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Institut für Neutronenphysik und Reaktortechnik

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Analysis of Fast Critical Assemblies and Large Fast Power Reactors with Group-Constant Sets Recently Evaluated at Karlsruhe*

by

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**On leave from TH Eindhoven.

Introduction

A satisfactory agreement between calculated and measured results of the most interesting integral quantities for the SNEAK-3A-1 core was reported by Küsters et al [1] and Stegemann et al. [2] at the IAEA Conference on Fast Reactor Physics in Karlsruhe 1967. This improvement was mainly due to the fact that in the new group constant set KFK-SNEAK low fission and capture data of ^{235}U in the range from 1 keV up to 200 keV were included compared to the previously used data in KFK 26-10 [3] and the Russian ABN cross section set [4] . The ^{238}U capture data are higher than both KFK 26-10 and ABN data between 5 keV and 40 keV resulting in a less pronounced effect on k_{eff} than the change in the ^{235}U fission data. The improved description of elastic moderation yielded a better agreement of the theoretical and experimental spectrum. The deviations between theory and experiments can be summarized as follows:

	KFK-SNEAK	KFK 26-10	ABN
Criticality (corrected for heterogeneity and transport effects)	-0.5%	+2%	+2%
Heterogeneity effect (center)			
Bunching (ΔK)	<10%	-	50%
Cell fine structure Rh(n,n')	satisfactory small		unsatisfactory underestimation
Void effect (center)	$\leq$10%	30%	50%
Spectrum (center) 10 keV-10 MeV	$\leq$10%	up to 30%	

The spectral index $\sigma_f(^{238}U)/\sigma_f(^{235}U)$ was underestimated by theory, while the ratio $\sigma_c(^{238}U)/\sigma_f(^{235}U)$ was in excellent agreement with experiment.

On the basis of this satisfactory agreement between theory and experiment for SNEAK-3A-1 one could have concluded that the nuclear data basis of the KFK-SNEAK set for uranium criticals was more or less correct. At the same conference, however, Beckurts discussed the necessity of a further reduction of the ^{238}U capture data above 40 keV due to measurements of Pönitz and Menlove [5]. At that time Beckurts [5a] also indicated the reduction of $\sigma_f(^{235}U)$ and $\sigma_c(^{235}U)$ even below the White data and later on Pönitz [36] measured indeed low $\sigma_f(^{235}U)$ in this range. We included the measured low $\sigma_c(^{238}U)$ and the renormalized lower capture and fission data of ^{235}U in our group sets; they are referred to as PMB data.

For plutonium fueled criticals there was not as good an agreement between theory and experiment as for SNEAK-3A-1. This discrepancy becomes even larger, if one uses in the "b-sets" a lower limit of the high $\alpha(^{239}Pu)$ reported by Schomberg [7] at the Karlsruhe Conference.

Since this conference still more measurements on important nuclear data have been reported which are discrepant to previously accepted values. To mention only the most important among these measurements, at the Second Washington Conference on Neutron Cross Sections and Technology in March 1968 Glass [20] presented final results of the Petrel capture data of ^{238}U below 2 keV, which are lower, on the average by about 10%, than the values included in the SNEAK set.

These new discrepancies in the most important microscopic nuclear data require a theoretical reinvestigation of the integral experiments in fast critical assemblies. Moreover, it can be stated generally that only a systematic study of fast cores with different neutron spectra combined with a thorough comparison and reevaluation of the main microscopic informations can provide more definite conclusions about the reliability of the main nuclear data to be used in a fast reactor calculation.

In this paper we are following this line. In a first chapter the basic data of the heavy isotopes, underlying the group sets mentioned above, are indicated briefly. A detailed discussion of the presently known uncertainties of these data is given in chapter 2. In chapter 4 we present the analysis of a series of critical and subcritical assemblies with the aim to gain more definite information about the quality of our group constant sets, particularly in view of new important microscopic data measurements.

In a last chapter we discuss the influence of the various data sets on the prediction of the neutronic behaviour of large fast power breeders with sodium, steam, and helium as coolants. For a steam-cooled fast reactor some results of the sensitivity of the safety coefficients to data uncertainties are given. Finally, we summarize the conclusions of our present investigations.

1. Microscopic nuclear data basis for the heavy elements in the group cross section sets

An almost complete extensive account for the microscopic cross sections which form the basis of the used group cross section sets is given in references [8] and [9]. In this chapter we give a brief explanation of the sources for the most important data of the heavy fertile and fissile materials. In chapter 2 the uncertainties of these data are discussed in detail.

1.1. KFK-SNEAK(NAP)-sets

1.1.1. ^{235}U

For ^{235}U below 20 keV down to the eV range the σ_f values are based on the very accurate measurements of Michaudon et al. [10]. Between 20 keV and 1 MeV we follow the Aldermaston data of Perkin et al. [11] and White [12]. Between 1 and 3 MeV the chosen σ_f values correspond to an average eye-guide curve through rather scattering data. Between 3 and 10 MeV we relied on Los Alamos fission data [13].

As no direct measurements of σ_c exist, but only of $\alpha = \sigma_c/\sigma_f$, σ_c values were throughout calculated as the product of α and σ_f. Below 10 keV the ^{235}U α values were determined as an arithmetic average of rather conflicting Russian, Harwell, and Oak Ridge data. Between 10 keV and 1 MeV an average curve through the rather well agreeing measurements of Weston et al. [14] and Diven et al. [15] was chosen. Above 1 MeV no experimental data are available: α was smoothly extrapolated to 10 MeV such as to correspond rather closely to a 1/E dependence of σ_c which has been observed for other elements and, which is about expected from statistical theory considerations.

Concerning $\bar{\nu}_{25}$ the thermal value (2.430) was taken over from the careful evaluation of Westcott et al. [16]. For the energy dependence of $\bar{\nu}_{25}$ all available experimental data prior to 1966 were considered and renormalized to common standards. In the particularly important range between thermal and 2.5 MeV least squares weighted averaging of the many experimental data yielded the following energy dependence (E in MeV)

$$\bar{\nu}_{25}(E) = 2.430+0.106\ E$$

The experimental information on inelastic scattering on ^{235}U being scarce and unreliable we chose Hauser-Feshbach calculations of Moldauer [17] and similar evaluations of Joanou and Drake [18] for getting $\sigma_{n'}$ between threshold and 2.3 MeV. Above 2.3 MeV up to 10 MeV $\sigma_{n'}$ was obtained by subtracting the reaction cross sections σ_f, σ_γ, and σ_{2n} from measured σ_X values. The inelastic scattering matrix was still entirely taken from the ABN group cross section set [4], but renormalized to our $\sigma_{n'}$ values.

1.1.2. ^{238}U

For ^{238}U group constants and shielding factors below a few keV are calculated from resolved resonance parameters. These were obtained by weighted least squares averaging of the available experimental data prior to 1966 with the largest weight attributed to the particularly accurate Columbia experiments [19]. As average capture width a value of 24.8±5.6 (meV) was obtained.

In the keV range below 50 keV two discrepant measurement series for σ_c^{28} were available due to Moxon and Rae [21] and to Macklin et al. [22]. A statistical theory estimate using more reliable s and p wave statistical resonance data drawn from resonance experiments and from fits to average total cross sections in the keV range was preferred to an unjustified averaging of the conflicting experimental data; it incidentally yielded some sort of an average curve through these data. Between 130 keV and 10 MeV we relied, among the various available measurements, on the σ_c^{28} data of Barry et al. [23], because these and only these were based on the best known standard, i.e. the hydrogen elastic scattering cross section. Between 50 and 130 keV a smooth interpolation was chosen.

$\sigma_f(E)$ for ^{238}U appears to be rather well established below 3 MeV by the old measurements of Lamphere [24] and above 3 MeV by the Los Alamos measurements [13] already mentioned for ^{235}U.

Concerning $\bar{\nu}_{28}(E)$ a weighted least squares fit to the available appropriately renormalized data yielded the following result valid between threshold and 15 MeV [8]

$$\bar{\nu}_{28}(E) = 2.3576+0.1557\ E$$

Concerning the inelastic scattering of ^{238}U a careful comparison and evaluation of all available information was made ([8], section VI 2) with the particular well founded result that in the range between 1.2 and 2 MeV our $\sigma_{n'}$ values are up to 20% higher than previous evaluations. As for ^{235}U the inelastic scattering matrix was still entirely taken from the ABN-set [4], but renormalized to our $\sigma_{n'}$ data.

1.1.3. ^{239}Pu

For ^{239}Pu the σ_f data below 10 keV were based on the Argonne measurements of Bollinger et al. [26]. Between 10 keV and 1 MeV the σ_f data recommended in reference [8] were lowered to the data of White [12].

Between 1 and 3 MeV we relied on two rather dense and compatible Russian measurement series [27,28]. Between 3 and 10 MeV the Los Alamos data of Smith et al. [13] already mentioned for ^{235}U and ^{238}U were used.

As for ^{235}U σ_c has to be calculated from σ_f and α data. Below 10 keV the α data of ^{239}Pu were based on the old KAPL average spectrum irradiation results [29]. Between 10 keV and 1 MeV the liquid scintillator measurements of Diven and Hopkins [30] were used. Above 1 MeV, as for ^{235}U, no experimental data were available, and again a rough 1/E decrease was chosen.

Concerning $\bar{\nu}_{49}$ the thermal value, 2.892, was calculated as weighted least squares average of all available experimental data prior to 1966 after suitable renormalization. The energy dependence of $\bar{\nu}_{49}$ was obtained to (E in MeV)

$$\bar{\nu}_{49}(E) = 2.89200+0.12791\ E + 0.00189\ E^2 - 0.00010\ E^3$$

by weighted least squares averaging of still rather scattering data in the keV and MeV ranges.

For $\sigma_{n'}^{49}$ below 2 MeV we used Hauser-Feshbach statistical theory estimates of Moldauer [17] and above 2 MeV values based on optical model systematics. Again the inelastic scattering matrix was taken from the ABN-set [4].

1.2. H2ØPMB(NAPPMB) sets

The microscopic nuclear data basis for these sets is the same as for the KFK-SNEAK(NAP)-sets; only σ_c of ^{238}U and σ_f and σ_c of ^{235}U (α is kept constant) are changed in certain energy ranges. Between 25 keV and 500 keV the σ_c data of ^{238}U were replaced by the results of Pönitz et al. [5], which above 100 keV are up to 12% lower than the data in the KFK-SNEAK-sets and the underlying Harwell data [23] . Pönitz's σ_γ(Au) data were used by Beckurts [5a] in order to renormalize those σ_f^{25} data measured relative to σ_c(Au) in the range 25 to 500 keV. The resulting σ_f^{25} values are still up to 15% lower than the already low White data [12].

1.3. H2ØPMB+α(NAPPMB+α)

These group cross section sets are the same as the H2ØPMB(NAPPMB) sets except that in the range 465 eV to 21.5 keV the old KAPL α data for ^{239}Pu are replaced by lower limits to the recent results of Schomberg et al. [7]. In particular the following values were incorporated

Groups (keV)	0.465-1.0	1.0-2.15	2.15-4.65	4.65-10.0	10.0-21.5
$\bar{\alpha}$	0.95	0.99	0.98	0.88	0.64

and used to change σ_c, but not σ_f.

2. Uncertainty limits of the most important microscopic nuclear data

In this chapter we discuss uncertainties of the microscopic nuclear data used particularly in the light of more recent experimental information. Discrepancies between different measurements are clearly stated, possible directions of changes and lower and upper uncertainty limits of our presently used data are derived in order to establish the actual confidence level of our data sets and to fix important points which need clarification by further experimental and evaluation work. As in chapter 1 we restrict ourselves to ^{235}U, ^{238}U, and ^{239}Pu, and to fission, capture, and inelastic scattering properties of these materials. It is emphasized, that in general only large inaccuracies and discrepancies at more important energies are discussed and not smaller deviations between experiments with rather small uncertainty limits.

2.1. ^{235}U

2.1.1. Fission

Concerning σ_f of ^{235}U for energies below 10 keV extensive comparisons of all measurements prior to 1966 to be found in KFK-120/part I, sections IV 1b and VI 1 [8], led to the recommendation of the measurements of Michaudon et al. [10]. This recommendation has to be assessed in the light of three more recent important σ_f measurements due to de Saussure et al. [31] with the RPI linear accelerator in the range 0.4 eV to 20 keV, to Cao et al. [32] with the Geel linear accelerator between 6 eV and 3 keV and to Brown et al. [33] from LA with neutrons from the Petrel underground nuclear explosion between 20 eV and 2 MeV. From intervalwise comparisons of fission cross section integrals and consideration of the statistical and systematic errors and deviations involved in the above measurements we conclude that the Michaudon data are generally confident to ±5 to 10%. One discrepancy, however, serves particular mentioning. Between 1 and 10 keV there is very good agreement to better than 2% between ORNL/RPI, Geel and Michaudon; the LA results agree with Michaudon to better than 1% between 300 eV and 3 keV, but are systematically by about 12% below Michaudon and ORNL/RPI between 3 and 10 keV. This discrepancy is still not understood and needs further study.

