{inel} Gr. 2-4 MOXTOT →ABN	P_{inel} Gr.5-9 MOXTOT →ABN	CII+ CIII	CIV+ CV	CII+CIII+ CIV+CV
SUAK U1B	+0.0064	+0.0038	-0.0055	+0.0019	-0.0065	-0.0016	-0.0048	-0.0059
SUAK UH1B	+0.0049	-0.0023	-0.0032	-0.0020	-0.0039	-0.0055	-0.0060	-0.0112
ZPRIII-10	+0.0061	+0.0069	-0.0039	+0.0031	-0.0053	+0.0030	-0.0024	+0.0009
ZPRIII-25	+0.0073	+0.0146	+0.0019	+0.0071	+0.0004	+0.0165	+0.0075	+0.0243
SNEAK-3A1	+0.0037	+0.0015	-0.0010	+0.0005	-0.0013	+0.0006	-0.0007	-0.0001
SNEAK-3A2	+0.0036	+0.0009	-0.0011	+0.0002	-0.0014	-0.0002	-0.0012	-0.0013
ZPRIII-48	+0.0037	+0.0027	-0.0001	+0.0016	+0.0002	+0.0026	+0.0018	+0.0043
ZEBRA-6A	+0.0033	+0.0009	-0.0005	+0.0008	-0.0003	+0.0005	+0.0005	+0.0010
SNEAK-5C	+0.0030	+0.0035	+0.0004	+0.0017	+0.0005	+0.0039	+0.0022	+0.0060
ZPRIII-55	+0.0058	+0.0130	+0.0033	+0.0069	+0.0041	+0.0163	+0.0113	+0.0275

