DIVISION ETUDES ET DEVELOPPEMENT DES REACTEURS
Département des Réacteurs à Neutrons Rapides

FR8100438

Topical meeting on advances in reactor physics and shielding.
Sun Valley, Ida, USA, September 14 - 17, 1980.
CEA - CONF 5517

FAST REACTOR PHYSICS AT CEA : PRESENT STUDIES AND FUTURE PROSPECTS

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RESUME :

This paper aims at giving a general survey of the fast reactor core physics and shielding studies wich are in progress at CEA (1979-1983) in order to solve the neutronic problems related to :

- core design optimization
- reactor operation and fuel management
- safety

for the developpement of fast commercial breeders in France after the SUPER-PHENIX 1 construction is achieved.

INTRODUCTION

1 - After the SUPER-PHENIX 1 design, presently under construction at Creys-Malville, the fast reactor core physics and shielding studies which are now in progress at CEA or which are sheduled in a near future (1979-1983) aim at the following goals :

- For SUPER-PHENIX 1, one wants to reduce the bias factors and their associated uncertainties which have to be applied to the calculated parameters either for the start-up core configuration (e.g. influence of the diluent subassemblies and of the partially inserted control rods on the core reactivity and power distribution[1]) or for the reactor operation (e.g. fuel management).

- For the next fast commercial breeders, one has to check and eventually to improve the design calculations which are made to optimize the core or shielding neutronic characteristics according to various possible criteria. Such neutronic optimizations are performed either by improving the core or shielding concepts used in SUPER-PHENIX 1 or by introducing new core or shielding concepts. A typical review of the present core design studies in progress at CEA is given in[2]. A special attention is paid to the heterogeneous concept for which a specific experimental programme has been developped on the critical facility MASURCA since 1976[3,4].

- Safety related neutronic problems have to be systematically investigated whatever will be the core concept used for the future fast breeders. At CEA a high priority is given to studies related to local accidents and to primary excursion of a whole core accident. From the neutronic point of view, the investigations concern the Doppler and the sodium void effects and in a second step the accidental configurations (steel and fuel slumping, molten pool situations).

2 - The studies which are made at CEA to improve the core, shielding and safety neutronic design calculations concern :

- the nuclear data
- the calculational methods.

As far as the nuclear data are concerned the CARNAVAL IV 25 group cross section set[5] and the PROPANE Do 45 group set[6] which are used for the SUPER-PHENIX I core and shielding calculations[7] have been adjusted by using integral experiment results, and only ponctual improvements have still to be made. The VASCO data set used for γ heating calculations which is presently at an earlier stage of development than CARNAVAL or PROPANE, is checked and improved by following the same approach.

3 - All the studies devoted to core physics and shielding problems which are now in progress at CEA are supported by specific experimental programmes which are now defined and performed in the framework of an international cooperation between CEA, CNEN and DEBENE. Such a cooperation provides to each partner an important amount of experimental results while limitating the associated efforts and investments for each one. On the other hand, an increasing number of PHENIX results are now integrated in the CEA core physics and shielding studies.

4 - This paper aims at giving a general survey of the studies now in progress or sheduled in a near future at CEA in the fast reactor core physics field, and then in the shielding area. The γ-heating problems are briefly examined. The calculational method developments which are made in order either to support the integral experiment analysis or to improve the design calculation are shortly summarized. The conclusion suggest some further developments which could be looked at in a longer term perspective.

CORE PHYSICS STUDIES

To meet the target accuracies on the main core design parameters studies are made or sheduled in order :

- to improve the CARNAVAL system which provides the multigroup cross sections used for the neutronic calculations
- to check and improve the design calculational methods.

The following table summarizes the main design target accuracies[8] and recalls the accuracies achieved for SUPER-PHENIX I[9]

	SUPER-PHENIX 1 accuracy	Target accuracy (any core type)
Reactivity of the clean fresh core	± 0.33% ΔK/K	± 0.3 % ΔK/K
Reactivity loss per cycle	± 0.7 % ΔK/K	± 0.5 % ΔK/K
Critical mass	± 1.1 % ΔK/K	± 1 % ΔK/K
Global breeding gain	± 0.05	± 0.03
q_{max}/q	± 4 %	± 3 %
Doppler effect	±15 %	±15 %
Sodium void effect	±40 %	±20 %

Multigroup cross section set improvment

1 - Main fissile isotopes data : after the CARNAVAL IV version adjustments, it appears that if the major Uranium and Plutonium isotope multigroup data give satisfactory results for the PHENIX and SUPER-PHENIX fissile media[9], some problems still remain especially for the capture cross sections in the softer spectra. A typical example is given by the discrepancy (≃ 20%) observed between the calculated and measured production of 240Pu in the PHENIX radial blanket subassemblies[10]. In order to study this problem which can have a significant influence in low enrichment core calculations, a detailed analysis of the PHENIX irradiated blanket subassemblieshas been undertaken and a complementary specific programme of K∞ = 1 type is scheduled on the ERMINE facility in 1981.

2 - Structural material data : the target accuracies on the Fe, Cr, Ni data[8,11] have not been fully met within the CARNAVAL IV adjustment. Moreover improved data are also required for Mo, Ti, Mn. Taking into account that few integral experiments are available, special efforts are in progress :

- to improve the adjustment method used with taking into account the energy and inter cross section correlations
- to analyze new K∞ = 1 experiments performed at ERMINE (Cadarache) or RB2 (Bologna) during 1980.

The media investigated in these two facilities have been defined using sensitivity studies to insure that the measured parameters are representative of the problems encountered in the power plant cores. As an example Fig. 1 provides a comparison of the SUPER-PHENIX 1 and ERMINE Keff sensitivity curves. Fig. 2 presents two basic cells of the media which are under study at ERMINE.