In the range 10 keV to 1 MeV the recommended Aldermaston data [11,12] are claimed to be accurate to ±2.5 to 3%. They are measured relative to the scattering cross section of hydrogen. The greater carefulness in the determination of the neutron flux gives these measurements a particularly strong weight over the most accurate older LA [34] (±3-6%) and Harwell [35] measurements (±1.3-3%) which are also measured relative to the scattering cross section of hydrogen, but are systematically higher than those of Aldermaston by about 7%. Recently Pönitz/ANL made σ_f shape measurements in the energy range 30 keV to 1.5 MeV with the grey detector method, normalized to the former absolute measurement of σ_f^{25} by Knoll and Pönitz [37] at 30 keV (2.19±0.06 b). Preliminary results were reported at the Second Neutron Cross Section and Technology Conference at Washington in March this year [36]. The normalization point agrees very well with the Aldermaston results. Between 30 and 300 keV Pönitz's data are systematically lower than and diverge more and more from the Aldermaston data, the measurements being still compatible within the experimental accuracy of Pönitz's data. Between 300 keV and 1.5 MeV Pönitz reaches a nearly constant σ_f value of 1.05 b which is about 15% below the Aldermaston data outside experimental error. This discrepancy is still not solved. If there are errors in Pönitz's data, they could lie in his fission measurements; so far the assumed energy dependence of the detector calibration is only based on theoretical calculations and is not yet checked by measurements; this check is underway.

The rather old LA σ_f data [13] between 2 and 10 MeV have meanwhile been corrected for errors in the efficiency of the long counter used for the neutron flux measurements; this leads to reductions in σ_f of the order of 10% [25]. These corrections could not be taken into account anymore. We note that these corrections lead to much better agreement with the low 5.4 MeV σ_f value of White [12].

2.1.2. Capture

Since the establishment of the group cross section sets used here, in addition to the $\sigma_f(E)$ measurements mentioned in 2.1.1., the final results of the $\sigma_c(E)$ measurements of de Saussure et al. [31] in the energy range 0.4 eV to 3 keV have been published. The epicadmium $\langle\alpha\rangle$ value calculated from 1/E integrals of these data above 0.5 eV is 0.50±0.02 in excellent agreement with the old integral KAPL measurements [38] and with recent direct measurements also with 0.5 eV low energy cutoff by Conway and Gunst [39] ($\langle\alpha\rangle_{epi-Cd}$ = 0.499±0.016) and by Redman and Bretscher [40] ($\langle\alpha\rangle_{epi-Cd}$ = 0.519±0.023). In addition a good agreement of the 1/E integral of de Saussure's capture cross section data [31] with direct measurements of the infinite dilute capture resonance integral (RI_c^{∞}) by Durham et al. [41] and by Conway and Gunst [39] and with the careful measurement and evaluation of this quantity by Feiner and Esh [42] can be noted from the figures below (the low-energy cutoff is always 0.5 eV):

de Saussure et al. [31]:	137±5 (b)
Durham et al. [41]:	143±7 (b)
Conway, Gunst [39]:	136±8 (b)
Feiner, Esh [42]:	140±8 (b)

The good agreement in $\langle\alpha\rangle$ and RI_c^{∞} means a good agreement in the infinite dilute fission resonance integral (RI_f^{∞}) of these authors:

de Saussure et al. [31]:	276.5±4 (b)
Conway, Gunst [39]:	275 ±16(b)
Feiner, Esh [42]:	280 ±10(b)

The corresponding numbers calculated from KEDAK cross sections underlying our group cross section sets are:

$$RI_c^{\infty} = 167.9 \text{ b}$$

$$RI_f^{\infty} = 267.5 \text{ b}$$

$$\alpha_{epi-Cd} = 0.63$$

giving about 20% higher RI_c^∞ and α_{epi-Cd} values. An intervalwise comparison between de Saussure's and KEDAK α values explains these high values and shows that below 300 eV de Saussure's α data are much lower than ours and also much lower than previous energy dependent measurements and estimates [43-46] discussed extensively in KFK-120/part I, section IV 2b [8]. One probable reason for our high capture data is that the fission widths used in their calculation are too small. A more thorough evaluation has still to be done.

Between 100 eV and 10 keV the available total capture integrals of de Saussure et al. [31], Wang-Shi-di et al. [45] and Uttley [46] agree to several %, whereas large discrepancies with alternating sign up to 50% and more are seen in subintervals of this range. Our recommended α values follow an average curve through these conflicting data and, because of the discrepancies mentioned, can be claimed to be accurate at best to ±20%. Between 10 and 200 keV our α values should be reliable to about ±10%, between 200 keV and 1 MeV to about ±20%; in this latter range Weston's data [14] are systematically somewhat lower than those of Diven et al. [15]. Because of the lack of experimental data no reliability estimate for α and consequently σ_c is possible above 1 MeV.

The reliability of our σ_c data is established by that of the product of α and σ_f. Below 300 eV σ_c has very probably to be lowered by up to 20%. At higher energies the reliability figures are: at best ±20% between 300 eV and 10 keV, ±10 to 20% between 10 and 200 keV and about ±20% between 200 keV and 1 MeV. However, when Pönitz's new low σ_f data prove to be correct, also σ_c definitely would have to be reduced.

2.1.3. $\bar{\nu}$

Most modern $\bar{\nu}$ measurements are made relative to $\bar{\nu}$ for spontaneous fission of ^{252}Cf. The recently measured ratios for thermal neutron fission of ^{235}U agree to better than 1% [47]; the accuracies of the individual ratio measurements are mostly between ±0.5 and 1%. Recent evaluations of best values for $\bar{\nu}_{spont.}(^{252}Cf)$ and $\bar{\nu}_{thermal}(^{235}U)$ [47-50] lead to $\bar{\nu}_{thermal}(^{235}U)$ values, delayed neutrons included, ranging from 2.422±0.005 [47] to 2.437±0.006 [49] which have to be compared with our accepted value 2.43 taken from reference [48]. However, the available individual $\bar{\nu}$ measurements on ^{252}Cf show still a spread of about ±1% due to still unresolved inconsistencies between the (higher) liquid scintillator and the (lower) boron pile and $MnSO_4$ bath measurements. According to de Volpi [51] there might be a systematic underestimate of the ^{252}Cf neutron emission rate and thus of $\bar{\nu}$ (^{252}Cf) in the $MnSO_4$ measurements. A correction of this underestimate would bring the $MnSO_4$ bath measurements in closer agreement with the liquid scintillator measurements and thus still strengthen the expectation that the boron pile measurements underestimate $\bar{\nu}$ by still undetected systematic effects. For the moment we therefore conclude that the unreliability of our thermal $\bar{\nu}(^{235}U)$ value is at worst ±1%. At higher energies the individual modern measurements are mostly accurate to better than ±1%. The spread of these measurements, however, around our average curve reaches peak deviations of ±2%.

2.1.4. Inelastic scattering

Concerning inelastic scattering on ^{235}U only the experimental data of Armitage et al [52] could not be taken into account anymore. These authors measured inelastic scattering spectra of ^{235}U by the time-of-flight method in the Harwell 3 MeV pulsed Van de Graaff at an observation angle of 90° at six energies between 130 keV and 1.5 MeV and deduced preliminary results for excitation cross sections for groups of levels by assuming isotropy of the angular distribution of the inelastically scattered neutrons. Below 1 MeV total and partial inelastic cross sections are mostly well above our data, whereas above 1 MeV the total inelastic cross sections are compatible, but the inelastic spectra harder than ours. The Harwell $\sigma_{n'}$ data are also well above the values of $\sigma_{n'}$ estimated from σ_n values free from inelastic scattering contributions measured at Argonne [53] and our recommended σ_T, σ_γ and σ_f values (see discussion in [8], section VI 1). With the only available other experimental data taken with the same method under the same observation angle due to

Cranberg [54] the Harwell data agree well for the high energy losses, but are much higher for the low energy losses. These discrepancies have still to be solved; in particular the validity of the assumption of the isotropy of the angular distribution has to be checked. In the MeV range the inelastic scattering total cross sections and matrix elements should be accurate to about ±20%.

2.2. ^{238}U

2.2.1. Capture

For ^{238}U in the resonance range our capture cross sections have to be assessed in the light of two more recent resonance measurements due to Asghar et al. [55] for capture and elastic scattering with the Harwell linear accelerator between 5 and 1000 eV and due to Glass et al. [20] for capture with the Petrel nuclear explosion between 30 and 2050 eV. Both experiments aimed particularly at gaining a more reliable knowledge of the ^{238}U individual and average capture widths. In addition low background, good resolution, and lack of potential scattering background in the bomb measurements allowed the detection and analysis of many small possible p-wave resonances and a derivation of the p-wave strength function. Whereas Asghar et al. obtain an average capture width of 23.74±1.09 (meV) in agreement within error limits with our value, the Petrel result 19.1±2.0 (meV) is more than 20% lower than ours outside experimental error. The average p-wave level spacing obtained in the Petrel experiment is 7.0±0.5 (eV) in good agreement with a value of 7.4 eV (see [8], section IV 2b) deduced from the known average s-wave level spacing under the assumptions of the validity of the Fermi gas nuclear model and the parity independence of $\bar{D}$. The value obtained for the p-wave strength function $S_1=(\bar{\Gamma}_{n,red.}/\bar{D})_{\ell=1}$, however, is much smaller than the values derived from fits to measured $\langle\sigma_T\rangle$ values in the keV range [56,57]. Here one has to take into account that S_1 is proportional to R^{-2} where R is the nuclear radius. The published Petrel S_1 value, $1.8\pm0.3(10^{-4})$, is valid for an assumed nuclear radius of $8.4\cdot10^{-13}$ cm. When this R value is corrected to $9.18\cdot10^{-13}$ cm, a value which follows from the very accurately known potential scattering cross section of ^{238}U, S_1 drops to $1.5\cdot10^{-4}$. This is 60% lower than the value $2.5 \cdot 10^{-4}$ derived from $<\sigma_T>$ fits. Because of the agreement in $\bar{D}$ this means that the average neutron widths deduced in the Petrel experiment are 60% lower than those following from $<\sigma_T>$ fits.

For the discrepancies in the average capture widths so far no explanation could be found. The only rather weak indication, that the Petrel capture widths might be too small, comes from the infinite dilute capture resonance integral (RI_c^∞). RI_c^∞ as calculated from KEDAK resonance parameters [8] is below the experimental best value, but only by a few barn. The lower Petrel capture widths would lead to a further reduction of the order of 10 barn.

The question which of the above mentioned S_1 values is more reliable is difficult to decide. The good agreement in $\bar{D}$ with the expectations from the well known s-wave level spacings seems to indicate that no p-wave levels were missed in the Petrel measurements and favours the low Petrel S_1 value. One has, however, to remind that only indirect arguments, namely the particular smallness of an observed cross section peak or deviations from the Porter-Thomas distribution of the s-wave neutron widths, were used to assign $\ell=1$ to a resonance. It is for example easy to show that the inclusion of only a few larger, but still small resonances, which were counted as s-wave, in the p-wave levels suffices to lead to an only slight reduction in $\bar{D}$, but to a large increase in $\bar{\Gamma}_{n,red.}$ thus giving a large increase in S_1. The missing of some p-wave levels on the low neutron width side in the experiment would also result in a too low S_1 value; however, the resulting changes in $\bar{\Gamma}_{n,red.}$ and $\bar{D}$ would be not very different and hence the change in S_1 be only small. On the other side the uncertainties in the determination of S_1 from fits to $<\sigma_T>$ are rather large. S_1 is determined from the p-wave contribution to the compound formation cross section, $\sigma_{CN}^{\ell=1}$. As this is the difference of two not too different large numbers, i.e. $<\sigma_T>_{exp.}-(\sigma_{CN}^{\ell=o}+\sigma_{pot})$, the rather small uncertainties in $<\sigma_T>_{exp.}$ (±5%), $\sigma_{CN}^{\ell=o}$ (±10%) and σ_{pot} (a few %) have a rather large effect on $\sigma_{CN}^{\ell=1}$ and thus S_1. The Petrel data would reduce our capture cross sections below a few keV, where s-wave capture is predominant, by about 10%. If one uses the Petrel S_1 and $\bar{\Gamma}_\gamma$ values and our recommended S_o value ($0.9 \cdot 10^{-4}$) [8] in order to extrapolate the Petrel data to higher energies, one would get reductions of the order of 20 to 30% for energies between a few keV and, say, 30 keV, where p-wave capture is predominant, particularly through the reduction of S_1. Finally, we note that these extrapolated σ_c values are below all other σ_c measurements, particularly still below the measurements of Moxon, Rae [21] and of Pönitz [5]. The discussion makes obvious that, in order to better understand and solve the discrepancies in $\bar{\Gamma}_\gamma$ and S_1, a thorough reevaluation of the available resonance data on ^{238}U particularly for capture is needed.

In the range 30 to 500 keV we have in particular to consider the measurements of Pönitz et al. [5] in addition to the previous data discussed in [8] and the extrapolation of the Petrel data to higher energies. The measurements of Pönitz are shape measurements with the grey detector relative to $\sigma_c(E)$ of Au and were normalized to an absolute measurement of σ_c^{28} at 30 keV (0.479 ± 0.014 b). The good agreement of their Au measurements with results of other authors obtained by independent methods, e.g. the associated activity method [6], gave these authors considerable confidence in their σ_c^{28} results and led to the incorporation of these data into the KFK-SNEAK sets in order to study the effects of this change on the prediction of reactor physics integral data. The data of Moxon and Rae [21] are still somewhat lower than Pönitz's measurements and fix the lower confidence level at about -20%. The measurements above our recommended curve, in particular those of Macklin et al. [22], yield an upper confidence level of about +20%. The systematic discrepancies between the various measurement series might in part be due to errors in normalization and have to be investigated further. Above 500 keV our capture cross section data should be accurate to about ±10%.

2.2.2. Fission

The LA σ_f data [13] used above 3 MeV have also recently been downgraded by several, but less % than σ_f of ^{235}U [25]; this change could still not be taken into account.

