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ANALYSIS OF SMALL-ZONE SODIUM-VOID EXPERIMENTS PERFORMED IN A HETEROGENEOUS FAST REACTOR CORE

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ABSTRACT

Calculational analyses have been made for a simple annular assembly of the joint UK/DeBeNe BIZET programme (DeBeNe stands for West Germany (Deutschland), Belgium and the Netherlands). The two groups used their own cross-section data and codes. The results were compared with each other and with the experimental values. The criticality calculations took account of the three-dimensional core arrangement, cell heterogeneity and transport theory corrections. The sodium-void reactivity worths were calculated by both first-order and exact perturbation theory. Transport theory corrections were applied to the diffusion theory values.

INTRODUCTION

Assembly BZD/3 of the joint UK/DeBeNe BIZET programme in the zero power fast reactor ZEBRA /1/ represented a heterogeneous core design with a large single fissile annulus. The assembly did not contain any simulated control-rod positions. The assembly became critical in October 1979.

From an extensive experimental programme the analysis of the k-values, the effective delayed neutron fraction β_{eff} and the small-zone sodium-void experiments are presented. Calculations were carried out by AEEW and KfK using their own cross-section data and methods similar to those applied to power reactor designs. The results are compared with each other and with the experimental values.

DESCRIPTION OF THE ASSEMBLY AND THE VOID EXPERIMENTS

Assembly BZD/3 contained a large inner breeder (47.5 cm equivalent radius) surrounded by an annulus of fissile material ($\simeq$ 45 cm thick, Fig.1) with a Pu/(Pu+U) enrichment of 24%. The core height was 89.2 cm. The inner breeder and most of the fissile annulus were built of platelet cells. The inner breeder cell contained UO_2 and sodium plates, the core cell contained plutonium metal, UO_2, sodium and steel plates. The rest of the fissile annulus contained pin cells. The core was surrounded radially and axially by a region composed of uranium, sodium and steel platelets and a natural uranium region, which together were more than 30 cm thick /1/.

The sodium-void experiments were performed in plate geometry at a variety of radial positions, namely at the centre and near the outer edge of the breeder island and at five positions across the fissile annulus (Fig.1). In each position, the central 40% of the core height was voided, thereby emphasising the non-leakage and radial-leakage contributions. In two positions, f and c. the voided regions were also extended over larger axial regions to enhance the axial-leakage contribution. The reactivity worths of voiding were measured by the compensating movements of a fine control rod calibrated by inverse-kinetics methods.

CALCULATIONS

The spatial calculations were performed by both groups using diffusion theory and appropriate XYZ models. In the AEEW analysis, the mesh in the XY plan corresponded to the average element pitch in ZEBRA of ~5.4 cm in each direction. The mesh size in the axial direction varied between 5.6 and 7.6 cm. The KfK analysis used a constant mesh size of half an element pitch in each direction of the XY plan. The axial mesh size was 2.7 cm, 2.8 cm and 3.8 cm in the core, the blanket and the natural uranium region, respectively.

The sodium-void reactivities were calculated using both first-order (FOP) and exact perturbation theory. The KfK calculations were run with 13 energy groups and the AEEW calculations with 37 groups. Both analysis teams used RZ models of BZD/3 to calculate some correction terms.

Basic 26-group cross-sections were prepared by KfK on the basis of the KFKINR001 data set /2/. The cross sections were corrected for the heterogeneity of core cells using the lattice code KAPER /3/, which calculated anisotropic diffusion coefficients according to the Benoist equation /4/ to allow for preferential streaming of neutrons in dilute regions. The KAPER calculations for the flooded and sodium-voided cells were run using multi-group axial and radial bucklings from a diffusion theory calculation in RZ geometry. The 26-group cross sections were collapsed to a 13-group structure using the method of bilinear weighting /5/.

AEEW prepared 37-group cross sections from the 2000-group FGL5 adjusted data set /6/ using the collision probability code MURAL /7/ in the single-buckling search option. Preferential streaming was taken into account by applying corrections to the group diffusion coefficients based on transport-theory methods /8/. Both KAPER and MURAL assumed the cells were present as an infinite array.

a) k-Values

The basic AEEW k-value of 0.9937 resulted from a calculation in XYZ geometry with the diffusion theory code TIGAR. The following corrections given in Table I were applied:

- a transport theory correction,
- a correction for the ^{241}Pu decay between the date for which the composition was evaluated (January 1978) and the date of the measurements in November 1979,
- a correction for the outer plenum and radial steel reflector not represented in the XYZ model /1/.

