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Analysis of Sodium-Void Experiments Performed in Large Heterogeneous Cores

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ABSTRACT

Calculational analyses habe been made for three assemblies of the joint France (CEA)/Italy (ENEA)/DeBeNe RACINE programme (DeBeNe stands for West Germany (Deutschland), Belgium, the Netherlands). The k-values and sodium-void reactivity worths calculated separately by the partners were compared with the experimental values. The criticality calculations took account of the three-dimensional core arrangement, the cell heterogeneity and transport theory corrections. The sodium-void reactivities were calculated using exact perturbation theory. Transport theory corrections were applied to the diffusion theory values.

INTRODUCTION

Physics parameters of large sodium-cooled fast breeder reactors were investigated in large assemblies containing internal breeder zones in the joint France (CEA)/Italy (ENEA)/DeBeNe RACINE programme in the zero power fast reactor MASURCA /1,2/. The experimental programme included measurements of critical size, reaction-rate ratios and distributions, sodium-void reactivities, and control-rod absorber worths. The experiments were analysed by CEA/ENEA and KfK using their own cross-section data and methods similar to those applied to power reactor designs, and the results were compared with each other and with the experimental values.

This paper concentrates on the calculation of k-values, the effective delayed neutron fractions β_{eff} and sodium-void reactivities in the RACINE configurations 1A, containing a central fertile zone, and 1D containing a central simulated control rod position, which was loaded either by absorber or follower material. Especially the effect of sodium-voiding near an inserted control rod is of interest is safety studies for a nuclear power reactor.

DESCRIPTION OF THE ASSEMBLIES

The RACINE assemblies 1A and 1D contained a heterogeneous core with one fertile annulus of about 10 cm thickness (Fig. 1). The core height was 91.4 cm. The assemblies differed in the central region and in the outer core region containing enriched uranium (cell R1). The central region of assembly 1A (Fig. 1, r = 0.0 to 14.6 cm) contained fertile material, and the critical outer core radius was 90.0 cm. The 1D configurations contained no central fertile zone but a central absorber or follower subassembly. The central absorber arrangement consisted of rodlets containing enriched and natural B_4C and some sodium filled rodlets, the total absorber cross section of 280 cm^2 being typical for a power reactor control rod. The follower subassembly consisted of sodium filled rodlets only. The outer core radii for the critical configurations were 96.1 and 91.3 cm, respectively. Fig. 2 shows the radial arrangement of the B_4C absorber rodlets with two different ^{10}B fractions -90.3 % (enriched) and 19.8 % (natural)- and of the sodium rodlets. The average ^{10}B enrichment was 69 %. The enriched B_4C absorber extended axially only over the core region. In the axial blanket regions, the enriched B_4C positions were occupied by natural B_4C rodlets. The B_4C and sodium rodlets had square cross sections with edge lengths of 1.3 cm. The different regions indicated in Figures 1 and 3 were loaded in the way shown in Figure 4: The fissile ZONA 1 zones consisted of PuO_2/UO_2, UO_2 and sodium rodlets with overall Pu/(Pu + U) ratios of about 20 %. The fissile annulus ZONA 1K (SNEAK Pu) was fuelled with SNEAK plates containing PuO_2/UO_2, depleted uranium and sodium, the Pu/(Pu + U) ratio in this region was 16.5 %. The outermost core zone contained the enriched uranium rodlet cell R1, the ^{235}U enrichment was 22.8 %. Only in the RACINE 1D absorber configuration, this core zone contained some additional elements with the enriched uranium plate cell R1 K. The internal breeder zones as well as the axial blanket consisted of depleted UO_2 and sodium rodlets. An axial blanket plate cell (UO_2 and sodium plates) was arranged above and below the core plate zones. The thicknesses of the blanket zones were 20.3 cm for the axial blanket and varied for the radial blanket between 25 and 19 cm in the various configurations. The axial and radial blankets were surrounded by a steel reflector.

SODIUM-VOID EXPERIMENTS

The sodium-void experiments were performed by voiding of sodium the inner fissile annulus between the central region and the fertile annulus over the total core height. The removed sodium masses were 100.3 kg and 95.2 kg for the assemblies RACINE 1A and 1D, respectively. The sodium-void reactivity was measured by the modified source multiplication method. In the assembly RACINE 1A, two additional experiments were performed with different axial sodium-void heights in order to study the axial reactivity contributions. The inner fissile annulus was voided of sodium axially over the central region of ± 25.4 cm and over the top and bottom core regions of 20.3 cm each.