2.2.3. $\bar{\nu}$

Our recommended $\bar{\nu}$ curve for ^{238}U (/‾8_7, section VI 2) agrees to within 0.5% with the more recent evaluation of Fillmore /‾47_7. In both evaluations the more recent measurements due to Fréhaut et al. /‾60_7 are still not considered. These cover 27 energy points between 1.4 and 14.8 MeV in mostly 1/2 MeV energy steps. The preliminary results so far available for which an accuracy of better than 1% is claimed, agree to much better than 1% with our data above 5 MeV; below 5 MeV they are so far systematically lower, on the average by about 2%, than our data and the underlying former experiments. Before further conclusions can be drawn, the issue of the final results of the French measurements has still to be awaited.

2.2.4. Inelastic scattering

The total inelastic scattering cross sections of ^{238}U in the energy range of resolved levels are only reliable to about ±10 to 20%. This still rather high inaccuracy reflects the inaccuracies of the individual measurements as well as the spread between different measurements. Furthermore, part of the inelastic excitation cross section measurements were only performed at an observation angle of 90° and were converted to cross sections over the full range of scattering angles by assuming an isotropic distribution. This is particularly true of the most extensive $\sigma_{n'}^{E_j}$ measurements of Barnard et al. /‾58_7 which lead to our recommended high $\sigma_{n'}$ values between 1 and 2 MeV /‾8_7. This isotropy assumption should be checked by theory and/or experiment in order to get more confidence in our inelastic scattering cross sections. In favour of the isotropy assumption is the fact, that available experimental $\sigma_{n'}^{E_j}$ and $4\pi \cdot \sigma_{n'}^{E_j}(90^\circ)$ data agree within experimental accuracy showing differences of alternating sign, but not systematic differences. Our high inelastic scattering cross sections between 1 and 2 MeV are furthermore supported by the following two facts (/‾8_7, section VI 2):

(1) With the exception of the very old (1945!) σ_X value of Olum /‾59_7 at 1.5 MeV all other $\sigma_{n'}$ values obtained from experimental σ_X results with due correction for inelastic scattering to the low lying levels are in close agreement with the presently recommended values.

(2) Available optical model predictions of $\sigma_{n'}$ (=σ (compound formation)-σ(compound elastic)-σ_f-σ_γ) do better agree with the present higher than with the previous lower $\sigma_{n'}$ values.

Compared to the renormalized ABN-matrix used in our present calculations the inelastic scattering distributions based on present KEDAK inelastic excitation cross sections [9] which will be used in future calculations will be slightly weaker.

In the range of unresolved rest nucleus levels above about 2 MeV $\sigma_{n'}$ should be accurate to about ±15%. In this range $\sigma_{n'}$ is not directly measured but deduced from σ_X measurements by subtracting our recommended σ_f, σ_γ and σ_{2n} values. Thus, the accuracy of $\sigma_{n'}$ quoted above is determined by the accuracies of σ_X, σ_f, σ_γ and σ_{2n}. As far as the simple Weißkopf evaporation model is valid for the interpretation of measured inelastic scattering energy distributions, the inelastic scattering matrices in the ABN set correspond to experimental nuclear temperatures within experimental error (±10 to 20%). The validity of the Weißkopf model will be further investigated particularly in the light of recent improved work on nuclear level density.

2.3. ^{239}Pu

2.3.1. Fission

We consider first the energy range between 1 and 20 keV. In reference [8] we discussed the unsystematic discrepancies which varied between + and - 20% in the σ_f measurements available prior to 1966. Recently data from several more measurements became available which seem to improve the reliability of the σ_f data in this range and to give preliminary indications in which direction our previously accepted values could be changed. We refer to the measurements listed in the following table.

Reference	Apparatus and method	Energy range
de Saussure et al. [61]	Saclay linear accelerator, Xe gas scintillator, detection of fission fragments	0.16 eV - 7 keV
James [62]	Harwell linear accelerator, gas scintillator, detection of fission fragments	1 eV - 25 keV (results only given for 1 - 25 keV)
Shunk et al. [63,64]	Nuclear underground explosion (Petrel), solid state detector, detection of fission fragments	20 eV - 5 MeV (data above 10 keV preliminary)
Ryabov et al. [65]	Fast pulsed IBR reactor at Dubna, liquid scintillation counter, detection of fission neutrons	5 eV - 23 keV
Patrick et al. [66]	Harwell linear accelerator, liquid scintillation counter, detection of fission neutrons	10 eV - 30 keV
Blons et al. [67,68]	Saclay linear accelerator, improved fission fragment detector	eV - keV
Gwin et al. [69]	RPI linear accelerator, liquid scintillation counter, detection of fission neutrons	thermal - 30 keV

In the next table we quote results (linear averages) of these new measurements for comparison purposes. We include in this table also earlier results of Dubrovina and Shigin [70]. Also averages of KEDAK data underlying our group sets are listed. Unfortunately, from the measurements of Blons et al. [67] we have only selected values available [68], from those of Gwin et al. [69] so far no results. The $^{239}Pu/^{235}U$ σ_f ratio measurements of Gilboy and Knoll [71] will be considered further below.

E(keV)	σ_f (b)							
	James /62/	Shunk /63,64/	Patrick /66/	Blons /67,68/	Dubrovina /70/	de Saussure /61/	Ryabov /65/	KEDAK /8,9/
1-2	-	-	3.71	-	-	5.43	6.36	4.01
2-3	-	2.63	2.89	-	-	3.88	3.85	3.35
3-4	2.81	2.75	2.78	~2.9	-	3.40	3.91	3.51
4-5	2.48	2.32	2.34	-	-	2.91	3.15	2.66
5-6	2.37	2.71	2.17	-	-	3.21	2.50	2.84
6-7	2.09	2.21	1.99	-	2.70	2.70	2.45	2.62
7-8	2.21	2.23	2.21	-	-	-	2.45	1.97
8-9	2.32	2.46	2.35	-	-	-	2.50	2.06
9-10	2.00	2.12	2.01	-	-	-	2.37	2.28
10-20	1.90	-	1.69	~1.8	1.88	-	2.01	1.91

First we note the good agreement to mostly within several % between the results of James /62/, Shunk et al. /63,64/, Patrick et al. /66/ and Blons et al. /67,68/ in spite of the quite different methods used. Between 1 and 7 keV these data are consistently lower than ours by 10 to 20%, between 7 and 9 keV about 15% higher, between 9 and 10 keV 10% lower and in good agreement with our value (with the exception of the low Patrick value) between 10 and 20 keV. There is a striking difference between these measurements and the results of de Saussure et al. /61/ and Ryabov et al. /65/. These in turn agree not too badly with each other and are, with only few exceptions, consistently higher than our data. The following reasons favour the results of the first mentioned group of authors: The measurements of Blons et al. /67,68/ were performed in order to improve the former Saclay results of de Saussure et al. /61/ . These suffered from difficulties due to resonance reactions in the Xe used as scintillation detector. The reliability of the measurements of Ryabov et al. /65/ is rather weak due to the large background of 50-70%; new measurements are underway in order to improve the results. Thus we conclude preliminarily that our σ_f^{49} data are correct to about 5% in the range 10 to 20 keV, but that they are probably too high by between 10 and 20% in most of the range between 1 and 10 keV.

Between 20 keV and 1 MeV we recommended in /‾8_7 still an average curve through the data of Dubrovina and Shigin /‾70_7. In reference /‾9_7 this curve is lowered to values going exactly through the data of Perkin et al. /‾11_7 and White /‾12_7. The reasons for this change were mainly to get consistency with the ^{235}U σ_f data also taken from White and in particular that since the publication of KFK 120/part I the low White/Perkin data were rather well confirmed by three independent more recent measurements due to James /‾62a7, Shunk et al. /‾63,64_7 and Gilboy and Knoll /‾71_7. Preliminary results of very careful new $^{239}Pu/^{235}U$ σ_f ratio measurements of Pfletschinger and Käppeler /72/, when normalized to our σ_f^{25} data based on White seem to confirm our σ_f^{49} data between 10 and 25 keV and above about 100 keV, but to give higher values between 25 and 100 keV. These measurements are performed in order to reduce the uncertainties and to resolve the discrepancies in the existing measurements. We note that a normalization of Pfletschinger's data to Pönitz's σ_f^{25} values would lead to up to 15% lower σ_f^{49} values above 100 keV and would thus still decrease the already too low k_{eff} values for ^{239}Pu fueled critical assemblies. This might be an indication that Pönitz's σ_f^{25} data in this range are too low.

Above 500 keV we extrapolated smoothly the White data below 500 keV to our recommended data above 1 MeV /‾9_7. Recently, White and Warner /‾73_7 measured $^{239}Pu/^{235}U$ σ_f ratios at 1.0, 2.25, 5.4, and 14.1 MeV. These ratios agree to better than 2% with KEDAK ratios as can be seen from the figures below.

E (MeV)	White, Warner /‾73_7	KEDAK /‾8,97
1.0	1.43	1.41
2.25	1.52	1.50
5.4	1.57	1.59

Transforming White and Warner's ratios to σ_f^{49} values by taking White's σ_f^{25} measurements /‾12_7 at the same energy points we obtain the following picture:

E (MeV)	White [12,73]		KEDAK [8,9]	
	σ_f^{25} (b)	σ_f^{49} (b)	σ_f^{25} (b)	σ_f^{49} (b)
1.0	1.22±0.03	1.74±0.06	1.22	1.72
2.25	1.30±0.04	1.98±0.07	1.32	1.98
5.4	1.00±0.05	1.57±0.06	1.14	1.82

Good agreement between White and KEDAK is seen at 1.0 and 2.25 MeV; the 14% lower White σ_f^{25} value at 5.4 MeV entails a corresponding lower σ_f^{49} value at that energy compared to KEDAK. Considering that the LA σ_f^{49} data, [13] accepted by us above 2.5 MeV, were made relative to the also accepted LA σ_f^{28} data [13] and, that these latter were downgraded as was discussed in sections 2.1.1. and 2.2.2. [25], also our σ_f^{49} data have to be reduced above 2.5 MeV. We conclude that, taking experimental errors and the scattering in the experimental results into account, our σ_f^{49} data between 500 keV and 2.5 MeV are confident to about ±5% and, that above 2.5 MeV our σ_f^{49} data have to be lowered by 5 to 10%. The latter consequence has also been drawn by Davey in his recent fission cross section evaluations [74].

2.3.2. Capture

The large discrepancies in the various α measurements in the range between a few 100 eV and 30 keV are so well known that a brief discussion of the present status suffices. The present knowledge of $\alpha(^{239}Pu)$ can be summarized as follows:

(1) In the energy range between a few 100 eV and 10 keV α is definitely higher than the previously accepted data based on the old KAPL integral measurements [75].

(2) The results of a few integral experiments [76,77] support the assumption of higher α values.

(3) In the prediction of the higher α values still descrepancies remain being due to different methods and, to a weaker extent, to different fission cross sections used in the derivation.

Below about 2 keV there is a very rough compatibility between the various experimental and evaluated data within very large experimental error limits with differences up to a factor of two. Above 2 keV one can roughly discern three discrepant groups of measurements and evaluations. The Harwell measurements due to Schomberg et al. [7] and Patrick et al. [79] are systematically much higher than the two other groups up to about 30 keV. The second group consists of the measurements of Gwin et al. [69] below 20 keV, which are in fair agreement with the evaluations of "best" $\langle\alpha\rangle$ values from evaluated experimental $\langle\sigma_T\rangle$ and $\langle\sigma_f\rangle$ data and theoretically estimated $\langle\sigma_n\rangle$ values due to Barre et al. [68] and Pitterle et al. [79]. The third and lowest lying group consists of the old KAPL data [75] and the recent measurements of Ryabov et al. [65]; these latter data above 2 keV are on the average even slightly lower than KAPL fluctuating around an average value of about 0.4.

We noted already that Ryabov's σ_f data [65] in the range 1 to 20 keV are systematically higher than the recent compatible Harwell [62,66], LA [63,64] and Saclay measurements [67,68], the differences amounting to 10-20%. The high background in Ryabov's measurements might be responsible for this discrepancy and result in a reduction of σ_f and consequently an increase in α. However, it is easily seen that differences in σ_f are by far not large enough in order to explain the large discrepancies in α. In the range 10 to 20 keV for example Patrick's and Ryabov's α values differ by a factor two, the σ_f values only by 20%. Thus, at best we can say that, as far as σ_f is concerned, above 2 keV Ryabov's α values are probably between 10 and 20% too low. Considering the Schomberg data as the opposite extreme there is still some question about the high value of the ratio of the detection efficiencies for γ-radiation released by fission and by capture [68] and about the single level parameter detector calibration [68,80] which could lead to a considerable reduction of Schomberg's α values. Obviously, more thorough assessments and comparisons of the available data are urgently needed. Without anticipating the results of such investigations we believe that at present the ORNL/RPI data of Gwin et al. [69], particularly because of their good agreement with the independent estimates of Pitterle et al. [79] and Barre et al. [68], are the most reliable.

In the range 500 eV to 1 keV this would mean an average increase of our KFK-SNEAK set α data (=KAPL) by about 50%, whereas between 10 and 20 keV there is good agreement between the ORNL/RPI and SNEAK set α data. The α data in the H2ØPMB+α sets would have to be reduced between 5 and 20 keV by 20 to 30%.