The corrected k-value of 0.9989 resulted in a calculation/experiment (C/E) value of 0.997, compared with a mean ratio of 1.001 in earlier conventional ZEBRA cores /9/.

The basic KfK value of 0.9982 was calculated in XYZ geometry and 13 energy groups with the diffusion theory code D3D. The calculated corrections are given in Table I:

- a transport theory correction ,
- the effect of collapsing the cross sections from 26 to 13 energy groups,

- the effect of using zone independent prompt and delayed fission neutron spectra instead of zone dependent values.

The two corrections for the ^{241}Pu decay and the presence of the outer plenum and radial steel reflector were taken from the AEEW analysis. The corrected k-value of 1.0061 yielded a C/E value of 1.0045. This value was higher than that for the conventional BIZET assembly, BZA/1, (1.001, /10/) but smaller than the mean value of 1.008 found in the analysis of SNEAK assemblies /11/.

b) Effective Delayed Neutron Fraction

The delayed neutron fraction β_{eff} was calculated by both sides. AEEW used the Smith re-evaluation /12/ of Tomlinson's delayed neutron survey /13/ with real and adjoint fluxes from the 37-group XYZ calculation. The resulting β_{eff} value was 0.003506. KfK used the recommended delayed neutron data from the Tuttle evaluation /14/ in connection with real and adjoint fluxes from both the 13-group XYZ and the 26-group RZ diffusion theory calculations. The resulting β_{eff} values of 0.003515 and 0.003525 respectively agreed well and differed from the AEEW value by about 0.5%. The AEEW value was used to determine the experimental reactivity scale.

c) Reactivity Changes Produced by Sodium Voiding

Table II gives the comparison of FOP sodium-void reactivity worths with the experimental values. All KfK FOP sodium-void reactivities were more negative (or less positive) than experiment probably due to an overestimated neutron leakage. The AEEW FOP values were also too negative in the fissile annulus but agreed with the experimental values in the inner breeder. The more negative C-E values of the KfK analysis resulted mainly from higher (negative) leakage terms. An overestimate of the neutron leakage and too negative FOP sodium-void worths are also reported from an analysis of sodium-void measurements in ZPPR assemblies /15/.

Both analyses were extended to the use of exact perturbation theory (unperturbed real flux, perturbed adjoint) for most positions. The reactivity terms of the KfK analysis are given in Table III. For the positions d and g, the reactivities were not calculated explicitly by exact perturbation theory in XYZ geometry. For position d, the FOP non-leakage and leakage terms were multiplied by the factors obtained from position a. For the central position g, a two-dimensional analysis has shown that FOP and exact perturbation theory terms differed only slightly. The exact perturbation theory increased the non-leakage terms by only 0.4 to 1.25 % but decreased the total leakage by 5 to 13%. But the total reactivities were still too negative. In the AEEW analysis, exact perturbation theory calculations were run for position b, close to the position of the peak flux in the fissile annulus, and for position e at the outer boundary of this annulus (Table IV). As the Exact/FOP corrections to the non-leakage, radial leakage and vertical leakage contributions were very similar for both positions, average corrections of +1.65% on the non-leakage term, -7% on radial leakage and -3.5% on vertical leakage were applied to the remaining positions in the fissile zone. The corrected values are given in Table IV. They were also still too negative.

In the AEEW analysis, a least squares fit was performed to obtain correction factors for the non-leakage and the leakage terms from the diffusion-theory exact perturbation calculations to give agreement with the experimental results in the fissile annulus. It assumed that the factors were spatially independent. Constant factors for the non-leakage and radial leakage terms calculated by exact perturbation theory were obtained such that the sum of the squares of the differences between the adjusted total and experimental worths are minimised. Any error in the small vertical leakage contribution was ignored. Depending on the sodium-void positions selected to provide the adjustments, the factors varied over the ranges 1.07 to 1.17 (non-leakage) and 0.91 to 0.99 (radial leakage). Using all of the 40% height results for the fissile annulus suggests an increase in the non-leakage term of 13.3% and a decrease in the radial leakage of 2.3%. The adjusted values for the fissile zone positions are given in Table IV.