Table 4 Differences in nuclear characteristics of large fast power reactors caused by using fission spectra different from the "standard" fission spectrum

		Changes in nuclear characteristics			
Case	Fission spectrum	Δk [%]	ΔM(Pu239) [kg]	ΔM/M [%]	ΔBR
A	U235	-0.060	+10.57	+1.10	-0.015
	Pu239	+0.032	- 5.68	-0.59	+0.008
B	U235	-0.057	+10.22	+0.98	-0.012
	Pu239	+0.028	- 5.00	-0.48	+0.007
C	U235	-0.067	+10.98	+1.14	-0.015
	Pu239	+0.029	- 4.72	-0.49	+0.007

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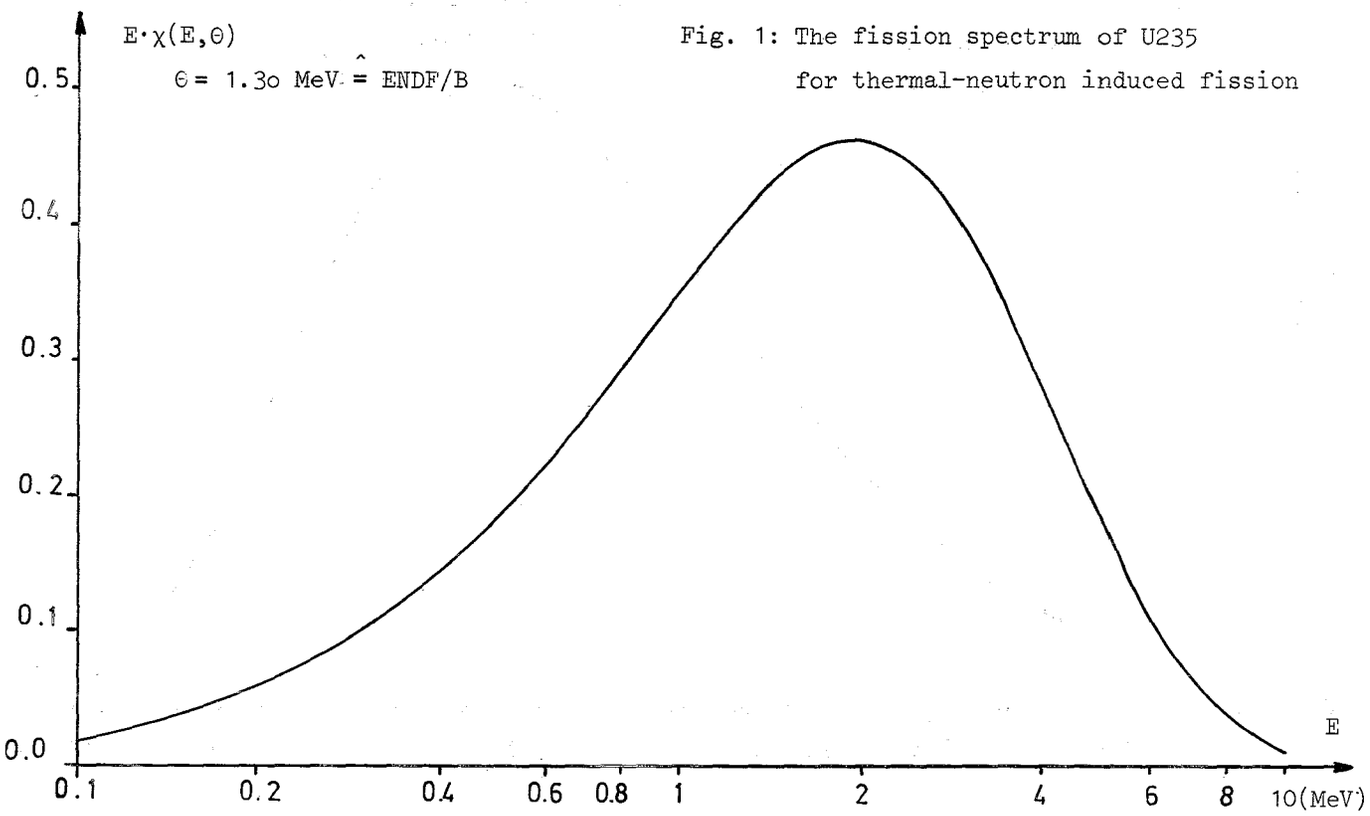
