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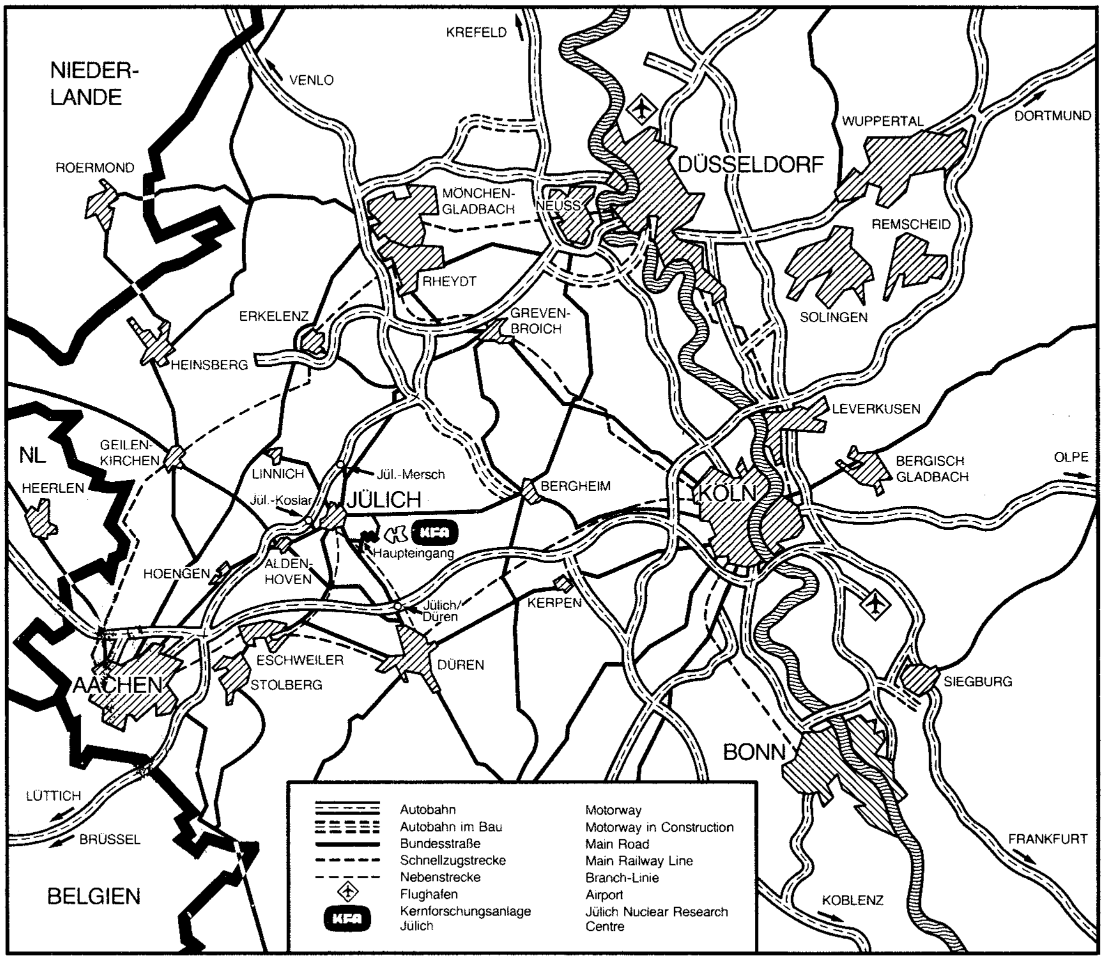

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* Zentralabteilung Forschungsreaktoren
** Heiße Zellen

ABSTRACT

For the German project "Forschungsvorhaben Komponentensicherheit" (FKS, i.e., Structural Integrity of Components) steel specimen irradiations have been carried out in the Jülich Merlin-type reactor (FRJ-1). The neutron monitoring to these irradiations is described in a German report (Jül-2087). In this context, some special considerations and results are given here, i.e., an experimental investigation of the fast neutron spectrum variation over a thick steel plate (in a special dosimetry test experiment); a comparison of the outcome of this investigation with the results from other FKS participants; and finally, the evaluation of the neutron exposure expressed in displacements per atom (dpa) in the centre of that steel plate.

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After Chapter 2:

1. INTRODUCTION

This report gives some special neutron measurement results from the spectral positions of the Jülich FKS steel irradiation capsules. The planning of the neutron measurements to the German project "Forschungsvorhaben Komponentensicherheit" (FKS, Structural Integrity of Components) has been described in /1/, the planning of a special dosimetry test experiment in connection with those measurements in /2/.

An overall account of the FKS irradiations with neutron measurements has been given in /3/; there also an outline of the measuring and evaluation procedure hs been included, and of the adjustment procedure for obtaining the neutron spectrum in the central position of the test experiment capsule, according to the algorithmus description in /4/. Particularly for the spectral positions in the FKS irradiation capsules in /3/ the measuring results (reaction rates, flux densities, fluences, and dpa values in different neutron energy regions) have been compiled and the correction treatment described.

In reactor irradiation investigations, generally the neutron spectrum must be known for determining the neutron exposure as an irradiation parameter. Moreover, particularly for bulky materials (like steel plates for LWR pressure vessels), the role of the local variation of the neutron spectrum and exposure has to be taken into account. To investigate this, the above mentioned special dosimetry test experiment hs been carried out in connection with the steel irradiations for the project FKS. In the Figures 1 to 4 the arrangement of the capsule and of the neutron detectors for the dosimetry test experiment has been displayed.

Since the fast neutron flux density and fluence values reported in /3/ have been obtained under the simplifying assumption that there is no neutron spectrum variation within all the test experiment detector locations, it is the purpose of Chapter 2 here to show (for the test experiment) whether a spectrum variation might be taken for confirmed or not between those locations; in Section 2.1. it will be discussed how to proceed with the variation assessment.

The spectrum variation results obtained from Chapter 2 need to be compared with those obtained by other participants in the FKS project which have carried out irradiations under conditions very similar to ours. Such a comparison (see Chapter 3) is of a twofold interest: the determination of the material exposure to radiation in different places must start from comparable conditions; and for similar radiation fields we should find similar effects. Furthermore, there is a special interest in this comparison here since from other sides there have been made theoretical investigations of the spectrum variation while our procedure was (see Chapter 2, beside the input spectrum for the adjustment in the reference position) relying on experimental values. To ask what deviations are to be stated between the reported spectrum variations and to judge their significance will be done (in Sec. 3.2.). The question of the spectrum variation relevance to the neutron fluence is studied (in Sec. 3.3.).

Finally (in Chapter 4) an account is given of the neutron exposure evaluation procedure in terms of displacements per atom (dpa). Starting with a description of the applied neutron measurement unfolding procedure to the dpa evaluation for our reference position, an outline will be given of the assessment of the dpa rate variation with the neutron spectrum over irradiated bulky steel samples. This assessment is restricted to the application of our measurement results. Finally (in Sec. 4.4), after a comparison of the obtained dpa cross section results incl. its spatial dependence with the results from other evaluations, the procedure of a practical determination of the location dependent dpa exposures will be given. It will be discussed whether the neutron spectrum variation found over the steel plates might influence the exposure values remarkably.

2. ESTIMATION OF THE FAST NEUTRON SPECTRUM VARIATION BY MEASUREMENT OVER A THICK STEEL PLATE

2.1. The variation assessment - aim and procedure

The aim of this arrangement has been /2/ to study the neutron spectrum variation along the x and z axes (cf. Fig. 2) in a device simulating the FKS original steel irradiation capsules as closely as possible. An assessment of the spectrum variation in the main travelling (x) direction of the neutrons is of primary importance because it may influence radiation-induced property changes of the steel. Furthermore it has been planned to study the neutron spectrum variation along the z axis, too, since this variation should be caused nearly purely by the material environment (steel and H_2O mainly), while the neutron intensity should change only slightly in the z direction. Besides, a spectrum variation study in the third Cartesian (y) direction seemed then to be superfluous.

For the spectral sets the (wider) stringer holes nos. 1, 3, 5 have been provided, for the gradient measurements the (narrower ones) nos. 2, 4 (Fig. 4).

Since for practical reasons it was not possible to arrange all the stringer holes along the x axis, the arrangement has been chosen as shown in Figs. 2 and 3, viz, the holes nos. 2, 3, 4 along the y direction, the holes nos 1, 3, 5 obliquely between the x and y axes. We did not expect that the differences in the y positions between the stringers 1, 3 and 5 will influence the results. Totally, resulting from the close stringer arrangement in the x direction and from the neutron field conditions not widely differing in the z direction, from the beginning we have not assumed to find large spectrum variations between the neutron measuring positions indicated in Fig. 4. Therefore we did not plan separate adjustment procedure applications for more than the one (central, No. 10) position the results of it having reported in /3/. Moreover we did find it attractive to use a special approximation procedure starting from the evaluated position No. 10. This should permit some systematic insight into the location dependency and also give an indication of the variation uncertainty which cannot be guessed by our adjustment procedure. Just because we have to expect small variations, unknown uncertainty contributions occurring in the adjustment procedure might superimpose each other so unhappily that real variations between different positions might be hidden or false ones simulated.

The spectrum variation is then aimed to be given in terms of a cross section variation $\delta\sigma_A(\vec{r})$ for calculating the flux density or fluence values in any position $\vec{r}$, using the measured reaction rate $R_A(\vec{r})$ for one (A) out of the reactions i = 1,..,n, to be compared with the cross section σ_A^c what has been obtained for the "c" (i.e., central, No. 10, cf. /3/) position. The assessment should make use of all the measuring reactions i successfully applied in position $\vec{r}$ according to their reaction rates and uncertainties. Finally a significance test should be applied to decide whether a stated variation against the "c" spectrum (i.e., in No. 10) could be taken for confirmed or not.

2.2. The spectrum index approach

A simple way for guessing differences in neutron spectra when using integral measuring methods would be to apply the well-known neutron spectrum index.

This index can be defined as follows:

$$I_i(\vec{r}) \equiv {}_f\phi_i(\vec{r}) \; / \; {}_f\phi_{Fe}(\vec{r}) \qquad (2.1)$$

where

i refers to one of the fast neutron threshold detector reactions,
F stands for the special reference reaction $^{54}Fe(n,p)^{54}Mn$,
${}_f\phi_i$ is the fission spectrum equivalent neutron flux density defined as follows:

$${}_f\phi_i(\vec{r}) \equiv R_i(\vec{r}) \; / \; \sigma_i^f \qquad (2.2)$$

with

R_i the reaction rate for the detector reaction i,
$\vec{r}$ the measuring detector position,
σ_i^f the cross section for the reaction i, averaged over the fission neutron spectrum

In Fig. 5 the slope of the neutron spectrum index I_i is displayed as a function of the neutron energy E. The arrows at the indicated reactions i = 1 to 11 point to the median energies I_i for an MTR spectrum /5/; the rectangles in Fig. 5 show the uncertainty windows for the reactions i, opened by the measurement uncertainty and by the 60 % energy response range (correspondingly from /5/).

While the I_i values in Fig. 5 have been obtained using m e a s u r e d σ_i^f cross sections reported by A. Fabry et al. /5/, the corresponding values (for the same "c" position cf. Sec. 2.2.) in Fig. 6 stem from e v a l u a t e d σ_i^f given in /6/.

The steepness of the I_i slope is an indication for the deviation of the fast neutron spectrum from the fission spectrum, viz, the steeper the left end slope of the curves, the weaker the spectrum. Since neutron scattering in iron causes weakening (cf. e.g. /7, 8, 9/, an increasing left end slope is correlated with the thickness of the steel layer penetrated by the fast neutrons from the reactor core. However, the large uncertainties and possible errors (connected, e.g., with the not doubtless selection of the cross sections σ_i^f) in the I_i curves make the spectrum index application to a procedure which seems to be too little reliable for discriminating neutron spectra. This all the more as there are relatively few "left end" measuring points available. Using the spectrum index one would hardly be able to judge whether two I_i curves belong to two different neutron spectra or to the same one.

So we have to look for another procedure to fulfil our task.

2.3. The double spectrum index approach

The "double spectrum index":

$$D_i \equiv \frac{R_i(\vec{r}) \cdot R_{Fe}(\vec{r}_c)}{R_i(\vec{r}_c) \cdot R_{Fe}(\vec{r})} \tag{2.3}$$

may be considered as consisting of purely experimental values, i.e., the reaction rates R for the measuring (i) reactions related to the

$^{54}Fe(n,p)^{54}Mn$ reaction, $\vec{r}$ denotes the measuring position where the spectrum has been determined (in our case by calculation and modified by adjustment /3/). If we denote the flux densities with the wanted real spectrum in the measuring ($\vec{r}$) and the "c" (central, $\vec{r}_c$) position as ϕ^M and ϕ^c, resp., then it follows from eq. (2.3):

$$D_i = \frac{\sigma_i^M \cdot \sigma_{Fe}^c}{\sigma_i^c \cdot \sigma_{Fe}^M} \tag{2.4}$$

with the so-called effective cross-section for the reaction i:

$$\sigma_i^M(E_L) \equiv \int_o^\infty \sigma_i(E)\ \phi_E^M(E)dE \ / \ \phi^M(E_L) \tag{2.4a}$$

with ϕ^M as the integral over the spectral flux density in the measuring position

$$\phi^M(E_L) \equiv \int_{E_L}^\infty \phi_E^M(E)dE = R_i(\vec{r}) \ / \ \sigma_i^M(E_L) \tag{2.4b}$$

The double ratio D_i is not affected by the questionable consistency of the cross sections for the set of reactions i = 1,...,n averaged over a reference (e.g., the fission) spectrum. For the wanted flux density ϕ^M there holds for any one of the reactions i

$$\phi^M \cdot \frac{\sigma_{Fe}^M}{\sigma_{Fe}^c} = \frac{R_i(\vec{r})}{\sigma_i^c} \cdot D_i^{-1} \tag{2.5}$$

and with eq. (2.4) and

$$C \equiv \sigma_{Fe}^M \ / \ \sigma_{Fe}^c \ , \qquad {}_c\phi_i^M \equiv R_i(\vec{r}) \ / \ \sigma_i^c \ ,$$

$$\delta_i\phi^M \equiv {}_c\phi_i^M \ / \ \phi^M - 1 \tag{2.6a}$$

there is

$$S_i \equiv CD - 1 = \delta_i \phi^M \ . \qquad (2.6b)$$

Since eqs. (2.6b) do exist with values on the right-hand side which are generally different and not zero, we may carry out a least-squares fit to determine ϕ^M.

Retaining Fe as the reference detector, we want to express the spectrum variation to be assessed in terms of the relative variation of the Fe cross section:

$$\delta\sigma_{Fe} \equiv (\sigma^M_{Fe} - \sigma^c_{Fe}) \ / \ \sigma^c_{Fe} \qquad (2.7)$$

We go on using the formal quantities from eqs. (2.6) for the reactions j, supplemented by

$$\delta\sigma_j \equiv (\sigma^M_j - \sigma^c_j) \ / \ \sigma^c_j = S_j \qquad (2.8)$$

for the reactions j = 1,...,n-1 beside the Fe reaction (for which holds: $S_{Fe} \equiv \delta\sigma_{Fe}$). To find the best-fitting $\delta\sigma_{Fe}$, we adopt arbitrary $\delta\sigma_{Fe}$ values one after another until we will have found

$$S_p^2 \equiv \sum_{j=1}^{n-1} p_j S_j^2 \ / \ \sum_{j-1}^{n-1} p_j = \text{Min!} \qquad (2.9)$$

where the S_j values have been weighted according to their measuring accuracies.

To assess the relative uncertainty $\rho(S_p)$ belonging to the found averaged spectrum variation $S_p \equiv \pm \sqrt{\text{Min } S_p^2}$, we apply the uncertainty propagation procedure:

$$\rho(S_p) = \frac{1}{S_p} \sqrt{\sum_{j=1}^{n-1} \left(\frac{\partial S_p}{\partial D_j} \cdot D_j \cdot \rho_j\right)^2}$$

$$= C \; \frac{\sqrt{\sum_{j=1}^{n=1} (p_j \cdot S_j \cdot D_j \cdot \rho_j)^2}}{\sum_{j=1}^{n-1} p_j \; S_j^2} \qquad (2.10)$$

In eq. (2.10) the relative double spectrum index uncertainty values:

$$\rho_j = \rho(D_j) \qquad (2.10a)$$

appear to be correlated insofar as each ρ_j is containing common contributions from the reference detector Fe. However, each consists only of two terms proportional to the j reaction contribution and two other ones uncorrelated to that (but stemming fromo the Fe reaction). So it is to expect that no correlation coefficients different from zero will occur /10/. Therefore the pure variance procedure as given in eq. (2.10) seems to be justified.