The error in the vertical leakage term was studied using the experimental and calculated results for the outer 60% void height of position c. The correction factor varied from 0.89 to 0.95. In an analysis of sodium-void worths in the fissile zones of conventional ZEBRA assemblies /16/, the correction factors of 1.04 ± 0.03, 1.00 ± 0.02 and 0.89 ± 0.08 were found for the calculated non-leakage, radial leakage and vertical leakage terms. The errors do not include any contributions from the experimental reactivity scale (~ 5%). The factors for the leakage terms in BZD/3 were not inconsistent with those values for the conventional ZEBRA assemblies, but the factor for the non-leakage term in BZD/3 was somewhat higher (by 3 to 12%).

In the KfK analysis, transport theory corrections were calculated by comparing FOP calculations for an RZ model in transport (S_4) and (isotropic) diffusion theory. The differences of the total Na-void reactivities for the regions investigated, which had to be annular in this model, were multiplied by the area ratios of experimental to annular region. These transport theory corrections were applied to the diffusion-theory exact perturbation theory values and resulted in good agreement (within 10%) with the experimental values (Table III). Fig.2 shows the calculated sodium-void reactivities of the KfK analysis and the experimental values. Fig.3 shows that the difference between diffusion-theory exact perturbation theory and FOP as well as the transport theory correction are largest near the boundaries of the fissile annulus with the inner and outer breeder regions, where there are large contributions from radial leakage.

CONCLUSIONS

The measured k-value was underestimated by the AEEW calculations (-0.003) and overestimated by the KfK analysis (+0.004) after all relevant corrections had been applied to the calculated k-values. These differences are acceptable for the design of a heterogeneous fast power reactor.

The sodium-void reactivities calculated by first-order perturbation theory were too negative due to an overestimated neutron leakage with the exception of those for the inner breeder in the AEEW analysis. The use of exact perturbation theory reduced the discrepancies, mainly by decreasing the neutron leakage, but still left differences between calculation and experiment. In the KfK analysis the application of transport theory corrections to the exact perturbation theory values resulted in good agreement (within 10%) with the experimental values. Power reactor designers should therefore bear in mind the errors associated with the use of diffusion theory and first-order perturbation theory in calculating small-region sodium-void worths.

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TABLE I

Criticality Prediction for Assembly BZD/3

Analysis Team	UK/AEEW	DeBeNe/KfK
Geometry, Number of Energy Groups	XYZ, 37	XYZ, 13
Basic k-Value (diffusion)	0.9937	0.9982
Correction Terms, δk, for		
Transport Theory	+0.0057	+0.0102
Plenum, Steel (outer regions)	+0.0011	+0.0011
^{241}Pu Decay	-0.0016	-0.0016
Few Group Collapsing	-	-0.0009
Material Dependent Fission Neutron Spectra	-	-0.0009
Final k-Value	0.9989	1.0061

Notes: 1. The experimental k-value corrected for control rod insertion and temperature effects was 1.0016 ± 0.0006.

2. The transport theory corrections refer to different meshes in the diffusion theory calculations.

TABLE II

Small-Zone Sodium-Void Worths in BZD/3 .
Comparison of AEEW and KfK FOP Results with Experimental Values
(Units $10^{-6}.\delta(-1/k)$)

Core Section	Position	Experiment E	AEEW C_z	$C_z - E$	KfK C_s	$C_s - E$
Fissile Annulus	a	-23.36±1.5	-65.21	-41.8	-79.38	-56.0
	b	+130.2 ±1.7	+100.5	-29.7	+102.10	-28.1
	c(40%c.h.)	+100.8 ±1.6	+83.7	-17.1	+80.52	-20.3
	c(100%c.h.)	+42.0 ±1.5	-11.21	-53.2	-31.12	-73.1
	d	-39.89±1.5	-64.89	-25.0	-93.25	-53.4
	e	-174.1 ±1.8	-204.2	-30.1	-253.23	-79.1
Inner Breeder	f(40%c.h.)	-54.6 ±1.6	-56.7	-2.1	-83.39	-28.8
	f(80%c.h.)	-107.3 ±1.6	-112.6	-5.3	-156.59	-49.3
	g	+12.88±1.5	+13.84	+1.0	+10.15	-2.7

Note : The errors on the measured values do not include the uncertainty from the reactivity scale (5%).