Between 20 keV and 1 MeV the recommended liquid scintillator measurements of Diven and Hopkins [30] were later on confirmed by the measurements of de Saussure et al. [81] between 17 and 600 keV in which also liquid scintillator detection is used. Both measurements together establish α(E) to an accuracy of about ±10 to 15% between 20 keV and 1 MeV. As for ^{235}U because of the lack of experimental data no reliability estimate is possible above 1 MeV.

For σ_c about the following reliability figures result: Between 500 eV and 10 keV our σ_c values in the SNEAK set are on the average by 50% too low; between 10 keV and 1 MeV they are accurate to about ±15%.

2.3.3. $\bar{\nu}$

In reference [8], section VI 3 we evaluated best $\bar{\nu}_{49}$ values for the following $\bar{\nu}$ standards

$$\bar{\nu}^{p}_{spont.}(^{252}Cf) = 3.764 \; ; \quad \bar{\nu}^{d}_{spont.}(^{252}Cf) = 0.009$$
$$\bar{\nu}_{spont.}(^{252}Cf) = 3.773$$
$$\bar{\nu}^{p}_{spont.}(^{240}Pu) = 2.180 \; ; \quad \bar{\nu}^{d}_{spont.}(^{240}Pu) = 0.009$$
$$\bar{\nu}_{spont.}(^{240}Pu) = 2.189$$

and took over the thermal best values of Westcott et al. [48] for ^{235}U

$$\bar{\nu}^{p}_{therm.}(^{235}U) = 2.414 \; ; \quad \bar{\nu}^{d}_{therm.}(^{235}U) = 0.016$$
$$\bar{\nu}_{therm.}(^{235}U) = 2.430$$

in order to reevaluate with inverse square error weighting the 16 available (before 1966) experimental thermal $\bar{\nu}$ (^{239}Pu) values to the following best value:

$$\bar{\nu}^{p}_{therm.}(^{239}Pu) = 2.886 \; ; \quad \nu^{d}_{therm.}(^{239}Pu) = 0.006$$
$$\bar{\nu}_{therm.}(^{239}Pu) = 2.892$$

With the same ^{252}Cf standard value other evaluations came to very similar results:

Westcott et al. [48]:	2.871 (-0.7%)
Sher, Felberbaum [49]:	2.893
BNL-325 [50]:	2.89
Fillmore [47]:	2.890

Recently Boldeman and Dalton [82] made $\bar{\nu}_p$ ratio measurements for various fissionable nuclei superior in accuracy to all previous measurements (0.3%!). For ^{239}Pu they got the following result:

$$\bar{\nu}^{p}_{therm.}(^{239}Pu) \;/\; \bar{\nu}^{p}_{spont.}(^{252}Cf) = 0.7674 \pm 0.0021$$

which, for our ^{252}Cf standard value above and adding $\bar{\nu}_d$, results in

$$\bar{\nu}_{therm.}(^{239}Pu) = 2.894 \pm 0.008$$

in excellent agreement with our recommended value. This result is, however, still subject to the inaccuracy in the ^{252}Cf $\bar{\nu}$ value discussed in section 2.1.3. In particular the above ^{252}Cf $\bar{\nu}$ value might at worst be 1% too small. Thus, we conclude that in view of the high accuracy of the Boldeman $\bar{\nu}$ value an increase of $\bar{\nu}_{therm.}(^{239}Pu)$ above our recommended value by more than 1% is rather improbable.

At higher energies we have to compare our recommended curve (see section 1.1.3.) with the more recent measurements of Fréhaut et al. [60] between 1.4 and 14.8 MeV already mentioned in section 2.2.3. for ^{238}U and of Condé et al. [83] between 4.2 and 15 MeV. Below 4 MeV Fréhaut's results agree to better than 1% with our values, above 4 MeV systematic deviations are observed increasing from about 1 to 4% with increasing energy from 4 to 15 MeV. Condé's results are in good agreement with those of Fréhaut. Thus, we have to conclude that above 4 MeV the slope of our $\bar{\nu}(E)$ curve is not steep enough and that our $\bar{\nu}$ data are underestimated in that range by 1 to 4%.

2.3.4. Inelastic scattering

The knowledge of inelastic scattering cross sections particularly in the range of resolved rest nucleus levels is still completely insufficient. The available experimental data and theoretical calculations show still spreads of the order of ±50% and more in this range, at higher energies above about 1 MeV $\sigma_{n'}$ might be accurate to about ±20%. The results of more systematic theoretical calculations and of experiments in progress at ANL, Harwell and Geel should be awaited before further conclusions concerning our present data can be drawn.

2.4. Conclusions from microscopic data measurements

The following table summarizes the conclusions of this chapter by presenting the uncertainty limits and directions of possible or necessary changes for fission, capture, and inelastic scattering for ^{235}U, ^{238}U, and ^{239}Pu.

^{235}U data uncertainties (%)

Fission:	3-10 keV	+5 to 10 -12 (Petrel [33])
	10 keV - 1 MeV	+7 up to -15 (Pönitz [36])
	>1 MeV	-10 (Corrected LA data [25])
Capture:	<300 eV	-20 (de Saussure [31])
	300 eV - 10 keV	±20) scattering results
	10 keV - 1 MeV	±10 to 20)
$\bar{\nu}$:	thermal	$\lesssim \pm 1$
	keV - MeV	±2 (peak deviation)
Inelastic scattering:	<1 MeV	+30 (Ferguson [52])

^{238}U data uncertainties (%)

Capture:	<30 keV	−10 to 20 (Petrel [20])
	30−500 keV	+20 (Macklin [22]) −20 (Pönitz [5], Moxon [21])
	>500 keV	±10 (scattering results)
Fission:	>3 MeV	−5 (corrected LA data [25])
$\bar{\nu}$:	<5 MeV	−2 (preliminary French data [60])
Inelastic scattering:	<2 MeV	±10 to 20 (scattering results)

^{239}Pu data uncertainties (%)

Fission:	1−7 keV; 9−10 keV 7−9 keV	−10 to −20 +15 (recent Harwell [62,66], LA [63,64] and Saclay measurements [67,68])
	10−25 keV	±5 (scattering results)
	25−100 keV	a few % higher (Pfletschinger [72])
	100−800 keV	+10 (peak deviation of scattering older results above White [12]) −5 (lower uncertainty limit of White [12])
	800 keV − 2.5 MeV	±5 (scattering results)
	>2.5 MeV	−5 to −10 (White, Warner [12,73], corrected LA data [13,25])
Capture:	500 eV − 10 keV	+50 (Gwin [69])
	10 keV − 1 MeV	±15 (LA and ORNL liquid scintillator results [30,81])
$\bar{\nu}$:	thermal	±1 (uncertainty in $\bar{\nu}(^{252}Cf)$)
	<4 MeV	±2 (scattering results)
	>4 MeV	+1 to 4 (Fréhaut [60], Condé [83])
Inelastic scattering:	<1 MeV	$\gtrsim \pm 50$

3. Preparation of the group constant sets and used calculational methods

The group constant sets are prepared with the code system MIGROS, which is described to some extent in [1]. A detailed documentation of Huschke [84] contains the calculational procedure and the data of the infinite dilute cross sections and the resonance self-shielding factors. The weighting spectrum used in the SNEAK and H2OPMB sets is the theoretical collision density spectrum of SNEAK 3A-2, which is typical for a steam-cooled fast reactor. In the NAP sets we used the collision density spectrum of a fast sodium prototype reactor (300 MWe). The treatment of the elastic slowing down is done according to method B of [1], furtheron referred to as REMO. By this method the macroscopic elastic removal group cross sections are calculated down to 1 keV from about 1000 energy points.

The determination of criticality was performed by diffusion theory for the homogenized core, correcting the results for transport effects (SN) and heterogeneity (ZERA [85], a multigroup-multizone collision probability code with a special treatment of space dependent resonance self-shielding). The diffusion calculations were mainly done with the code TDS in 26 groups. This code is a pseudo two dimensional diffusion code, calculating in one dimension both r and z flux distributions. The transverse bucklings are automatically calculated from the previous calculation. For some cases two dimensional calculations were done with the DIXY code [86]. The influence of different weighting spectra, of recalculated self-shielding factors, different background cross sections σ_o for resonance self-shielding are discussed in section 4.3.

4. Analysis of fast critical and subcritical assemblies

In this chapter we summarize only those results, which can give an indication for certain incorrect cross sections used in the different sets.

4.1. Lines of investigations

We draw our attention on two main areas of data uncertainties, which had been stated in chapter 2:

A) The low keV range with the discrepant data for $\sigma_c(^{238}U)$, (Petrel) $\alpha(^{239}Pu)$(Schomberg, Gwin, Ryabov), $\sigma_f(^{239}Pu)$

B) The higher keV range around 100-500 keV: $\sigma_f(^{235}U)$, $\sigma_c(^{238}U)$: PMB-data.

These data cause the following effects in fast assemblies.

a) Lowering the capture data of ^{238}U in the low keV range and increasing the fission data of ^{239}Pu in the 25-100 keV range will yield an increase in neutron importance in this range and thus an increase in criticality, particularly for assemblies with soft neutron spectra. The enlargement of $\sigma_c(^{239}Pu)$ due to the recent α measurements and a decrease of $\sigma_f(^{239}Pu)$ below 10 keV gives the opposite tendency. The positive contribution of the Doppler effect in Plutonium samples should be reduced remarkably.

To check these indications, we investigated a series of uranium and plutonium fueled assemblies with a varying amount of moderator content. If the deviations of the recent microscopic data measurements from the data included in the SNEAK set are true, then with increasing moderator concentration and spectrum softening for instance the criticality prediction must be increasingly underestimated.

b) In comparison to the SNEAK data PMB data have mainly three effects: In uranium fueled assemblies the importance is somewhat decreased, resulting in a decreased criticality prediction. Furthermore, the leakage is increased when using PMB data. For plutonium fueled assemblies the neutron importance is increased in the 100 keV range yielding a higher criticality. Clearly these data will affect the neutronics of all fast reactor systems, but should be largest in cores with hard neutron spectra and a high leakage component. The theoretical results for such systems will therefor be a check on the PMB data. Cores with a high ^{238}U content especially give information about the reliability of the capture data in the PMB and SNEAK sets.

In the following sections we first discuss the facts and present the main conclusions of this chapter in section 4.4.

4.1. Uranium fueled assemblies

The calculations have been performed with the group sets KFK-SNEAK and KFK-H2OPMB.

4.1.1. Results for SNEAK assemblies with varying steam density

In table 1 the k_{eff} values and the reactivity changes due to voiding and "flooding" of the assemblies 3A-1 and 3A-2 [87] are summarized. The k values are taken from a recently published report by Engelmann [88].

4.1.1a. Prediction of k_{eff} and reactivity changes

The k_{eff}-value of 3A-2 is calculated as follows:

	SNEAK	H2OPMB
Diffusion theory, 26 groups TDS, (homogeneous)	0.9838	0.9789
Correction due to REMO (improved calculation of elastic moderation)	$+3\cdot10^{-4}$	$+1\cdot10^{-3}$ *)
Diffusion theory, DIXY	$-2\cdot10^{-3}$	$-2\cdot10^{-3}$
S_4 correction	$+4\cdot10^{-3}$	$+4\cdot10^{-3}$
Heterogeneity correction	$+2.5\cdot10^{-3}$	$+3.9\cdot10^{-3}$
Best result	0.989	0.986

A revised version of the ZERA code now predicts a smaller heterogeneity correction, but this does not change the line of arguments. What we want to show is that the corrections due to more refined methods are relatively small. We will investigate this point to some extent in section 4.3.

From table 1 we note that for 3A-2 k_{eff} is underestimated by 1.1% for the SNEAK set and by 1.4% by the H2OPMB set. The 3A-1 assembly with about half the hydrogen content of 3A-2 is calculated excellently by the SNEAK set, the H2OPMB set predicting less criticality because of the reduced importance in the higher energy range. The calculations of the void experiments for 3A-1 and 3A-2 result in a better agreement with

*) The large difference between SNEAK and H2OPMB set is not yet understood, but is not essential for the given comparison.

experiment for the PMB data. Because the leakage component dominates the spectral shift component, the void effect is negative. $(\Delta k/k)_{Loss}$ is more negative with the PMB than with the SNEAK data, because the decrease of the macroscopic transport cross section is relatively larger for PMB in the loss case than in the normal case. This also explains the larger steam density coefficient in 3A-2 for the PMB set.

Doubling the hydrogen content of 3A-2 both SNEAK and PMB data underestimate the reactivity increase by about 20%.

Summary: a) Increasing underestimation of k_{eff} with higher hydrogen content with SNEAK and PMB, a marked effect especially for the "flooded" case with $3.6 \cdot 10^{21}$ hydrogen atoms/cm^3,

b) better prediction of the void effect by PMB,

c) k_{eff} prediction with PMB lower than with SNEAK.

4.1.1b. Spectral indices, β/ℓ-values

In table 2 some important central fission ratios and β/ℓ-values are listed for 3A-1 and 3A-2. The spectral indices for 3A-2 are taken from a report by Böhme and Seufert /89/.
In /89/ the results are obtained for the heterogeneous as well as for the homogeneous core. Here only the homogeneous quantities are quoted in order to compare with 3A-1 results. A reliable comparison between theory and experiment should be made with heterogeneous calculations exactly at the detector position. But nevertheless the quoted numbers can provide information.

The $\sigma_f^{28}/\sigma_f^{25}$ ratio is underestimated with both group sets for 3A-1 and 3A-2. This deviation may be due to three effects:

a) Too low σ_f^{28} data,

b) group structure error in and weighting procedure for $\sigma_f(^{238}U)$ group constants in the slope of the ^{238}U fission threshold.

c) the theoretical neutron spectrum is underestimated in this range as a consequence of too large inelastic scattering or too large leakage.