For judging whether the found minimal averaged spectral variation S_p as well as the cross section variation belonging to S_p: $\delta\sigma_{Fe}(S_p)$ will deviate significantly from the reference "c" spectrum, the known T values from Student's distribution will be used. This will be demanded for both quantities S_p and $\delta\sigma_{Fe}(S_p)$ because $\rho(S_p)$ represents the mean uncertainty for each $\delta\sigma_j$ and also for the $\delta\sigma_{Fe}$ found out of them. We require then analogously to the well-known relation:

$$-T \cdot S_p \cdot \rho(S_p) < u - u_c < +T \; S_p \; \rho(S_p) \qquad (2.11)$$

that for both the absolute quantities:

$$|u| = \begin{cases} |S_p| \\ |\delta\sigma_{Fe}(S_p)| \end{cases} \qquad (2.12a)$$

should hold

$$|u| > |T \cdot S_p \cdot \rho(S_p)| \tag{2.12b}$$

if a spectrum variation from the reference "c" spectrum appears as shown. In eq. (2.11) it has to be supposed:

$$u_c = \{ \begin{array}{l} S_p^c \equiv 0 \\ \delta\sigma_{Fe}^c \equiv 0 \end{array} \tag{2.12c}$$

The T values refer to n-2 degrees of freedom and to the significance probability p.

The approach according to the equations (2. 11, 12) is well known as a zero hypothesis assumption outgoing from u_c. It affords a certain limit for avoiding the so-called statistical risk of the first kind, i.e., to neglect the zero hypothesis. The risk of the second kind (i.e., to adopt the zero hypothesis instead of an alternative one), however, is generally more difficult to contain because the most probable (or theoretical) value to be assigned to an alternative hypothesis may often be unknown. The significance probability (confidence level) P should be chosen taking into account such considerations in the practical case (cf., e.g., /11/).

2.4. Results, uncertainties, and discussion of the found spectrum variation

In the Tables I-1 to -9 (Chapter 2) the double spectrum indices have been compiled in $(100D_i-1)\%$ with D_i according to eq. (2.3), together with their constituent reaction rates and with the uncertainties, for the successfully applied measuring reactions j in the measuring positions including fast fission detectors in the test experiment capsule. Particularly in Table I-5 (Chapter 2) the same presentation is given for the calculated reaction rates according to the adjustment procedure /3/ related to the measured ones, both in the "c" position (No. 10).

The spectrum variation assessment following to the equations (2.9) to (2.12) to the same positions has been displayed in the Tables II-1 to -4, -6 to -9 (Chapter 2). While we have used the zero hypothesis as given in Section 2.3 as a one-sided significance test, instead of an alternative hypothesis we have applied the same procedure as for the measuring values for the calculational ones in the "c" position (s. Table II-5 (Chapter 2) for No. 10 calc.). From that we have chosen the significance probability P as high as there is any spectrum variation to be excluded between reference values "position No. 10 measured" and the values "position No. 10 calculated". On the other side, we have chosen the probability P as low as there is to find a shown spectrum variation in at least one measuring point. We did choose P = 92,5 % as an intermediate value between the common ones = 90 and = 95 %. The T values belonging to the chosen P have been taken from /12/.

The results in the Tables II-1 to -9 (Chapter 2) appear to be reasonable since it is a priori most likely to find the largest possible variations in the stringers 1 and 5 against stringer 3 and not within stringer 3 itself. Beside of the variations shown for the x axis distances positions Nos. 3 and 17, a spectrum variation has been confirmed with our significance test procedure also in the z axis distance position No. 5. In accordance with our remarks in Sections 2.1 and 2.2, it is reasonable as well that we found p o s i t i v e cross section variations $\delta\sigma_{Fe}(S_p)$ in the positions Nos. 3 (and 5), i.e., a relatively h a r d e r spectrum after a s h o r t e r neutron travelling distance in the x direction than in the "c" position (No. 10). Correspondingly, in position No. 17 we found a negative $\delta\sigma_{Fe}(S_p)$, i.e., a relatively weaker spectrum.

In Fig. 7 the curve "here" gives the found Fe cross section deviation $\delta\sigma_{Fe}(x)$ for the measuring positions Nos. 3, 10, and 17; these positions are the closest ones to the reactor core mid-plane CM (z=0) with the assumption that there is no spectrum variation in the y direction (cf. Figures 2 and 4 and the discussion in Sec. 2.1). The $\delta\sigma_{Fe}$ values were taken out of the Tables II-1 to -9 (Chapter 2). The slope of the x dependent deviation $\delta\sigma_{Fe}$ has been extrapolated to the inner and outer edges of the steel block. (The other curves given in Fig. 7 for comparison will be discussed in Chapter 3).

From Fig. 7 the Fe cross section deviation averaged over all x locations in the block in the z plane of the three above mentioned positions (i.e., for nearly z=0) may then be guessed to

$$\delta\sigma_{Fe}(\bar{x};\ z=0) \approx \pm\ 0.096 \tag{2.13a}$$

Far away from z=0 there is to expect in the block, according to Tables II-1 to -9 (Chapter 2):

$$\delta\sigma_{Fe}(\bar{x};\ |z|>>0) \approx \pm\ 0 \tag{2.13b}$$

Uncertainties (as reported in those Tables) were neglected in eqs. 2.13. The wanted fast neutron flux density ϕ^M in a location x;z (neglecting any y dependency) may then according to eq. (2.4b) be expressed by the formula:

$$\phi^M(E_L,x;z) = \frac{R_{Fe}(x;z)}{\sigma^c_{Fe}(E_L)\ \cdot\ \left[1+\delta\sigma_{Fe}(E_L,x;z)\right]} \tag{2.14}$$

with:

- $R_{Fe}(x;z)$ the $^{54}Fe(n,p)^{54}Mn$ reaction rate in the x;z position,

- $$\sigma^c_{Fe}(E_L=1MeV) = \frac{\int_o^\infty \sigma_{Fe}(E)\phi^c_E(E)dE}{\int_{1MeV}^\infty \phi^c_E(E)dE} = 4.37\cdot 10^{-26}\ cm^{-2} \tag{2.14a}$$

  the effective cross section for the $^{54}Fe(n,p)^{54}Mn$ reaction in the "c" position (i.e., No. 10) according to the spectrum calculation and adjustment /3/.

- $\delta\sigma_{Fe}(E_L>1MeV;x;z)$ the Fe cross section deviation as defined above, for measuring reactions j=1,...n-1 with energy response ranges from and above E_L; figures may be inserted from Tables II-1 to -4 or -6 to -9 (Chapter 2) or, e.g., according to eqs. (2.13).

The "corrected flux densities for the measuring positions" given in Tables II-1 to -9 (Chapter 2) have been evaluated using eq. (2.14).

Table I-1

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS — Irrad.: E 57 — Source: FRJ-1
Ref.Pos.: No.10 — Meas.Pos.: No. 1

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	1.36222E-11	2.31	-13.1042	6.49189
In115(n,n')	7.9648E-13	3.15	9.19771E-13	3.14	-6.7853	7.15923
U238(n,f)	1.0892E-12	1.85	1.29769E-12	2.36	-3.8293	6.36118
Th232(n,f)	2.7131E-13	5.37	3.11078E-13	5.55	-7.44859	9.54526
Ti47(n,p)	4.5325E-14	4.34	5.44126E-14	4.33	-3.0961	8.31006
Ni58(n,p)	2.3206E-13	3.2	2.90256E-13	3.21	.962567	7.21226
Fe54(n,p)	1.6173E-13	4.5	2.0036E-13	3.35	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	2.35702E-14	3.43	4.02862	7.326
Ti48(n,p)	5.4095E-16	2.55	6.59558E-16	2.8	-1.58182	6.76868
Al27(n,a)	1.2365E-15	2.72	1.53831E-15	2.69	.422072	6.79022

Table I-2

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS Irrad.: E 57 Source: FRJ-1
Ref.Pos.: No.10 Meas.Pos.: No. 3

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	1.4033E-11	2.3	-14.4748	7.27778
In115(n,n')	7.9648E-13	3.15	9.3906E-13	3.2	-9.07361	7.90586
U238(n,f)	1.0892E-12	1.85	1.3345E-12	1.84	-5.51076	7.01057
Ti47(n,p)	4.5325E-14	4.34	5.6058E-14	4.33	-4.61696	8.94005
Ni58(n,p)	2.3206E-13	3.2	2.9872E-13	3.2	-.726008	7.92591
Fe54(n,p)	1.6173E-13	4.5	2.0971E-13	4.7	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	2.3336E-14	3.29	-1.59706	7.97477
Ti48(n,p)	5.4095E-16	2.55	6.6829E-16	2.43	-4.72494	7.39915
Al27(n,a)	1.2365E-15	2.72	1.6054E-15	2.68	.129175	7.54459

Further Remark: Th232(n,f) Outlier

Table I-3 Cap. 2

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS Irrad.: E 57 Source: FRJ-1
Ref.Pos.: No.10 Meas.Pos.: No.5

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	1.1484E-11	2.31	-12.1741	6.97469
In115(n,n')	7.9648E-13	3.15	7.86313E-13	3.15	-4.46169	7.60389
U238(n,f)	1.0892E-12	1.85	1.03163E-12	1.86	-8.34139	6.69748
Th232(n,f)	2.7131E-13	5.37	2.54164E-13	5.34	-9.34219	9.76354
Ti47(n,p)	4.5325E-14	4.34	4.44672E-14	4.33	-5.05788	8.69245
Ni58(n,p)	2.3206E-13	3.2	2.36086E-13	3.21	-1.54746	7.64972
Fe54(n,p)	1.6173E-13	4.5	1.67122E-13	4.21	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.89967E-14	3.6	.518334	7.83371
Ti48(n,p)	5.4095E-16	2.55	5.36109E-16	2.53	-4.0924	7.13285
Al27(n,a)	1.2365E-15	2.72	1.29002E-15	2.69	.962317	7.25318

Table I-4

Cap. 2

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS   Irrad.: E 57   Source: FRJ-1
Ref.Pos.: No.10   Meas.Pos.: No. 6

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	6.8162E-12	2.32	-18.4141	7.71952
In115(n,n')	7.9648E-13	3.15	5.3771E-13	3.16	2.25251	8.29341
U238(n,f)	1.0892E-12	1.85	7.4791E-13	1.87	4.00213	7.4694
Th232(n,f)	2.7131E-13	5.37	1.855E-13	5.39	3.55682	10.3325
Ti47(n,p)	4.5325E-14	4.34	3.0881E-14	4.35	3.19393	9.30756
Ni58(n,p)	2.3206E-13	3.2	1.6027E-13	3.2	4.60502	8.32782
Fe54(n,p)	1.6173E-13	4.5	1.0678E-13	5.35	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.3152E-14	3.58	8.91869	8.49246
Ti48(n,p)	5.4095E-16	2.55	3.6274E-16	2.53	1.56378	7.85977
Al27(n,a)	1.2365E-15	2.72	8.4239E-16	2.68	3.18571	7.96576

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS Irrad.: E 57 Source: FRJ-1
Ref.Pos.: No.10 Meas.Pos.: No.10 calc.

Measuring ent Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	1.2425E-11	2.31	2.83183	7.15348
In115(n,n')	7.9648E-13	3.15	8.1664E-13	3.15	7.37786	7.76821
U238(n,f)	1.0892E-12	1.85	1.1057E-12	1.85	6.31353	6.88077
Th232(n,f)	2.7131E-13	5.37	2.6305E-13	5.37	1.53863	9.98827
Ti47(n,p)	4.5325E-14	4.34	4.396E-14	4.34	1.57313	8.84145
Ni58(n,p)	2.3206E-13	3.2	2.3769E-13	3.2	7.26786	7.80897
Fe54(n,p)	1.6173E-13	4.5	1.5443E-13	4.5	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.8945E-14	3.23	8.48348	7.83364
Ti48(n,p)	5.4095E-16	2.55	5.0682E-16	2.55	-1.88045	7.31471
Al27(n,a)	1.2365E-15	2.72	1.3207E-15	2.72	11.8585	7.43618

Further Remark: Test whether same spectrum produces"significant"spec.variation

Table I-6

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS   Irrad.: E 57   Source: FRJ-1
Ref.Pos.: No.10   Meas.Pos.: No. 14

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	7.2138E-12	2.32	-5.68057	7.17561
In115(n,n')	7.9648E-13	3.15	5.0985E-13	3.15	5.90893	7.78563
U238(n,f)	1.0892E-12	1.85	6.7104E-13	1.88	1.93085	6.90853
Th232(n,f)	2.7131E-13	5.37	1.6766E-13	5.47	2.24183	9.97641
Ti47(n,p)	4.5325E-14	4.34	2.7142E-14	4.35	-.923896	8.86166
Ni58(n,p)	2.3206E-13	3.2	1.4427E-13	3.2	2.8586	7.8263
Fe54(n,p)	1.6173E-13	4.5	9.7752E-14	4.53	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.1466E-14	3.36	3.72583	7.90528
Ti48(n,p)	5.4095E-16	2.55	3.1924E-16	3.66	-2.36061	7.78903
Al27(n,a)	1.2365E-15	2.72	8.0102E-16	2.7	7.18008	7.4471

Table I-7

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS | Irrad.: E 57 | Source: FRJ-1
Ref.Pos.: No.10 | Meas.Pos.: No. 15

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	1.00524E-11	2.31	4.80562	7.00499
In115(n,n')	7.9648E-13	3.15	6.14766E-13	3.15	1.83042	7.63169
U238(n,f)	1.0892E-12	1.85	8.18924E-13	2.37	-.807577	6.88745
Th232(n,f)	2.7131E-13	5.37	2.01713E-13	5.42	-1.91318	9.82909
Ti47(n,p)	4.5325E-14	4.34	3.35359E-14	4.35	-2.38542	8.72673
Ni58(n,p)	2.3206E-13	3.2	1.76625E-13	3.21	.414062	7.67735
Fe54(n,p)	1.6173E-13	4.5	1.22588E-13	4.26	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.39507E-14	3.33	.634921	7.74077
Ti48(n,p)	5.4095E-16	2.55	3.81497E-16	3.46	-6.95852	7.54134
Al27(n,a)	1.2365E-15	2.72	1.06185E-15	2.73	13.2952	7.29719

Table I-8

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS   **Irrad.: E 57**   Source: FRJ-1
Ref.Pos.: No.10   Meas.Pos.: No. 17

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	1.0441E-11	2.31	10.377	7.54534
In115(n,n')	7.9648E-13	3.15	6.5117E-13	3.15	9.36642	8.1305
U238(n,f)	1.0892E-12	1.85	8.5325E-13	1.86	4.79317	7.28987
Ti47(n,p)	4.5325E-14	4.34	3.1508E-14	4.35	-7.00761	9.16614
Ni58(n,p)	2.3206E-13	3.2	1.8251E-13	3.2	5.20847	8.16946
Fe54(n,p)	1.6173E-13	4.5	1.209E-13	5.1	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.4212E-14	3.31	3.95124	8.2249
Ti48(n,p)	5.4095E-16	2.55	4.198E-16	2.5	3.81248	7.68196
Al27(n,a)	1.2365E-15	2.72	9.7626E-16	2.69	5.61744	7.80349

Further Remark: Th232(n,f) Outlier

Table I-9

** Double Spectrum Index Related to Fe-54(n,p)Mn-54 And to Reference Position **

Exper.: FKS | Irrad.: E 57 | Source: FRJ-1
Ref.Pos.: No.10 | Meas.Pos.: No.19

Measuring Reaction	Reference Pos. React.Rate,1/s	Its Unc.,+/-%	Measuring Pos. React.Rate,1/s	Its Unc.,+/-%	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	1.2654E-11	2.31	7.87278E-12	2.32	5.04812	6.50062
In115(n,n')	7.9648E-13	3.15	5.13547E-13	3.16	8.86629	7.17271
U238(n,f)	1.0892E-12	1.85	6.73657E-13	1.88	4.42853	6.20456
Th232(n,f)	2.7131E-13	5.37	1.60841E-13	5.75	9.65118E-02	9.66639
Ti47(n,p)	4.5325E-14	4.34	2.74685E-14	4.34	2.32579	8.31931
Ni58(n,p)	2.3206E-13	3.2	1.45402E-13	3.23	5.7933	7.22582
Fe54(n,p)	1.6173E-13	4.5	9.57861E-14	3.36	0	0
Ti(n,x)Sc46	1.8289E-14	3.23	1.09901E-14	3.36	1.46115	7.29809
Ti48(n,p)	5.4095E-16	2.55	3.18104E-16	2.13	-.711256	6.52526
Al27(n,a)	1.2365E-15	2.72	7.60944E-16	2.69	3.90742	6.79515