CALCULATIONS

The spatial calculations were performed by both analysis teams using diffusion theory and appropriate RZ models (Fig. 3). The sodium-void reactivities were calculated using exact perturbation theory, taking the real flux from the reference case and the adjoint flux from the sodium-voided case. The k-values of successive iterations converged to an accuracy of better than 0.0001.

The cross sections of the fissile and internal fertile cells were corrected for the heterogeneity of these cells. The absorber, follower and external fertile cells were considered as homogeneous media.

KfK prepared 26-group cross sections on the basis of the KFKINR001 data set /3/. The lattice code KAPER /4/ calculated heterogeneity-corrected cross sections for the core cells and anisotropic diffusion coefficients according to the Benoist equation /5/ to allow for preferential streaming of neutrons in dilute regions. The KAPER calculations for the flooded and sodium-voided core cells used multi-group bucklings derived from diffusion theory calculations in RZ geometry for the assembly RACINE 1A. For the absorber, both a homogenised composition and a more realistic 3-zone representation were studied.

CEA/ENEA prepared 25-group cross sections using the CARNAVAL IV system /6/ and the lattice code HETAIRE /7/. The fissile zone cross sections corresponded to the asymptotic mode. For fertile, absorber and follower zones, the neutron source spectrum was determined by the leakage spectrum of the adjacent fissile zone. Only for fertile zones, leakage was accounted for by introducing a buckling, which was deduced from geometrical considerations. For the core cells, directional diffusion coefficients were calculated according to the Benoist equation /5/ to allow for preferential streaming of neutrons.

a) k-Values

The basic k-values resulted from calculations in RZ geometry. The RZ models were half-height representations of the assemblies (e.g. Fig. 3). The radial mesh size (almost the same in KfK and CEA/ENEA calculations) was approximately 3 cm in the fissile zones, about 4 cm in the fertile zones and approximately 1 cm in the central region of RACINE 1D. The mesh size in the radial blanket and steel reflector was approximately 5 and 6 cm, respectively. The axial mesh size was 2.54, 4.2 and 10.2 cm in the core, the blanket and the steel reflector, respectively.

The KfK k-values obtained with the diffusion theory code DIXY and 26 energy groups are given in Table I. The calculated corrections given in Table I took account of

- the cylindricalisation effect,
- the effect of smearing the top and bottom steel plugs of the fuel rodlets,
- the ^{241}Pu decay,
- the effect of using zone independent fission neutron spectra instead of zone dependent values,
- the effect of neglecting the heterogeneity of axial blanket cells,
- the transport effect.

Applying these corrections, the criticality of the various assemblies was overestimated by about 1 to 1.2 %. The overestimates are greater than in the analysis of SNEAK assemblies (1.008, /8/) and will be studied. The overestimates for the RACINE 1D configurations were somewhat greater than in the case of assembly RACINE 1A. Further studies showed that this effect is correlated with the higher importance of the larger outer core region containing enriched uranium /2/.

The CEA/ENEA k-values calculated with the diffusion theory code CODI 2 and 25 energy groups are given in Table I together with the applied corrections. These corrections took account of

- the cylindricalisation effect,
- the fuel rodlet end caps,
- the ^{241}Pu decay,
- the transport effect.

One finds that CARNAVAL IV cross sections underestimate the multiplication factor by 0.40 to 0.46 % δk. This tendency, usually found with the French set, is due to the cross-section adjustment chosen.

An interesting observation is made considering the transport effect to the multiplication factor. The difference of 0.2 to 0.3 % δk in the transport corrections calculated by CEA and KfK is explained by the fact that this correction is partly taken into account in the cross-section preparation by CEA. Only for the central absorber configuration, a heterogeneity correction has been calculated by a detailed description (rodlet by rodlet) of the B_4C absorber rod. The results obtained by a two-dimensional transport theory calculation in XY geometry have been compared with those obtained in the same conditions with a homogenised central absorber (footnote c in Table I).

b) Effective Delayed Neutron Fractions

The delayed neutron fractions β_{eff} were calculated by both analysis teams using the delayed neutron data from the Tuttle evaluation /9/. KfK used the recommended values, and CEA/ENEA modified the ^{239}Pu data /10/. The KfK β_{eff} values for the assembly RACINE 1A and for the 1D absorber and follower configurations were 0.00448, 0.00492 and 0.00454, respectively and agreed well with the respective CEA/ENEA values of 0.00455, 0.00492 and 0.00451. The latter values were used to determine the experimental reactivity scale.

c) Reactivity Changes Produced by Sodium Voiding

The sodium-void reactivities (for the inner fissile annulus over the total core height) resulting from diffusion theory calculations are given in Table II and compared with the experimental values. For the assembly RACINE 1A and the RACINE 1D central follower configuration, the values were slightly overpredicted by CEA/ENEA and underpredicted by KfK. The comparison between the two assemblies shows

- a small reduction of the scattering term due to the degradation of the neutron spectrum in the presence of the central sodium rod and
- an increase of the radial leakage component in the presence of the sodium rod due to the change of the neutron flux gradient.