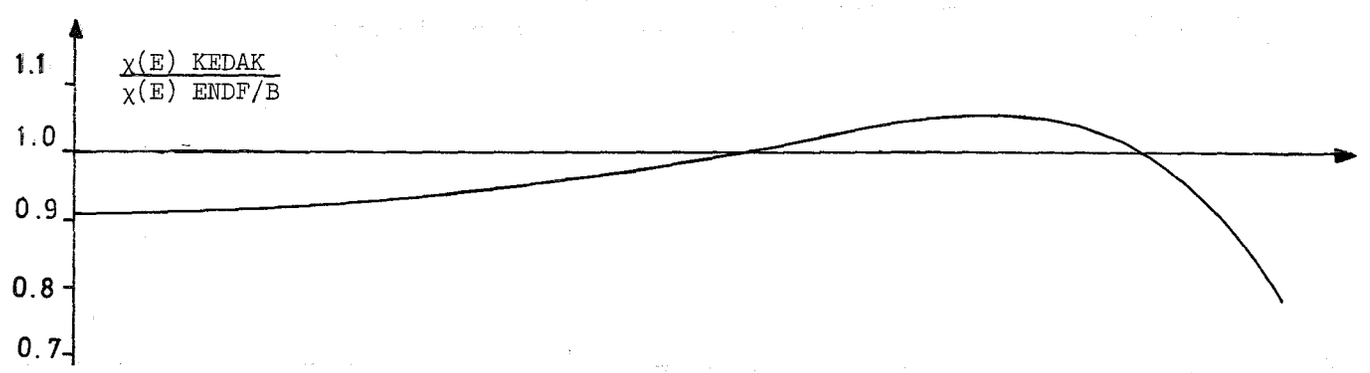
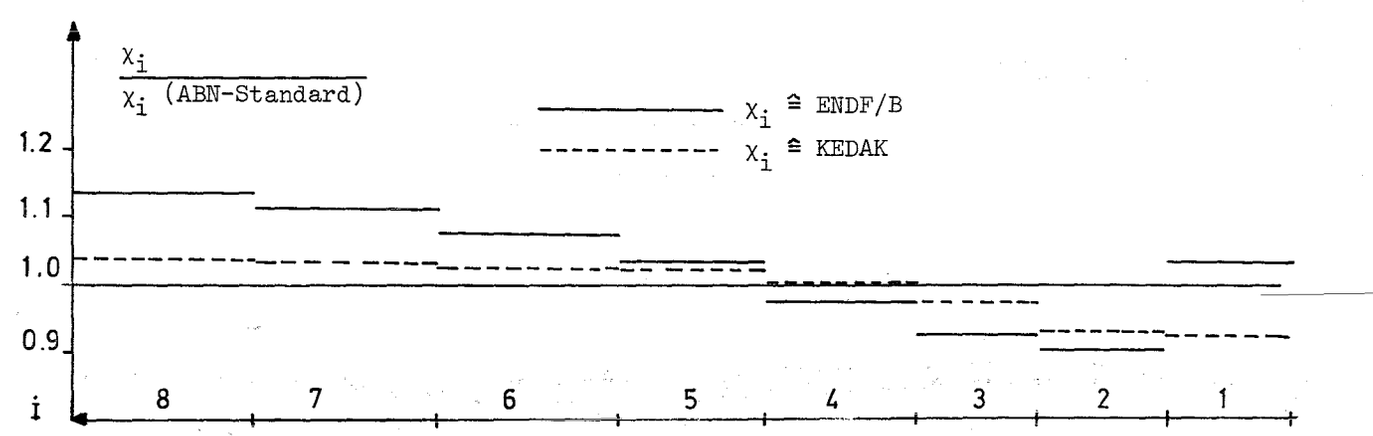


Fig. 1: The fission spectrum of U235 for thermal-neutron induced fission





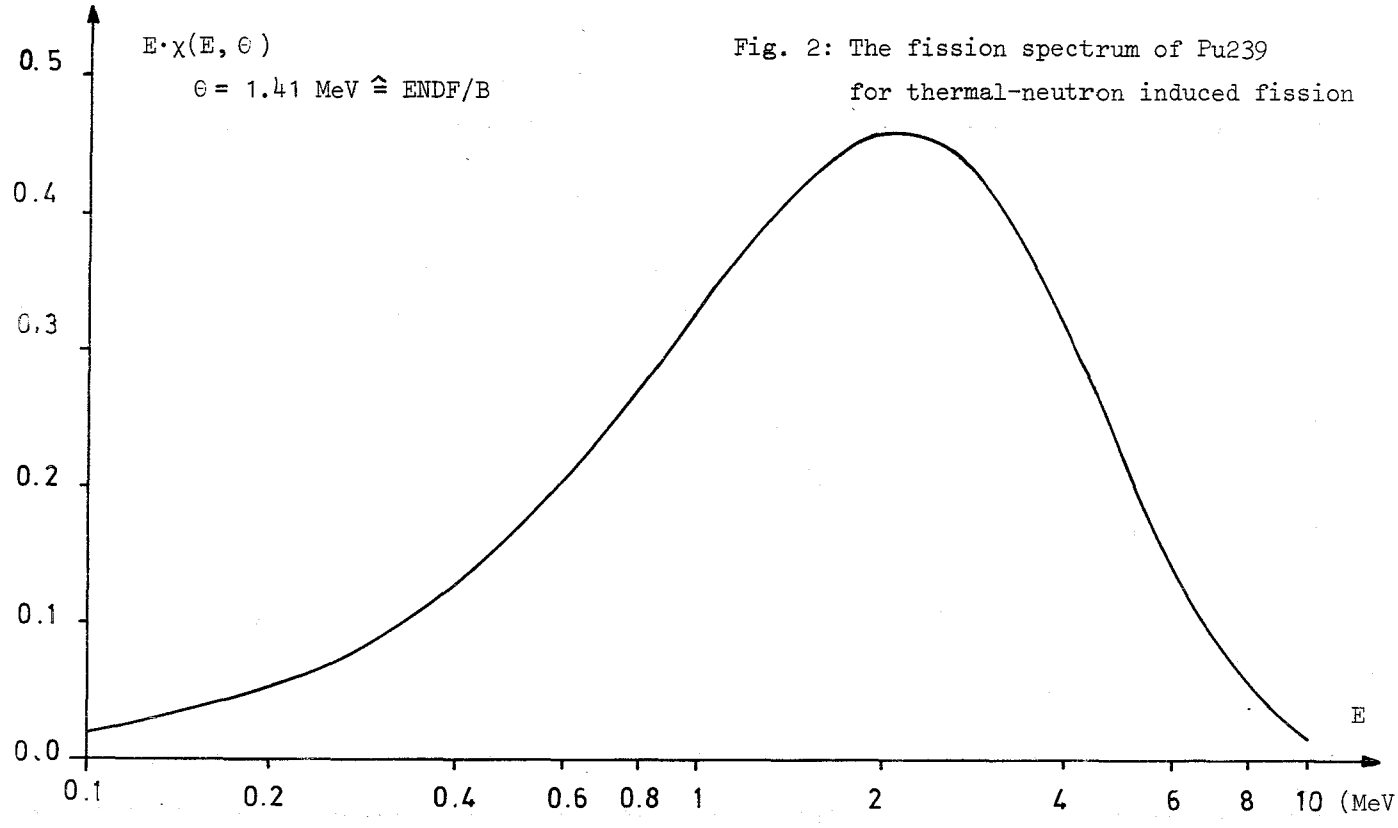
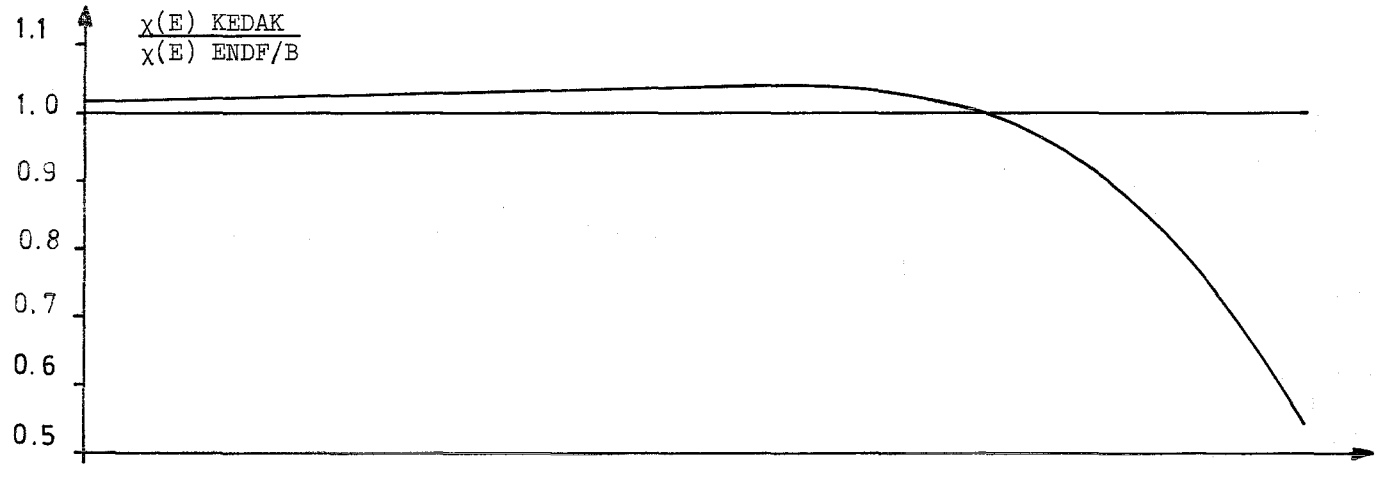


Fig. 2: The fission spectrum of Pu239 for thermal-neutron induced fission