Table II-1

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: **FKS** **Irradiation: E 57**
Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: **No. 1**
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%	Mean Spectrum Variation	Variation Uncert.,+/-%
Np237(n,f)	-13.1042	6.49189		
In115(n,n')	-6.7853	7.15923		
U238(n,f)	-3.8293	6.36118		
Th232(n,f)	-7.44859	9.54526		
Ti47(n,p)	-3.0961	8.31006		
Ni58(n,p)	.962567	7.21226		
Ti(n,x)Sc46	4.02862	7.326		
Ti48(n,p)	-1.58182	6.76868		
Al27(n,a)	.422072	6.79022		
	For the Adopted	Fe Cross Sec.Dev.: 0 %	.060803	35.448
	For the Adopted	Fe Cross Sec.Dev.: 1 %	5.64101E-02	38.774
	For the Adopted	Fe Cross Sec.Dev.:-1 %	.066325	32.1732
	For the Adopted	Fe Cross Sec.Dev.: 2 %	5.34255E-02	41.8032
	For the Adopted	Fe Cross Sec.Dev.:-2 %	7.27193E-02	29.1329
	For the Adopted	Fe Cross Sec.Dev.: 3 %	5.20919E-02	44.0317
	For the Adopted	Fe Cross Sec.Dev.:-3 %	7.97764E-02	26.3983
	For the Adopted	Fe Cross Sec.Dev.: 4 %	5.25351E-02	44.9684
	For the Adopted	Fe Cross Sec.Dev.:-4 %	8.73359E-02	23.9787
	For the Adopted	Fe Cross Sec.Dev.: 5 %	5.47119E-02	44.4215
	For the Adopted	Fe Cross Sec.Dev.:-5 %	9.52781E-02	21.8535
	For the Adopted	Fe Cross Sec.Dev.: 6 %	5.84289E-02	42.6241
	For the Adopted	Fe Cross Sec.Dev.:-6 %	.103515	19.9909
	For the Adopted	Fe Cross Sec.Dev.: 7 %	.063416	40.0563
No.of Reactions I= 10	With the Found	Fe Cross Sec.Dev.: 3.25056 %	5.20361E-02	43.6757

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 3.61868
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as **Not Confirmed** with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
4.58118E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1

The corrected flux density for this measuring position is then: **4.58118E+12** 1/(cm^2*s)

Table II-2

04LP2052 05/14/85 10:30:50

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS Irradiation: E 57

Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: No. 3

Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%		Mean Spectrum Variation,Abs.Val.	Variation Uncert.,+/-%
Np237(n,f)	-14.4748	7.27778			
In115(n,n')	-9.07361	7.90586			
U238(n,f)	-5.51076	7.01057			
Ti47(n,p)	-4.61696	8.94005			
Ni58(n,p)	-.726008	7.92591			
Ti(n,x)Sc46)	-1.59706	7.97477			
Ti48(n,p)	-4.72494	7.39915			
Al27(n,a)	.129175	7.54459			
	For the	A d o p t e d	Fe Cross Sec.Dev.: 0 %	.06994	34.4582
	For the	A d o p t e d	Fe Cross Sec.Dev.: 1 %	6.34874E-02	38.1601
	For the	A d o p t e d	Fe Cross Sec.Dev.:-1 %	7.70231E-02	31.148
	For the	A d o p t e d	Fe Cross Sec.Dev.: 2 %	5.78766E-02	42.1724
	For the	A d o p t e d	Fe Cross Sec.Dev.:-2 %	8.45784E-02	28.2349
	For the	A d o p t e d	Fe Cross Sec.Dev.: 3 %	5.33738E-02	46.2734
	For the	A d o p t e d	Fe Cross Sec.Dev.:-3 %	9.24903E-02	25.6886
	For the	A d o p t e d	Fe Cross Sec.Dev.: 4 %	5.02774E-02	50.0298
	For the	A d o p t e d	Fe Cross Sec.Dev.:-4 %	.100675	23.4662
	For the	A d o p t e d	Fe Cross Sec.Dev.: 5 %	4.88557E-02	52.7956
	For the	A d o p t e d	Fe Cross Sec.Dev.:-5 %	.109071	21.5234
	For the	A d o p t e d	Fe Cross Sec.Dev.: 6 %	4.92538E-02	53.9224
	For the	A d o p t e d	Fe Cross Sec.Dev.:-6 %	.117632	19.8193
	For the	A d o p t e d	Fe Cross Sec.Dev.: 7 %	5.14297E-02	53.1536
No.of Reactions I= 9	With the	F o u n d	Fe Cross Sec.Dev.: 5.28124 %	4.87837E-02	52.3131

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 4.12563
using STUDENT's cut-off value T925(I-2)= 1.61661
So a variation from the reference spectrum appears as Shown with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
4.79496E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1.05281

The corrected flux density for this measuring position is then: **4.55443E+12** 1/(cm^2*s)

Table II-3

03LP2052   05/10/85   14:30:53
** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS   Irradiation: E 57
Source: FRJ-1   Ref.Pos.: No.10   Meas.Pos.: No. 5
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%	Mean Spectrum Variation	Variation Uncert.,+/-%
Np237(n,f)	-12.1741	6.97469		
In115(n,n')	-4.46169	7.60389		
U238(n,f)	-8.34139	6.69748		
Th232(n,f)	-9.34219	9.76354		
Ti47(n,p)	-5.05788	8.69245		
Ni58(n,p)	-1.54746	7.64972		
Ti(n,x)Sc46	.518334	7.83371		
Ti48(n,p)	-4.0924	7.13285		
Al27(n,a)	.962317	7.25318		
	For the A d o p t e d	Fe Cross Sec.Dev.: 0 %	6.50039E-02	35.2385
	For the A d o p t e d	Fe Cross Sec.Dev.: 1 %	5.85474E-02	39.464
	For the A d o p t e d	Fe Cross Sec.Dev.:-1 %	7.21428E-02	31.5252
	For the A d o p t e d	Fe Cross Sec.Dev.: 2 %	5.30235E-02	44.091
	For the A d o p t e d	Fe Cross Sec.Dev.:-2 %	7.97814E-02	28.3177
	For the A d o p t e d	Fe Cross Sec.Dev.: 3 %	.04875	48.7731
	For the A d o p t e d	Fe Cross Sec.Dev.:-3 %	8.77891E-02	25.5627
	For the A d o p t e d	Fe Cross Sec.Dev.: 4 %	4.60762E-02	52.812
	For the A d o p t e d	Fe Cross Sec.Dev.:-4 %	9.60738E-02	23.1956
	For the A d o p t e d	Fe Cross Sec.Dev.: 5 %	4.52865E-02	55.2477
	For the A d o p t e d	Fe Cross Sec.Dev.:-5 %	.10457	21.1543
	For the A d o p t e d	Fe Cross Sec.Dev.: 6 %	4.64768E-02	55.3667
	For the A d o p t e d	Fe Cross Sec.Dev.:-6 %	.113229	19.3847
	For the A d o p t e d	Fe Cross Sec.Dev.: 7 %	4.95048E-02	53.2575
	For the A d o p t e d	Fe Cross Sec.Dev.:-7 %	.122017	17.8416
	For the A d o p t e d	Fe Cross Sec.Dev.: 8 %	5.40623E-02	49.7027
No.of Reactions I= 10	With the F o u n d	Fe Cross Sec.Dev.: 4.89884 %	4.52764E-02	55.3888

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 3.993
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as Shown with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
3.8212E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1.04899

The corrected flux density for this measuring position is then: 3.64275E+12 1/(cm^2*s)

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS Irradiation: E 57
Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: No. 6
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%	Mean Spectrum Variation,Abs.Val.	Variation Uncert.,+/-%
Np237(n,f)	-18.4141	7.71952		
In115(n,n')	2.25251	8.29341		
U238(n,f)	4.00213	7.4694		
Th232(n,f)	3.55682	10.3325		
Ti47(n,p)	3.19393	9.30756		
Ni58(n,p)	4.60502	8.32782		
Ti(n,x)Sc46	8.91869	8.49246		
Ti48(n,p)	1.56378	7.85977		
Al27(n,a)	3.18571	7.96576		
	For the A d o p t e d	Fe Cross Sec.Dev.: 0 %	7.78167E-02	31.7442
	For the A d o p t e d	Fe Cross Sec.Dev.: 1 %	8.05014E-02	31.8672
	For the A d o p t e d	Fe Cross Sec.Dev.:-1 %	7.63914E-02	31.1618
	For the A d o p t e d	Fe Cross Sec.Dev.: 2 %	8.43253E-02	31.5294
	For the A d o p t e d	Fe Cross Sec.Dev.:-2 %	.076296	30.1995
	For the A d o p t e d	Fe Cross Sec.Dev.: 3 %	8.91418E-02	30.801
	For the A d o p t e d	Fe Cross Sec.Dev.:-3 %	7.75355E-02	28.9813
	For the A d o p t e d	Fe Cross Sec.Dev.: 4 %	9.47998E-02	29.7892
	For the A d o p t e d	Fe Cross Sec.Dev.:-4 %	8.00479E-02	27.6232
No.of Reactions I= 10	With the F o u n d	Fe Cross Sec.Dev.:-1.57146 %	7.61734E-02	29.7558

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 3.60895
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as **Not Confirmed** with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
2.4415E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1

The corrected flux density for this measuring position is then: **2.4415E+12** 1/(cm^2*s)

Table II-5

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS Irradiation: E 57
Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: No. 10 calc.
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%	Mean Spectrum Variation,Abs.Val.	Variation Uncert.,+/-%
Np237(n,f)	2.83183	7.15348		
In115(n,n')	7.37786	7.76821		
U238(n,f)	6.31353	6.88077		
Th232(n,f)	1.53863	9.90827		
Ti47(n,p)	1.57313	8.84145		
Ni58(n,p)	7.26786	7.80897		
Ti(n,x)Sc46	8.48348	7.83364		
Ti48(n,p)	-1.88045	7.31471		
Al27(n,a)	11.8585	7.43618		
	For the Adopted	Fe Cross Sec.Dev.: 0 %	6.64261E-02	42.3876
	For the Adopted	Fe Cross Sec.Dev.: 1 %	7.52227E-02	37.7518
	For the Adopted	Fe Cross Sec.Dev.:-1 %	5.82085E-02	47.907
	For the Adopted	Fe Cross Sec.Dev.: 2 %	8.44174E-02	33.913
	For the Adopted	Fe Cross Sec.Dev.:-2 %	5.08512E-02	54.1801
	For the Adopted	Fe Cross Sec.Dev.: 3 %	9.38933E-02	30.7335
	For the Adopted	Fe Cross Sec.Dev.:-3 %	4.47803E-02	60.5062
	For the Adopted	Fe Cross Sec.Dev.: 4 %	.103573	28.0829
	For the Adopted	Fe Cross Sec.Dev.:-4 %	4.05775E-02	65.2071
	For the Adopted	Fe Cross Sec.Dev.: 5 %	.113405	25.8535
	For the Adopted	Fe Cross Sec.Dev.:-5 %	3.88536E-02	66.0718
	For the Adopted	Fe Cross Sec.Dev.: 6 %	.123353	23.9602
	For the Adopted	Fe Cross Sec.Dev.:-6 %	3.99312E-02	62.3676
	For the Adopted	Fe Cross Sec.Dev.: 7 %	.13339	22.3371
	For the Adopted	Fe Cross Sec.Dev.:-7 %	4.36029E-02	55.8037
No.of Reactions I= 10	With the Found	Fe Cross Sec.Dev.:-5.11535 %	.038835	66.266

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 4.09751
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as **Not Confirmed** with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
3.531E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1

The corrected flux density for this measuring position is then: **3.531E+12** 1/(cm^2*s)

Table II-6

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS   Irradiation: E 57
Source: FRJ-1   Ref.Pos.: No.10   Meas.Pos.: No. 14
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%		Mean Spectrum Variation,Abs.Val.	Variation Uncert.,+/-%
Np237(n,f)	-5.68057	7.17561			
In115(n,n')	5.90893	7.78563			
U238(n,f)	1.93085	6.90853			
Th232(n,f)	2.24183	9.97641			
Ti47(n,p)	-.923896	8.86166			
Ni58(n,p)	2.8586	7.8263			
Ti(n,x)Sc46	3.72583	7.90528			
Ti48(n,p)	-2.36061	7.78903			
Al27(n,a)	7.18008	7.4471			
	For the	A d o p t e d	Fe Cross Sec.Dev.: 0 %	4.30831E-02	62.452
	For the	A d o p t e d	Fe Cross Sec.Dev.: 1 %	4.81436E-02	57.0605
	For the	A d o p t e d	Fe Cross Sec.Dev.:-1 %	4.00163E-02	65.4201
	For the	A d o p t e d	Fe Cross Sec.Dev.: 2 %	5.46465E-02	51.0344
	For the	A d o p t e d	Fe Cross Sec.Dev.:-2 %	3.94112E-02	64.4197
	For the	A d o p t e d	Fe Cross Sec.Dev.: 3 %	6.21408E-02	45.4004
	For the	A d o p t e d	Fe Cross Sec.Dev.:-3 %	4.13761E-02	59.7507
	For the	A d o p t e d	Fe Cross Sec.Dev.: 4 %	7.03101E-02	40.513
	For the	A d o p t e d	Fe Cross Sec.Dev.:-4 %	4.55797E-02	53.262
No.of Reactions I= 10	With the	F o u n d	Fe Cross Sec.Dev.:-1.73545 %	3.93213E-02	63.7981

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 3.99431
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as **Not Confirmed** with >92.5% significance probability(one-sided test)
The flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
2.23507E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1

The corrected flux density for this measuring position is then: **2.23507E+12** 1/(cm^2*s)

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS Irradiation: E 57
Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: No.15
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%	Mean Spectrum Variation,Abs.Val.	Variation Uncert.,+/-%
Np237(n,f)	4.80562	7.00499		
In115(n,n')	1.83042	7.63169		
U238(n,f)	-.807577	6.88745		
Th232(n,f)	-1.91318	9.82989		
Ti47(n,p)	-2.38542	8.72673		
Ni58(n,p)	.414062	7.67735		
Ti(n,x)Sc46	.634921	7.74077		
Ti48(n,p)	-6.95852	7.54134		
Al27(n,a)	13.2952	7.29719		
	For the Adopted	Fe Cross Sec.Dev.: 0 %	5.63763E-02	49.4015
	For the Adopted	Fe Cross Sec.Dev.: 1 %	6.01324E-02	47.1583
	For the Adopted	Fe Cross Sec.Dev.:-1 %	5.42837E-02	50.0736
	For the Adopted	Fe Cross Sec.Dev.: 2 %	6.52656E-02	44.0033
	For the Adopted	Fe Cross Sec.Dev.:-2 %	5.40482E-02	48.8318
	For the Adopted	Fe Cross Sec.Dev.: 3 %	7.14796E-02	40.5418
	For the Adopted	Fe Cross Sec.Dev.:-3 %	5.56934E-02	45.9329
	For the Adopted	Fe Cross Sec.Dev.: 4 %	7.85183E-02	37.163
	For the Adopted	Fe Cross Sec.Dev.:-4 %	5.90623E-02	42.0724
	For the Adopted	Fe Cross Sec.Dev.: 5 %	8.61799E-02	34.0581
	For the Adopted	Fe Cross Sec.Dev.:-5 %	6.38828E-02	37.9538
No.of Reactions I= 10	With the Found	Fe Cross Sec.Dev.:-1.62522 %	5.39161E-02	48.1723

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 4.13544
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as **Not Confirmed** with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
2.80294E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1

The corrected flux density for this measuring position is then: **2.80294E+12** 1/(cm^2*s)

Table II-8

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS Irradiation: E 57
Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: No. 17
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%
Np237(n,f)	10.377	7.54534
In115(n,n')	9.36642	8.1305
U238(n,f)	4.79317	7.28987
Ti47(n,p)	-7.00761	9.16614
Ni58(n,p)	5.20847	8.16946
Ti(n,x)Sc46	3.95124	8.2249
Ti48(n,p)	3.81248	7.68196
Al27(n,a)	5.61744	7.80349

		Mean Spectrum Variation	Variation Uncert.,+/-%
	For the Adopted Fe Cross Sec.Dev.: 0 %	.066743	44.9296
	For the Adopted Fe Cross Sec.Dev.: 1 %	.075102	40.4691
	For the Adopted Fe Cross Sec.Dev.:-1 %	5.90724E-02	49.9324
	For the Adopted Fe Cross Sec.Dev.: 2 %	8.39442E-02	36.6275
	For the Adopted Fe Cross Sec.Dev.:-2 %	5.23936E-02	55.1122
	For the Adopted Fe Cross Sec.Dev.: 3 %	9.31319E-02	33.3605
	For the Adopted Fe Cross Sec.Dev.:-3 %	4.71301E-02	59.5942
	For the Adopted Fe Cross Sec.Dev.: 4 %	.102572	30.5867
	For the Adopted Fe Cross Sec.Dev.:-4 %	4.37952E-02	62.014
	For the Adopted Fe Cross Sec.Dev.: 5 %	.112202	28.2234
	For the Adopted Fe Cross Sec.Dev.:-5 %	4.28417E-02	61.2767
	For the Adopted Fe Cross Sec.Dev.: 6 %	.121976	26.1976
	For the Adopted Fe Cross Sec.Dev.:-6 %	4.44232E-02	57.5872
	For the Adopted Fe Cross Sec.Dev.: 7 %	.131861	24.4491
	For the Adopted Fe Cross Sec.Dev.:-7 %	4.82912E-02	52.2299
	For the Adopted Fe Cross Sec.Dev.: 8 %	.141836	22.9289
	For the Adopted Fe Cross Sec.Dev.:-8 %	5.39563E-02	46.4726
No.of Reactions I= 9	With the Found Fe Cross Sec.Dev.:-4.87613 %	4.28223E-02	61.0252

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 4.22459
using STUDENT's cut-off value T925(I-2)= 1.61661
So a variation from the reference spectrum appears as Shown with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
2.76434E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: .951239

The corrected flux density for this measuring position is then: **2.90604E+12** 1/(cm^2*s)