Low σ_f^{28} and low inelastic scattering data are not indicated by the investigation in chapter 2 and will therefore be omitted at present. The assumptions b) and c) are due to the methods used and will be discussed in section 4.3. The ratio $\sigma_c^{28}/\sigma_f^{25}$ is outside experimental error in 3A-2. Because of the softer spectrum in 3A-2 this discrepancy seems to indicate that the errors are due to incorrect $\sigma_c(^{238}U)$ values below the energy range of the PMB data (below 20 keV), noting the good agreement of the corresponding ratio for 3A-1. The plutonium to uranium fission ratio is better predicted by PMB, and also the β/ℓ-values.

<u>Summary:</u> a) Underestimation of $\sigma_f^{28}/\sigma_f^{25}$ with both sets for 3A-1 and 3A-2,

b) overestimation of $\sigma_c^{28}/\sigma_f^{25}$ for 3A-2 with both sets,

c) better agreement for $\sigma_f^{49}/\sigma_f^{25}$ and β/ℓ for 3A-1 with PMB data.

4.1.2. Results for the subcritical SUAK facility with different moderator content.

Experiments have been performed in the pulsed SUAK [90] facility with different material compositions. We compare the following systems with theory:

U1B:	20% enriched uranium metal
UH1B:	20% enriched uranium metal mixed with polyethylene, atomic ratio H/U ≈ 0.45.
EURECA:	30% enriched uranium metal rods (diameter 12.7 mm) in graphite, atomic ratio C/U = 6.9.

The results obtained with the SNEAK set are taken from Mitzel and Schroeter [91], the corresponding PMB results are provided by Mitzel [92]. Table 3 shows the comparison between theory and experiment for the subcriticality and the prompt neutron decay constant α. These data are corrected for transport and heterogeneity effects as well as for anisotropic neutron scattering on hydrogen. The elastic downscattering was treated with REMO, for EURECA the collision density spectrum in this assembly was used as a weighting spectrum.

The significant quantity in table 3 is $1/\alpha$, which can be determined experimentally to better than 2%, while k_{eff} has a rather poor experimental accuracy especially for $k_{eff} \approx 0.9$ But one should note that k_{eff} is better predicted for EURECA than for UH1B: Because the ^{238}U content in EURECA is less by about a factor of 5, this system would be less sensitive to incorrect ^{238}U capture data in the low keV range.

For increasing $1/\alpha$ theory yields an increasing underestimation. The k_{eff} values for PMB are always less than those for SNEAK, due to the reduced importance in the 100 keV range. But it should be emphasized that for the hard spectrum system U1B with the high leakage component the PMB results give a larger discrepancy compared to experiment than SNEAK. We will investigate this in the next section.

Summary: a) With increasing $1/\alpha$ increasing deviation between theory and experiment.

b) Better agreement for EURECA than for UH1B in k_{eff} with the SNEAK set.

c) Larger discrepancies for U1B with PMB data than with the SNEAK set.

4.1.3. Comparison of uranium systems with hard neutron spectra

In this section we investigate the trends of criticality prediction with the SNEAK and PMB sets with increasing leakage for uranium metal cores with a varying amount of ^{238}U. Especially the systems with a high ^{238}U content (ZPR3-25) are a very sensitive check to ^{238}U capture data in the high energy range. The k_∞ of these assemblies will not be very different between both sets, because PMB reduces the fission data ^{235}U as well as the capture of ^{235}U and ^{238}U. With increasing leakage component the reduction of the transport cross sections of the heavy isotopes must yield an increasing difference in k_{eff} between SNEAK and PMB data. For non moderating systems the problem of proper weighting spectra does not arise, so that deviations between theory and experiment are due to cross section deviations. Because of the increased leakage and the reduced importance connected with the PMB data compared to

SNEAK set results, PMB can give better results compared to experiments only then, if the criticality is overpredicted by the SNEAK set. Up to now we have done precise calculations only for the SUAK subcritical facility, as has been shown in section 4.1.2. The subcriticality as well as $1/\alpha$ were underestimated.

Preliminary one dimensional diffusion theory calculation in spherical geometry have been performed with the SNEAK set for ZPR3-25 (a uranium metal core with $^{238}U/^{235}U \approx 10$), yielding a critical experimental homogeneous, spherical core radius of 47 cm (S_4) as given by Baker [93]. Despite the fact that the analysis of non spherical, heterogeneous cores cannot appropriately be done in spherical geometry, we conclude that the SNEAK set underpredicts criticality for this assembly. This is in complete agreement with the results of Baker obtained with the modified Russian ABN set and the British FD2 set, which both included the low fission data of White as we did in the SNEAK set. The same is true for ZPR3-11, a very small uranium metal core. Here definitely the reduction of fission of ^{235}U below the White data should yield a further underestimation of k_{eff} compared to the SNEAK set results. In table 4 we compare the relative changes in the k_{eff} prediction with the PMB and SNEAK set for SUAK-U1B, ZPR3-10 (similar to ZPR3-11, $^{238}U/^{235}U \approx 5$) and ZPR3-25. For U1B the corresponding deviations for the Russian ABN and the previous KFK 26-10 set are listed. Between 20 keV and 400 keV the ^{238}U capture data of KFK 26-10 and SNEAK are nearly the same, but the KFK 26-10 fission data of ^{235}U in this range are lower than in the ABN set. The SNEAK σ_f^{25} data are even lower than KFK 26-10 [1].

With increasing buckling the increased underestimation of criticality with the PMB data can be seen from table 4. For U1B the higher fission data in KFK 26-10 yield good agreement with experiment. Because of the poor experimental accuracy in k_{eff} for U1B, a new experiment will be performed with a lower subcriticality.

From this preliminary investigation we have the

Summary: a) For high leakage cores the PMB data underestimate k_{eff} more then the SNEAK set.

b) Lower $\sigma_c(^{238}U)$ and/or higher $\sigma_f(^{235}U)$ compared to SNEAK set data in the 200 keV range could account for the deviations to experiments. This favors the low capture data of PMB, but definitely not the low fission data.

c) A correction to the ν value of ^{235}U could not account for the trend given in table 4.

4.2. Results for plutonium fueled fast critical assemblies

Fast critical assemblies with plutonium fuel have been analysed with the NAP, NAPPMB and the NAPPMB+α sets.

4.2.1. Prediction of criticality

In table 5 the predicted criticality for ZPR3-48 and ZEBRA-VIa is given. First results for the mixed plutonium/uranium assembly SNEAK 3B-2 [94], calculated with the SNEAK and H2OPMB sets, are also given.

Criticality is underpredicted by an intolerable amount for the NAP and NAPPMB+α sets. It should be noted that with both sets the criticality of assembly ZEBRA-VIa is even more underpredicted by about 1% than that of ZPR3-48. Because ZEBRA VIa has the softer neutron spectrum, this again is an indication for incorrect "low" energy capture cross sections of ^{238}U. The PMB sets give roughly 1% deviation from experiment and an increase by about 1% over the NAP data. This is due to the reduced capture cross section of ^{238}U, increasing the importance in the higher keV range. (The NAPPMB value for ZEBRA-VIa is being recalculated, because the large difference to the NAP-k_{eff} is not yet understood, spherical S_4 calculations show now a 1% difference between NAP and NAPPMB.)

Both the new Gwin data for $\alpha(^{239}Pu)$ and the Petrel data for $\sigma_c(^{238}U)$ yield an increase in criticality compared to PMB+α data. We have checked this by spherical diffusion calculations for ZPR3-48. The results are listed in the last two columns of table 5. The Gwin-α and Petrel capture data compensate, so that together with "best" $\alpha(^{239}Pu)$ and low Petrel $\sigma_c(^{238}U)$ the PMB set predicts k_{eff} = 0.99, together with NAP data k_{eff} = 0.98. The remaining difference leads to the assumption that the fission data for ^{239}Pu should be increased over the White data. This is in agreement with preliminary experimental results /‾72_7 stated in chapter 2.

Summary: a) Increasing underprediction of criticality with softer spectra (ZPR ZEBRA).

b) Untolerable underprediction with the lower limits of α-Schomberg.

c) Deviation of about 1 to 1.5% for PMB data from experiment.

d) Compensating effects of Gwin- and Petrel $\sigma_c(^{238}U)$ for ZPR3-48.

4.2.2. Spectral indices

Table 6 contains the main spectral indices for the different assemblies. Here we note a good agreement in $\sigma_f^{28} / \sigma_f^{25}$ contrary to what was observed for hydrogen moderated assemblies in table 2. This will be discussed in section 4.3. The $\sigma_c^{28}/\sigma_f^{25}$ ratio is too large with all sets, indicating again a lowering of the ^{238}U capture data or an increase of the ^{235}U fission data. On the other side the $\sigma_f^{49}/\sigma_f^{25}$ ratios are too small, indicating higher fission data for ^{239}Pu or lower fission data for ^{235}U. Both effects can obviously not be explained by a change of σ_f^{25}, but by a simultaneous lowering of σ_c^{28} and increase of σ_f^{49} in the higher keV range.

The integral capture to fission ratio for ^{239}Pu is in better agreement with experiment for the α set. The reduction of the "low" Schomberg-α limits to the Gwin-α values will reduce this ratio, but also an increase of σ_f^{49}. But this has to be carefully investigated because of spectrum effects. This question will be investigated thoroughly in a k_∞-experiment.

<u>Summary:</u> a) Good agreement between theory and experiment for $\sigma_f(^{238}U)/\sigma_f(^{235}U)$.

b) An increase of $\sigma_f(^{239}Pu)$ and a decrease of $\sigma_c(^{238}U)$ is indicated by the corresponding fission ratios.

c) The integral α value for ^{239}Pu is in better agreement with the α-set, but will be reduced by using Gwin's data.

4.3. Some remarks on calculational methods

Before we summarize the results of chapter 4, we investigate in this section some of the corrections, which have to be applied to the results of diffusion theory and SN calculations. This is done in order to fix the uncertaintiy due to methodical procedures.

4.3.1. Weighting spectrum and σ_o-concept

In a reactor calculation we normally use an average background cross section in each group for the calculation of resonance self-shielding (σ_o-concept, see [1], [4], and [84]). A more elaborate determination of elastic down scattering is performed by REMO. Instead of the σ_o-concept (see chapter 3) REMO uses a collision density weighting spectrum for the direct calculation of the macroscopic elastic removal group constants. For the comparison presented here, the weighting spectrum in most cases has been determined by iteration. This yields the following corrections for k_{eff}

SNEAK-3B-2:	$+1.5 \cdot 10^{-3}$	(included in table 5)
ZPR3-48:	$+3 \cdot 10^{-3}$	" " " "
ZEBRA-VIa:	$+3.6 \cdot 10^{-3}$	" " " "
SNEAK-3A-2:	$+3 \cdot 10^{-4}$	" " " 2; small, because SNEAK set weighting
SNEAK-3A-1, Void	$-2.3 \cdot 10^{-3}$	(not " " " 2)

The magnitude of these corrections is less than 0.5%.

If one uses the σ_o-concept throughout, the determination of σ_o in each group is normally done with the infinite dilute total cross sections with one exception: the background cross section of ^{238}U is taken as its potential scattering cross section. This procedure was compared with σ_o' determined by the effective total cross sections with the strongest resonance self-shielding. The effect of the different procedures on criticality is:

SNEAK-3A-2: $+1.2\cdot10^{-3}$
ZPR3-48: $+2.3\cdot10^{-3}$

Because both methods are approximations to the true situation, a possible error of about 0.2% can occur.

All of the results quoted in the tables are calculated with self-shielding factors taken from the Russian ABN set for ^{235}U and ^{239}Pu; ^{238}U new shielding factors had already been determined and incorporated. Meanwhile the lacking shielding factors have been calculated and are given in [84]. We checked the results with these new shielding factors and found for SNEAK-3A-2 a decrease in k_{eff} by $-5\cdot10^{-4}$. This is in agreement with results obtained for the steam-cooled large fast reactor D1 [98]. But this effect naturally depends on the core mixture under investigation and may even change the sign.

4.3.2. The sensitiveness of the fission ratio $\sigma_f(^{238}U)/\sigma_f(^{235}U)$ to the neutron spectrum. Treatment of anisotropic scattering.

Comparing tables 2 and 6, the underprediction of $\sigma_f(^{238}U)/\sigma_f(^{235}U)$ for SNEAK-3A-1 and SNEAK-3A-2 is striking. On the other hand this index is rather well predicted for systems containing no hydrogen. So this discrepancy in 3A-1 and 3A-2 reflects an underestimation of the neutron spectrum in the MeV energy range and could very well be due to the theoretical treatment of the scattering process of neutrons with hydrogen. Because there is no reason to doubt the scattering cross sections themselves, a reason for the observed discrepancy can be an incorrect description of the anisotropic downscattering. In diffusion theory this process enters the transport cross section. From the P1 equations the following relation can be derived:

$$\Sigma_{tr}^{i} = \Sigma_{t}^{i} - \underset{j\leq i}{S} \Sigma_1^{j\to i} \frac{J_j}{J_i},$$ where $\Sigma_1^{j\to i}$ is the total anisotropic scattering matrix (including $\mu^{j\to i}$) and J_j is the net current in group j.