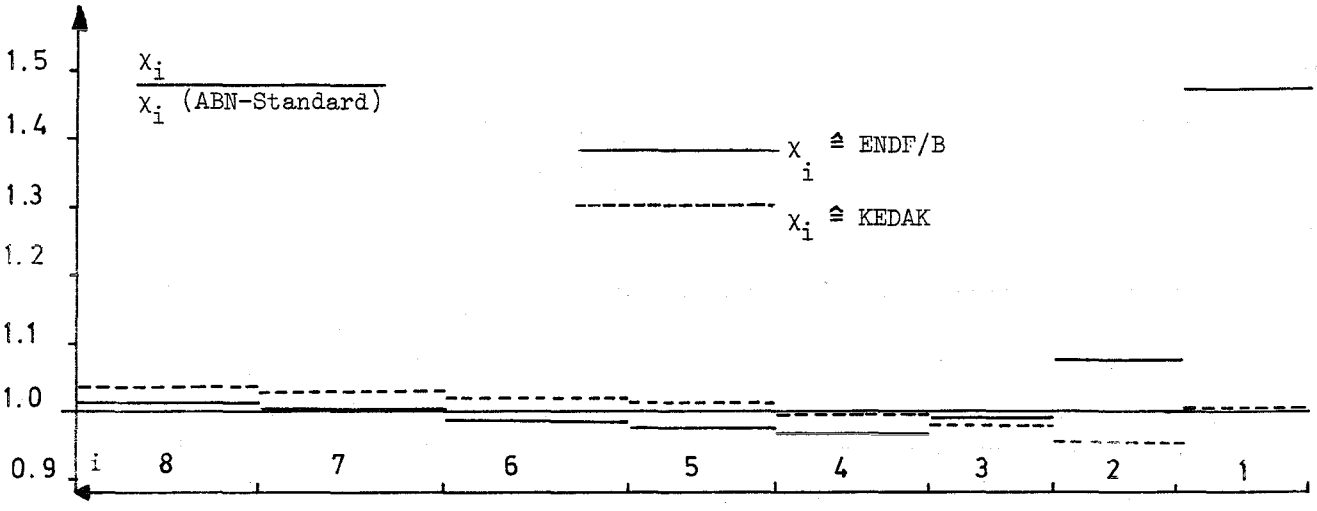
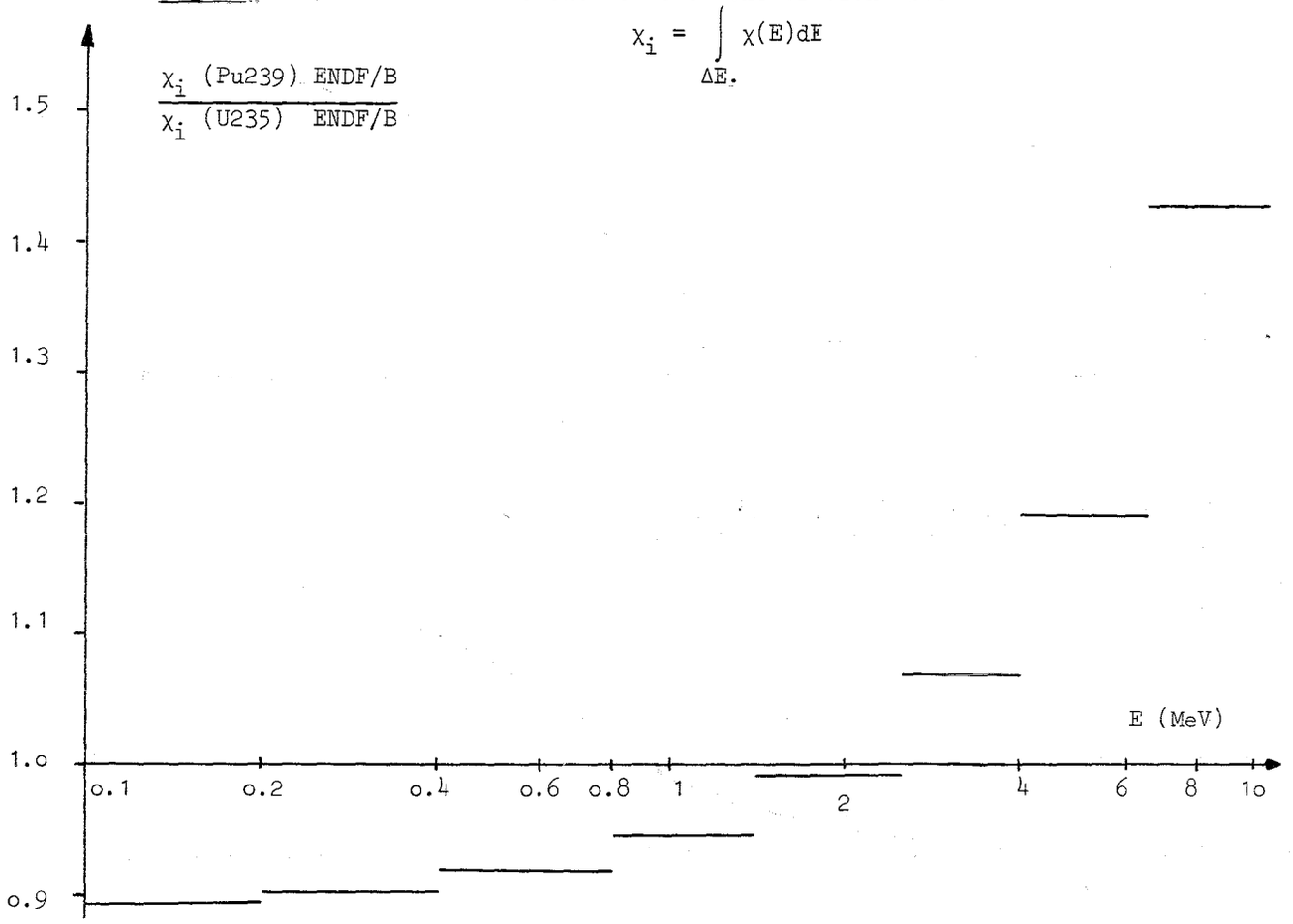
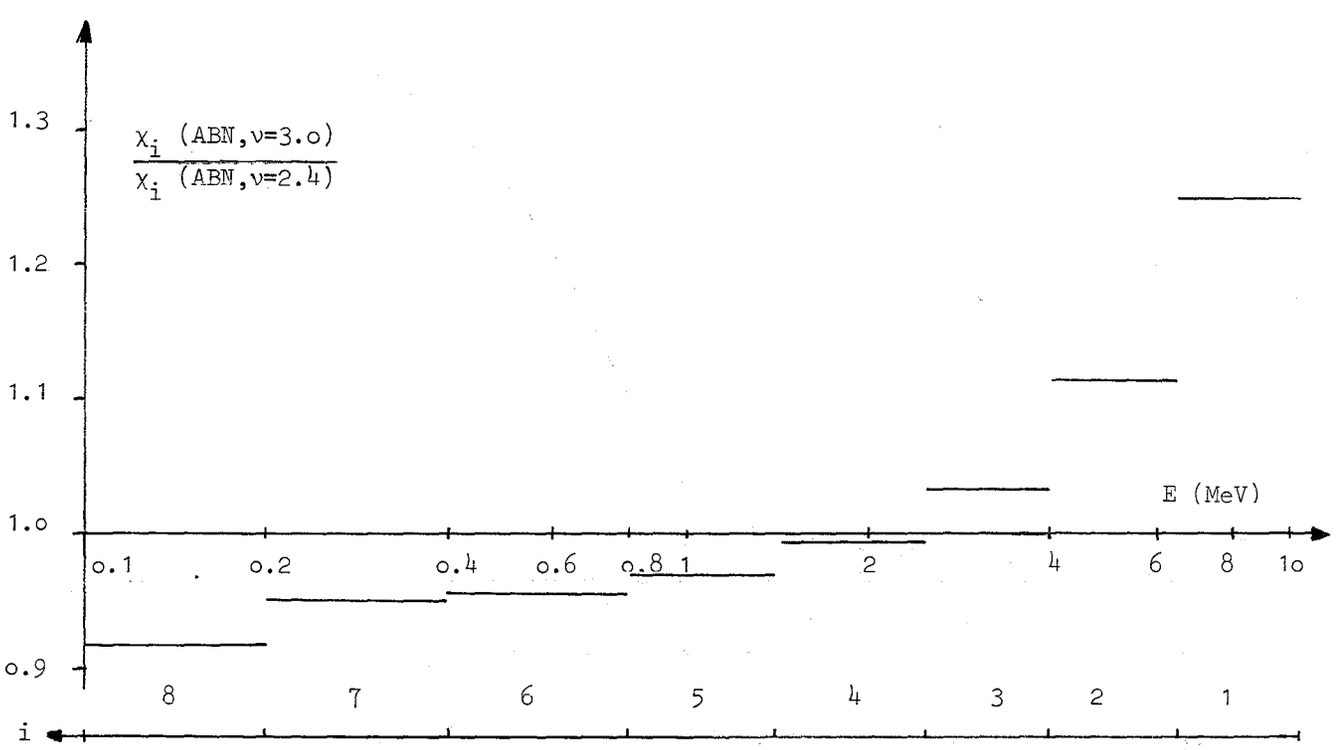


Fig. 3: Comparison of different forms of the fission spectrum

$$\chi_i = \int_{\Delta E_i} \chi(E)dE$$