Table II-9

** Neutron Spectrum Variation Assessment by Least Squares Fit **

Experiment: FKS Irradiation: E 57
Source: FRJ-1 Ref.Pos.: No.10 Meas.Pos.: No. 19
Measuring Reactions Related to the Reference One: Fe54(n,p)

Measuring Reaction	Doub.Spec.Ind. %	DSI Uncert. +/-%	Mean Spectrum Variation,Abs.Val.	Variation Uncert.,+/-%
Np237(n,f)	5.04812	6.50062		
In115(n,n')	8.86629	7.17271		
U238(n,f)	4.42853	6.20456		
Th232(n,f)	9.65118E-02	9.66639		
Ti47(n,p)	2.32579	8.31931		
Ni58(n,p)	5.7933	7.22582		
Ti(n,x)Sc46	1.46115	7.29809		
Ti48(n,p)	-.711256	6.52526		
Al27(n,a)	3.90742	6.79515		
	For the Adopted	Fe Cross Sec.Dev.: 0 %	.045954	55.0174
	For the Adopted	Fe Cross Sec.Dev.: 1 %	5.47015E-02	46.5704
	For the Adopted	Fe Cross Sec.Dev.:-1 %	3.80307E-02	65.9014
	For the Adopted	Fe Cross Sec.Dev.: 2 %	6.39355E-02	40.1424
	For the Adopted	Fe Cross Sec.Dev.:-2 %	3.15585E-02	78.4001
	For the Adopted	Fe Cross Sec.Dev.: 3 %	7.34731E-02	35.1992
	For the Adopted	Fe Cross Sec.Dev.:-3 %	2.75786E-02	87.754
	For the Adopted	Fe Cross Sec.Dev.: 4 %	8.32098E-02	31.3255
	For the Adopted	Fe Cross Sec.Dev.:-4 %	2.72076E-02	86.3042
	For the Adopted	Fe Cross Sec.Dev.: 5 %	9.30833E-02	28.2289
	For the Adopted	Fe Cross Sec.Dev.:-5 %	3.05772E-02	74.8789
	For the Adopted	Fe Cross Sec.Dev.: 6 %	.103054	25.7073
	For the Adopted	Fe Cross Sec.Dev.:-6 %	3.66703E-02	61.5015
No.of Reactions I= 10	With the Found	Fe Cross Sec.Dev.:-3.59918 %	2.69071E-02	84.5252

100*Mean spec.var.to and with the found Fe cross sec.dev.in % both to be compared with the T value: 3.62125
using STUDENT's cut-off value T925(I-2)= 1.59223
So a variation from the reference spectrum appears as **Not Confirmed** with >92.5% significance probability(one-sided test)
The Flux density >1MeV as found using the reference spectrum and reaction for this measuring position is:
2.19012E+12 1/(cm^2*s)
Correction factor for the spectrum variation according to the significance test above: 1

The corrected flux density for this measuring position is then: **2.19012E+12** 1/(cm^2*s)

3. COMPARISON OF THE RESULTS OF OUR ESTIMATION WITH OTHER RESULTS

3.1. The effective Fe-54(n,p) cross section variation over a CT100 specimen from different evaluations

The flux density of fast (i.e., >1 MeV) neutrons is determined by measurement with the reference reaction Fe-54(n,p) in a position $\vec{r}$ as follows:

$$\phi(>1\mathrm{MeV},\vec{r}) = R_{Fe}(\vec{r}) \;/\; \sigma_{eff,Fe}(>1\mathrm{MeV},\vec{r}) \;. \qquad (3.1)$$

Here $R_{Fe}(\vec{r})$ is the reaction rate measured in $\vec{r}$, and

$$\sigma_{eff,Fe}(>1\mathrm{MeV},\vec{r}) \equiv \int_{o}^{\infty} \sigma_{Fe}(E)\,\phi_E(E,\vec{r})\,dE \;/ \int_{1\mathrm{MeV}}^{\infty} \phi_E(E,\vec{r})\,dE \qquad (3.2)$$

denotes the so-called effective Fe-54(n,p) cross section. While the reaction rate R can be determined solely by measurement, the effective cross section determination requires at least some theoretical consideration. From its definition, σ_{eff} must be expected more or less to depend on the local spectral neutron flux density $\sigma_E(E,\vec{r})$. In the following, we want to focus on the spatial $\sigma_{eff,Fe}$ variation characterizing the neutron spectrum variation.

FKS project irradiations have been performed in the GKSS Research Centre at Geesthacht and in the KFA Jülich. The irradiation sources at Geesthacht and Jülich (FRJ-1) were both swimming-pool reactors with quite well comparable irradiation conditions; the FKS irradiation capsules which have been designed at Geesthacht for use in the FRG-2 /13/ have been adapted at Jülich for the FRJ-1 /14/. So it could be expected to find similar spectral variations of the effective cross section $\sigma_{eff,Fe}(\vec{r})$ for the irradiation arrangements in both places.

Among the reports on the FKS irradiations and their - in particular dosimetric - results from Geesthacht (e.g., /15, 16, 17/, we focus on a display of $\sigma_{eff,Fe}(x)$ values especially determined for a CT100 (or as called in Jülich: CK100) steel specimen with the aid of a two-dimensional transport calculation using the code TWOTRAN and EURLIB neutron cross section input data /18/. The $\sigma_{eff,Fe}$ distribution given there was to be compared with the results obtained with a two-dimensional (2D) as well as with a one-dimensional (1D) transport calculation /19/ for the FRJ-1 dosimetry test experiment. These theoretical evaluations in turn should be compared with the mainly experimental evaluation of the FRJ-1 dosimetry test experiment (Chapter 2). The latter evaluation was theoretically only connected to the 1D calculation in /19/ which served as the input spectrum for the Jülich adjustment procedure applied in the central position of the dosimetry test experiment /3/.

The evaluated $\sigma_{eff,Fe}$ points - together with some more extra- or intra-polated ones using a quadratic approximation - have been presented in Fig. 7 showing the absolute values and slopes of $\sigma_{eff,Fe}(x)$ in the region of maximum flux densities depending from the transverse coordinates y,z for the evaluations mentioned above. Besides in Table I (Chapter 3) the percent deviations of compared $\sigma_{eff,Fe}$ pairs have been shown for these points. For the FRG-2, the slope appears to be more bent than for the FRJ-1, which may result from the fact that for the FRG-2 values for the capsule boundaries have been evaluated while for the FRJ-1 the corresponding values were extrapolated only. Measurements near the boundary were not possible for technical reasons, the comparing calculation /19/ was consequently also not carried out there. On the other side, the test experiment allows to guess the uncertainty for reproduction of the $\sigma_{eff,Fe}$ values; the bars of it has been included in Fig. 7.

3.2. Comparison and discussion of the variation results

Under the four cases presented in Tab. I (Chapter 3) the FRG-2 values stemming from a two-dimensional (2D) calculation /18/ was compared with the 2D under FRJ-1 calculations /19/. On the other side, to compare the FRJ-1 calculations with the measured and adjusted results there (Chapter 2) one should at first take into account the 1D calculation insofar as the adjustment procedure applied at Jülich /3/ has been based on this 1D calculation (but could not be based on the 2D one).

All $\sigma_{eff,Fe}$ values in Fig. 7 and Table I are presented as a function of the x coordinate. While the FRJ-2 values /18/ apparently are given for constant (e.g., maximum) values of the transverse coordinates y,z, in the FRJ-1 dosimetry test experiment the $\sigma_{eff,Fe}(x)$ could be investigated for technical reasons only with slightly variating y simultaneously (Fig. 1, Chapter 2). Concerning the dependence on the transverse coordinates the experiment has studied only the z (and neglected the y) direction. In the 2D calculation /19/ for the FRJ-1 the $\sigma_{eff,Fe}$ determination has been carried out for the same x,y points as the experiment could do, and in the flux density maximum in the z direction. The dependence on the transverse coordinates (for z by the measurement, for y by comparing the 1D to the 2D slope in /19/) has been found rather weak. So it should be allowed to compare the $\sigma_{eff,Fe}(x,\ y=0,\ \text{or} = \pm 13\ \text{mm})$ values from these with the $\sigma_{eff,Fe}(x)$ slope for the FRG-2 evaluations /18/ as we have done.

According to the assessment in Chapter 2 after the measurement evaluation 1σ uncertainties have been entered into Fig. 7. This assessment does not include the uncertainty to the absolute $\sigma_{eff,Fe}$ values. For the reproduction of the reaction rates after the unfolding ± 3.249 % mean deviation was found, cf. Table IV (Chapter 1) in /3/.

As a rough guess for the minimally expected uncertainty to the neutron flux density $_c\phi(>1\text{MeV})$ in that reference position the average uncertainty to the fission equivalent flux densities $_f\ \phi_{Fe}(>1\text{MeV})$ can be taken, for about ± 7 %. So the gross $|1\sigma|$ uncertainty to the effective cross section values according to the measurement evaluation can be estimated to more than 8 %. To the calculated effective cross section values no uncertainty amounts are known.

If we - as far as the measurement evaluation is concerned - compare that admittedly rough lower limit uncertainty guess with the small but obvious "Deviations (between the) Values I and II" in Table I (Chapter 3), it seems to us that we do not find sufficiently high probabilities for significant differences between the $\sigma_{eff,Fe}(x)$ values. Moreover, in consequence of the rotation of the FKS capsules during the mid pause of their irradiation time, the spectrum variation was smoothed; the question of its relevance will be discussed in Sect. 3.3. The differences between the slopes of the $\sigma_{eff,Fe}$ values ("Dev. (i) - Dev. (i-1)" in Table I (Chapter 3)) show the found spectrum variation nearly in parallel for all cases, i.e., without an express indication for a divergence of the values.

3.3. Is the found neutron spectrum variation relevant to the searched fluence?

The relevance of the found neutron spectrum variation over the irradiated FKS specimens is studied in the following with assessing the measuring quantities:

- neutron flux density $\phi(E>1MeV, 0 \leq x \leq D)$ for the required reactor power during the irradiation,
- neutron fluence $\Phi(E>1MeV, 0 \leq x \leq D)$,
- averaged neutron fluence $\bar{\Phi}^x(E>1MeV)$

$x = 0, D$ is the entrance and the exit position for neutrons directed from the reactor core on the specimen, resp. $\bar{\Phi}^x$ denotes the fluence averaged over the specimen in x direction. The assessed results are compared under the following conditions:

A. FKS capsule not rotated during the irradiation time,

B. FKS capsule rotated after the irradiation mid time,

I. A and B without neutron spectrum variation,

II. A and B with neutron spectrum variation.

The distributions in x,y,z of the flux density ϕ and in x,z of the fluence $\bar{\Phi}$ in a simulated CT steel specimen has been investigated in a pilot test experiment /8/; measurement results from this experiment for the cracking plane of the simulated specimen are reproduced in the Figures 8 and 9. From this we may guess w i t h o u t spectrum variation:

$$\phi(x) \approx \phi(0)e^{-\mu x} \qquad (3.1)$$

with the neutron weakening coefficient $\mu \approx .2\ cm^{-1}$ (cf. Chapter 5 in /3/) and

$$\Phi(x) \simeq C \cdot \phi(x) \qquad \text{for "rotation: no"} \qquad (3.2)$$

$$\Phi(x) = C_1 \cdot \phi(x) + C_2 \cdot \phi(D-x) \qquad \text{for "rotation: yes"} \qquad (3.3)$$

with the constants C, C_1, C_2 denoting the irradiation time (intervals) times the corresponding irradiation history correction factor(s). Analogously, with spectrum variation:

$$\phi(x) = \frac{\phi(0)e^{-\mu x}}{1 + \delta_0 x} \tag{3.4}$$

$$\Phi(x) = C\,\phi(x) \qquad \text{for "rotation: no"} \tag{3.5}$$

$$\Phi(x) = \phi(0)\,\frac{C_1 e^{-\mu x}}{1+\delta_0 x} + \frac{C_2 e^{-\mu(D-x)}}{1+\delta_0(D-x)} \qquad \text{for "rotation: yes"} \tag{3.6}$$

with $\delta_0 \approx -.04\ cm^{-1}$, i.e. the effective Fe-54(n,p) cross section deviation per cm in x direction over the specimen, according to Fig. 7.

Under the above-mentioned conditions, we consider the deviation $\delta\Phi$ of neutron fluences without (N) - to - with (W) - spectrum variation:

$$\delta\Phi \equiv 100\,\frac{\Phi_N - \Phi_W}{\Phi_N}\ \% \tag{3.7}$$

- for $\Phi(x)$, i.e., for the end position (x = 0 or = D) compared with the mid (x = D/2) position, giving the maximum deviation,
- for Φ^x, i.e., averaged over $0 \le x \le D$.

To evaluate the average fluence, we assume in the case "rotation: no" for the fluence naturally the same slope as for the flux density; in the case "rotation: yes" the slope of a quadratic parabola with minimum in x = D/2, approximating the slope in Fig. 9. The results are compiled in Table II (Chapter 3). The condition "no rotation" has been taken into account there only for a CK (or CT) 60 capsule because the only irradiation in Jülich without rotation (it was capsule E56 /3/) has been carried out with a CK 60 type capsule.

We have now to compare the assessed deviations in Table II (Chapter 3) with guessed uncertainties $\rho(\Phi)$ for the fluence values Φ. As $|1\sigma|$ uncertainties we expect:

- for the fluence in a particular point x:
  $|\rho(\Phi(x))| > 8\ \%$ according to Sect. 3.2 (3.8)
- for the average fluence
  $$|\rho(\Phi^x)| > \frac{8}{\sqrt{3-1}} \approx 5.7\ \%\ . \tag{3.9}$$

Starting from these guessed amounts, the average fluence deviations in Table II (Chapter 3) lie always within the $\pm 2\sigma$ confidence level, i.e., within the 95 % confidence interval. Under the end position fluences, only those for the capsule CK120 possibly exceed the 95 % confidence interval and only in the close vicinity of the end points.

Summarizing, the relevance of the found neutron spectrum variation appears to be negligible in terms of the evaluated fluence. The ability to determine neutron field quantities seems to have grown better than needed, which is reassuring with respect to the requirements in the reliability of those determinations.

Table I

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** Fe Effective Cross Section F(X) Comparison in Steel Plate with Thickness X **

For Experiment: FKS (Forschungsprogramm Komponentensicherheit/Structural Integrity of Components)
Measuring Reaction: Fe-54(n,p)Mn-54 Effective Cross Section for Neutrons >1 MeV
To Be Compared for: Aequival.Capsule Arrangm.i.GKSS(FRG-2)and KFA(FRJ-1)
Values I from: IKE-6 KS- 4(1980)
Values II from: IKE-6 KS-11(1984) 2D Calc.
e: Evaluated,p: (Extra/Intra-)polated Value

i	X cm		Value I F(X) mb		Value II F(X) mb	Value II-I Deviation %	Dev.(i)-Dev.(i-1) %
1	0	e	52.14	p	49.49	-5.07569	0
2	3.7	p	43.52	e	42.4	-2.58222	2.49347
3	5	e	41.43	e	40.1	-3.21025	-.628028
4	6.3	p	39.82	e	37.9	-4.82524	-1.61499
5	10	e	37.9	p	32.19	-15.0769	-10.2517

For Experiment: FKS (Forschungsprogramm Komponentensicherheit/Structural Integrity of Components)
Measuring Reaction: Fe-54(n,p)Mn-54 Effective Cross Section for Neutrons >1 MeV
To Be Compared for: Aequival.Capsule Arrangm.i.GKSS(FRG-2)and KFA(FRJ-1)
Values I from: IKE-6 KS- 4(1980)
Values II from: KFA-ZBB-TN-16/85 – *i.e., here*
e: Evaluated,p: (Extra/Intra-)polated Value

i	X cm		Value I F(X) mb		Value II F(X) mb	Value II-I Deviation %	Dev.(i)-Dev.(i-1) %
1	0	e	52.14	p	53.64	2.87842	0
2	3.7	p	43.52	e	46	5.68909	2.81067
3	5	e	41.43	e	43.7	5.47912	-.209966
4	6.3	p	39.82	e	41.6	4.46622	-1.0129
5	10	e	37.9	p	36.72	-3.11946	-7.58568

For Experiment: FKS (Forschungsprogramm Komponentensicherheit/Structural Integrity of Components)
Measuring Reaction: Fe-54(n,p)Mn-54 Effective Cross Section for Neutrons >1 MeV
To Be Compared for: the Same Capsule Arrangm.i.KFA(FRJ-1)
Values I from: IKE-6 KS-11(1984) 1D Calc.
Values II from: KFA-ZBB-TN-16/85 – *i.e., here*
e: Evaluated,p: (Extra/Intra-)polated Value

i	X cm		Value I F(X) mb		Value II F(X) mb	Value II-I Deviation %	Dev.(i)-Dev.(i-1) %
1	0	p	48.83	p	53.64	9.86239	0
2	3.7	e	40.9	e	46	12.4694	2.60703
3	5	e	38.5	e	43.7	13.5065	1.03707
4	6.3	e	36.3	e	41.6	14.6005	1.09404
5	10	p	31.13	p	36.72	17.9378	3.33721

Table I, cont.

