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CONTROL-ROD PARAMETRICAL STUDIES IN THE FRAMEWORK OF THE PRE-RACINE AND RACINE PROGRAMS

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RESUME :

In this paper, a control-rod experimental program is presented. This program, established in the frame of PRE-RACINE and RACINE common DEBENE, Italian and French experiments at MASURCA facility, is still under progress at the moment. The results, limited to single central rod worth are already available. For these experiments, a parametrical approach has been used. The effects of rod worth, varied separatly by rod side, boron enrichment and core size, on experiment to calculation relative discrepancy (E-C)/C can be drawn out.

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I - INTRODUCTION

The bias factors to be applied to large fast power reactor control-rod design are of major interest. According to a widely accepted point of view, these factors are deduced from experiment to calculation comparisons, in which the various parameters of interest are studied separately and calculations are run with the most accurate methods at hand.

This paper deals with the control-rod part of the experimental program set-up and realized in the frame of the commun Italian-French PRE-RACINE |1| and Italian-DEBENE-French RACINE |2| programs at critical facility MASURCA/CEA Cadarache.

(E-C)/C values and variations versus boron enrichment, rod size and core size are planed to be analyzed for the following involved topics :

- rod efficiency,
- flux shape variations due to the absorbers and relation to rod efficiency,
- rods interactions.

The results related to central-rod worth are now available. The calculation to experiment discrepancies and their associated analysis are given.

II - EXPERIMENTAL PROGRAM

II.1 - The experimental program which is reported started in 1977. In a first phase, the main experiments concerned a single control-rod in PuO_2-UO_2 clean core (PRE-RACINE |1|). The present program includes control-rod studies in a heterogeneous configuration (RACINE |2|). In particular, the control-rod studies are performed in a heterogeneous one-fissile ring configuration with or without a central fertile zone. Moreover, a part of single control-rod program of PRE-RACINE is reanalyzed to study core size effects. A detailed program has been also set up for the study of multiple control-rod configurations with large interactions. This was possible both taking advantage of the expanded fuel inventory of the cooperative program and of the physical characteristics of a heterogeneous core. However, this part of the program, now underway, will not be discussed at the present stage.

The main characteristics of the control-rod program can be summarized as follows :

- continuity between the PRE-RACINE and RACINE programs. The same basic compositions are used in the PRE-RACINE and RACINE configurations ;
- parametrical approach : the central-rod worth is studied with respect to several parameters (size, absorber enrichment, core size...) ;
- use of a heterogeneous configuration to enhance flux tilting effects and interaction factors in the multiple rod experiments.

II.2 - Core and blanket cells description

The description of the cells used in MASURCA cores, covering the range of the PHENIX and SUPER-PHENIX cores neutronic characteristics are given in other papers |1,2,3|.

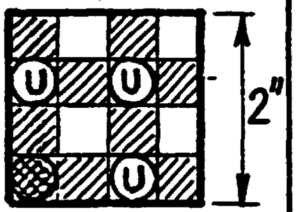
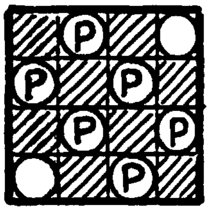
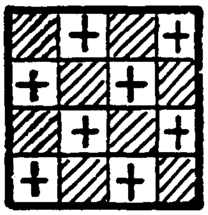
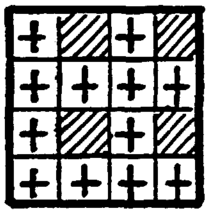
In the PRE-RACINE and RACINE programs, only the medium enrichment cells are used. Platelet type materials provided from SNEAK, are combined in either Plutonium or Uranium cells of nearly the same characteristics.

In figure I and table I, these descriptions and characteristics are shortly resumed.