These effects decrease the positive sodium-void effect.

The experimental sodium-void reactivity in the central absorber configuration was strongly underpredicted by diffusion theory in both analyses. The calculation / experiment (C/E) values were 0.47 (CEA/ENEA) and 0.34 or 0.50 (KfK, homogenised or 3-zone representation). The insertion of the central absorber causes large gradients, and the sodium-void effect should be calculated by transport theory. The comparison of the reactivity terms with those of the above mentioned assemblies shows

- a decrease of the non-leakage term due to the decrease of the flux and the importance in the inner fissile annulus,
- a decrease of the vertical leakage due to the flattening of the vertical flux and importance gradient and
- an incraese of the radial leakage due to the deep flux depression near and in the absorber rod.

These effects lead to an overall decrease of the positive sodium-void effect.

Transport theory corrections were calculated by KfK and CEA/ENEA as the difference between the summed-up reactivity terms resulting from transport and isotropic diffusion theory calculations. All transport theory corrections for the void effect were positive (Table III). The KfK differences between the values for the three assemblies were small. The application of these corrections to the total reactivity values resulting from the anisotropic diffusion theory calculations reduced the calculation - experiment (C-E) differences in all cases yielding an agreement between calculation and experiment of better than 10 %.

If our transport methods are used directly one doesn't take into account the anisotropy of neutron transport in the core cells. As derived from anisotropic and isotropic diffusion theory calculations, this effect amounts to $\delta k/k = -0.00022, -0.00011$ and -0.00023 for the assembly RACINE 1A, and the RACINE 1D absorber and follower configurations, respectively, corresponding to 12 to 13 % of the anisotropic diffusion theory sodium-void reactivities. However, one arrives at the same best calculated results as above starting with the transport sodium-void worths and adding a diffusion-calculated correction for anisotropic neutron leakage. If diffusion calculations are used in connection with a transport correction, one should not introduce anisotropic diffusion coefficients in the diffusion calculations for the follower channel, as this effect is properly taken into account by the transport calculation.

In the case of CEA/ENEA transport corrections we note:

- in the presence of the absorber rod, the correction is larger than those calculated for the other configurations,
- the application of all these corrections to the total reactivity values resulting from diffusion theory calculations reduce the C-E differences only for the sodium-void reactivity around the B_4C absorber rod; in the other cases, these positive corrections make the agreement between calculation and experiment slightly worse. The C-E differences become usually positive and vary between 0 and + 20 %.

Table IV gives the analyses of the experiments performed in the assembly RACINE 1A voiding the sodium from the inner fissile annulus axially over three different heights. In the KfK analysis, the diffusion theory values were less positive for the central core region and more negative for the outer axial core regions than the experimental values. This is attributed to an overestimated neutron leakage. The sum of the transport theory corrections for the sodium-void reactivity in the subregions was nearly equal to the transport correction for the sodium-void reactivity over the total core height. For the top and bottom core regions, the transport theory correction resulted in a sodium-void reactivity less negative than the experimental value ($C-E = +0.13 \cdot 10^{-3}\ \delta(-1/k)$). In the case of voiding the central region of the inner fissile annulus, the transport theory correction resulted in $C-E = -0.31 \cdot 10^{-3}\ \delta(-1/k)$ or $(C-E)/E = -0.12$, which can be accepted.

In the CEA/ENEA analysis, the diffusion theory values showed the same tendency found in the KfK analysis: Compared with the experiment, the calculated sodium-void reactivity worth was less positive for the central core region and more negative for the outer axial core regions. The calculation-experiment (C-E) differences are very small, and the transport corrections, always positive, change the sign of these differences. The agreement is still satisfactory. One remarks that the sums of the sodium-void reactivities and the transport theory corrections in the subregions are nearly equal to the respective values calculated over the total core height.

The difference between the sodium-void effects with the central follower and the central absorber present means an increase of the reactivity worth of the absorber (relative to the sodium follower) inserted in the sodium-voided central core zone compared with the absorber reactivity worth in the flooded core. This difference was consistently derived from calculated and measured sodium-void worths taking into account the difference in core radius during these measurements. The measured reactivity worth of the enriched B_4C absorber inserted in the flooded central follower configuration was $-0.02420\ \delta\ (-1/k)$ /2/. Removing of sodium from the adjacent inner fissile annulus would increase this reactivity worth by 2%.