Applying this formula only to hydrogen as the most dominant constituent with anisotropic scattering, in [1] we omitted the energy dependent ratio of the currents. This leads to a too small λ_{tr}^{i} in the high energy groups above the maximum of the current, because of $J_j/J_i < 1$. As a consequence the leakage is overestimated and the calculated spectrum is softer in this range. This is also the experimental evidence comparing flux traverse measurements with theory.

To have an indication how much the difference between experimental and calculated spectrum affects $\sigma_f(^{238}U)/\sigma_f(^{235}U)$ and k_{eff}, we took the experimental neutron spectrum of 3A-1 as a weighting for $\sigma_f(^{238}U)$ between 0.8 and 4 MeV. The yields for instance a 25% increased group constant between 0.8 and 1.4 MeV. This change in k_{eff} is about +0.4% for SNEAK-3A-1. The fission ratio then is increased by about 6%.

For SUAK-UH1B the correction for anisotropic scattering with current weights gives +0.7% in k_{eff} compared to the average cosine concept.

A great part of the questions referred to in this section will be clarified with our space dependent 200 group consistent P1 approximation.

4.4. Conclusions drawn from the analysis of integral experiments

(1) The analysis of fast systems with varying moderator content (tables 1,2,3,5,6) shows an increasing underprediction of criticality and overestimation of $\sigma_c(^{238}U)/\sigma_f(^{235}U)$. In the low keV range there is no indication from the analysis of chapter 2, that $\sigma_f(^{235}U)$ should be increased. Therefore, we conclude that the capture data of ^{238}U have to be decreased in this range. This is in agreement with the recently published final results of the Petrel measurements. From table 5 it follows that the influence of these low capture data on k_{eff} is +1% for ZPR3-48, for systems with softer spectra as the hydrogen and graphite moderated cores the effect will be larger.

(2) The analysis of fast uranium systems with hard neutron spectra and a high $^{238}U/^{235}U$ content shows that with the data included in the SNEAK set the criticality is underpredicted. The PMB set yields an even

stronger underestimation. As a consequence a lowering of the SNEAK set ^{238}U capture data and/or an increase of the ^{235}U fission data over the White data can account for this discrepancy. Smaller $\sigma_f(^{235}U)$ data than those of White, as are given by PMB, enlarge the discrepancies. Thus, we conclude that the low fission data for ^{235}U as discussed by Beckurts and later on measured by Pönitz should at present be excluded from our data sets. The low $\sigma_c(^{238}U)$ data in the higher energy range improve the criticality prediction of all systems listed here. Because in the assemblies ZPR3-48 and ZEBRA-VIa plutonium is used as fuel, the criticality is predicted to about 1% deviation from experiment compared with 2 to 3% deviation for the data included in the SNEAK set.

(3) The analysis of plutonium fueled assemblies shows that the recently published data of Gwin for $\alpha(^{239}Pu)$ give a reactivity increase by 1% compared to the data included in the α-sets. This stems from lower α-values above 3 keV. Theoretical investigations of the Doppler coefficient of Pu samples in SNEAK [10] give a good agreement with experiment, if the recommended resonance parameters of Pitterle [79] are taken. Because both Gwin and Pitterle's α data are very similar (see chapter 2), the relative good agreement for the Pu Doppler coefficient favors the Gwin data. Thus, we exclude the lower limits of the Schomberg α from our sets.

(4) Because the present Petrel and Gwin data compensate each other nearly with respect to criticality, an underestimation of criticality by about 1% for Pu-assemblies remains. This and also the spectral index $\sigma_f(^{239}Pu)/\sigma_f(^{235}U)$ indicate that the fission data of ^{239}Pu have to be increased. Preliminary results of Pfletchinger's measurements (see chapter 2) support this assumption.

(5) The underestimation of the fission ratio $\sigma_f(^{238}U)/\sigma_f(^{235}U)$ for hydrogen moderated assemblies and the relatively good agreement for other systems together with a comparison of theoretical and experimental flux and reaction rate traverses indicate that the neutron leakage in the MeV range is overestimated. This could very well be due to an incorrect description of anisotropic downscattering.

5. Analysis of large fast power reactors with different group sets

We have calculated the nuclear behavior of fast reactors under investigation at Karlsruhe with different group constant sets. The results of these calculations are summarized in this chapter in order to allow a comparison of the nuclear behavior of fast reactors with different coolants. The following reactors have been studied:

(a) The sodium-cooled reactor Na1 /‾96_7, 1000 MWe.

(b) The sodium-cooled reactor Na2 /‾97_7, 300 MWe (prototype).

(c) The steam-cooled reactor DSA-5, similar to D1 /‾98_7, 1000 MWe.

(d) The steam-cooled reactor D2-2, 300 MWe (prototype).

(e) The helium-cooled reactor G33, 1000 MWe.

In table 7 characteristic data of these reactors are given.

The calculations have been performed with following group sets:

ABN	DSA-5, D2-2, G33
KFK 26-10	Na1, Na2
NAP NAPPMB NAPPMB+α	Na1, Na2, G33
SNEAK H2ØPMB H2ØPMB+α	DSA-5, D2-2

The results obtained with the different group sets are listed in the tables 8 to 12. The tables contain the critical enrichment γ (fissile to fissile + fertile material), critical mass M ($^{239}Pu+^{241}Pu$), reactivity change due to loss of coolant Δk_L, reactivity change due to flooding Δk_F, the Doppler constant $DC=T\frac{dk}{dT}$ referring to 900°C, the reduced steam density coefficient $\frac{dk}{k} / \frac{d\rho}{\rho}$ R.S.D.C., the internal conversion ratio C.R., the total breeding ratio B.R. and the doubling time D.T. in years. All the calculations have been performed in the diffusion theory approximation using the REMO procedure. The suffixes (0), (1) and (2) stand for fundamental mode, one and two dimensional calculations respectively. It should be noted that D.C. is calculated in perturbation theory with the

D.C.P. code [99], using the same resonance parameters for the different sets. Thus, the different values reflect only the change in neutron spectra and the change in the enrichment. Furthermore, the quasistationary plutonium composition was not changed for the different sets. The doubling time is calculated according to

$$DT = \frac{0.69 \cdot 10^3 \frac{0.95}{1+\bar{\alpha}}}{(BR-1) b_o \cdot K} \left(1 + BR \frac{t_w}{t_{st}}\right)$$

b_o = rating in MW_{th} / kg fissile material (core)
K = loading factor (K=0.8)
t_w = fuel out of pile time
t_{st} = fuel in pile time (t_w/t_{st} = 1/3)
$\bar{\alpha}$ = $\bar{\Sigma}_c$ (fissile)/ $\bar{\Sigma}_f$ (fissile)

5.1. Discussion of tables 8-12

The changes in the various quantities obtained with different group sets can be explained in a similar way for all reactors. Here we give only brief comments, because in [1] and [3] we already have compared the influence of the Russian ABN, the KFK 26-10 and the SNEAK-set data on integral parameters of large fast power reactors. The changes due to the PMB and α-sets can easily be understood by following the discussion in the preceding chapters.

The low enrichment and critical mass for the ABN and KFK 26-10 sets are caused by high ^{239}Pu fission and in addition in ABN the low capture cross sections of structural materials (Fe,Ni).

A comparison of Δk_L-values for the different sets requires a very detailed and careful investigation of the partly compensating effects in the high energy range (positive contribution to Δk_L) and the low energy range (negative contribution to Δk_L) together with the changes in leakage and enrichment. Worth mentioning is the drop of Δk_L from 1.8% to 1.4% for Na1 going from KFK 26-10 to NAP. The reason is that all data in the tables 8 and 9 obtained with the KFK 26-10 set, were calculated with the σ_o-concept, not with the REMO procedure. These methodical problems will be discussed elsewhere.

In all cases, however, we note a considerable increase of Δk_L using the high α values of ^{239}Pu. The enlargement of Δk_L is caused by a flattening of the importance in the energy range below 20 keV resulting in a smaller negative part of the Δk_L-value. Moreover, this effect will be emphasized by the higher enrichment to keep the reactors critical. The effect is strongest for the large steam-cooled reactor, because this reactor has the softest neutron spectrum. Note that with the more recent α-data of Gwin the effect is reduced.

For the gas-cooled system the void reactivity is very small and the influences of different data sets are negligible.

In the steam-cooled systems the reduced steam density coefficient is very sensitive to data changes. The trend with different data sets is strongly connected to the trend in Δk_L.

The reactivity change Δk_F due to flooding the steam- and gas-cooled reactors shows that for the α set Δk_F is less negative in steam-cooled reactors than in gas cooled reactors. This is due to the relatively higher enrichment for DSA-5 and D2-2 than for G33 to keep criticality in the normal case, so that the increase in neutron production in the flooded steam systems is more enlarged than the increase in absorption.

The trend of the Doppler constant DC is explained by changes in spectrum and enrichment. The resonance parameters are not changed for the different calculations (but see section 5.2).

The conversion and breeding ratios as well as the doubling time are strongly influenced by the α-set. The prototype version D2-2 does not breed any more, the 1000 MWe plant has a very small breeding gain. The gas-cooled system also is affected by the high Pu-α data, the effect is somewhat smaller.

Note that with Gwin's lower α-data the reduction in the breeding performance will be smaller.

In this context we have to discuss the effects due to a data consistent quasistationary plutonium composition Pu^{∞}. We have calculated the plutonium vector for a closed cycle according to the model of Jansen and Ott [100]. As expected there only is a large difference in Pu^{∞} for the α-set. Therefore, we compare here only the changes of Pu^{∞} obtained with the α-set to those of the PMB-data. This is given in table 13. The values for D1 are taken from [101]. The breeding ratio is increased over the values given in tables 8-12, only about 60% of the shown reduction due to the high α-values remains. This is due to the higher ^{240}Pu and ^{241}Pu content.

It must be emphasized, however, that such quasistationary fast reactor plutonium is not available for the start up of a fast reactor family. This particularly is important for the steam-cooled system suffering mostly from the α-data.

5.2. The influence of the nuclear data uncertainties on the safety and the stability of a large steam-cooled fast reactor (D1-design)

For the D1 design the influence of the nuclear data uncertainties on some reactor parameters was examined [95]. The reactor parameters considered are: the ratio of the fertile to the fissile material of the core y; the conversion ratio of the core C.R.; the loss of coolant reactivity Δk_L; the reduced steam density coefficient R.S.D.C. = $\frac{dk}{k} / \frac{d\rho}{\rho}$; the Doppler constant D.C. The evaluation of the nuclear data uncertainties was performed prior to the evaluation in chapter 2, where more recent information has been included. In tables 14-16 the uncertainty limits of ^{239}Pu and ^{238}U are listed groupwise with respect to the group constants of the SNEAK set. The investigations were performed with the help of fundamental mode calculations using the multigroup diffusion approximation and the group constants of the SNEAK set as basic group constant set. The R.S.D.C. and the D.C., being the most important parameters for the safety and the stability, are primarily investigated. Particularly, the R.S.D.C. proved to be very sensitive to the variations of σ_γ and σ_f. The largest influences come from the energy regions 50 eV to 1 keV and 10 keV to 1 MeV. The influence of the data uncertainties on the D.C. is smaller. In the tables 17 and 18 the results are collected. "σ_γ MAX.GR 1-4" means that the capture cross section has the maximal expected value (of the tables 14-16) in the energy groups 1 to 4. Also the maximal variations of the R.S.D.C. caused by the uncertainties of respectively ^{239}Pu and ^{238}U and ^{239}Pu+^{238}U are determined (table 19). A remarkable effect was observed for the self-shielding factors of ^{239}Pu. In table 19 also is given the influence on the reactor parameters, if the self-shielding factors of the SNEAK set are changed by the self-shielding factors for ^{239}Pu of the ABN set. The D.C. is calculated by successive k-calculations. The influence of the data uncertainties on the safety and stability of the D1 design is shown in fig. 1. For some power levels P and power variations $\frac{\Delta P}{P}$ the boundaries for the power coefficient $A = \frac{\Delta k_f}{\Delta P/P} = 0$ dependent on the R.S.D.C. and the D.C. are taken from a study of Frisch [103].

6. Final conclusions

In this chapter we summarize the conclusions drawn in this report.

6.1. Microscopic data and integral experiments

(1) The ^{238}U capture data in the keV range should be decreased below the SNEAK set values.

Indication: k_{eff}, spectral indices - supported by measurements of Pönitz and Glass (Petrel)

(2) ^{235}U fission data lower than White should be excluded.

Indication: k_{eff} for hard spectrum systems.

(3) The ^{239}Pu high α values of Schomberg above 2 keV should be lowered.

Indication: k_{eff}, spectral index, Doppler coefficient of ^{239}Pu - supported by measurements of Gwin and DC-measurements in SNEAK.

(4) The ^{239}Pu fission data in the keV range should be increased above the SNEAK set data.

Indication: k_{eff}, spectral indices - supported by measurements of Pfletschinger.

(5) Anisotropic scattering in hydrogen systems to be improved.

Indication: $\sigma_f^{28} / \sigma_f^{25}$, flux traverse measurements.

6.2. Prediction of important nuclear parameters of large power reactors.

The present data uncertainties lead to the conclusion that the prediction of large fast power plants is not yet sufficiently ascertained. Only a comparison of theory and experiment for a series of fast critical assemblies with different compositions and additional specific clean experiments will bring fast reactor physics investigations to a more confident status.

Enrichment and critical mass

The recent Karlsruhe group sets underpredict the criticality. For large power systems this may lead to considerable overestimation of critical mass. The PMB sets, excluding the low ^{235}U fission data, at present, would yield the best results. We remind that the effects of Gwin's and the Petrel data nearly compensate; then a 1 to 1.5% underprediction of criticality remains, which, at present, we believe, can then be assumed for large power reactors. We are going to improve our data sets according to the indications presented in this report.