3 - Fission product data : the pseudo fission product deduced from the CARNAVAL IV data which are adjusted for the main fission product isotopes leads to predict the associated reactivity loss per cycle within ± 16%. The target accuracy for this component of the global reactivity loss is ± 10%[12], especially to take into account the situations corresponding to low enrichment cores and to residence times longer than the SUPER-PHENIX1 one. It is worthwhile to note that the pseudo fission products issued from the RCN.2A and CARNAVAL IV adjusted sets are consistent within ± 5%[13]. Nevertheless significant discrepancies between these two sets are still observed for some individual isotopes. Some major discrepancies are listed here under[13] :

Isotopes	151Sm	147Pm	109Ag	143Nd	100Mo	154Sm	110Pd
$\frac{RCN-C.IV}{RCN}$ %	- 122	+ 19	- 17	+ 23	- 33	- 60	- 100

These discrepancies which may be attributed either to some of the integral experiments used in the adjustments, or to the adjustment methods themselves are under investigation. From the experimental point of view, some complementary informations are waited either from ERMINE or from PHENIX (PROFILII) and in a further step from SUPER-PHENIX (SUPER-PROFIL experiment where, among others, 133Cs, 109Ag, 143Nd, 100Mo, 104Pd samples should be irradiated).

4 - Actinide data : the preliminary adjustment performed in CARNAVAL IV for 238Pu, 241Am will be completed by new irradiation results issued either from PHENIX (PROFIL II, 1980-1981 : U, Pu, Am and Cm isotopes) or from fuel analysis (TRAPU) and in some cases (243Am, 244Cm) by fission rate measurements performed in various spectra within the RACINE programme (1980). Within the CEA-CNEN-DEBENE cooperation, a special effort is made to evaluate the actinide data. For 241Am, a close cooperation between evaluators and reactor physicists has permitted to improve significantly the final multigroup data[14].

5 - HETAIRE cell core improvment : it must be mentionned that besides the nuclear data improvment, efforts are going on to improve the calculational methods which have been set up in the HETAIRE cell code for the non multiplying media. As far as blankets are concerned new options are tested with using experimental results issued either from the NEFERTITI programme for the external blankets or the PRE-RACINE one (1976-1979 : cf[3,4]) for the internal ones.

Design parameters

At CEA, the fast breeder design parameters are usually calculated with the diffusion approximation and this method is checked against integral experiments. Presently the main problems investigated are related to :

- the SUPER-PHENIX 1 operation which involves the study of the control rod interaction effect on the core reactivity and the power distribution
- the prediction of an heterogeneous core characteristics (critical

mass, breeding gain, power distribution)

- the blanket characteristics (power distribution, external breeding gain, flux spectrum variation and flux attenuation).

In order to study the two first points, the RACINE programme is being performed on MASURCA in the framework of the CEA-CNEN-DEBENE cooperation (1979-1982 : see[17]).

Fig. 3 presents the reference RACINE 1A configuration loaded in MASURCA, which includes one central fertile zone (15 cm diameter) and one fertile ring (10 cm thick) inserted in a 90 cm radius core where the Pu fissile zone has a ≈ 18% enrichment.

One must note that this configuration is consistent with the previous PRE-RACINE ones, so that the main integral parameters may be studied versus the fertile volumic content [17]. The preliminary results obtained up to now for the critical mass listed in the following table, are presently under analysis :

	Fertile containt : % v/o	Keff: (E-C) 10^{-5} $\frac{\Delta K}{K}$
PRE-RACINE : be an core[4]	0	550 ± 100
PRE-RACINE : core with a single fertile zone[4]	6%	360 ± 100
RACINE 1A	13%	660 ± 150

Fig. 4 shows the first 239Pu fission rate radial distribution. The dissymetry observed, which is being analyzed at this moment, shows the sensitivity of the power distribution to the loading dissymetry (due to the structure of the MASURCA cells) in a large heterogeneous configuration. It must be noted that an equivalent dissymetry may occur in a power plant core when one loads a fresh element in a burnt core.

The next step of the RACINE programme aims at checking the sensitivity calculation of the radial power form factor to the fertile ring location which plays an decisive part in the minimization of the in pile fuel inventory[2,18].

Fig. 7 gives the radial power form factor variation which is expected in the RACINE programme by the fertile ring displacements.

The RACINE II step (1981) will concern control rod studies with configurations devoted to :

- elementary interactions between various pairs of rods
- global effects between two rings including respectively 4 and 8 rods.

Due to the heterogeneous configuration, strong interaction effects are expected (≈100%), similarly to the ones observed in ZPPR7[19]. They will help significantly the transposition of the results obtained up to now on critical facilities, only for limited interactions (< 20%), to power plants of both homogeneous and heterogeneous types.

The reactivity and power distribution measurements which are scheduled should also contribute to improve :

- the in-core fuel management calculation model,
- the reactivity measurement technique for the control rod calibration

As far as the external blankets properties are concerned (breeding gain, power distribution, flux spectrum variation), the results obtained either in critical experiments[15] or in PHENIX[10] show that the calculational method presently used have still to be improved as shown in the following table :

	Present uncertainty	Target accuracy
External breeding gain	± 0.04	± 0.02
Mean power in the blanket	≈ ± 20%	≈ ± 10%

In order to improve the blanket calculation studies of the blanket characteristics (NEFERTITI : programme 1980-1982) are performed at the TAPIRO source reactor.

The following table summarizes all the parameters which are taken into account in these systematic studies :

Blanket composition	UO2, UO2-Na, Pu build up studies
Enrichment of the core zone feeding the blanket	15%, 22.5%, 30%
Composition of the shielding following the blanket	SS/Na : 50/50 75/25 0/100

Sensitivity studies have been made to optimize the TAPIRO configurations so that they represent the problems encountered both in axial and in radial breeder blankets, as shown on Fig. 5 for one typical parameter. Fig. 6 presents the configurations built at TAPIRO.

A special attention is paid to the core/blanket and blanket/shielding interfaces which have significant influences on the cross section definition through the self shielding problem, and on the flux variation calculation. The flux variation at the interface vicinity can be described with the use of an improved diffusion approximation[16].

Safety related parameters

Among the neutronic parameters which are tightly related to the safety analysis, the sodium void effects are systematically studied within the PRE-RACINE[3,4] and the RACINE programmes.