CONCLUSIONS

The measured k-values were underpredicted by the CEA/ENEA calculations (-0.004) and overpredicted by the KfK analysis (~ +0.01 to 0.012) after all relevant corrections had been applied to the calculated k-values.

The experimental sodium-void reactivity in the absorber configuration was strongly underpredicted by diffusion theory in both analyses. In the other configurations, the differences between diffusion theory and experimental values were not so consistent: The CEA/ENEA C-E values ranged from -5 to $+24\cdot10^{-5}\ \delta k/k$, and the KfK C-E values were significantly negative, between -46 and $-6\cdot10^{-5}\ \delta k/k$.

The transport corrections to the Na-void calculations were always positive. In the KfK analysis, their application to the diffusion theory worths reduced the differences between calculation and experiment to less than 10 %. In the CEA/ENEA analysis, the transport theory corrections resulted in (C-E)/C values ranging from 0 to 20 %.

ACKNOWLEDGEMENT

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TABLE I

Criticality of RACINE Assemblies

Analysis Team		RACINE 1A	RACINE 1D		
			Follower	Central Absorber	
				Homogenised	3-Zone Repres.
KfK	Basic Diffusion Theory k-Value	1.0054	1.0063	1.0069	1.0077
	Cylindricalisation δk	-0.0006	-0.0005	-0.0012	-0.0012
	Fission Spectra[a] δk	-0.0017	-0.0023	-0.0023	-0.0023
	Transport Theory[b] δk	+0.0063	+0.0069	+0.0077	+0.0077
	Calculated k-Value	1.0094	1.0104	1.0111	1.0119
CEA/ ENEA	Diffusion Theory k-Value[a]	0.9912	0.9914	0.9906	
	Cylindricalisation δk	-0.0005	-0.0010	-0.0013	
	Transport Theory[b] δk	+0.0043	+0.0043	+0.0050	
	Calculated k-Value	0.9950	0.9947	0.9943[c]	
	Experimental k-Value	0.9994	0.9994	0.9993	

[a] including ^{241}Pu decay and end cap (plug) corrections and, for KfK, axial blanket cell heterogeneity.

[b] transport theory corrections were obtained using two-dimensional calculations with cross sections for homogeneous compositions.

[c] a heterogeneity correction of about + 0.0013 $\delta k/k$ has been calculated by a detailed description of the B_4C absorber rod and has to be added.

Table II

Sodium-Void Worths in the Inner Fissile Annulus of RACINE Assemblies. Comparison of KfK and CEA Diffusion Theory Results with Experimental Values.

		Reactivity Terms in Units 10^{-5} $\delta(-1/k)$								
Assembly	Analysis Team	Absorption	Source	Scattering	Non-Leakage	Vertical Leakage	Radial Leakage	Total C	Experiment E	C-E
RACINE 1A	KfK	+103.0	-31.7	+300.1	+371.4	-198.3	-10.5	+162.5	+204±9	-41.5
	CEA	+105	-29	+338	+414	-198	- 8	+208		+ 4
RACINE 1D Follower	KfK	+105.3	-33.3	+285.6	+357.6	-195.7	-35.1	+126.8	+143±7	-16.2
	CEA	+102	-31	+319	+390	-192.8	-30.3	+167.		+24.0
RACINE 1D Absorber	KfK	+42.6	-15.6	+207.7	+234.7	- 89.6	-100.8	+44.2	+88±5	-43.8
	CEA	+38.1	-12.7	+217.9	+243.3	-122.8	- 79.4	+41.1		-46.9

Notes:
1. The inner fissile annulus was voided of sodium over the total core height.
2. The calculations used exact perturbation theory.
3. The experimental uncertainties do not include the systematic error in reactivity scale (∿5 %)
4. The absorber was represented by 3 zones in the KfK analysis and by a homogeneous composition in the CEA analysis.

TABLE III

Comparison of Measured and Calculated Sodium-Void Worths in the Inner Fissile Annulus of the Assemblies RACINE 1A and RACINE 1D

	Reactivity Values in Units $10^{-5}\delta(-1/k)$					
Assembly	RACINE 1A		RACINE 1D Central Follower		Central Absorber	
Analysis Team	KfK	CEA	KfK	CEA	KfK	CEA
Total Worth, Diffusion	+162.5	+208	+126.8	+167	+44.2	+41
Transport Correction	+ 34.6	+ 17	+ 28.2	+ 14	+36.8	+45
Total Worth, C, Diffusion + Transport	+197.1	+225	+155.0	+181	+81.0	+86
Experimental Value, E	+ 204 ± 9		+ 143 ± 7		+ 88 ± 5	
C - E	- 6.9	+ 21	+ 12	+ 38	- 7	- 2

Notes:
1. The inner fissile annulus was voided of sodium over the total core height.
2. The calculations used exact perturbation theory.