Loss of coolant reactivity

For large sodium-cooled power reactors this quantity is very important due to accidental situations connected with sodium ejection yielding eventually large reactivity ramp rates. Here especially the high α values of ^{239}Pu give a remarkable increase. If the dry meltdown can be excluded by design, then the larger Δk_L for the steam-cooled system is not an alarming figure, because the ramp rates associated with voiding are smaller than for sodium-cooled reactors with sodium ejection accidents. For gas-cooled systems the reactivity change due to coolant loss is about 1\$ and this value is not very sensitive to different data sets.

Flooding reactivity

For steam-cooled systems Δk_F is well enough negative. For the gas-cooled reactor G33 Δk_F is just negative and can well be positive, if one includes heterogeneity corrections. Δk_F is sensitive to the nuclear data, the assumed burn up, the coolant volume fraction, the clad material.

Reduced steam density coefficient

The R.S.D.C. in steam-cooled reactors is very sensitive to changes in nuclear data. As has been shown in section 5.2, the stability boundary can be crossed with present data uncertainties. We believe, however, that the infavorable data can be ruled out. From this it would follow that a very reliable prediction of the R.S.D.C. is not possible at present. But note that PMB data predict the R.S.D.C. for SNEAK-3A-2 to a satisfactory agreement with experiment.

Doppler coefficient

The sensitivity of the DC on nuclear data uncertainties in a steam-cooled system is not very large. Taking most unfavorable and most favorable data, an uncertainty of ±20% results. The uncertainty of the DC is larger in sodium- and gas-cooled systems, as has been shown by Greebler [104] and can be read from the corresponding tables in this report.

Breeding, Doubling time

The prediction of breeding is one of the essentials for the determination of the long range potential of fast reactors. The most important impact on the breeding performance occurs in the α sets. Even the reduction of the α values make the here presented steam designs not very attractive with respect to long range potential.

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Assembly	Quantity	SNEAK	H20 PMB	Exper.
SNEAK 3A-1	K_{eff}	0,995	0,989	1,0
	$\left(\frac{\Delta K}{K}\right)_{Loss}$ [%]	-2,8	-3,2	-3,2
SNEAK 3A-2	K_{eff}	0,989	0,986	1,0
	$\left(\frac{\Delta K}{K}\right)_{Loss}$ [%]	-5,9	-6,7	-7
	$\frac{\Delta K}{K} / \frac{\Delta \rho}{\rho}$	0,047	0,051	0,058*)
	$\left(\frac{\Delta K}{K}\right)_{2\rho_N}$ [%]	3,7	3,9	4,8

Table 1 Comparison of calculated and measured criticality and reactivity changes

*) reevaluated, The value in ref. (88) is 0.053

Central Fission Ratios β/l	3A - 1			3A - 2		
	Exp.	SNEAK	H2O PMB	Exp.	SNEAK	H2O PMB
$\frac{\sigma_f(U238)}{\sigma_f(U235)}$	0,0336 ±0,001	0,0301	0,0304	0,0338 ±0,001	0,0297	0,0295
$\frac{\sigma_c(U238)}{\sigma_f(U235)}$	0,142 ±0,008	0,143	0,142	0,130 ±0,004	0,137	0,136
$\frac{\sigma_f(Pu239)}{\sigma_f(U235)}$	1,03 ± 0,03	0,960	0,993	—	—	—
$\beta/l * 10^{-4}$	2,05 ±0,04	2,42	2,30	—	—	—

Table 2 Central fission ratios and β/l values for assemblies SNEAK 3A-1 and SNEAK 3A-2

Assembly	k_{eff}				$1/\alpha$ [µs]			
	Exp. (1/M)	SNEAK	PMB	Δk(Exp. - SNEAK)	Exp.	SNEAK	PMB	$\frac{1/\alpha(SNEAK)}{1/\alpha(Exp)}$
U1B	0,86 ± 0,01	0,852	0,836	$+8 \times 10^{-3}$	0,230 ± 0,003	0,223	0,213	0,97
UH1B	0,945 ± 0,01	0,928	0,925	$+1,7 \times 10^{-2}$	3,8 ± 0,03	3,23	3,23	0,85
EURECA	0,957 ±0,003	0,948	0,935	$+9 \times 10^{-3}$	6,66 ± 0,12	5,4	—	0,81

Table 3 Subcriticality and prompt neutron decay constants for SUAK assemblies

Assembly	SUAK-U1B	ZPR 3-10	ZPR 3-25	ZPR 3 - Infinite
(k(s)-k(PMB))/k(s)	+1.9 %	1.6 %	1 %	0.4 - 0.5 %
(k(s)-k(ABN))/k(s)	-2 %	—	—	—
(k(s)-k(KFK))/k(s)	-1.6 %	—	—	—
B^2/B^2(U1B)	1	≈ 0.4	≈ 0.2	0
k_{eff} (s)	0.85 (under-predicted)	underpredicted	underpredicted	—

Table 4 Relative changes in k_{eff} for systems with hard neutron spectra with different group sets (s = SNEAK-Set, B^2 = Buckling).

Fac. \ Set	NAP	NAPPMB	NAPPMB+α	k(PMB)-k(GWIN)	k(PMB)-k(Petrel)
SNEAK3B-2	0,983 [a)]	0,989 [b)]	0,974 [c)]	—	—
ZPR3-48	0,979	0,990	0,974	+1 %	-1 %
ZEBRA VI a	0,970	0,988	0,965	—	—

Table 5 Criticality prediction of plutonium fuelled facilities

a) SNEAK b) H2OPMB c) H2OPMB+α

Central Fission ratios	ZPR3-48				ZEBRA VIa			
	Exp.	NAP	PMB	PMB+α	Exp.	NAP	PMB	PMB+α
$\frac{\sigma_f(U238)}{\sigma_f(U235)}$	0,0307 ±0,0003	0,030	0,0309	0,0314	0,0364	0,0347	0,0357	0,0365
$\frac{\sigma_c(U238)}{\sigma_f(U235)}$	0,138 ±0,007	0,146	0,144	0,145	—	—	—	—
$\frac{\sigma_f(Pu239)}{\sigma_f(U235)}$	0,976 ±0,01	0,908	0,941	0,951	0,961 ±0,013	0,899	0,928	0,940
$\frac{\sigma_c(Pu239)}{\sigma_f(Pu239)}$	—	—	—	—	0,36 ±0,09	0,214	0,215	0,29

Table 6 Central fission ratios for ZPR3-48 and ZEBRA VIa

Reactor	Symbol	Na1	Na2	DSA-5	D2-2	G33
Total Power (therm)	P [MWth]	2500	730	2500	750	2500
Coolant	-	Na	Na	H_2O	H_2O	He
Pressure	p_s [at]	-	-	170.	120.	100.
Core-Height	H_c [cm]	95.5	95.	150.	72.2	131.6
Core-Radius Zone 1	R_1 [cm]	102.7	54.2	91.	79.55	116.82
Zone 2	R_2 [cm]	143.	76.5	128.85	112.5	165.2
Coolant Vol.Fraction	α	0.5	0.5	0.32	0.286	0.55
Average Density	ρ_α [g cm^{-3}]			0.0722	0.0449	0.00666
Struct.and Clad.-Mat.		Incoloy 800	16/13CrNi-Steel	Inconel 625	Inconel 625	16/13 CrNi-Steel Inconel 625
Vol. Fraction	β	0.196	0.205	0.213	0.246	0.07/0.08
Vol.Fract.Oxide Fuel	ω	0.304	0.295	0.451	0.416	0.303
Pu-Composition	(239/240/241/242)	(75/22/2.5/0.5)	(72.6/23.6/3.2/0.6)	(74./22.7/2.3/1.)	(74./22.7/2.3/1.)	(74./22.7/2.3/1.)
Burn-up	Atom %	5.	3.55	2.75	2.75	2.75

Table 7

Characteristic data of the calculated reactors.

Set	$\bar{\gamma}$	M [kg]	$\Delta K_L \cdot 10^2$	CR
KFK26-10(*)	0,129	2103	1.82	0.90
NAP	0,138	2255	1.42	0.92
NAPPMB	0.136	2215	1.39	0.90
NAPPMB + α	0.140	2276	1.93	0.82

(*) σ_0-concept, not REMO procedure.

Table 8

Results for Na1 (fundamental mode calculations with $B^2 = 7.98 \cdot 10^{-4}$, for the voided case $B_v^2 = 7.43 \cdot 10^{-4}$)

Set	$\bar{\tau}$ (2)	M [kg] (2)	$\Delta K_L \cdot 10^2$ (1)	$-DC \cdot 10^2$ (1)	CR (Zone 1) (2)	CR(Zone 2) (2)	BR (2)	DT (2) [a]
KFK26-10 (*)	0.196	773	0.58	0.304	0.69	0.45	1.21	13.3
NAP	0.213	839	0.70	0.323	0.70	0.46	1.24	11.3
NAPPMB	0.210	828	0.703	0.337	0.69	0.45	1.21	14.1
NAPPMB + α	0.215	848	1.05	0.264	0.63	0.41	1.12	23.7

(*) σ_0-concept, not REMO procedure.

Table 9

Results for Na 2

Set	$\bar{\gamma}$ (0)	M [kg] (1)	$\Delta K_L \cdot 10^2$ (0)	$-\Delta K_F \cdot 10^2$ (0)	$-DC \cdot 10^2$ (0)	$RSDC \cdot 10^2$ (0)	CR (1)	BR (2)	DT [a]
ABN	0.109	3351	3.60	3.96	1.69	-1.59	0.94	1.13	24.8
SNEAK	0.121	3709	4.04	7.12	1.67	-2.44	0.97	1.15	22.8
H2OPMB	0.119	3648	4.27	7.34	1.71	-2.60	0.96	1.14	24.3
H2OPMB+α	0.123	3778	5.13	7.22	1.54	-2.89	0.87	1.05	71.0

<u>Table 10</u>

Results for DSA-5

Set	$\bar{\gamma}^{(0)}$	M [kg] $^{(2)}$	$\Delta K_L \cdot 10^{2\,(0)}$	$-\Delta K_F \cdot 10^{2\,(0)}$	$-DC \cdot 10^{2\,(0)}$	$RSDC \cdot 10^{2\,(0)}$	$CR^{(0)}$	$BR^{(2)}$	DT [a]
ABN	0.15	1452	1.41	1.73	0.96	-0.73	0.73	1.05	98
SNEAK	0.162	1567	1.54	5.30	0.97	-1.01	0.76	1.07	74
H2OPMB	0.160	1546	1.64	5.52	1.0	-1.08	0.75	1.06	86
H2OPMB+α	0.165	1594	2.30	5.48	0.86	-1.48	0.68	0.99	-

Table 11

Results for D2-02

Set	$\bar{\gamma}$ (2)	M [kg] (2)	$\Delta K_L \cdot 10^2$ (0)	$\Delta K_F \cdot 10^2$ (0)	$-DC \cdot 10^2$ (1)	CR (2)	BR (2)	DT [a]
ABN	0.11	3378	0.32	+2.29	0.60	0.94	1.30	12
NAP	0.132	3857	0.32	-0.11	0.48	0.98	1.35	12
NAPPMB	0.129	3779	0.32	-0.21	0.50	0.96	1.32	13
NAPPMB+α	0.132	3850	0.35	-0.44	0.41	0.89	1.23	17

Table 12

Results for G33

System	Pu239	Pu240	Pu241	Pu242
Na1	0.93	1,59	2.12	1.44
DSA-5 (≈D1)	0,90	1.27	1.28	1.40
G33	0.94	1.30	1.33	1.40

Table 13

Relative change of quasistationary Plutonium composition due to α (Pu239), relative to PMB sets.