The PRE-RACINE programme results (1979) have permitted to reduce the uncertainty applied to the sodium void effect prediction to ± 10% for a clean core, even for a fuel including a high amount of Pu higher isotopes[20].

The RACINE programme (1980-1981) will give complementary informations on three major points :

- bias factor and uncertainties which must be applied for heterogeneous configurations
- validation of the sensitivity calculation of the sodium effect to the fertile ring thickness which plays an important role when one wants to reduce the maximum positive effect
- bias factors and uncertainties affecting the sodium void effect in a SUPER-PHENIX type control rod vicinity.

When performing local sodium voids, one is not only interested in the reactivity variation out also in the power distribution modification in the voided zone and in its vicinity.

Another parameter of interest is the Doppler coefficient for which complementary information are required in order to guarantee a ± 15% maximum uncertainty not only for SUPER-PHENIX 1 but also for new core concepts : cores with low enrichments or with internal fertile zones. To achieve this goal, Doppler measurements will be included in the ERMINE programme (1981) devoted to the study of a low enrichment medium (≃ 4% in Pu enrichment).

Accidental configurations (cavity effects, steel and fuel slumping, molten pool configurations) will be investigated in the SNEAK 12 experimental programme (1980-1982)[21] . The corresponding results will be analyzed at CEA, starting from 1981.

SHIELDING STUDIES

The shielding studies presently performed at CEA have two major goals :

- to improve the actual PROPANE formulaire in order to meet the target accuracies on the design parameters for the classical steel sodium shielding media. The following table gives the target design accuracies and the uncertainties obtained with the PROPANE formulaire at its present state of development :

	Target accuracy	Present uncertainties
Secondary Na activation	± 50%	± 300%
Damage on the steel structure near the core	± 20%	± 40%

- to extent the validation of PROPANE to new shielding concepts which differ from the previous ones either by the materials used (e.g. B_4C) or by the configuration (e.g. localized shield).

The PROPANE 45 group data set adjustment for classical shielding media (various Na stainless steel mextures) uses mainly integral experiments performed on HARMONE and TAPIRO[22,23]. The data to be adjusted are issued from the 113 group BABEL library[24] and the adjustment will be achieved by the end of 1980. The following (E-C)/C on two detector responses are typical results obtained with the present version of PROPANE :

Propagation in :	Au(n,γ)	S(n p)*
Pure sodium (≃ 250cm) HARMONIE	.15 ± .10	.20 ± .15
Steel/sodium 50/50 v/o (≃ 120cm) TAPIRO	.30 ± .10	.40 ± .15

*Values relative to ≃ 50 cm propagation in both experiments

For the future fast breeders, parametric studies have shown the interest of using different materials : natural B_4C or special stainless steels, with eventually different shieldinf configurations. As an example the following table allows to compare for a classical radial shield configuration the number of shielding assembly rings which are necessary to obtain the same secondary sodium activation either with stainless steel or natural B_4C :

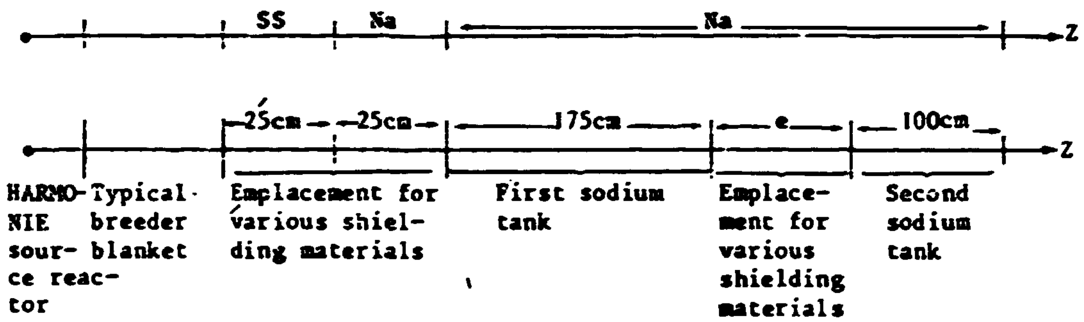
	Number of shielding rings
SS shield : SS/Na 50/50 v/o	12 ÷ 13
B_4C shield : 2÷3 SS rings + 2÷3 B_4C rings	5 ÷ 6

In order to improve the calculations related to these new shielding concepts, the "JASON programme" has been set up on HARMONIE (1980-1982).

This programme includes parametric studies of the flux propagation in a sodium medium (3.75 m length) versus :

- the composition of the zone which is located between the blanket and the sodium medium (B_4C, special steels, H_2Z_r)
- the location of a given material, either at the blanket/sodium tank interface or at the middle of the sodium medium.

The following schemes show the reference configuration (already studied at HARMONIE) and the possible configurations which can be loaded :



The propagation measurements use the classical detectors : S, Rh, Mn, Na and all the results will be compared to the reference configuration ones (25 cm steel + Na medium) from two points of views :

- variation of the attenuation obtained with respect to the values corresponding to the reference configuration
- variation of the calculation to experiments deviations when going from the reference configuration to the new ones.

Some typical predicted values of the attenuations involved in the configurations investigated are listed hereunder :

a) attenuation after 25 cm shield (located against the breeder blanket) + 140 cm Na

b) attenuation through 30 cm Na + a localized shield (located between the two Na tanks) + 30 cm Na.

	a)		b)	
	Total flux	Equivalent thermal flux	Total flux	Equivalent thermal flux
Reference	87.5	5.2	-	-
Steel	437	20.8	58.1	45.7
Steel including 1%	616	23.7	322	732
Steel with 35% Ni + B_4C	2100	127	-	-
B_4C	-	-	2580	14800

For what concerns the sensitivity to cross section data, in Fig.7 we show the sensitivity profile of the thermal equivalent flux to Na data in the two types of configurations (B_4C "around the sources" or as a localized shield).

γ-HEATING "VASCO FORMULAIRE"

The γ-heating gives a major contribution to the power dissipated in control rods, where one must avoid the B_4C fusion, and in the blankets especially at the fertile/fissile interfaces.