TABLE I - Neutronic characteristics of core cells

	B_m^2 m^{-2}	K^*	D	$\frac{Pu}{U+Pu}$ or $\frac{U_5}{U_8+U_5}$	$\frac{\sigma_{F8}}{\sigma_{f5}}$
ZONA 1 (Pu)	14.8	1.61	1.93	18.3%	.0332
ZONA 1 K (Pu) (Platelets)	15.8	1.58	1.79	≈ 18.3%	.0310
R1 (U)	16.1	1.51	1.75	22.3%	.0345
R1 K (U) (Platelets)	16.0	1.51	1.76	≈ 22.3%	.0329

(From multizone cells calculations / Carnaval IV)

	Enrichment e $\frac{Pu}{U+Pu}$ or $\frac{U5}{U_5+U_8}$	
R1 (U)	22,3 %	
ZONA 1 (Pu)	18,3 %	
Axial blanket and in core blanket zone	Depleted U	
Radial blanket	Depleted U	
SUPER PHENIX externe zone	18 %	

(U) Metalic U 35%

Metalic depleted U

(P) Mixted oxyde $(UPu)O_2$ 25% Pu

Natural U oxyde

[+] Depl. U oxyde

Fe_2O_3

Na

Fig. 1

PRE RACINE/RACINE Core and blanket cells

II.3 - Control-rod descriptions

All the rods are measured using as a reference the normal Na rodlets follower along the total core + axial blanket heigh without any absorber material at the rod position. These followers have the same geometrical cross-sections than the corresponding absorber rods.

Absorbers rods are varied by :

- geometrical cross-section (110 or 280 cm^2) for single central rod
- boron enrichment by use of
  - . natural boron B_4C rodlet (or SNEAK boron powder in boxes)
  - . 90% enriched boron B_4C rodlets (or SNEAK boron powder in boxes)
  - . mixed configurations

For the 280 cm^2 rod, simulating a power reactor rod, some Na is included in the rod component : effect of absorber concentration in the central part of the rod has been studied.

In teractions between rods will be measured for the extreme boron enrichments with rods pairs, and for natural enrichement for more complex configurations. Particular configurations with emphasized flux tilting effects are planed, using natural boron rods.

The various rods are described figure II and table II.

TABLE II - Rods description

Rod N°	Fig. II	ROD	Geometrical cross-section cm^2	Absorber			Steel % V	Na % V	Void % V
				Nature	$\frac{10B}{10B+11B}$	% V			
01	a	Na follower	112.36				8	90.5	1.5
02	d	Na follower	273.88				8	90.5	1.5
11	a	Natural boron	112.36	B_4C (sintered)	20%	85.5	13	0	1.5
12	b	Natural boron	98.32	"	20%	85.5	"	0	1.5
13	c	Enriched boron	"	"	47%	85.5	"	0	1.5
14	b	Enriched boron	"	"	90%	85.5	"	0	1.5
21	e	Enriched boron + Na (heterogeneous)	273.88	"	69%	45	"	41	1
22	f	Enriched boron + Na (homogeneous)	"	"	69%	45	"	41	1
23	f	Natural boron + Na (homogeneous)	"	"	20%	45	"	41	1
31	/	Natural boron	112.36	B_4C (powder)	20%	85.5	"	0	1.5
32	/	Enriched boron	112.36	"	90%	85.5	"	0	1.5