TABLE III

Comparison of Calculated and Experimental Sodium-Void Worths of BZD/3 in Fissile and Fertile Element Locations, KfK Analysis (Units $10^{-6}\cdot\delta(-1/k)$)

Position	Calc. *)	Absorption	Source	Scattering	Non-Leakage	Radial Leakage	Vertical Leakage	Transport Correction	Total,C Diff.+ Transport	Experiment E	C - E
a	FOP	+22.489	+7.694	+134.659	+164.842	-230.078	-14.140	+23.780	-55.596	-23.36	-32.2
	E.P.	+22.490	+7.724	+135.632	+165.846	-199.948	-12.289	+23.780	-22.611		-0.7
b	FOP	+41.117	-36.711	+140.275	+144.681	-22.618	-19.963	+12.140	+114.240	+130.2	-16.0
	E.P.	+41.157	-36.777	+141.156	+145.536	-20.384	-17.992	+12.140	+119.300		-10.9
c (40%c.h.)	FOP	+41.541	-44.702	+137.526	+134.365	-30.070	-23.771	+11.015	+91.539	+100.8	-9.3
	E.P.	+41.576	-44.795	+139.139	+135.920	-26.860	-21.233	+11.015	+98.842		-2.0
c (100%c.h.)	FOP	+73.570	-76.548	+245.793	+242.815	-44.316	-229.614	+38.738	+7.623	+42.0	-34.4
	E.P.	+73.570	-76.662	+248.936	+245.844	-42.195	-218.627	+38.738	+23.761		-18.2
d	FOP	+28.912	-25.493	+101.423	+104.842	-181.954	-16.136	+20.076	-73.172	-39.89	-33.3
	E.P.				+105.47	-158.30	-14.04	+20.076	-46.79		-6.9
e	FOP	+11.715	+3.744	+61.188	+76.647	-322.722	-7.152	+28.859	-224.368	-174.1	-50.3
	E.P.	+11.665	+3.755	+61.501	+76.920	-279.353	-6.190	+28.859	-179.764		-5.7
f (40%c.h.)	FOP	+23.818	-0.848	+103.854	+126.824	-205.384	-4.830	+9.935	-73.455	-54.6	-18.9
	E.P.	+23.927	-0.852	+104.272	+127.347	-187.244	-4.403	+9.935	-54.365		+0.2
f (80%c.h.)	FOP	+39.351	-1.368	+169.624	+207.607	-330.575	-33.619	+17.860	-138.727	-107.3	-31.4
	E.P.	+39.519	-1.373	+170.278	+208.424	-301.474	-30.659	+17.860	-105.849		+1.5
g	FOP	+2.452	+0.023	+9.111	+11.586	-1.269	-0.171	-0.007	+10.139	+12.88	-2.7

*) Non-Leakage and leakage terms resulted from diffusion theory first-order (FOP) and exact perturbation (E.P.) theory calculations

TABLE IV

Comparison of Calculated and Experimental Sodium-Void Worths in Fissile Elements, AEEW Analysis (Units 10^{-6} dk/k)

Position		Non-Leakage	Radial Leakage	Vertical Leakage	C	E	C-E	C-E Fitted
a	FOP	135.7	-188.6	-12.34	-65.21	-23.36	-41.85	-
	'Exact'	137.9	-175.4	-11.91	-49.41	"	-26.05	-
	Adjusted	156.2	-171.3	"	-27.01	"	-	-3.65
b	FOP	139.9	-21.85	-17.51	100.5	130.2	-29.7	-
	'Exact'	142.4	-20.25	-16.91	150.23	"	-25	-
	Adjusted	161.3	-19.78	"	124.6	"	-	-5.6
c	FOP	131.6	-30.36	-17.59	83.7	100.8	-17.1	-
	'Exact'	133.8	-28.23	-16.97	88.59	"	-12.2	-
	Adjusted	151.5	-27.57	"	107.0	"	-	6.2
c (100%)	FOP	236.8	-53.08	-194.9	-11.21	42.0	-53.2	-
	'Exact'	240.7	-49.36	-188.1	+3.24	"	-38.8	-
	Adjusted	272.7	-47.88	-188.1	36.72	"	-	-5.3
d	FOP	98.64	-151.1	-12.43	-64.89	-39.89	-25	-
	'Exact'	100.3	-140.5	-11.99	-52.19	"	-12.3	-
	Adjusted	113.6	-137.2	"	-35.59	"	-	4.3
e	FOP	61.17	-259.3	-6.124	-204.2	-174.1	-30.1	-
	'Exact'	62.16	-244.6	-5.904	-188.3	"	-14.2	-
	Adjusted	70.42	-238.9	"	-174.4	"	-	-0.3

Notes:

1. 'Exact' terms were obtained from XYZ exact perturbation theory calculations for positions b and e. Average Exact/FOP corrections for these two positions were then applied to the remaining positions (non-leakage terms +1.65%, radial leakage -7%, vertical leakage -3.5%).