The following table provides a comparison between the target accuracies and the present uncertainties on the γ-heating in these two media :

	B_4C rod	Axial or radial blanket
Target accuracies	± 5%	± 10%
Present uncertainties	± 15%	± 25%

In order to improve the present calculations which use SN codes (ANISN or DOT) and rather old γ-data (DLC2) two efforts are in progress :

- to change the DLC2 17 γ group library by the BABEL 113 neutron group - 36 γ group coupled library
- to validate the calculations against γ-heating measurements performed in the PRE-RACINE and RACINE programmes for various media (B_4C at stainless steel central rods, fertile or fissile media). These measurements use either iron ionization chambers or various kinds

of TLD (^7LiF, Al_2O_3, $CaSO_4$).

CALCULATIONAL METHOD DEVELOPMENT

In order to improve the design calculation methods from both the accuracy and cost points of view and to support the experimental analysis and the data adjustment, the following studies which are now in progress at CEA are listed hereunder :

Method investigated	Purpose
Finite element method	3D calculations for design (HEX. geometry) or experiment analysis (XYZ geometry)
Few group collapsing	Direct and adjoint 3D calculation
Anisotropic diffusion	Avoid transport correction in design or integral experiment analysis calculations
Higher harmonics calculation	Flux perturbation reconstruction for parametric design studies or for fuel management calculations
Time and spatial (1D) sensitivity studies	Burn up problems studies and associated data adjustment
Adjustment method	- LSQ including correlation information - consistent method (basic parameter adjustment for actinide data)

CONCLUSION

1 - The present core physics and shielding studies which are going on at CEA in the 1979-1983 period aim at :

- improving the design calculations related to the SUPER-PHENIX 1 start-up and operation, including the fuel management
- contributing to the choice of core and shielding for the future French fast commercial breeders
- improving the safety analysis for what concerns the neutronic parameters.

2 - The improvements of core parameter calculations requires complementary efforts on the nuclear data and on the calculational methods. As far as nuclear data are concerned, two major points are studied to improve the CARNAVAL adjusted data set with the support of new experimental programmes : structural material and actinide data. As to the design calculational methods, the present studies concern primarily the blanket characteristics with a specific programme "NEFERTITI" running at TAPIRO and the control rods interaction effects which will be investigated within the "RACINE" programme performed at MASURCA.
As to the new core concepts which are examined in view of the future commercial breeders, systematic studies have been undertaken on the radial heterogeneous core concept within the PRE-RACINE (1976-1979) and RACINE (1979-1982) programmes, the last one being performed in the framework of a CEA-CNEN-DEBENE cooperation on MASURCA and using ≃ 2T of fuel. In a longer term future other problems which will have to be investigated concern :

- the compatibility between homogeneous and heterogeneous cores which could be successively loaded in the same vessel

- low enrichments cores (with the problems related to long subassembly residence times).

3 - At CEA shielding calculations are performed with the PROPANE formulaire. The corresponding 45 group data set adjustment for classical shielding media will be completed by the end of 1980. The extension of PROPANE for shieldings using either new materials (e.g. B_4C) or new configurations (e.g. localized shield) will be performed during the 1980-1982 period on the basis of the JASON programme which has just started on HARMONIE. Further studies will concern either the fuel transportation, or the fuel storage for the tests and improvements of criticality codes.

4 - The safety analysis related parameters which are presently investigated at CEA for both the homogeneous and heterogeneous concepts are the sodium void and the Doppler effects. The sodium void is extensively studied within the RACINE programme and complementary experiments on the Doppler effect will be carried out on ERMINE (1981).
The further CEA investigation will concern accidental configurations (steel and fuel slumpings, molten pool configurations) which will be realized within the SNEAK 12 programme performed at Karlsruhe, or later in MASURCA.

5 - All these studies are accompanied by a parallel effort on calculational method development either to improve the design calculations from the accuracy and cost points of view or to refine the experiment analysis and data adjustment, necessary to improve the adjusted data sets used at CEA.