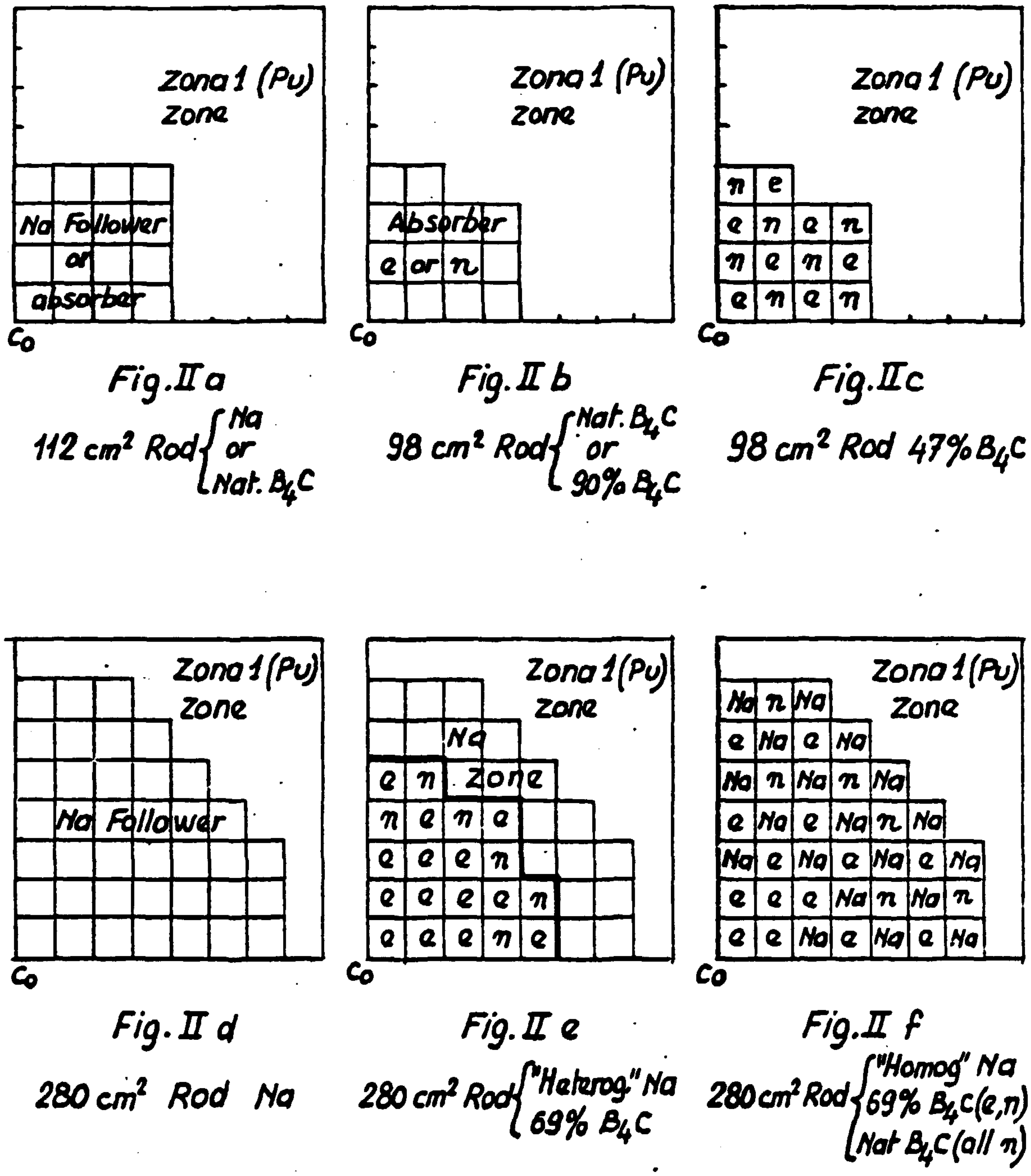


Fig. II a — 112 cm² Rod { Na or Nat. B_4C

Fig. II b — 98 cm² Rod { Nat. B_4C or 90% B_4C

Fig. II c — 98 cm² Rod 47% B_4C

Fig. II d — 280 cm² Rod Na

Fig. II e — 280 cm² Rod { "Heterog" Na, 69% B_4C

Fig. II f — 280 cm² Rod { "Homog" Na, 69% B_4C (e, n), Nat B_4C (all n)

C_o = Core Center (NE Masurca subassembly represented)

n = Nat. boron rodlet e = 90% enriched boron rodlet

Fig. II. Central single rods (NE 1/4)

II.4 - Cores description

For our purpose we have to look at the three following steps of the PRE-RACINE/RACINE configurations :

- the PRE-RACINE core, without in core fertile zone, which is a single two zones core with a central single rod position (figure IIIa) ;
- the RACINE 1D core, with a ring fertile zone and a central single rod position (figure IIIb) ;
- the RACINE 1E and following cores, with a central fertile zone and a ring fertile zone, and 12 rod positions in two rings (4 + 8) for multiple rods experiments (figure IIIb).

In these core configurations, the following parameters remain unchanged :

- core fissile and fertile cells used (central fissile zone Pu, ZONA 1 cell, external fissile zone U, R1 cell) ;
- core heigh : 91 cm ;
- axial blanket cell and thickness ;
- radial blanket cell and thickness (18 to 23 cm) (except for PRE-RACINE : radial blanket without Na).

II.5 - Experimental program and measurement technics

Main rod parameters have been studied with the single central rod in the PRE-RACINE program. However, it appeared that some questions concerning core size effect and interaction effects needed more efforts. The previously established multi-rod program in RACINE |2| has been expanded with :

- a single central rod study in the large RACINE core ;
- emphasis on rods interaction and flux tilting measurements aspects.