TABLE IV

Calculated Sodium-Void Worths in the Inner Fissile Annulus of the Assembly RACINE 1A. Comparison of KfK and CEA Results for Different Heights of the Sodium-Voided Annulus with the Experimental Values

	Reactivity Values in Units $10^{-5}\delta(-1/k)$					
	Total Core Height ± 45.72 cm		Central Region ± 25.4 cm		Top and Bottom Regions, 20.32 cm	
Perturbation Term \ Analysis Team	KfK	CEA	KfK	CEA	KfK	CEA
Absorption	+103.0	+ 105	+ 72.1	+ 73	+ 31.3	+ 32
Source	− 31.7	− 29	− 22.6	− 21	− 9.1	− 9
Scattering	+300.1	+ 338	+208.6	+244	+ 89.9	+ 96
Non-Leakage	+371.4	+ 414	+258.1	+296	+112.1	+119
Vertical Leakage	−198.3	− 198	− 39.5	− 38	−151.0	−154
Radial Leakage	− 10.5	− 8	− 7.4	− 6	− 3.1	− 3
Total, Diffusion	+162.5	+ 208	+211.2	+252	− 42.0	− 38
Transport Correction	+ 34.6	+ 17	+ 15.0	+ 8	+ 18.9	+ 9
Total, C, Diffusion+Transport	+197.1	+ 225	+226.1	+260	− 23.1	− 29
Experimental Value, E	+204±9		+257±10		−36±4	
C − E	− 6.9	+ 21	− 30.9	+ 3	+ 12.9	+ 7

Note: The experimental uncertainties do not include the systematic error in reactivity scale (∿5%).