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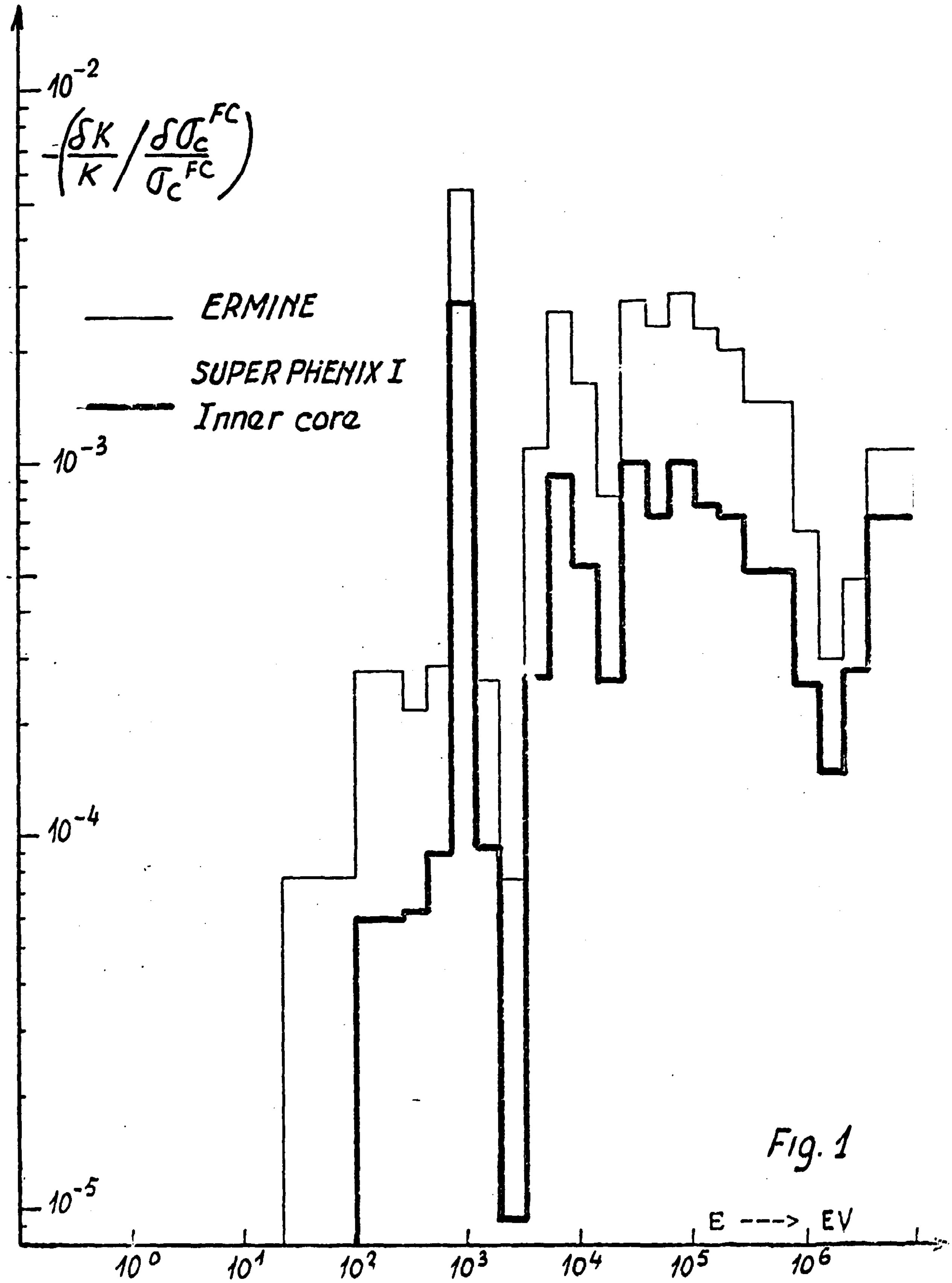
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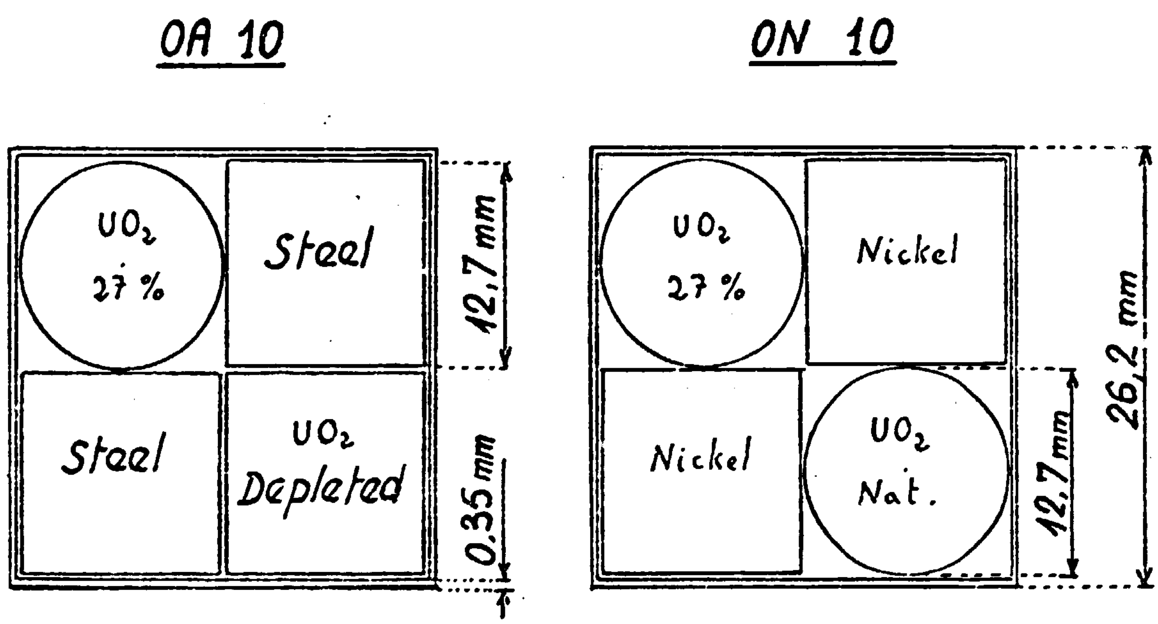
Fig. 1