Table III gives a general survey of the whole program, measurements technics used, and the expected values of the main parameters.

Once more, it should be stressed that the RACINE 1E experiments will not be reported at the present stage.

TABLE III - General plan of control-rods measurements in the PRE-RACINE and RACINE program

Core/(dates)	Rod N° *	Measurements: Parameters	Measurements: Technics	Attempted results
PRE-RACINE (1979) Single Central rod	01	Ref.	Critical radius Variation + Calibrated driving rod (ΔR)	C/E on ΔK versus - rod worth - rod size - core size
	11	ΔR		
	12	ΔR		Rod heterogeneity effect
	13	ΔR		ΔK to Δϕ relation
	14	ΔR	Fission chambers	
	02	ΔR ϕ	Radial channel	Max ΔK insertion = 9%
	21	ΔR ϕ	Through the rod	Min ΔK insertion = 4%
	22	ΔR	(ϕ)	
RACINE 1D (End 05/1982) Single Central rod	02	Ref. ϕ	id. (ΔR) + subcritical (ΔK)	
	22	ΔK ΔR ϕ		
	23	ΔK	id. + foils near the rod and inside the rod (ϕ)	
RACINE 1E (Begin 06/1982) Multirod configuration	01 12 Pos.	Ref. ϕ	Subcritical (ΔK) + Critical (id) (ΔR)	C/E on rods interactions versus : - positions - rod worth
	31 (1 to 12 rods)	ΔK		
	32 (1 and 2 rods)	ΔK		ΔK to Δϕ relation; Max ΔK insertion = 8%
	31 (1 and 2 rods)	ΔR ϕ	Fission chambers	Interaction factors : 0.1 < f - 1 < 1.0
	32 (1 and 2 rods)	ΔR ϕ	Radial Channel; Through the rods +	One rod over 8 ; amplification factor > 2
	31	ΔR ϕ	Foils near the rods - inside the rods (ϕ)	Axial distributions with partly inserted rods. Particular flux tilt with partial outer rod-ring