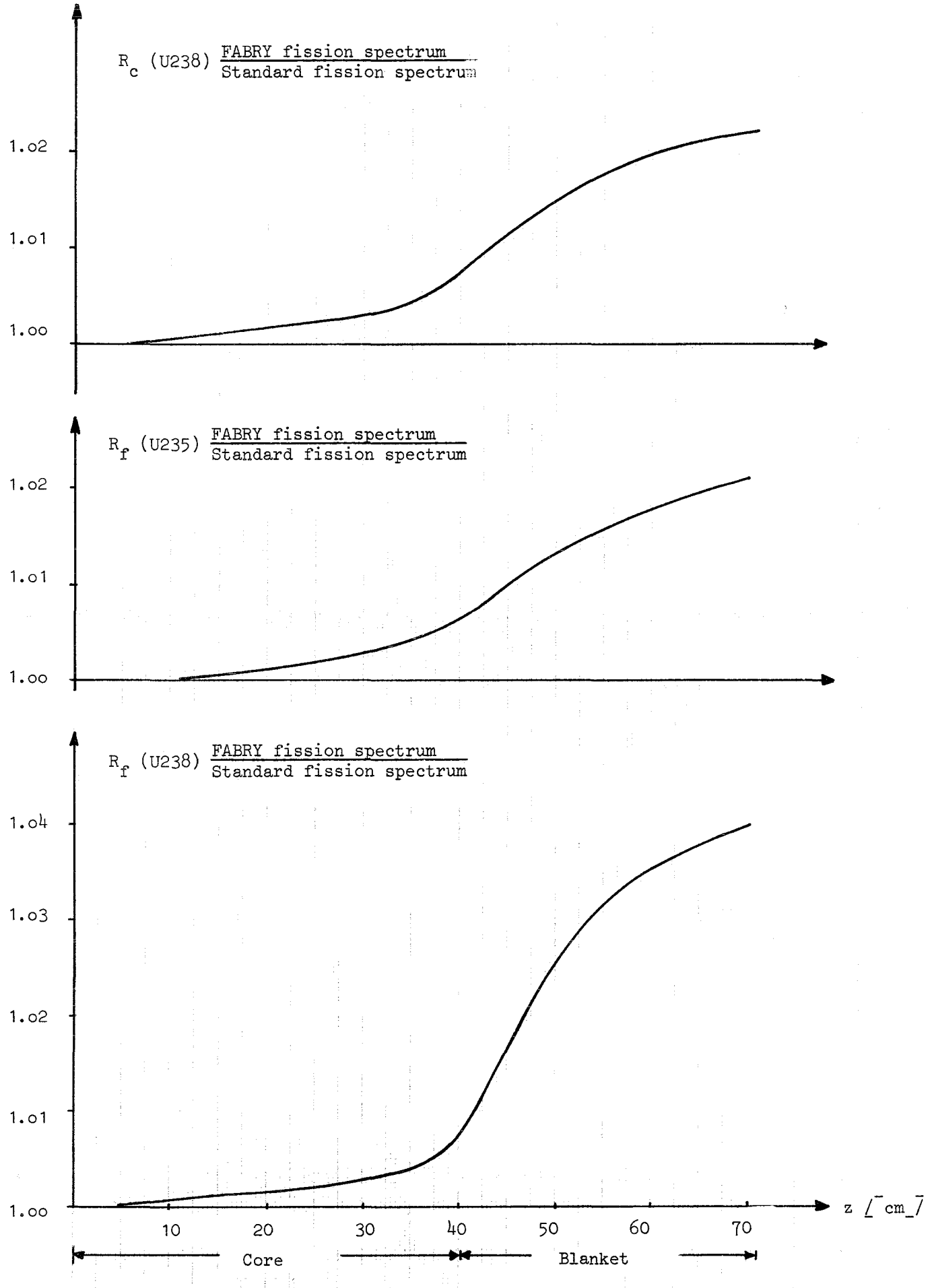


Fig. 4: Influence of FABRY's fission spectrum on the axial reaction rate traverses in SNEAK 3A2

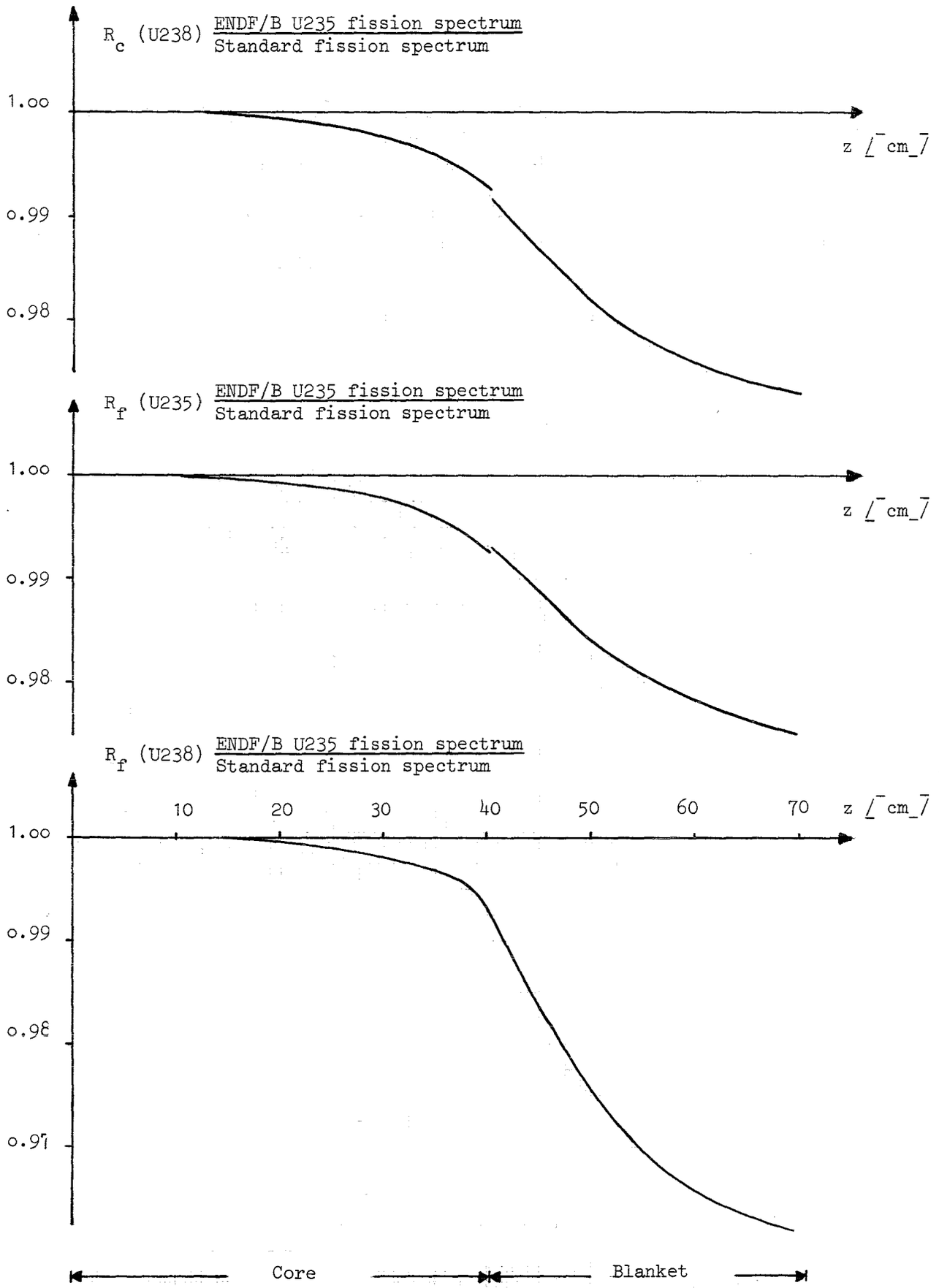


Fig. 5: Influence of the ENDF/B-U235 fission spectrum on the axial reaction rate traverses in SNEAK 3A2