Fig. 2. ERMINE CELLS



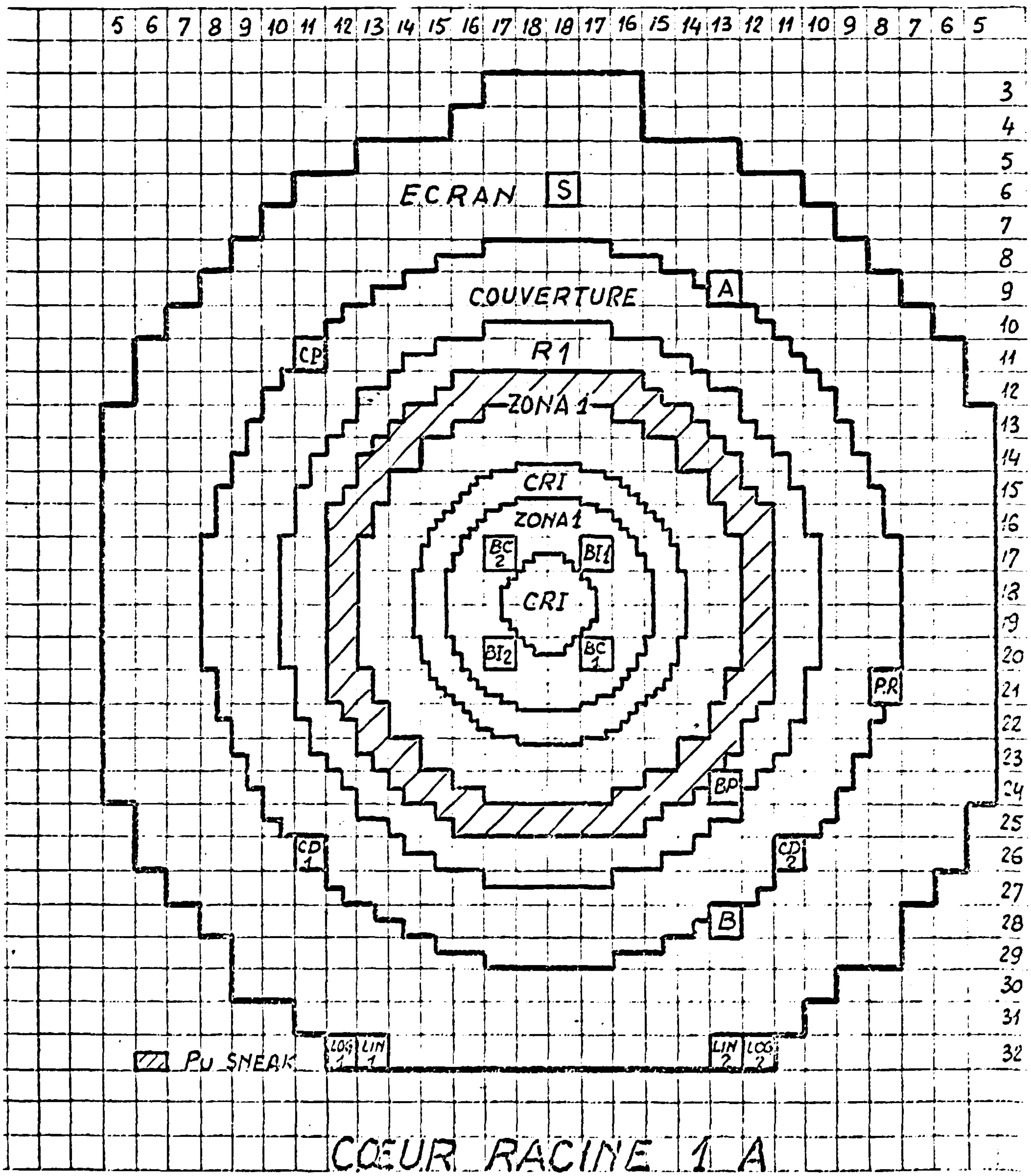

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Fig. 3

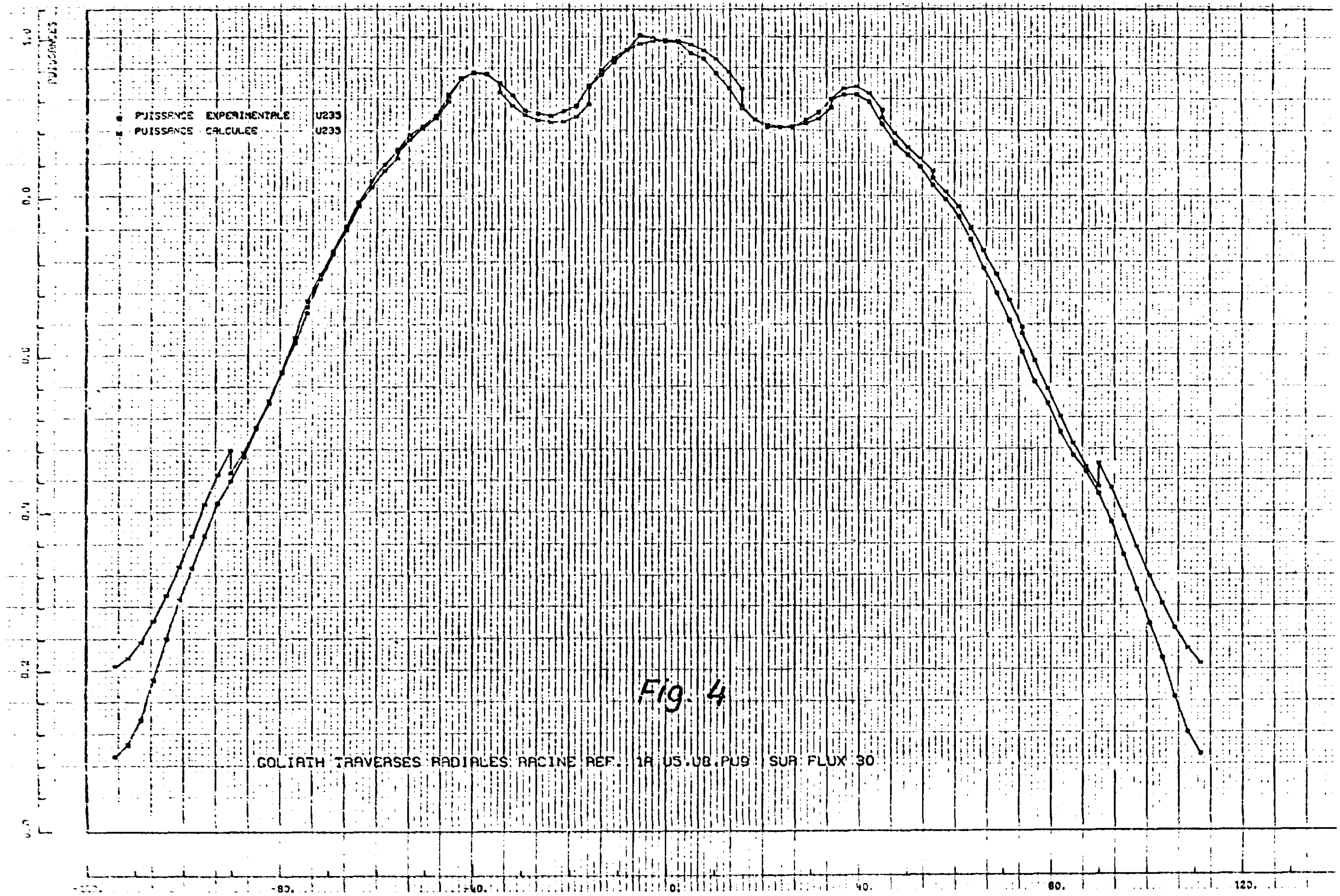
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Fig. 4