2. To obtain 'adjusted' values, non-leakage terms of 'exact' values were increased by 13.3%, and radial leakage terms decreased by 2.3% to minimise sum of squares of (C-E). No adjustment was applied to the vertical leakage.

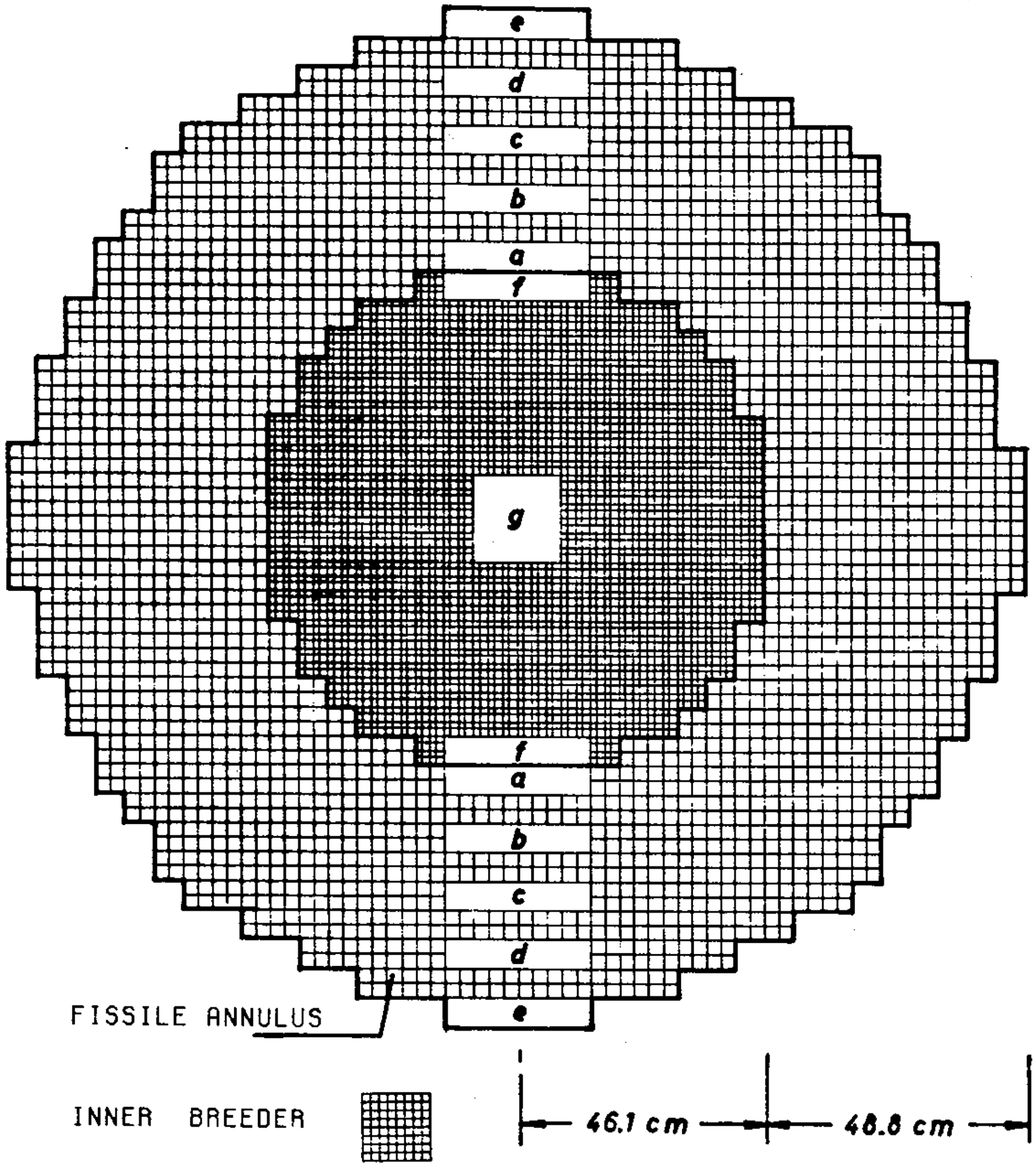

FIG. 1 POSITIONS OF SMALL-ZONE SODIUM-VOIDS IN ASSEMBLY BZD/3

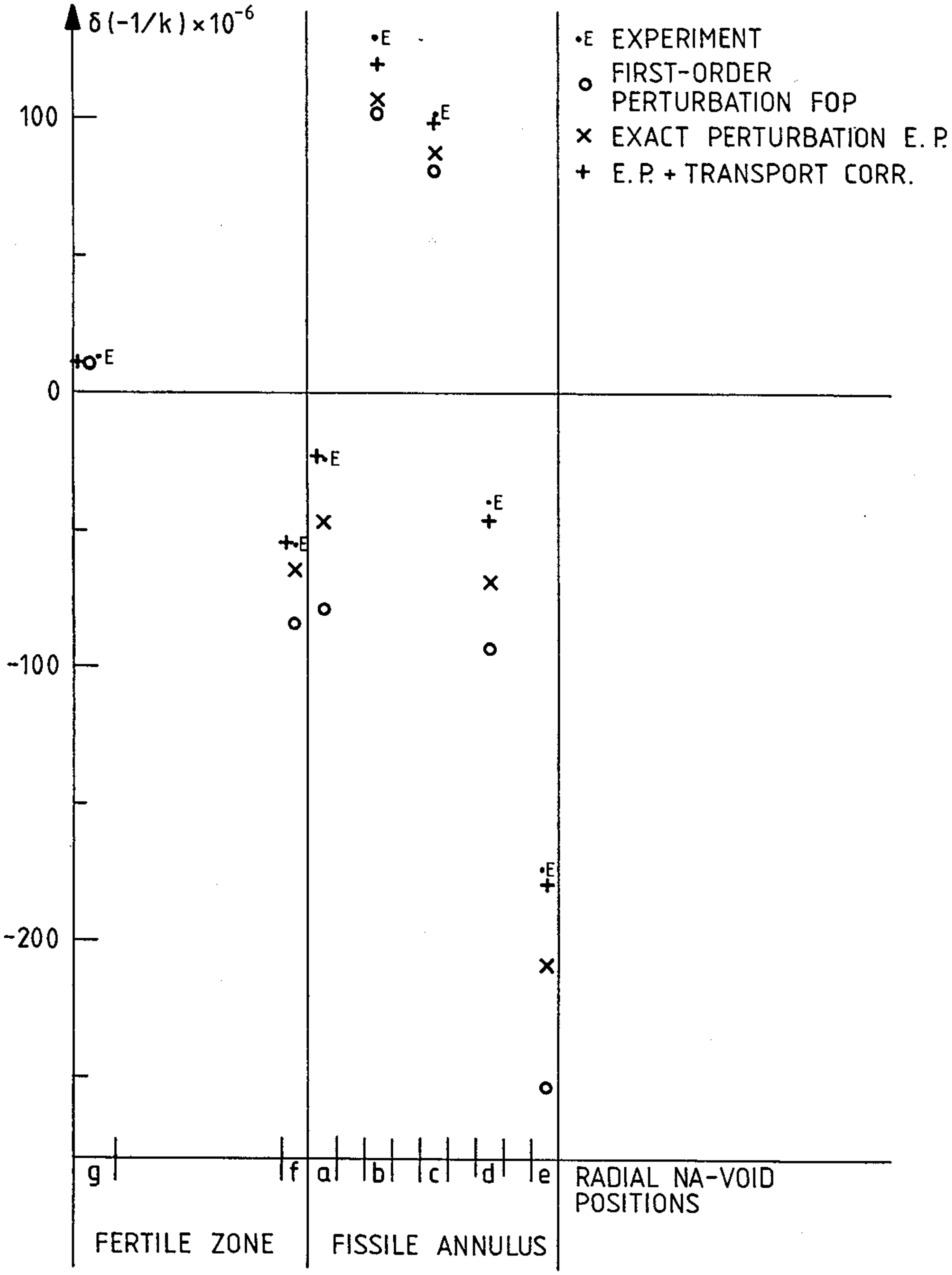

FIGURE 2 SMALL-ZONE SODIUM-VOID WORTHS IN ASSEMBLY BZD/3 (SODIUM-VOIDS OF 40% CORE HEIGHT, KfK ANALYSIS)