Group	Energy range	Capture +%	Capture -%	Fission +%	Fission -%	inelastic scattering +%	inelastic scattering -%
1	6.5MeV-10.5MeV	10	10	10	10	15	15
2	4.0 - 6.5	10	10	10	10	15	15
3	2.5 - 4.0	10	10	15	15	15	15
4	1.4 - 2.5	10	10	7	7	20	20
5	0.8 - 1.4	10	10	7	7	15	15
6	0.4 - 0.8	10	10	7	7	15	15
7	0.2 - 0.4	20	20	7	7	15	15
8	0.1 - 0.2	20	20			15	15
9	46.5keV- 100keV	20	20			15	15
10	21.5 - 46.5	20	20				
11	10.0 - 21.5	20	20				
12	4.65 - 10	20	20				
13	2.15 - 4.65	20	20				
14	1.0 - 2.15	20	20				
15	0.465 - 1.0	15	15				
16	215 eV- 465 eV						
17	100 - 215						
18	46.5 - 100						
19	21.5 - 46.5						
20	10.0 - 21.5						
21	4.65 - 10.0						
22	2.15 - 4.65						
23	1.0 - 2.15	15	15				
24	0.465 - 1.0	2	2				
25	0.215 - 0.465	2	2				
26	0.0252	1	1				

Table 14:

Data uncertainties of U^{238} (beginning 1968)

Group	Energy range	Fission +%	Fission -%	$\alpha = \sigma_c/\sigma_f$ +%	$\alpha = \sigma_c/\sigma_f$ -%	Capture +%	Capture -%	$\bar{\nu}$ +%	$\bar{\nu}$ -%
1	6.5 - 10.5 MeV	7	7	20	20	20	20	2	2
2	4.0 - 6.5	7	7	20	20	20	20	2	2
3	2.5 - 4.0	7	7	20	20	20	20	2	2
4	1.4 - 2.5	7	7	20	20	20	20	2	2
5	0.8 - 1.4	7	10	10	10	12	15	2	2
6	0.4 - 0.8	10	10	10	10	15	15	1	1
7	0.2 - 0.4	10	10	10	10	15	15		
8	0.1 - 0.2	15	10	10	10	20	15		
9	46.5 - 100 keV	20	7	15	15	25	20		
10	21.5 - 46.5	20	7	30	0	40	10		
11	10.0 - 21.5	10	10	80	0	80	10		
12	4.65 - 10.0	20	20	100	0	100	20		
13	2.15 - 4.65	20	20	100	0	100	20		
14	1.0 - 2.15	20	20	80	0	80	20		
15	0.465- 1.0	20	20	70	0	75	20		
16	215 - 465 eV	20	20	40	0	45	20		
17	100 - 215	20	20	25	0	30	20		
18	46.5 - 100	20	20	20	20	30	30		
19	21.5 - 46.5	20	20	20	20	30	30		
20	10.0 - 21.5	20	20	20	20	30	30		
21	4.65 - 10.0	15	15	20	20	25	25		
22	2.15 - 4.65	15	15	20	20	25	25		
23	1.0 - 2.15	15	15	20	20	25	25		
24	0.465- 1.0	7	7	20	20	20	20		
25	0.215- 0.465	7	7	10	10	15	15		
26	0.0252	2	2	3	3	3	3	1	1

Table 15:

Data uncertainties of Pu^{239} (beginning 1968)

Group	Energy range	inelastic scattering +%	-%
1	6.5 MeV- 10.5 MeV	20	20
2	4.0 - 6.5	20	20
3	2.5 - 4.0	20	20
4	1.4 - 2.5	20	20
5	0.8 - 1.4	20	20
6	0.4 - 0.8	20	20
7	0.2 - 0.4	50	50
8	0.1 - 0.2	50	50
9	46.5 keV- 100 keV	50	50
10	21.5 - 46.5	50	50
11	10.0 - 21.5	50	50

Table 16:

Inelastic scattering cross-section uncertainty of Pu^{239} (beginning 1968)

Variation	δy *) (%)	δC.R.x10^2 *)	$\delta \Delta K_L$ (%) *) T = 900°K	$\delta \Delta K_L$ (%) *) T = 2100°K	δ R.S.D.C. (%) *) T = 900°K	δ R.S.D.C. (%) *) T = 2100°K	δ D.C. *) (%)
σ_f MAX GR 1 - 7	+ 1.73	+ 1.47	- 3.7	- 2.3	+ 2.8	+ 1.9	- 0.3
σ_γ MAX ALL GROUPS	- 8.32	+ 7.16	+ 15.1	+ 12.9	- 13.5	- 13.2	+ 2.1
σ_γ MAX GR 1 - 4	- 0.10	+ 0.03	+ 0.1	+ 0.1	0	0	+ 0.1
σ_γ MAX GR 1 - 9	- 2.68	+ 1.44	- 14.0	- 12.0	+ 13.3	+ 10.8	+ 2.8
σ_γ MAX GR 5 - 9	- 2.60	+ 1.82	- 14.1	- 12.0	+ 13.5	+ 10.8	+ 2.7
σ_γ MAX GR 10 - 14	- 4.72	+ 1.63	+ 11.5	+ 9.7	- 2.6	- 2.7	+ 1.9
σ_γ MAX GR 15 - 18	- 1.27	+ 1.14	+ 16.5	+ 14.6	- 19.4	- 17.8	- 5.5
σ_γ MAX GR 19 - 26	- 0.13	+ 0.18	+ 2.6	+ 2.1	- 5.8	- 8.9	+ 0.2
σ_{IN} MAX GR 1 - 4	- 1.48	- 0.86	+ 1.4	+ 1.2	- 0.7	- 0.8	- 0.2
σ_{IN} MAX GR 1 - 9	- 1.79	- 0.94	- 1.9	- 1.6	+ 2.3	+ 1.9	- 0.5

*) The parameters calculated at maximum burn up (55.000 MWd/t) with the KFK-SNEAK set are: y = 7.3931; C.R. = 0.9857; ΔK_L = + 11.30 % at 900°K and ΔK_L = 13.61 % at 2100°K; R.S.D.C. =-2.14 10^{-2} at 900°K and R.S.D.C. = - 2.58 10^{-2} at 2100°K; D.C. = - 1.54 10^{-5} $°K^{-1}$ at 900°K.

The parametervariations tabulated, are absolute variations.

Table 17. Influence of the nuclear data uncertainties of U^{238}.

Variation	δy *) (%)	δ C.R.x10[2] *)	$\delta \Delta K_L$ (%) *) T = 900°K	T = 2100°K	δ R.S.D.C. (%) *) T = 900°K	T = 2100°K	δ D.C. *) (%)
σ_γ MAX ALL GROUPS	- 7.36	- 6.98	+ 54.6	+ 44.0	- 54.6	- 44.5	+ 13.3
σ_γ MAX GR 1 - 4	- 0.01	- 0.01	0.0	+ 0.7	0	- 0.4	0
σ_γ MAX GR 5 - 9	- 0.38	- 0.97	- 3.5	- 1.8	+ 2.1	+ 1.9	+ 0.4
σ_γ MAX GR 10 - 14	- 4.12	-10.39	+ 18.3	+ 14.8	- 7.3	- 6.2	+ 7.3
σ_γ MAX GR 10 - 11	- 1.05	- 2.96	- 2.8	- 2.3	+ 3.5	+ 2.7	+ 1.3
σ_γ MAX GR 12 - 14	- 3.11	- 7.75	+ 20.7	+ 16.8	- 10.5	- 8.9	+ 6.1
σ_γ MAX GR 15 - 18	- 2.65	- 5.34	+ 34.8	+ 28.1	- 40.6	- 33.3	+ 5.0
σ_γ MAX GR 19 - 26	- 0.28	- 0.63	+ 4.0	+ 3.3	- 9.6	- 7.4	+ 0.7
σ_γ MIN GR 12 - 18	+ 2.14	+ 4.86	- 23.1	- 19.2	+ 26.8	+ 22.8	- 3.7
σ_γ MIN GR 5 - 11	+ 0.49	+ 1.33	+ 2.4	+ 2.1	- 2.6	- 1.9	- 0.5
σ_f MAX ALL GROUPS	+ 5.08	+ 4.27	- 31.4	- 24.7	+ 42.5	+ 34.1	- 11.7
σ_f MAX GR 1 - 4	+ 0.77	+ 0.23	- 1.2	- 1.0	+ 0.9	+ 0.8	- 0.1
σ_f MAX GR 5 - 9	+ 6.89	+ 1.44	+ 34.0	+ 28.4	- 34.3	- 28.2	- 0.6
σ_f MAX GR 10 - 14	+ 5.91	+ 1.36	- 4.9	- 4.2	+ 6.6	+ 5.1	- 1.2
σ_f MAX GR 10 - 12	+ 3.35	+ 0.72	+ 11.4	+ 9.5	- 13.3	- 10.9	- 0.3
σ_f MAX GR 13 - 14	+ 2.56	+ 0.50	- 16.7	- 13.9	+ 6.8	+ 5.8	- 0.9
σ_f MAX GR 15 - 18	+ 4.15	+ 1.32	- 53.7	- 43.7	+ 66.9	+ 48.1	- 5.6
σ_f MAX GR 19 - 26	+ 0.51	+ 0.05	- 7.6	- 6.0	+ 17.5	+ 14.0	- 1.7
σ_f MIN GR 5 - 12	- 6.00	- 1.37	- 25.8	- 21.4	+ 26.9	+ 22.5	+ 0.7
σ_{in} MAX GR 1 - 11	- 0.16	- 0.12	- 0.4	- 0.4	+ 0.5	+ 0.4	- 0.10

*) See note table 17

Table 18. Influence of the nuclear data uncertainties of Pu^{239}

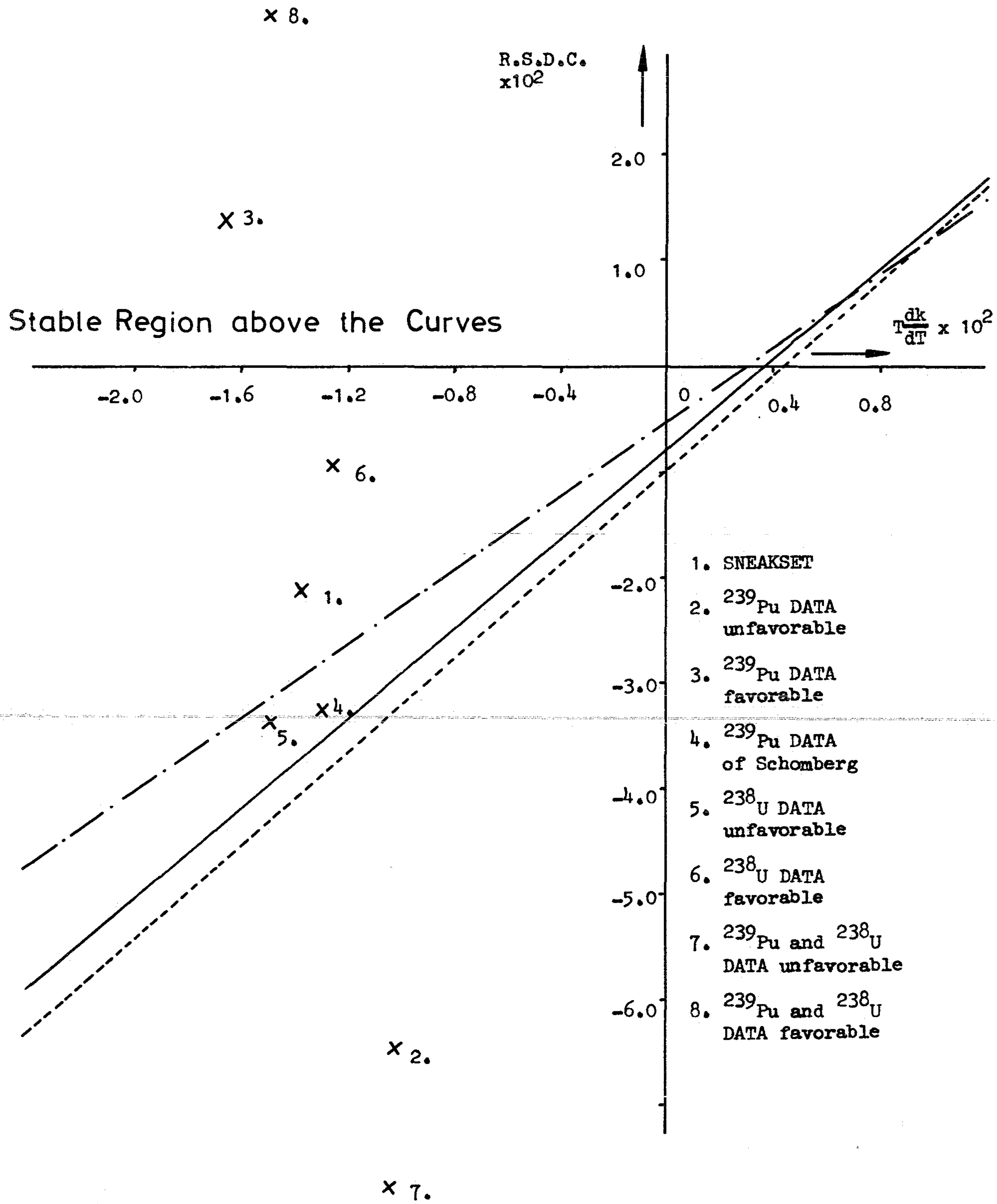
Variation	δ y ж) (%)	δ C.R.x10^2 ж)	δ Δ K_L (%) ж) T = 900°K	T = 2100°K	δ R.S.D.C. (%) ж) T = 900°K	T = 2100°K	δ D.C. ж) (%)
U^{238} DATA FAVOURABLE жж)	- 0.69	0	- 6.1	- 5.2	+ 57.0	+ 45.7	- 8.6
U^{238} DATA UNFAVOURABLE	+ 0.69	0	+ 6.1	+ 5.2	- 57.0	- 45.7	+ 8.6
Pu^{239} DATA FAVOURABLE	- 0.77	- 1.50	- 132.5	- 107.5	+ 164.0	+ 133.5	- 20.5
Pu^{239} DATA UNFAVOURABLE	- 0.80	- 9.26	+ 180.0	+ 145.0	- 200.0	- 164.0	+ 22.8
U^{238}+Pu^{239} DATA FAVOURABLE	+ 3.18	- 3.28	- 206.0	- 169.0	+ 266.0	+ 203.0	- 9.6
U^{238}+Pu^{239} DATA UNFAVOURABLE	- 0.18	- 9.03	+ 242.0	+ 197.0	- 264.0	- 215.0	+ 24.1
ABN f-factors of Pu^{239} жжж)	+ 0.20	+ 0.95	+ 14.7	+ 6.9	- 17.8	- 6.2	+ 23.1 жжж)

ж) See note table 17

жж) Favourable and unfavourable with respect to the R.S.D.C.

жжж) See text.

Table 19. <u>Influence of the nuclear data uncertainties of Pu^{239} and U^{238}.</u>



	$\frac{\Delta P}{P}$	P/P_n
————	0.01	1
--------	0.75	1
—·—	0.01	0.6

Fig. 1 Influence of Data Uncertainties with Respect to Stability (D1-CORE)