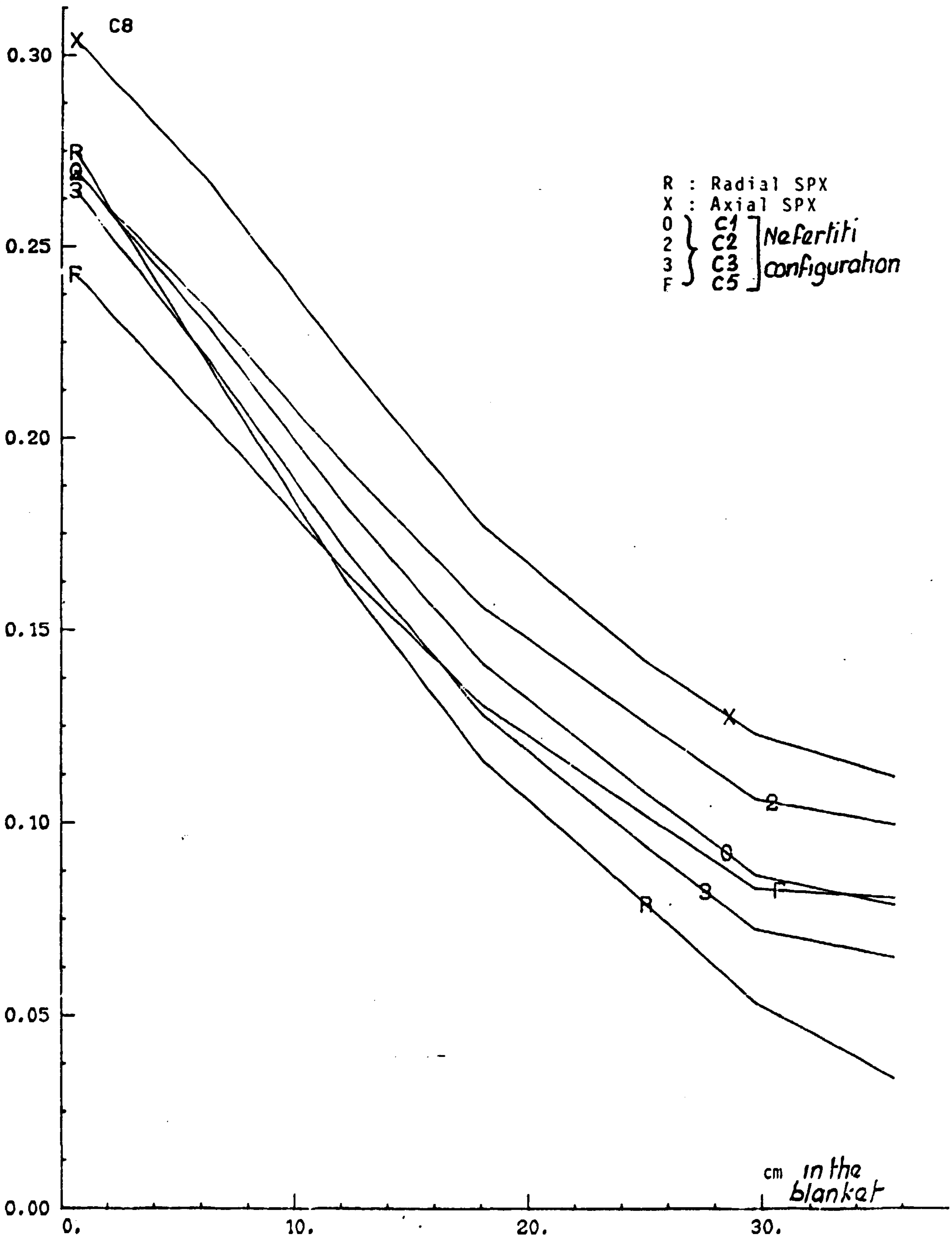
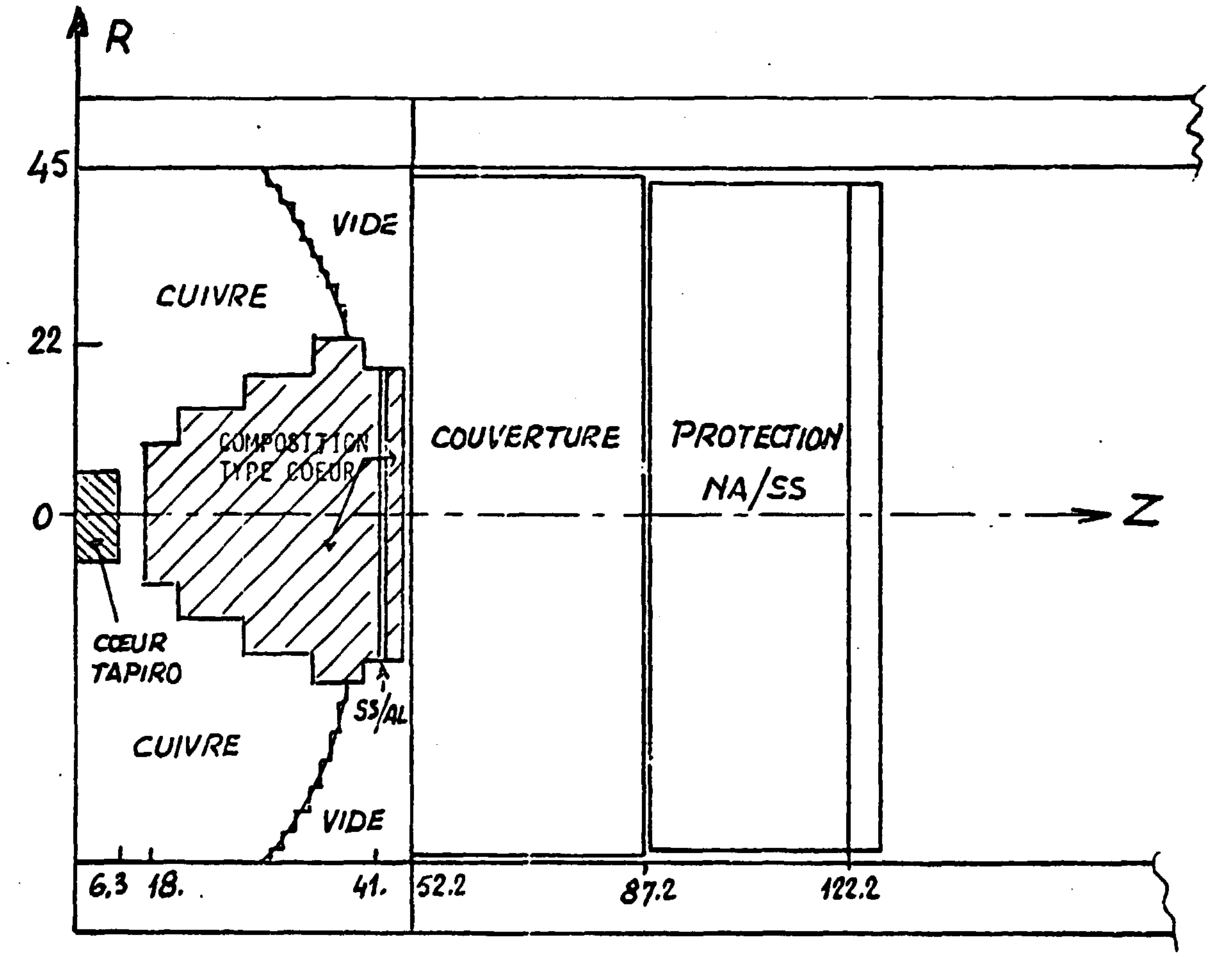