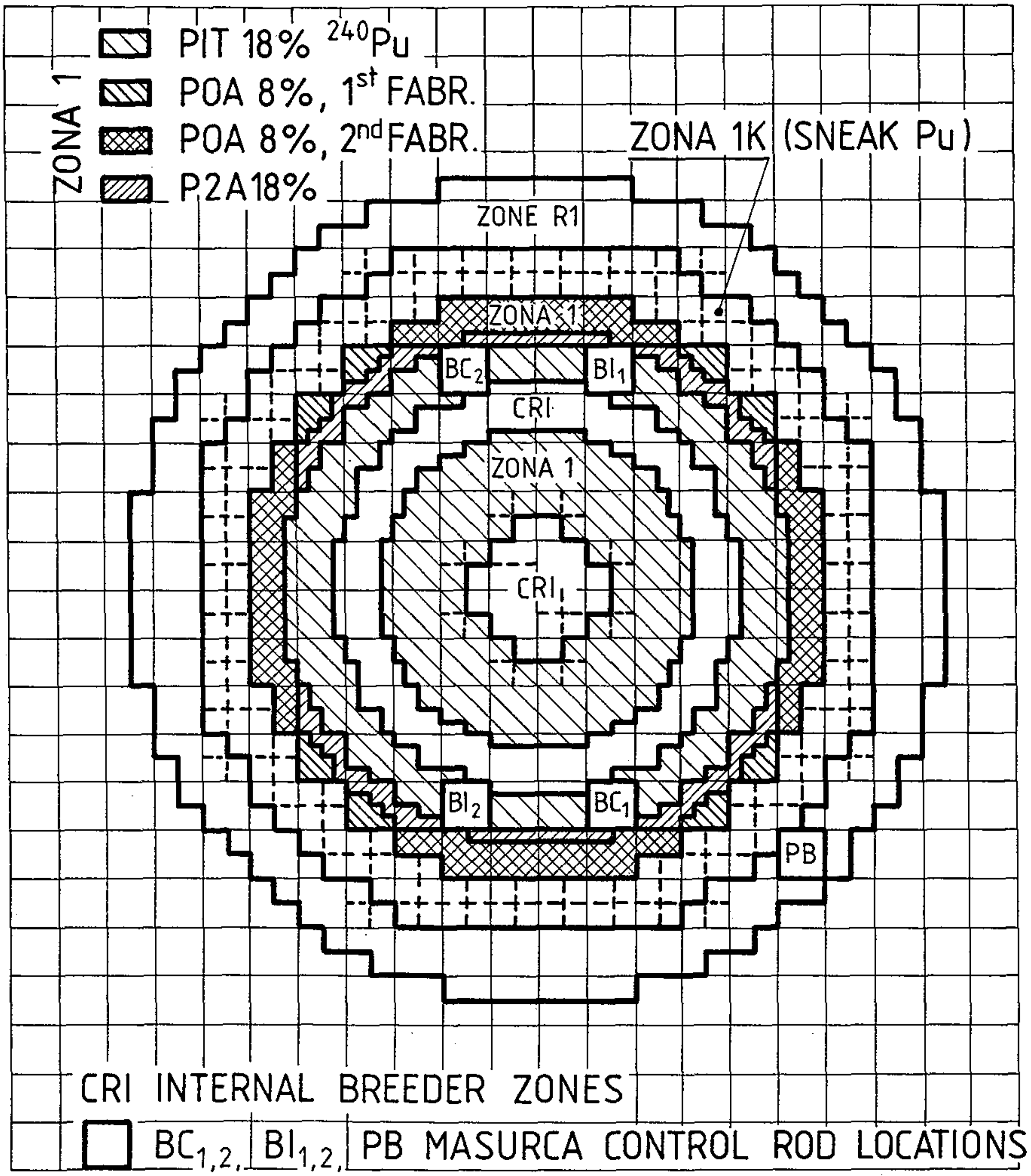

FIG.1 HORIZONTAL CROSS SECTION OF THE RACINE 1A CORE

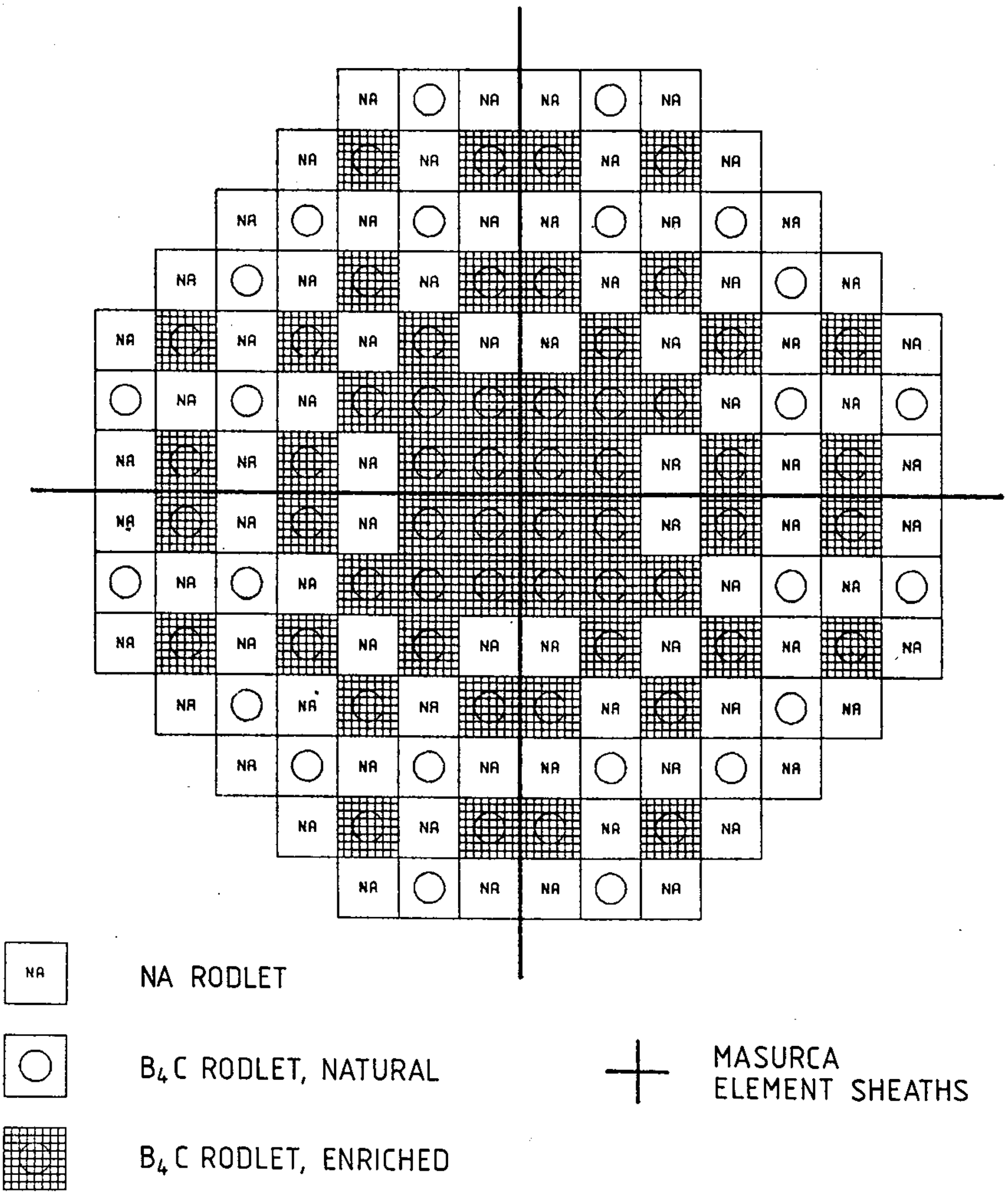