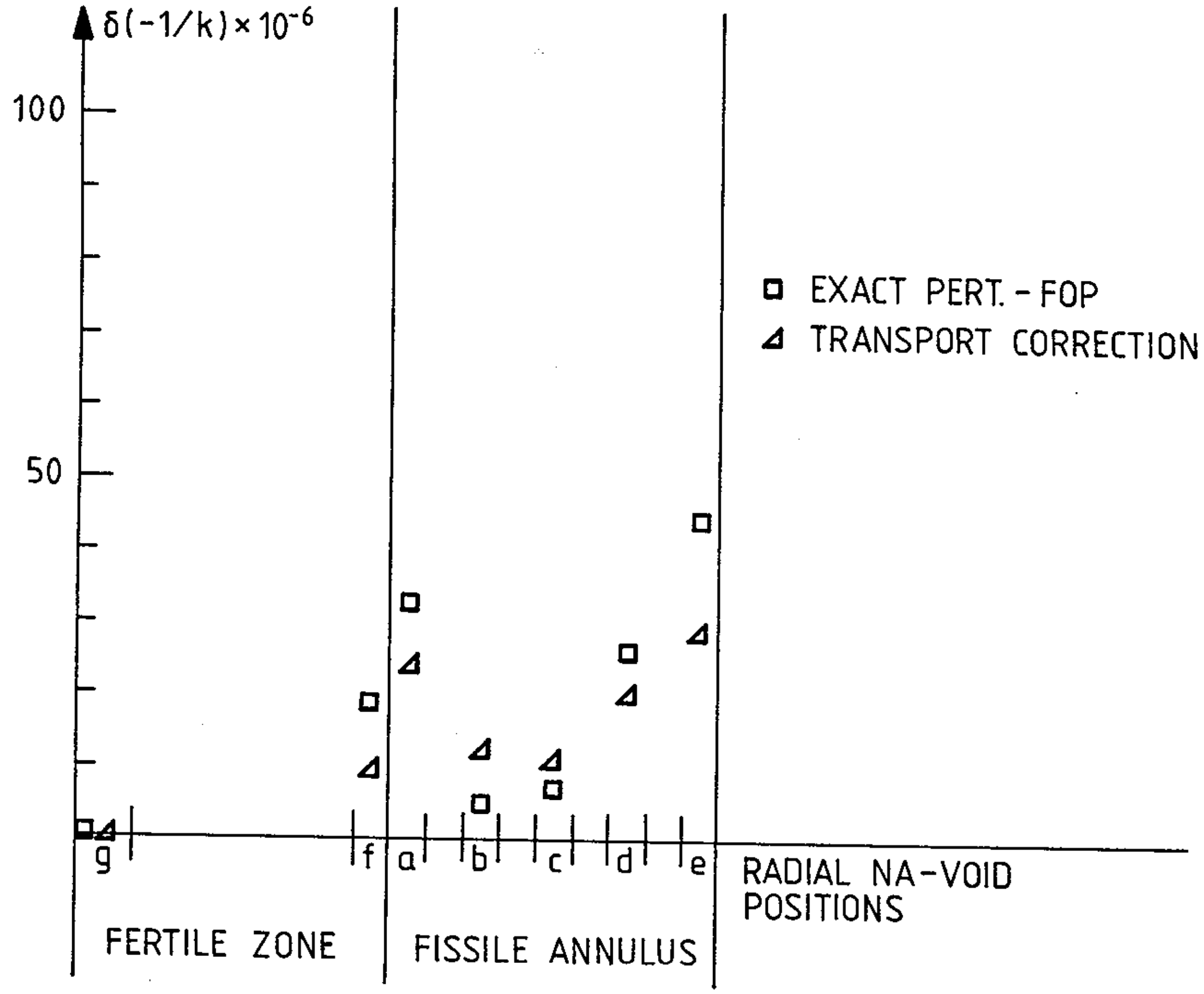

FIGURE 3 SMALL-ZONE SODIUM-VOIDS IN ASSEMBLY BZD/3, TRANSPORT THEORY CORRECTION AND DIFFERENCE BETWEEN DIFFUSION-THEORY EXACT PERTURBATION AND FIRST-ORDER PERTURBATION (FOP) THEORY VALUES (KfK ANALYSIS)