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** Fe Effective Cross Section F(X) Comparison in Steel Plate with Thickness X **

For Experiment: FKS (Forschungsprogramm Komponentensicherheit/Structural Integrity of Components)
Measuring Reaction: Fe-54(n,p)Mn-54 Effective Cross Section for Neutrons >1 MeV
To Be Compared for: the Same Capsule Arrangm.i.KFA(FRJ-1)
Values I from: I? IKE-6 KS-11(1984) 2D Calc.
Values II from: KFA-ZBB-TN-16/85 – i.e., here
e: Evaluated,p: (Extra/Intra-)polated Value

i	X cm		Value I F(X) mb		Value II F(X) mb	Value II-I Deviation %	Dev.(i)-Dev.(i-1) %
1	0	p	49.49	p	53.64	8.37943	0
2	3.7	e	42.4	e	46	8.49056	.111128
3	5	e	40.1	e	43.7	8.97757	.487019
4	6.3	e	37.9	e	41.6	9.76252	.784952
5	10	p	32.19	p	36.72	14.0804	4.31785

Table II

* Deviation of Fluence of Neutrons without/with Spectrum Variation in Steel * 10BP2074
Experiment: FKS End pos.fluences,=1 in the mid x position 12/11/85 08:47:40
Steel capsule rotated or not after irradiation mid-time

Capsule CK-No.	Rotated	End pos.rel.fluence without spec.var. / with spec.var.	End pos.rel.fluence without spec.var. / with spec.var.	% End pos.fce.dev. without-with sp.v.
60	no	1.8221	1.8221	
		1.6152	1.6152	12.8096
60	yes	1.18547	1.18547	
		1.12527	1.12527	5.34982
100	yes	1.54308	1.54308	
		1.36254	1.36254	13.2503
120	yes	1.81066	1.81066	
		1.53691	1.53691	17.8117

* Deviation of Fluence of Neutrons without/with Spectrum Variation in Steel * 10BP2074
Experiment: FKS Average fluences,=1 in the mid x position 12/11/85 08:50:31
Steel capsule rotated or not after irradiation mid-time

Capsule CK-No.	Rotated	End pos.rel.fluence without spec.var. / with spec.var.	Average rel.fluence without spec.var. / with spec.var.	% Average fce.dev. without-with sp.v.
60	no	1.8221	1.06107	
		1.6152	1.03876	2.14805
60	yes	1.18547	1.06182	
		1.12527	1.04176	1.92624
100	yes	1.54308	1.18103	
		1.36254	1.12085	5.36916
120	yes	1.81066	1.27022	
		1.53691	1.17897	7.73981

4. EVALUATION OF THE NEUTRON EXPOSURE (in dpa) IN A FERRITIC STEEL PLATE

4.1. Definitions for reporting the neutron exposure in terms of dpa

Beyond the report on the neutron fluences determination to the Jülich FKS irradiations (s. /3/ and Chapter 1 to 3), here will be given the procedure how to evaluate the neutron exposure in terms of displacements per atom (dpa). Using the quantity dpa exposure we follow the international recommendations /20, 21, 22; s. also Standard E693 in /23/ particularly for ferritic steels as the irradiated material. The transition from fluence to the dpa exposure apparently improves the comparability between irradiations in different places just for this irradiated material.

We start in the following with definitions and (in Sec. 4.2) with a description of the application of a neutron detector set measurement unfolding procedure to the evaluation of dpa for our reference position. Furthermore, an assessment of the expected dpa rate variation with the neutron spectrum over such irradiated bulky steel samples will be outlined (Sec. 4.3). Finally (Sec. 4.4), after a comparison of the obtained dpa cross section results incl. its spatial dependence with the results from other evaluations, the procedure of the practical determination of the location dependent dpa exposures will be given. Moreover, it will be discussed whether the neutron spectrum variation found over the steel plates might influence the exposure values remarkably.

The neutron exposure (in an irradiation field characterized by a neutron spectrum called I, over the irradiation time t_I) should generally not be reported by the neutron fluence:

$$\Phi^I(E_L,t_I) = \int_o^{t_I} \int_{E_L}^{\infty} \phi_E^I \, dEdt \; . \tag{4.1}$$

Instead, taking into account the energy response of the irradiated material m (in our case: ferritic steel) on the impinging neutrons, the exposure will - following the recommendations quoted above - be expressed as the time integral of the dpa rate $\dot{d}$, viz.

$$d_m^I(t_I) = \int_o^{t_I} \dot{d}(t)dt = \int_o^{t_I} \int_o^{\infty} \sigma_{d,m}(E)\ \phi_E^I(E)\ dE\ dt\ . \qquad (4.2)$$

One has further defined the "Effective dpa cross section in the material m (corresponding to the Effective cross section for a neutron measurement reaction, cf. Chapter 2):

$$\sigma_{d,m}^I(E_L) \equiv \dot{d}_m^I \;/ \int_{E_L}^{\infty} \phi_E^I(E)dE \qquad (4.3)$$

Practically, the transition from the fluence values to the desired dpa exposure values d can then be expressed by the relation

$$d_m^I = \sigma_{d,m}^I(E_L) \cdot \Phi^I(E_L) \qquad (4.4)$$

In eq. (4.4) the quantity d refers to the whole neutron spectrum while the fluence $\Phi^I(E_L)$ refers only to the neutrons with energies above E_L; correspondingly, $\sigma_{d,m}^I(E_L)$ according to eq. (4.3) is referred to the whole spectrum and normalized to the flux density or fluence above energy E_L.

4.2. The dpa evaluation for the reference position

4.2.1. The calculation and its results

The central position ("No. 10") in the FKS dosimetry test experiment (with irradiation capsule E57) we have defined as the reference position /3/. The neutron spectrum there has been determined applying the adjustment or unfolding procedure as described in /3/. Calculated values for the neutron flux densities $\phi^c(E_L)$ above varying energies E_L (with index "c" for the reference position) are presented in Table I (Chapter 4); these values (after a slightly improved re-evaluation, using the same experimental data) are so close to the former reported ones (s. Table V (Chapter 1) in /3/) that the differences - at least for the more interesting higher energies - may be neglected. For the dpa rate evaluation a FORTRAN computer programme has been used based on a section-wise integration applying a NEWTON interpolation polynominal with four nodes respectively /4/.

Because we do not have the correct presentation of the damage cross section set for just our material m, three dpa cross section sets have been used:

1. for ferritic steel from the American reference Standard E693 in /23/,
2. for Fe from the (European) reference /25/ and using the i groups format according to /24/,
3. the same as 2. for "Steel" according to /24/ from /25/.

The obtained results for $\sigma^c_{d,m}$ according to eq. (4.3) with the evaluated $\hat{d}^c_m$, and with 1. to 3. for the material choice m, are shown in Table II (Chapter 4).

One out of the three $\sigma^c_{d,m}$ values from Table II (Chapter 4) or, e.g., their arithmetic mean $\bar{\sigma}^c_{d,m}$:

$$\bar{\sigma}^c_{d,m} = 2.177 \cdot 10^{-21}\ cm^2 \tag{4.5}$$

which obviously is no better value than the three values themselves may be used to evaluate the dpa exposure d for the measuring position $\vec{r}$ (or its corresponding neutron spectrum M), according to eq. (4):

$$d_m(\vec{r}) = \sigma^c_{d,m}(E_L{=}1MeV) \cdot F(\vec{r}_c,\vec{r}) \cdot \Phi^M(E_L{=}1MeV) \ . \tag{4.6}$$

F denotes a factor correcting for the use of σ^c (to position $\vec{r}_c$) instead of σ^M (to $\vec{r}$) and will be assessed later on, s. eq. (4.17). In the Sections 4.3 and 4.4 the index "m" will be omitted because in our case there will be only the result from /23/ in Table II (Chapter 4) under discussion.

4.2.2. Discussion of the uncertainties involved

The mean deviation between the three effective dpa cross sections as reported in Table II (Chapter 4) amounts to

$$\delta(\sigma_{d,m}) = \pm\ 2.4\ \% \ . \tag{4.7}$$

This deviation could be taken for the relative standard deviation $\rho(\sigma_{d,m})$ of this cross section if there existed no other uncertainty contributions to the reported cross sections and if they were actually equivalent. Since we do not know any more we may at least adopt the deviation in eq. (4.7) as a lower limit for the cross section uncertainty $\rho(\sigma_{d,m})$.

Correspondingly, if we make the (admittedly improbable) assumption that the flux density did not change and the neutron spectrum were nothing else than the fission spectrum then (again because of missing knowledge) we may adopt the uncertainty values reported to the fission equivalent neutron flux densities in Table VII (Chapter 1) in /3/ for the fluence uncertainties, viz,

$$\rho({}_f\phi_{Fe}) = \rho({}_f\Phi_{Fe}) = \pm\ 7.7\ \%\ . \qquad (4.8)$$

We prefer here to use the Fe fission equivalent fluence (or flux density) because we have used Fe-54(n,p) as a reference measuring reaction (s. Chapter 2 and /3/);otherwise for anyone out of the detectors i reported in Table VII (Chapter 1) in /3/ we would obtain: $4.0<|\rho({}_f\Phi_i)|<11.4\ \%$. Adding the variances from eqs. (4.7) and (4.8) we would obtain as a figure for the uncertainty of the dpa rate (or exposure) according to eq. (4.6)

$$\rho(d^c) = \pm\ 8.1\ \%\ . \qquad (4.9)$$

Of course, the assumptions made here have strongly to be questioned because they are very optimistic: not only with respect to the fluence or flux density but also to the damage (here: the dpa) cross section values. This is so because we cannot estimate the uncertainty of our input dpa cross section data and of their usefulness for the irradiated FKS steel material. So the figure $\rho(d)$ as given in eq. (4.9) can at best be considered as a lower uncertainty limit.

4.3. Assessment of the dpa rate varying with the neutron spectrum over the irradiated FKS steel plates

4.3.1. The assessment procedure

For considering the neutron spectrum variation effect over an extended material m - in our case: thick plates of ferritic steel -, we take at first the time-dependent (rate) quantities $\dot{d}_m$ and ϕ instead of the exposure quantities d_m and Φ in eq. (4.6). In Section 4.4, a guess will be reported for the transition from the rate to the exposure quantities; this is of special importance since nearly all of the FKS irradiations have been carried out with rotating the irradiation capsules in the mid-time of their irradiation; this resulted in a change of the neutron flux density level for all positions outside the capsule midplanes (cf. /3/).

For giving $\dot{d}_m(\vec{r})$ we start from the results for the reference position $\vec{r}_c$ as they have been reported in Table II (Chapter 4) for the effective dpa cross section σ_d^c and from Table VII (Chapter 1) in /3/ for the neutron flux densities ϕ_i^c. To pass from the reference position $\vec{r}_c$ to another one $\vec{r}$ within the material we have to consider variations in the cross section as well as in the flux density. We may apply the considerations in Chapter 2 for the flux density variation. However, we cannot use an analogous empirical procedure for assessing the $\sigma_d(\vec{r})$ variation with $\vec{r}$ because we did not make measurements of the damage or dpa rate in this context.

To circumvent this difficulty the following ways may be deliberated:

- At first, as we are intending, to use a simple approximation procedure of analytical character, i.e., by a variation:

$$\delta\sigma_d \equiv \left[\sigma_d(\vec{r})-\sigma_d^c\right] / \sigma_d^c \qquad (4.10)$$

  going to zero when we approximate $\vec{r}\to\vec{r}_c$. To find an experimental approach for the dpa cross section variation corresponding to that in Chapter 2 we examine the cross sections $\sigma_i(E)$ of the applied measuring reactions i (cf. /3/).

- At second, the unfolding procedure for the carried out neutron activation detector measurements may be used, as reported in Section 4.2.1 and in /3/, for some more measurement positions than in the reference one. This should be considered in second place because of the effort accompanied by it.
- At third, one may also apply so-called damage detectors for an experimental assessment of the cross section variation $\delta\sigma_d$.

Under these detectors are the graphite (GAMIN) or tungsten monitors (both from France) or the sapphire monitor (UK) /26/ which all seem to need particular caution and corrections in application. These procedures would demand an additional extensive enlargement in engaged man-power and apparatus which is beyond our possibilities.

So we do here restrict ourselves on the first way as the easiest one. Under the applied measuring reactions /3/ Np-237 (n,f) appears to be the best comparable one to the displacement reaction in iron or steel, for the following reasons (cf. Fig. 10):

- both the Np and the dpa cross section show threshold-like ascents to high neutron energies E; the steepest part of the $\sigma_{Np}(E)$ cross section ascent lies between E = 10^{-1} and 1 MeV and therefore closer than all the other applied reactions to the steepest ascent of the dpa cross section (between 10^{-2} and 10^{-1} MeV).

- Besides the Np as well as the dpa cross section show contributions towards low energies E which are relatively low, including resonances and 1/v ascents.

Using the double spectrum index approach (Chapter 2), we introduce (with denoting the Np-237(n,f) reaction by the index "k"):

the double spectrum index $$D_k \equiv \frac{R_k^M \, R_{Fe}^c}{R_k^c \, R_{Fe}^M} = \frac{1+\delta\sigma_k}{1+\delta\sigma_{Fe}} \qquad (4.11)$$

where

M	stands	for	the	measuring position,
c	"	"	"	reference position,
Fe	"	"	"	reaction Fe-54(n,p),
R	"	"	a	measured reaction rate and

$$\delta\sigma_k \equiv \left[\sigma_k^M - \sigma_k^c\right] / \sigma_k^c \qquad (4.12)$$

is the relative deviation of the cross section σ for the reaction k. If we assume roughly that the relative deviation $\delta\sigma_k$ can be used instead of the searched dpa cross section deviation then we may set:

$$\delta\sigma_d \approx \delta\sigma_k = D_k \ (1+ \delta_{Fe}) - 1 \qquad (4.13)$$

and - corresponding to eq. (4.4) -:

$$\dot{d}^M = \sigma_d^M \cdot \phi^M \qquad (4.14a)$$

with

$$\sigma_d^M = \sigma_d^c(1+\delta\sigma_d) \approx \sigma_d^c(1+\delta\sigma_k) \qquad (4.14b)$$

Results of this rough "first" way will be given in Sec. 4.3.2. In cases where such an evaluation could not be satisfying the above-mentioned "second" way should be gone.

4.3.2. Results of and uncertainties to the assessed dpa rate variation

Using the selected procedure (the "first way" in Section 4.3.1), we confine ourselves to those FKS irradiation capsules and measuring positions there for which significant deviations within a confidence interval of >90 % from the reference position (No. 10 in capsule E57) could be found for the effective cross section σ_{Fe}(>1MeV): These are the positions Nos. 3 and 17 in the E57 capsule. Moreover, we restrict the spatial variation of the measuring position $\vec{r}$ on the x direction, viz, the direction out of the reactor core on constant height. I.e., we do consider neither variations in the y direction (transversely to the core but on constant height) nor in the z (height) direction, correspondingly to Chapter 3.

Assuming that there are no correlations between the contributions, the uncertainties to eqs. (4.14a,b) have been evaluated using the simple variance procedure:

$$\rho(d(x)) = \pm \sqrt{\rho^2(\sigma_d(x)) + \rho^2(\phi(x))} \quad , \tag{4.15a}$$

$$\rho(\sigma_d(x)) = \pm \sqrt{\rho^2(\sigma_d^c) + \rho^2(D_k(x)) + \rho^2(\delta\sigma_{Fe}(x))} \quad . \tag{4.15b}$$

Here only the double spectrum index uncertainty $\rho(D_k)$ can immediately be taken from the measurement results; this and the uncertainty to the Fe cross section deviation $\rho(\delta\sigma_{Fe})$ has been consequently used according to Chapter 2. For the last two contributions, i.e, for the dpa cross section uncertainty in the reference position $\rho(\sigma_d^c)$ and for the flux density uncertainty $\rho(\phi)$ there are only lower limit values available to us, cf. Sec. 4.2.2. We use for the first one the mean deviation from eq. (4.7). For the last one we use

$$\rho(\phi(x)) = \pm \sqrt{\rho^2({}_f\phi_{Fe}(>1MeV)) + \rho^2(\delta\sigma_{Fe}(x))} \tag{4.15c}$$

with the fission equivalent Fe flux density uncertainty $\rho({}_f\phi_{Fe}(>1MeV))$ as the lower limit uncertainty for the reference flux density $\phi(>1MeV, x_c) = R_{Fe}(x_c) / \sigma_{Fe}^c(>1MeV)$, according to Chapter 3 and Chapter 5 in /3/.

The results of this evaluation are presented in Table III. The uncertainties denoted there by ">/=" indicate that these are lower limit uncertainties, as mentioned before. For the effective dpa cross section in the reference position we have used the ASTM value, cf. TAble II (Chapter 4), which has been applied very frequently in the last time.

From Table III (Chapter 4) we may take the arithmetic mean deviation δ_1 per cm in x direction:

$$\delta_1 = .058\ (1 \pm \geq .06)\ cm^{-1} \tag{4.16}$$

From here we will (also for the sake of comparability) use δ_1 for the mean dpa cross section deviation related to 1 cm thickness of steel penetrated by neutrons.