Fig. 5. 238 U CAPTURE DISTRIBUTION



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PROTECTION NA/SS
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41.
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87.2
122.2

Fig. 6

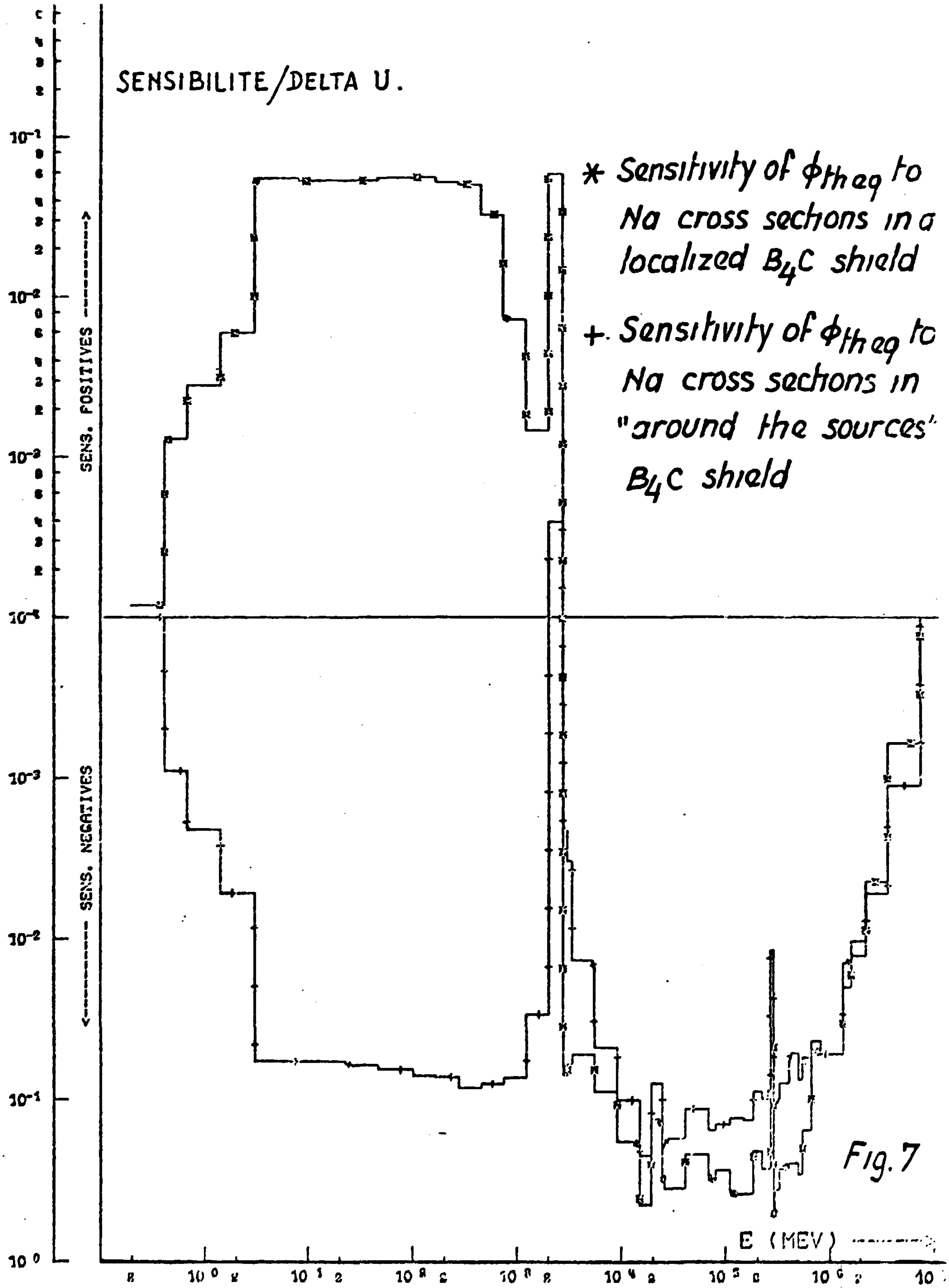
SENSIBILITE/DELTA U.
* Sensitivity of $\phi_{th\,eq}$ to Na cross sections in a localized B_4C shield
+ Sensitivity of $\phi_{th\,eq}$ to Na cross sections in "around the sources" B_4C shield
SENS. POSITIVES
SENS. NEGATIVES
E (MEV)

Fig. 7