FIG.2 RADIAL ARRANGEMENT OF ABSORBER (B_4C) AND SODIUM (NA) RODLETS IN THE CENTRAL ENRICHED B_4C ABSORBER

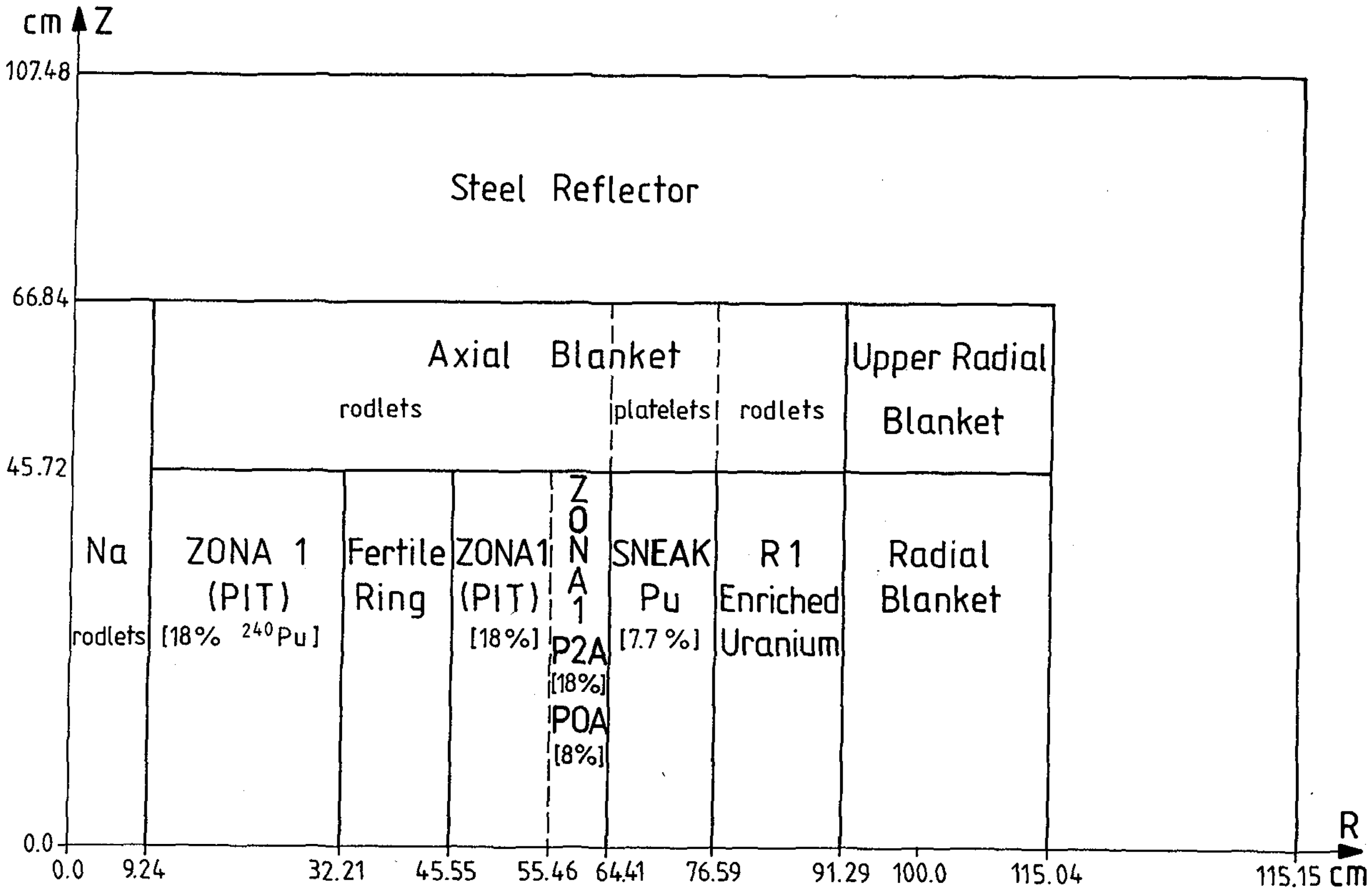