4.4. Discussion: The dpa exposure and its variation with the neutron spectrum

4.4.1. Comparison of the dpa cross section and of its variation as found with corresponding evaluations

In Table IV (Chapter 4) the Effective dpa cross section $\sigma_d(x)$ and its relative spatial δ_1 within thick steel plates is given with guessed uncertainty figures, according to Table II (Chapter 4) and with eq. (4.16); this our δ_1 deviation is displayed in brackets to remind the reader that it has been assessed only by analogy using the Np-237 fission (instead of the dpa) energy-dependent cross section behaviour. Furthermore in Table IV (Chapter 4) are presented for comparison some other evaluation results for irradiation arrangements with thick steel plates. The second and the third line show results from the neutron spectrum calculation /19/ the last of which has been used as the input spectrum to our adjustment procedure. The absolute cross sections according to /19/ lie higher than our ones while the Fe-54(n,p) cross section turned out to be lower from /19/ than after our adjustment (Chapter 3). On the other side, our semi-empirical relative deviations appear quite well comparable with the calculated ones: not only for the Fe (Chapter 3) but also for the dpa cross section; the latter comparison can be made only reservedly because of our Np approach.

It should be mentioned that - beside the two more evaluation results presented in Table IV (Chapter 4) from other irradiation arrangements than at Jülich - a large list of values for the Effective dpa cross section and for other neutron irradiation environment parameters has been compiled in the Matrix E706 in /23/.

4.4.2. The dpa exposure and the relevance of its neutron spectrum variation to the FKS irradiations at Jülich

According to the comparison in Sec. 4.4.1 we do not seem to make a big mistake by estimating the dpa exposure d(x) from eq. (4.6) as follows:

$$d(x) = \sigma_d^c \cdot (1 + \delta_1 x) \cdot \Phi^M(1\text{MeV},x) \quad . \qquad (4.17)$$

Here may be taken:

- σ_d^c, the Effective dpa cross section in the reference position, from Table II (Chapter 4),
- δ_1, the mean dpa cross section deviation per cm steel thickness ($0 \leq x \leq D$), from eq. (4.16),
- the neutron fluence $\Phi^M(1MeV,x) = \phi^M(1MeV,x) \cdot t_I$ with the flux density ϕ^M according to eq. (2.14) (without dependency of z which could not be confirmed);in ϕ^M the reaction rate $R_{Fe}(x)$ should be taken for the corresponding irradiation position (x) and capsule from Table VII (Chapter 3) in /3/; and - only if a variation from the reference spectrum appears as "shown" - the cross section deviation $\delta\sigma_{Fe}(x)$ according to Table II (Chapter 2)(or Table V (Chapter 5) in /3/),for the irradiation position and capsule under consideration; furthermore with the irradiation time t_I for this capsule.

On the other side, we may ask to which extent the found neutron spectrum variation effect over the irradiated FKS capsules is relevant at all. The following procedure to assess this relevance is in parallel to Sec. 3.3. We write then for the dpa rate with taking into account the spectrum variation:

$$\dot{d}(x) = \sigma_d^c \; (1+\delta_1 x) \quad \frac{\phi(0) \; e^{-\mu x}}{1 + \delta_o x} \; . \tag{4.18}$$

Here we may insert for the neutron weakening coefficient: $\mu = .2 \text{ cm}^{-1}$, for the neutron flux density deviation coefficient: $\delta_o = -.04 \text{ cm}^{-1}$, and for the dpa rate deviation coefficient: $\delta_1 = .06 \text{ cm}^{-1}$ according to eq. (4.16).

W i t h o u t spectrum variation we obtain instead of eq. (4.18):

$$\dot{d}(x) = \dot{d}(0) \cdot e^{-\mu x} \; . \tag{4.19}$$

For the exposure we have to differ whether the concerning irradiation capsule has been rotated after the irradiation mid-time or not rotated. Thereupon we write:

$$d(x) = C\,\dot{d}(x) \qquad \text{for "rotation: no:} \qquad (4.20)$$

and

$$d(x) = C_1\dot{d}(x) + C_2\dot{d}(D-x) \qquad \text{for "rotation: yes"} \qquad (4.21)$$

with the constants C, C_1, C_2 denoting the irradiation time (intervals) multiplied by the corresponding irradiation history correction factor(s). Especially, eq. (4.21) has to be written in detail w i t h spectrum variation:

$$d(x) = \sigma_d^c\ \phi(0)\ \left[C_1 \frac{1+\delta_1 x}{1+\delta_o x}\, e^{-\mu x} + C_2 \frac{1+\delta_1(D-x)}{1+\delta_o(D-x)}\, e^{-\mu(D-x)}\right] \qquad (4.22)$$

To evaluate the average exposure, we assume in the case "rotation: no" for the exposure naturally the same slope as for the dpa rate; in the case "rotation: yes" the slope of a quadric parabola with minimum in x = D/2, approximating the slope in Fig. 9. The results are compiled in Table V (Chapter 4). The condition "no rotation" has been taken into account only for a CK (or CT) 60 capsule because the only irradiation in Jülich without rotation (it was capsule E56 /3/) has been carried out with a CK 60 type capsule.

In consequence of eq. (4.18), the dpa rate d(x) deviates slightly more from the value in the reference position d(D/2) as this holds for the neutron flux density $\phi(x)$. Therefore we define at first a "Mean" exposure $d_{\bar{N}}$ as the arithmetic mean between the exposure without spectrum variation d_N and the exposure in the mid (or reference) position:

$$d_{\bar{N}} \equiv (d_N + d(\tfrac{D}{2}))\ /\ 2\ . \qquad (4.23)$$

In Table V (Chapter 4) is still given this "Mean" $d_{\bar{N}}$ and the deviation d from d_N to the exposure with spectrum variation d_W, as a measure of the usefulness of the simple "Mean" approximation in eq. (4.23):

$$\delta d \equiv 100\ (d_{\bar{N}} - d_W)\ /\ d(\tfrac{D}{2})\ \% \qquad (4.24)$$

- for d_N, $d_W = \bar{d}^x$, i.e., averaged over 0 x D,
- for d_N, $d_W = d(x = \{ {D \atop o} \})$, i.e., in the end x positions, giving the maximum deviations.

For the exposure uncertainties $\rho(d)$ which are to be compared with the assessed deviations in Table V (Chapter 4) we set:

- for the exposure in a particular point x:
  $|\rho(d(x))| > 8$ % according to Sec. 4.2.2, (4.25)
- for the averaged exposure (cf. Sec. 3.3):

$$|\rho(\bar{\Phi}^{x})| > \frac{8}{\sqrt{3-1}} = 5.7\ \% \ . \qquad (4.26)$$

Starting from these guessed amounts, the average exposure deviations in Table V (Chapter 4) lie always within the $\pm 2\sigma$ confidence level, i.e., within the 95 % confidence interval. Under the end position exposures, those for the capsules CK 100 and CK 120 possibly exceed the 95 % confidence interval.

Summarizing may be said that the obviously small effect of the spatial neutron spectrum variation upon the irradiations of extended FKS steel specimens at Jülich approximately may be taken into account in a very simple way in terms of the average dpa exposures, without further spectrum variation considerations. This simple "Mean" exposure expression possibly does not hold for the end position exposures to the larger specimens.

Table I

E (MeV)	$\phi^c(E)$	E (MeV)	$\phi^c(E)$	E (MeV)	$\phi^c(E)$	E (MeV)	$\phi^c(E)$	E (MeV)	$\phi^c(E)$
1.00E-07	3.433E+13	5.00E-04	2.933E+13	3.00E-01	1.316E+13	1.00E+00	3.557E+12	8.00E+00	1.193E+10
5.00E-07	3.418E+13	1.00E-03	2.862E+13	4.00E-01	1.147E+13	2.00E+00	1.089E+12	9.00E+00	6.525E+09
1.00E-06	3.401E+13	5.00E-03	2.670E+13	5.00E-01	9.786E+12	3.00E+00	3.919E+11	1.00E+01	3.609E+09
5.00E-06	3.318E+13	1.00E-02	2.604E+13	6.00E-01	7.867E+12	4.00E+00	1.695E+11	1.10E+01	1.933E+09
1.00E-05	3.268E+13	5.00E-02	2.220E+13	6.90E-01	5.903E+12	5.00E+10	8.289E+10	1.20E+01	1.077E+09
5.00E-05	3.142E+13	1.00E-01	1.933E+13	8.00E-01	4.843E+12	6.00E+00	4.212E+10	1.30E+01	5.450E+08
1.00E-04	3.079E+13	2.00E-01	1.575E+13	8.80E-01	4.280E+12	7.00E+00	2.202E+10	1.40E+01	2.205E+08

Neutron flux density ("Phi") $\phi^c(E)$ in $cm^{-2} .s^{-1}$ above energy E in the Jülich FKS irradiation E57 position 10 ("reference") after unfolding re-evaluation

Chapter 4

Table II

Effective displacement cross section $\sigma_{d,m}$ for neutrons above 1 MeV in the Reference position (No. 10, irradiation E57) for the Jülich FKS steel irradiations

Cross Section $\sigma_{d,m}$(>1MeV) 10^{-21} cm^2	for $\sigma_{d,m}(E)$ with material choice "m" from /references/
2.163	"m" = "Ferritic steel" from E 693 in /23/
2.133	"m" = "Fe-L-Displ" from /24/
2.235	"m" = "Steel-L-Displ" from /24/

** Displacement Rate and Effective Cross Section Variation Assessment ** 10BP2083 05/26/86 10:36:40

Experiment: FKS Source: FRJ-1 Irradiation: E 57
Ref.Pos.No.10 Eff.dpa Cross Sec.>1 MeV: 2.163E-21 *(1+/- .024) cm^2
Meas.Reaction K with Cross Section Compared with dpa: Np237(n,f)

Pos. No.	K Double Spec.Index	+/- Uncert.	Fe Cross Sec.Deviation / Eff.dpa Cross Sec.>1 MeV cm^2	+/- Uncert. / +/- Uncert.	Flux Density>1 MeV 1/(cm^2*s) / dpa Rate 1/s	+/- Uncert. / +/- Uncert.
10	1	0	0	0	3.531E+12	>/= 7.72723E-02
			2.163E-21	>/= .024	7.63756E-09	>/= 8.09136E-02
3	.855252	7.27778E-02	5.28124E-02	.026	4.55443E+12	>/= 8.15292E-02
			1.94761E-21	>/= 8.09235E-02	8.87025E-09	>/= .114872
17	1.10377	7.54534E-02	-4.87613E-02	.026	2.90604E+12	>/= 8.15292E-02
			2.27104E-21	>/= .083338	6.59973E-09	>/= .116586

Chapter 4

Table IV

Effective dpa cross section evaluation over thick steel plates from test irradiation facilities

Evaluation origin (and kind)	Reactor (-facility)	Position M behind steel thickness from core x/cm	Eff. dpa cross section norm.to 1 MeV $\sigma_d(x)cm^2 10^{-21}$	σ_d deviation per cm steel thickness δ_1/cm^{-1}	Energy-dependent dpa cross section origin
This one (semi-empirical)	FRJ-1	14.6	2.163 ($\pm$>2.4%)	[0.058] ($\pm$ >6%)	/23/ E 693
/19/ (2 D calculation)	FRJ-1	14.6	2.3509	0.054	
/19/ (1 D calculation)	FRJ-1	14.6	2.6331	0.064	
/16/	FRG-2	6.0 .. 11.0	1.800 .. 2.140	0.035	/23/ E 693
/23/ E 706 (PVSDIP evaluation)	ORR (-PSF)	11.25 from /27/	2.238	0.039	/23/ E 693

* Deviation of dpa Exposure without/with Spectrum Variation in Steel * 20BP2074
Experiment: FKS Average dpa exp.,=1 in the mid x position 05/27/86 16:08:09
Steel capsule rotated or not after irradiation mid-time

Capsule CK-No.	Rotated	End pos.rel.dpa exp. without spec.var. / with spec.var.	Average rel.dpa exp. without spec.var. / with spec.var.	Mean exp.betw. without sp.v.+mid pos.	% Average exp.dev. Mean-with sp.v.
60	no	1.8221	1.06107	1.03053	
		1.3465	1.01482		1.54878
60	yes	1.18547	1.06182	1.03091	
		1.03498	1.01166		1.90298
100	yes	1.54308	1.18103	1.09051	
		1.09173	1.03058		5.81585
120	yes	1.81066	1.27022	1.13511	
		1.12629	1.0421		8.92559

* Deviation of dpa Exposure without/with Spectrum Variation in Steel * 20BP2074
Experiment: FKS End pos.dpa exp.,=1 in the mid x position 05/27/86 16:26:00
Steel capsule rotated or not after irradiation mid-time

Capsule CK-No.	Rotated	End pos.rel.dpa exp. without spec.var. / with spec.var.	End pos.rel.dpa exp. without spec.var. / with spec.var.	Mean exp.betw. without sp.v.+mid pos.	% End pos.exp.dev. Mean-with sp.v.
60	no	1.8221	1.8221	1.41105	
		1.3465	1.3465		4.79391
60	yes	1.8221	1.8221	1.41105	
		1.3465	1.3465		4.79391
100	yes	1.54308	1.54308	1.27154	
		1.09173	1.09173		16.4702
120	yes	1.81066	1.81066	1.40533	
		1.12629	1.12629		24.7751

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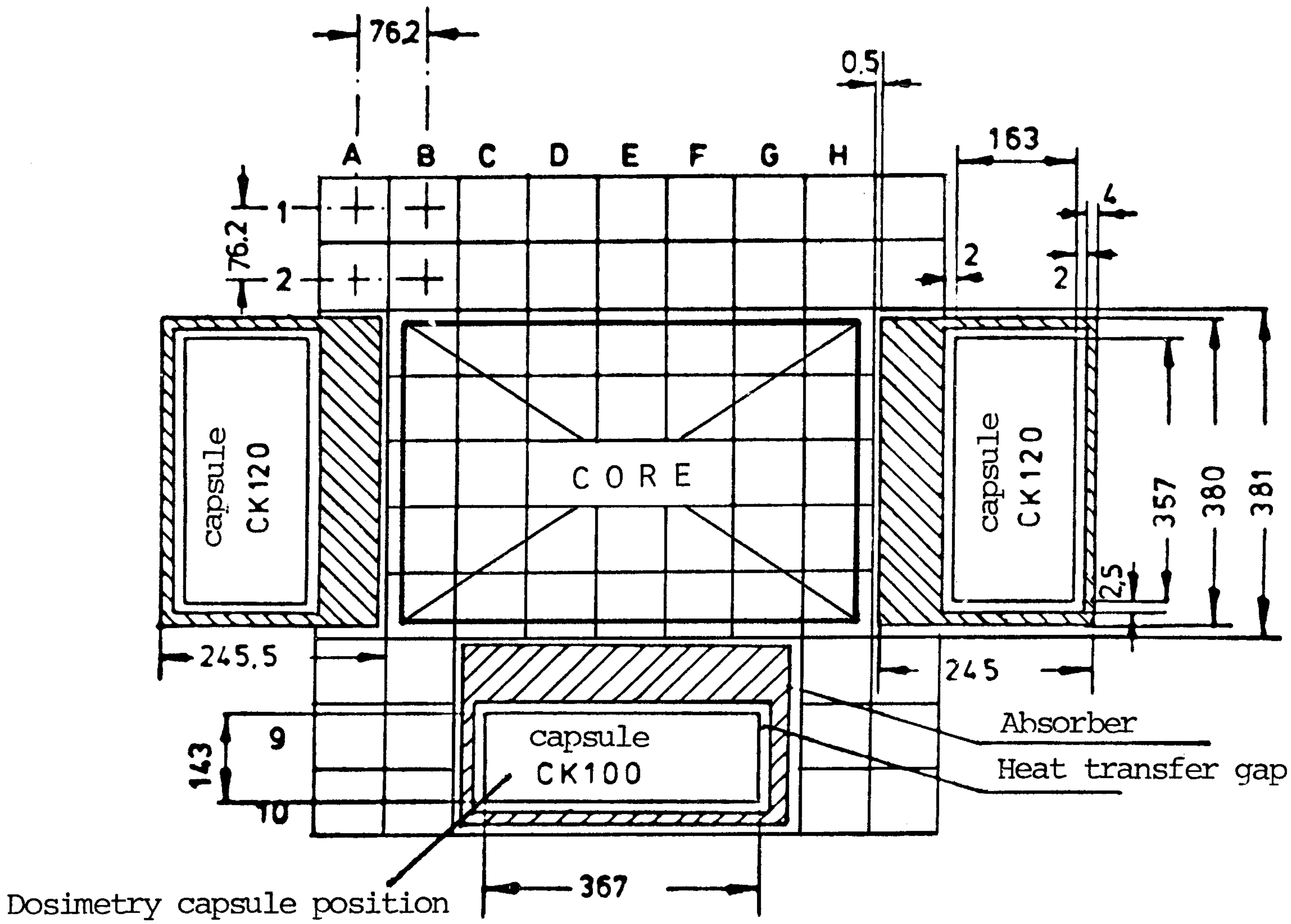


FIG. 1 SPECIMEN ARRANGEMENT FOR THE FKS STEEL IRRADIATION IN THE FRJ-1

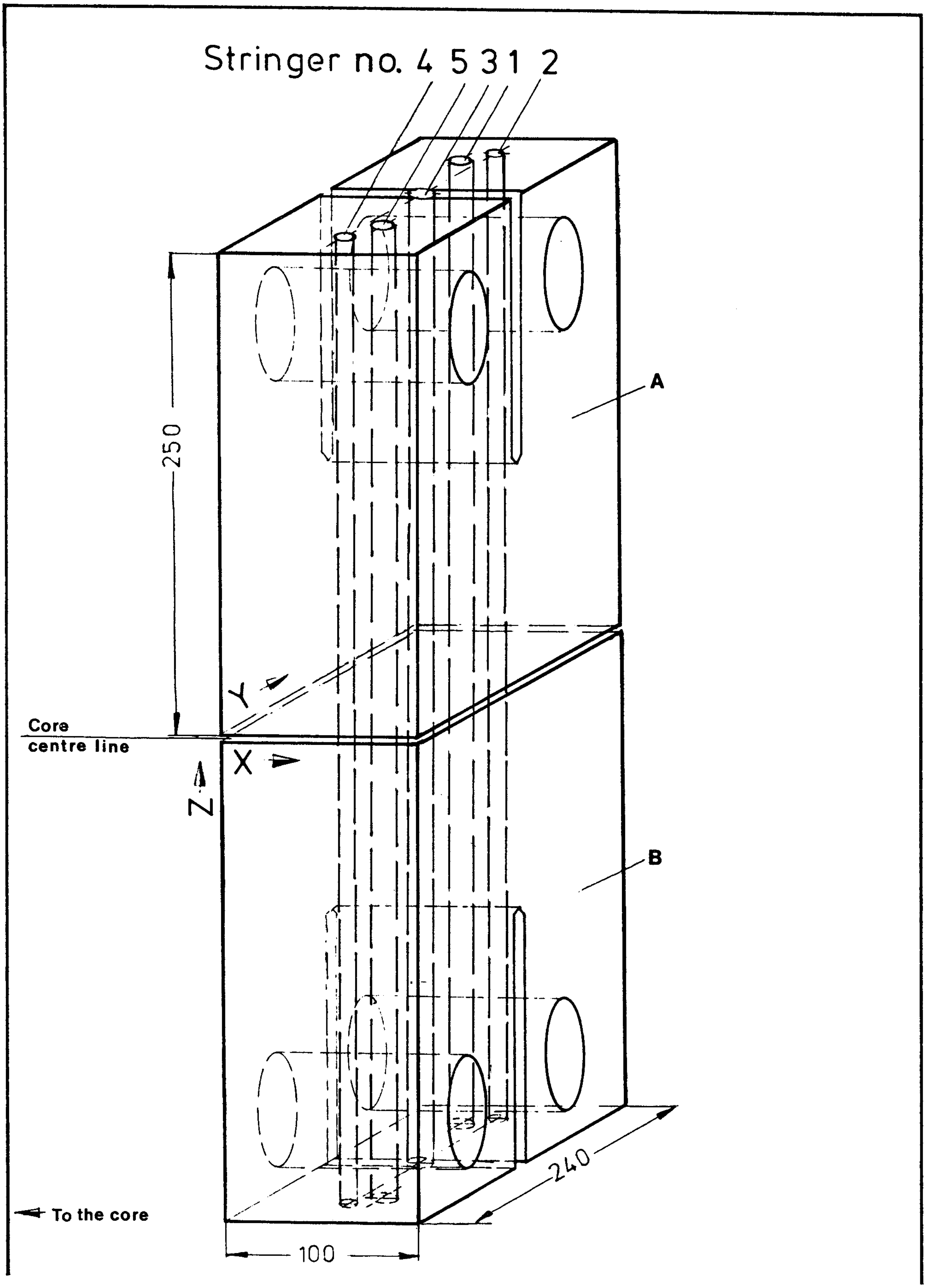


FIG. 2: STRINGER HOLES (1-5) THROUGH THE STEEL SPECIMENS (A,B) FOR THE FKS DOSIMETRY TEST EXPERIMENT

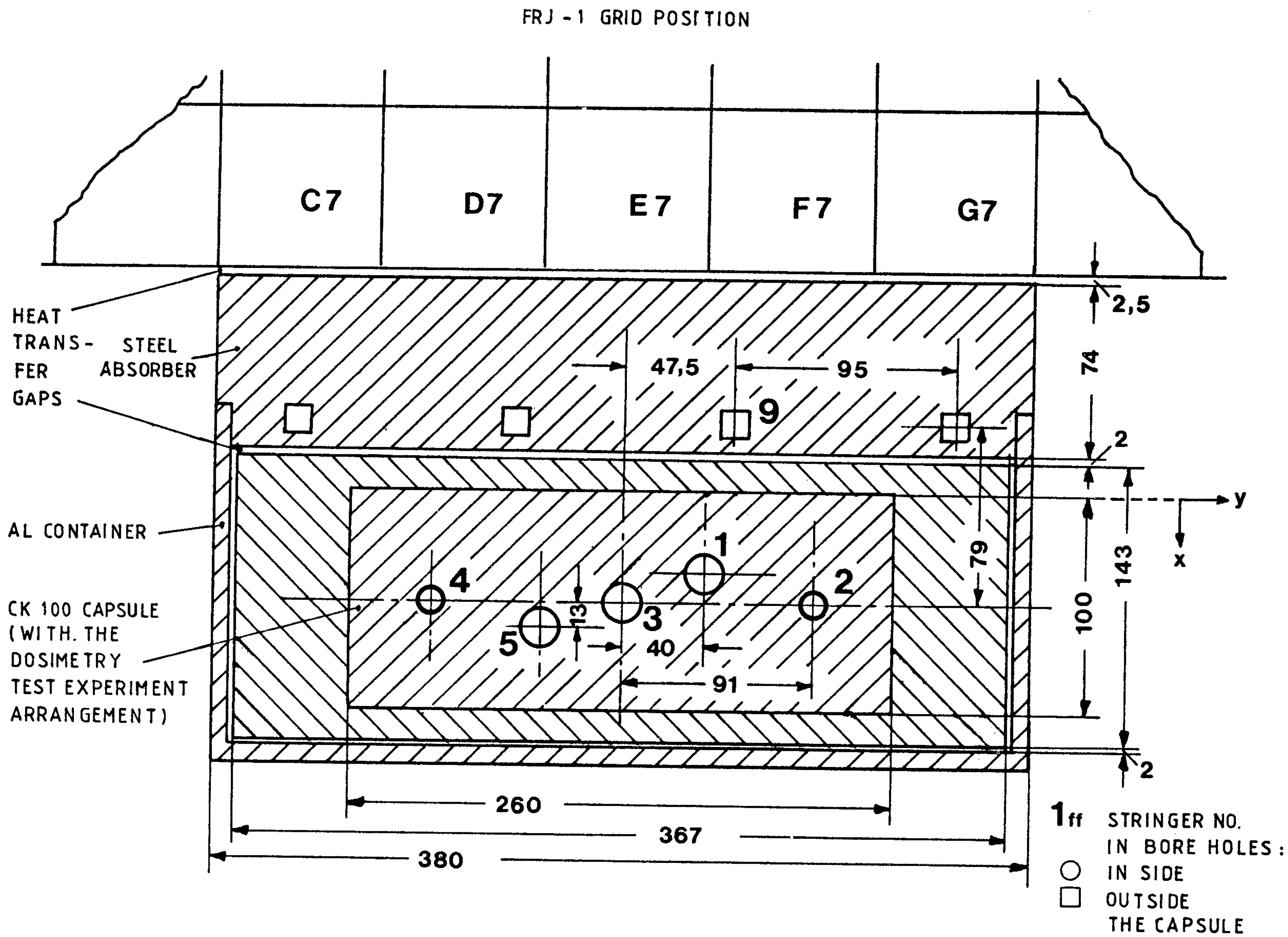


Fig. 3. Cross section of the FKS Dosimetry Test Experiment Capsule (E57) with the stringer locations

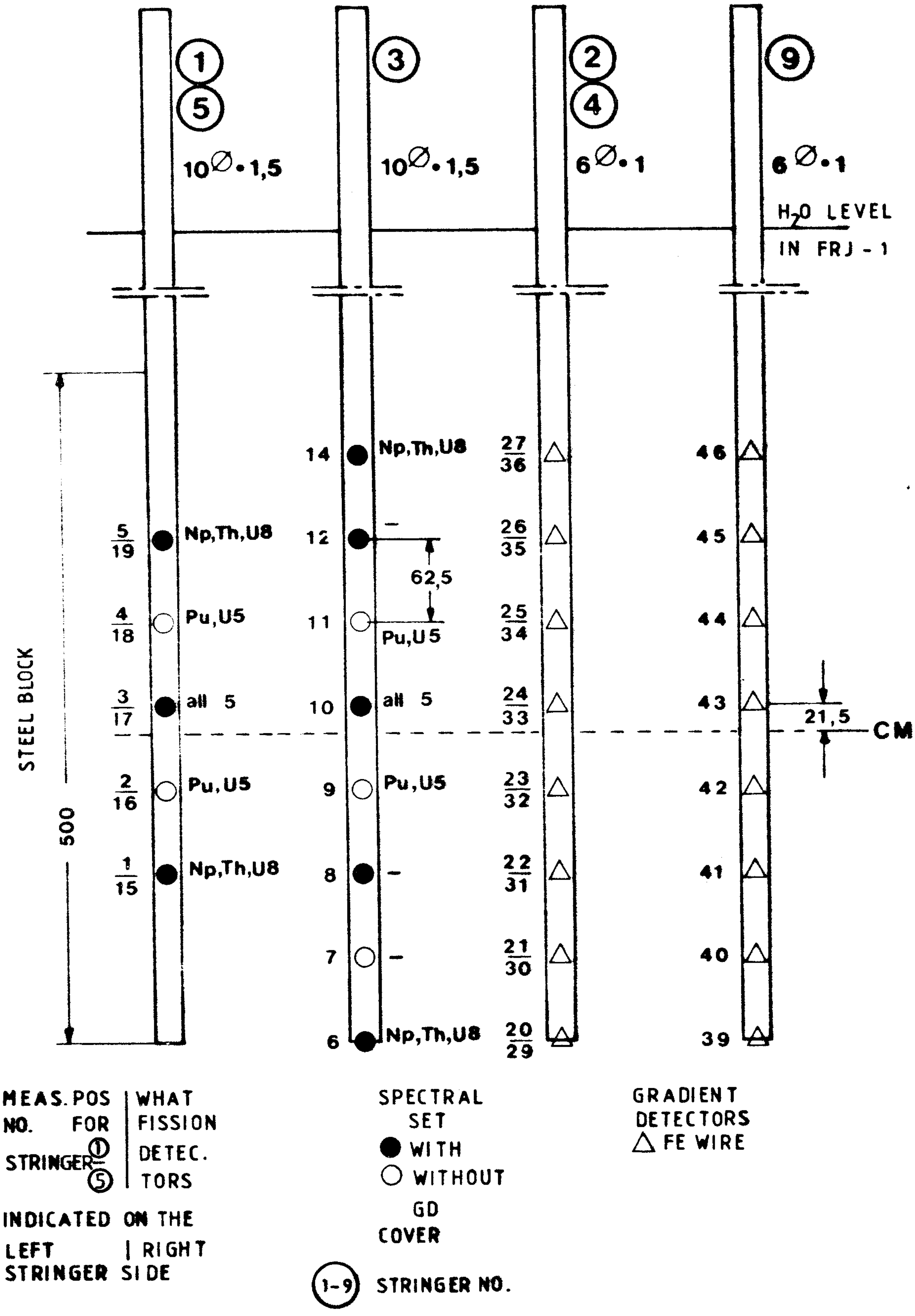
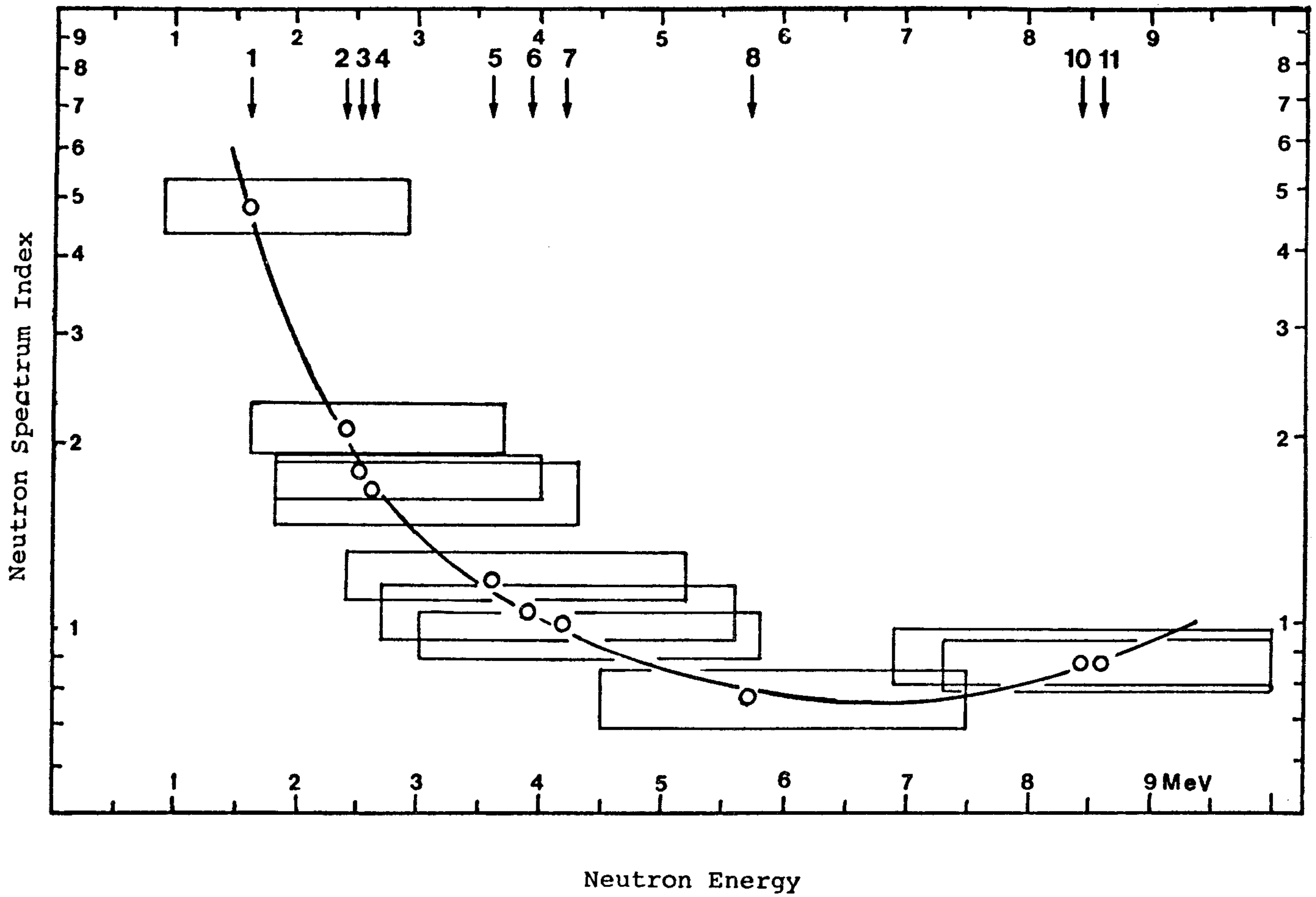


Fig. 4 Detector arrangement in the stringers in the FKS Dosimetry Test Experiment Capsule (E 57)