FIGURE 3 RZ MODEL OF RACINE 1D CENTRAL FOLLOWER CONFIGURATION

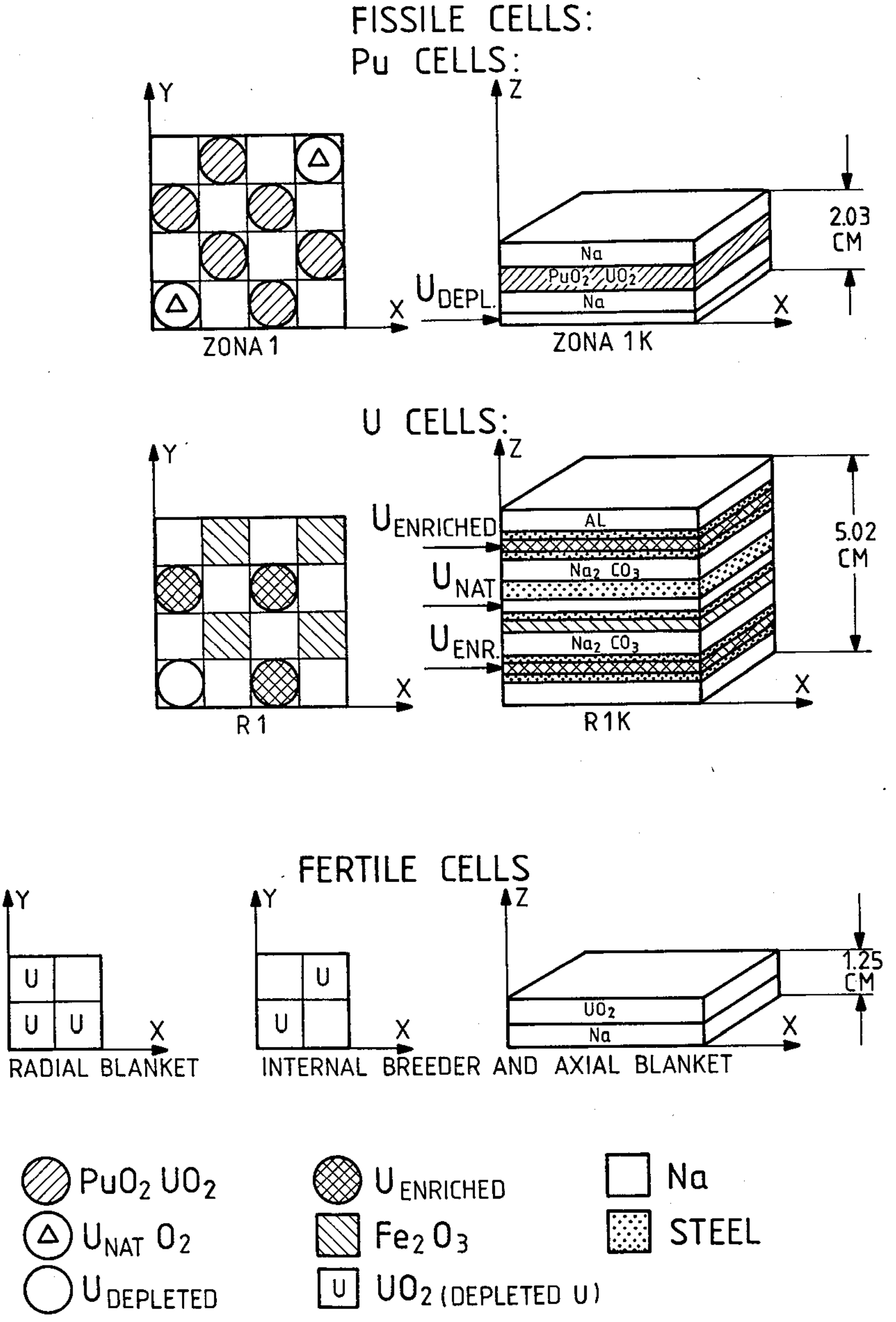

Fig. 4 FISSILE AND FERTILE CELLS USED IN RACINE CONFIGURATIONS