NEUTRON SPECTRUM INDEX

in a Steel Block Centre

in the FRJ-1 Reflector

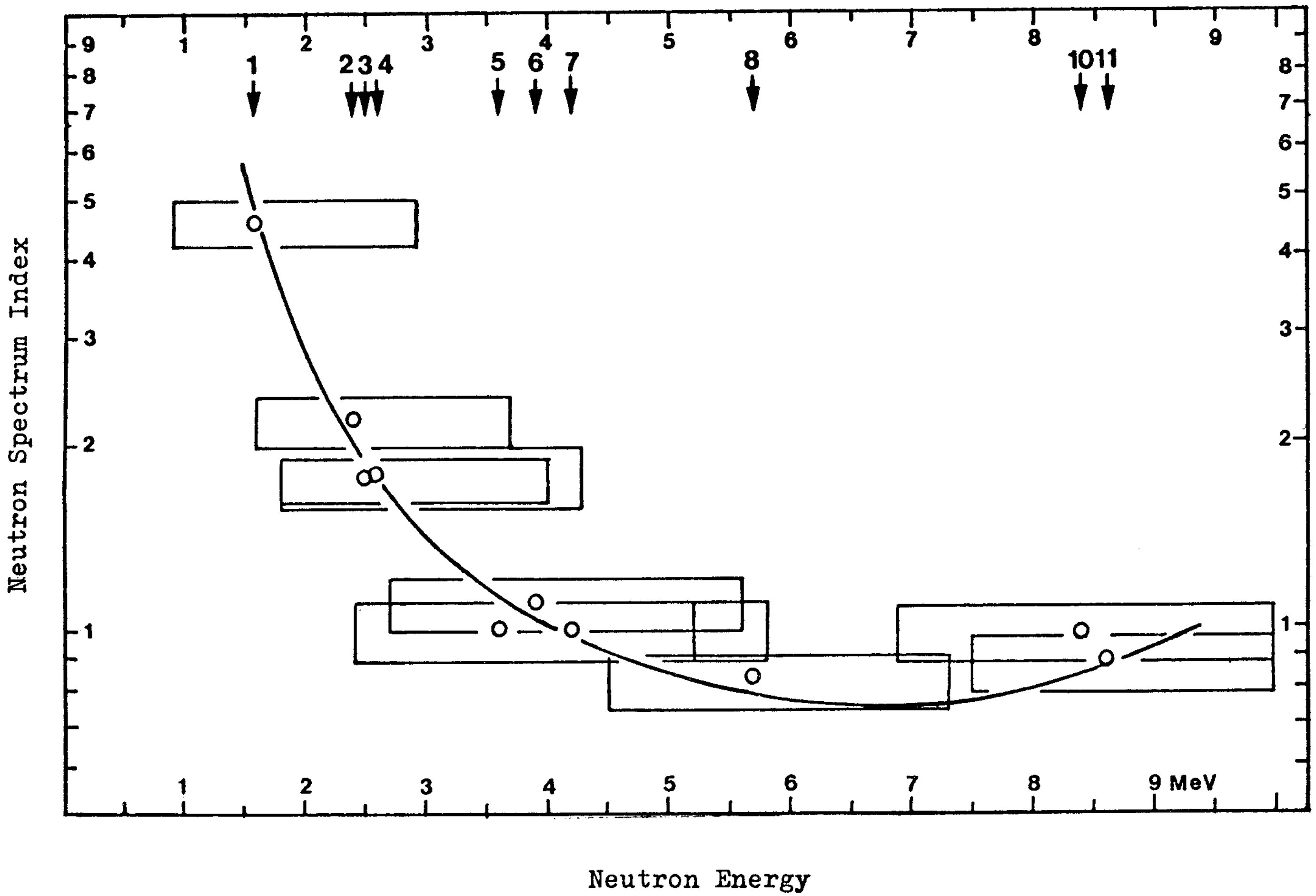
for the Following Measuring Reactions:

1	Np237(n,f)
2	In115(n,n')
3	U238(n,f)
4	Th232(n,f)
5	Ti47(n,p)
6	Ni58(n,p)
7	Fe54(n,p)
8	Ti(n,x)Sc46
9	Cu63(n,a)
1o	Ti48(n,p)
11	Al27(n,a)

Fig. 5

with Measured Cross Sections

(from /4/)



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11	Al27(n,a)

Fig. 6

with Evaluated Cross Sections

(from /5/)

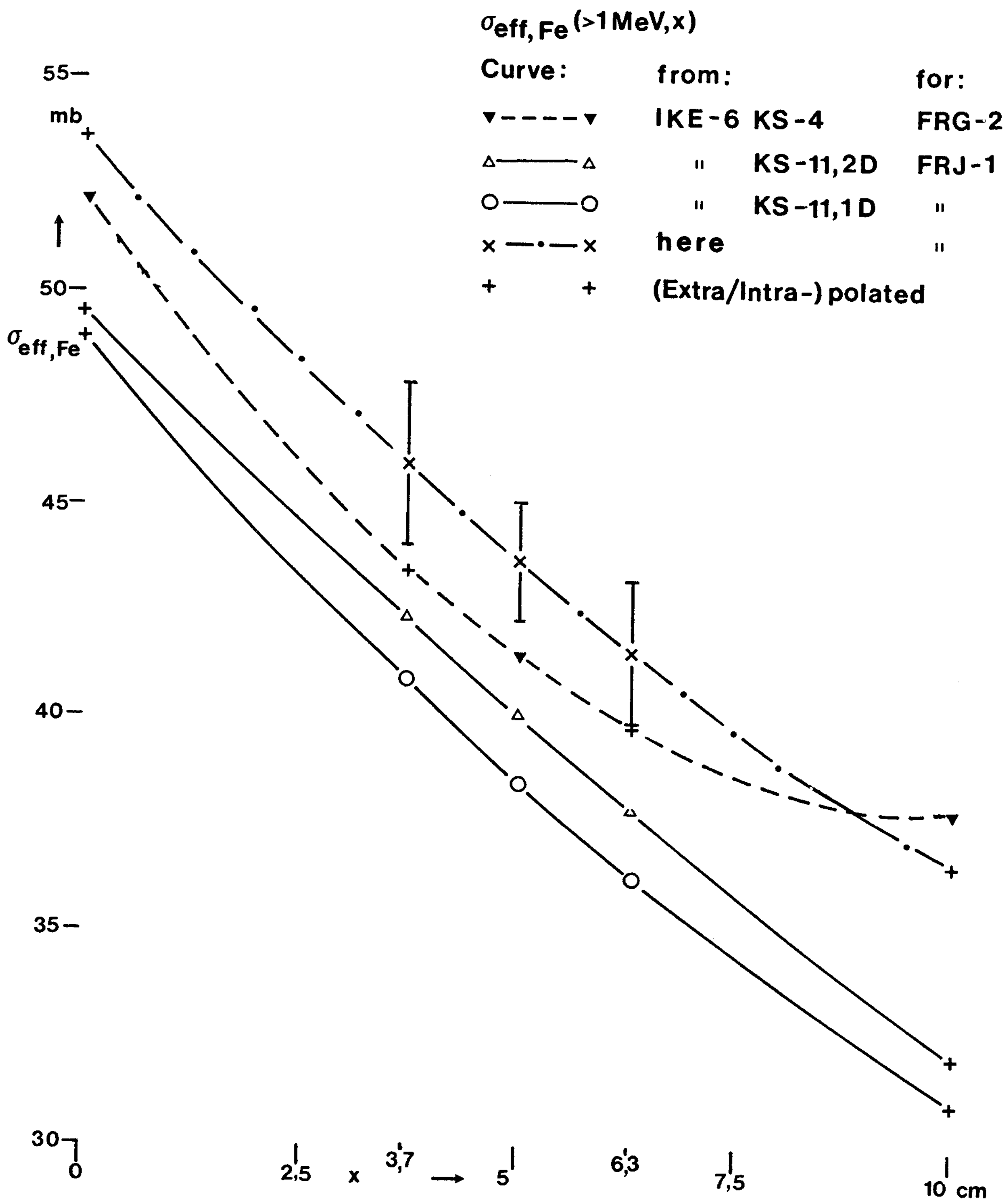

Fig. 7. Comparison of different estimations for the effective Fe54(n,p) cross section variation through a CK(=CT) 100 steel specimen

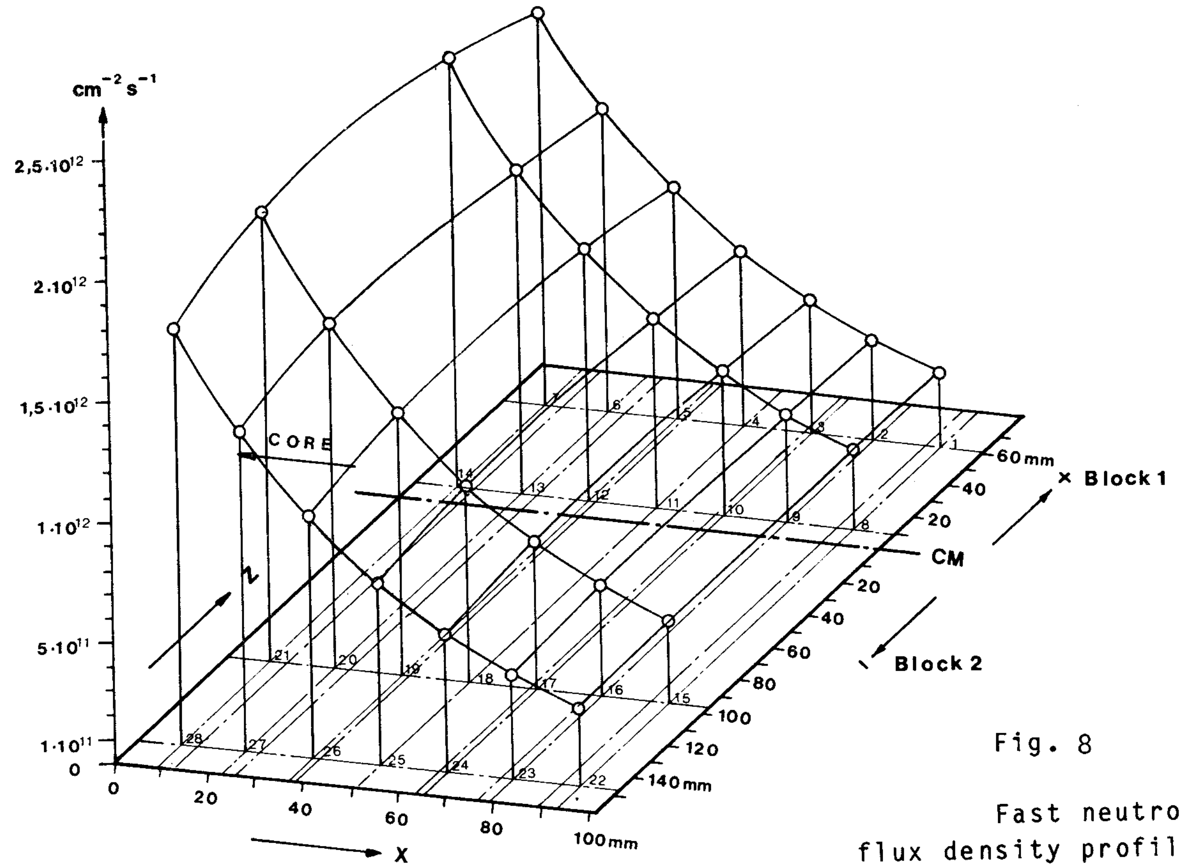

Fig. 8

Fast neutron
flux density profile
in the cracking plane
of a CK(=CT)100 steel specimen

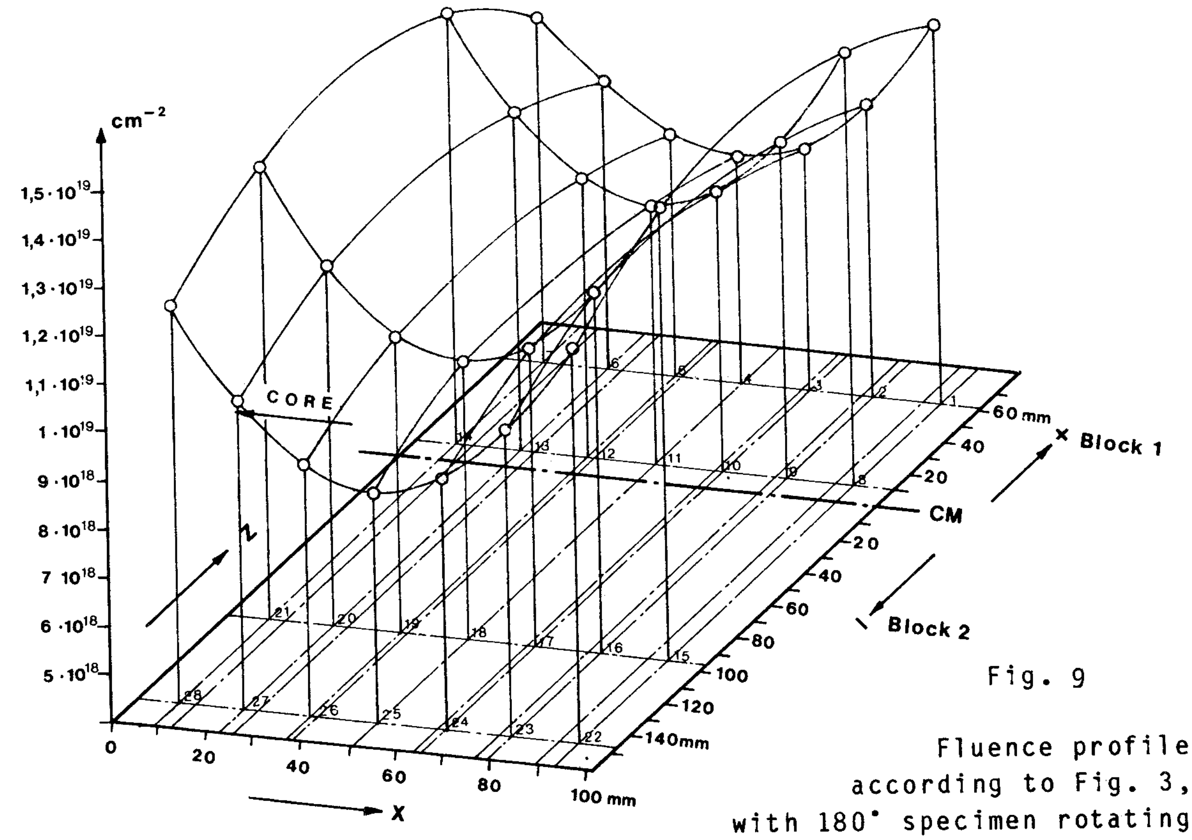

Fig. 9

Fluence profile
according to Fig. 3,
with 180° specimen rotating
after irradiation mid-time

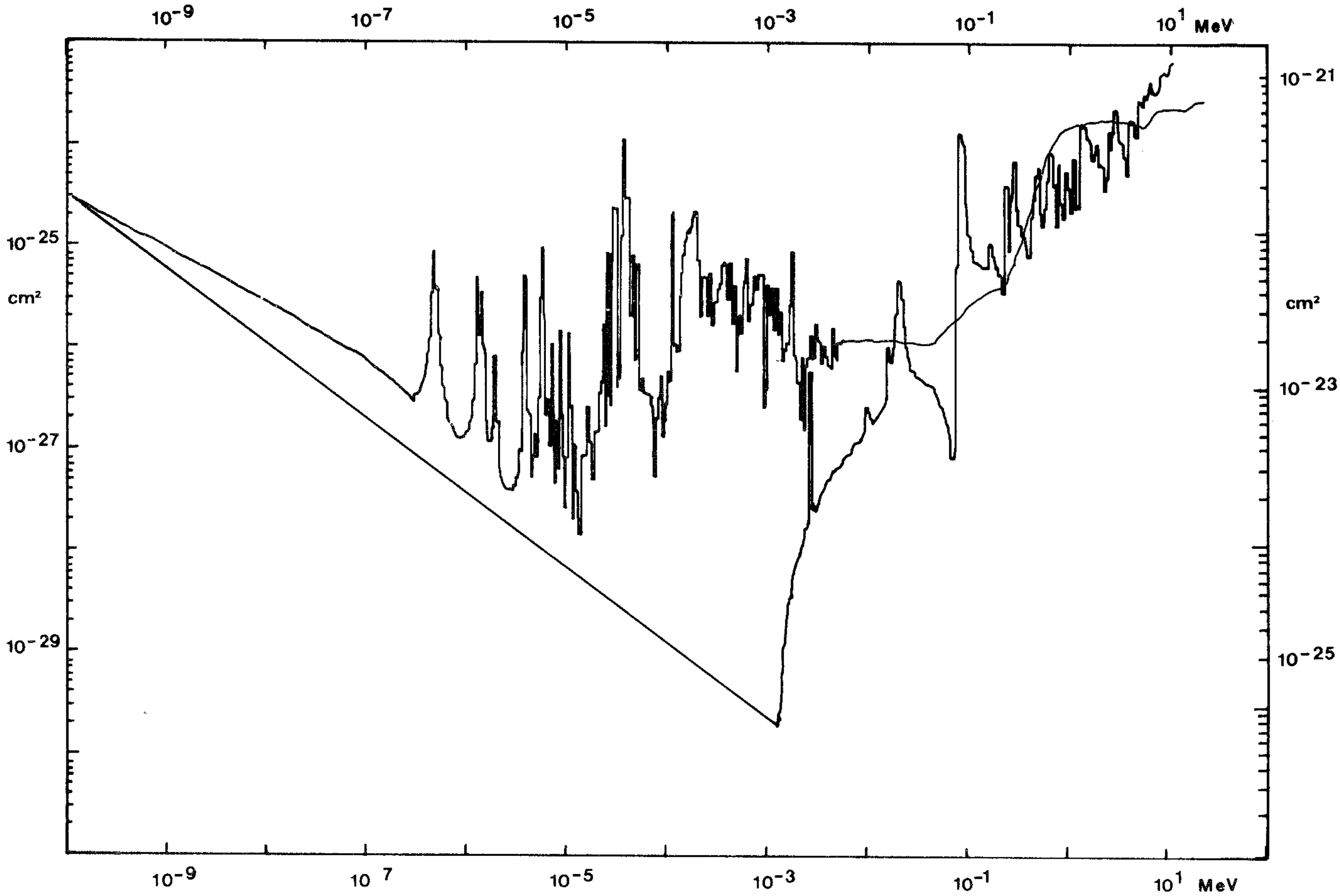

Fig. 10

Displacement cross section for Fe (ASTM E693/23/), compared with Np237(n,f) cross section (red) /6/, as functions of neutron energy (in MeV)