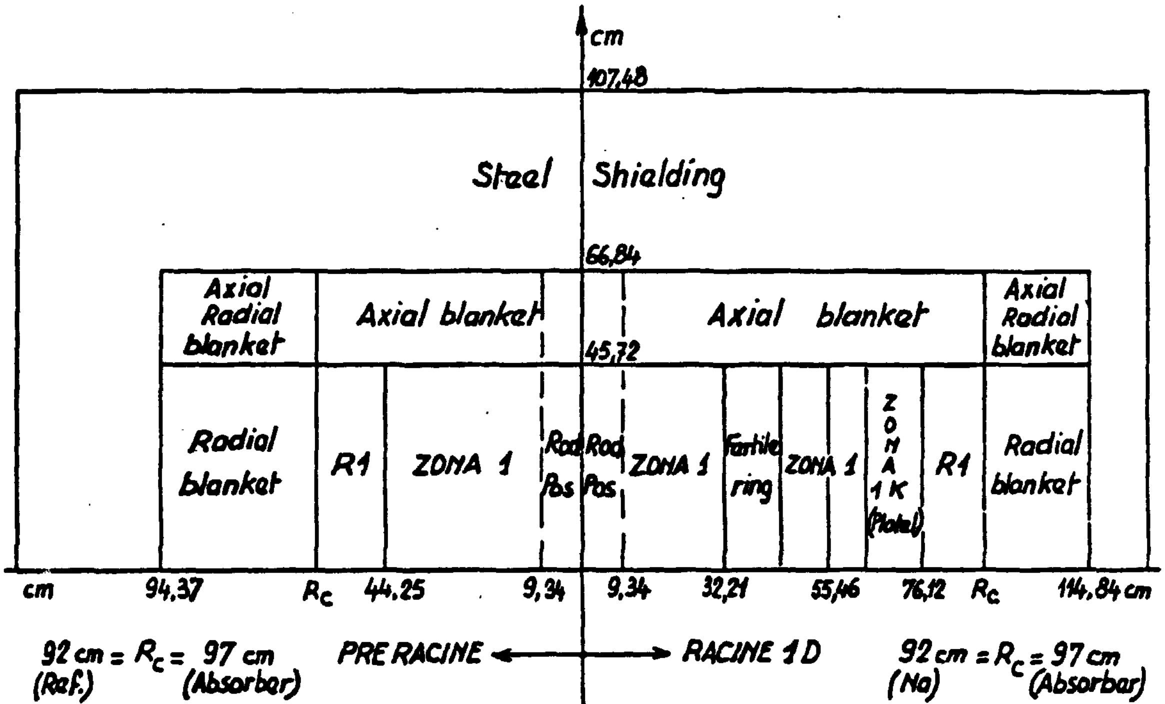


Fig. III a

Fig. III b

Fig. III c

RACINE 1 E

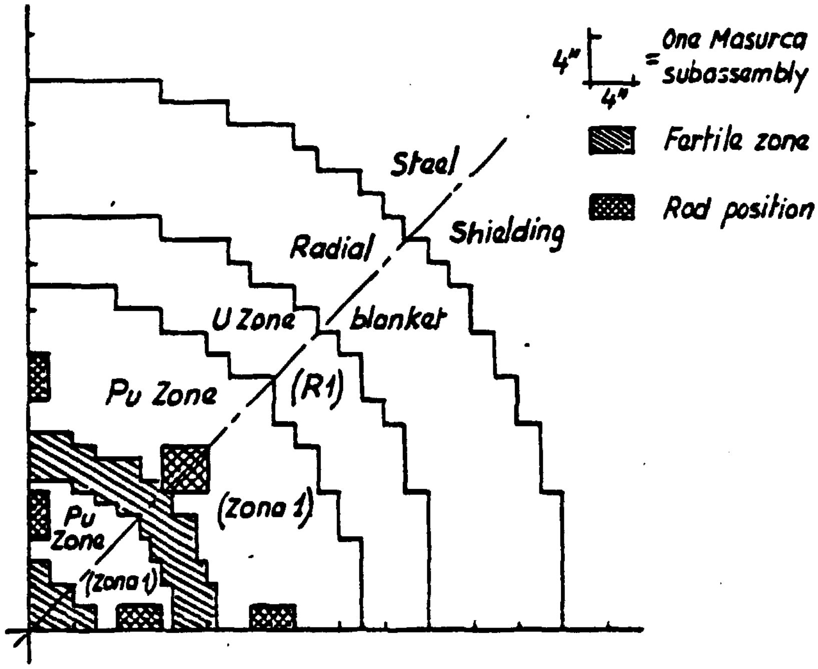


Fig. III. PRE RACINE and RACINE Cores. Rods Positions

III - CALCULATION METHODS, CORRECTIONS AND (E-C)/C VALUES

III.1 - The basic Keff and flux calculations use classical multigroup diffusion theory. Configurations are described in XY geometry. The normal mesh size fits approximately to one MASURCA rodlet (about 1/2") for the core zone. The 25 energy groups approximation of Carnaval IV cross-section set and cell code is used :

- for fissile zones, the so called HH 25 groups cross-sections are issued from a 2 zones cell "HETAIRE" calculation. (Pu isotopes number densities are calculated at the date of rod measurements. Other dates experimental results are corrected of number densities variation effet (41Pu decay)).
- for fertile in core zones, they are issued from a 2 zones cell calculation with the neighbouring core neutron leakage spectrum used as a spectrum for the neutron source ;
- for other zones, including absorbers, an homogeneous cell calculation is performed with a standard spectrum used for the source.

The axial bucklings of the XY calculations are zone and group dependant, issued from a 6 groups RZ calculation.

This basic calculation includes some approximations coming from methods (diffusion theory, mesh size, axial streaming) and from experiment description versus actual experimental conditions (core dissymetries, cell heterogeneity for reaction rates traverses,...).

For some of the approximations, the effect on the (E-C)/C result can be evaluated, with an associated uncertainty, by particular calculations which are described there after.

III.2 - Calculated corrections

III.2.1 - Diffusion to transport theory correction

This correction is to be applied to the reference core value of rod worth of previous diffusion calculation. It is calculated in XY geometry with 6 energy groups homogeneous cross-sections : it is assumed that the main point for this correction is to have an exact representation of the rod/core boundary. Secondary effects, related to the approximation made in this calculation (groups collapsing, axial buckling treatment), are introduced as an uncertain on the correction, after 1D order of magnitude evaluation |4|.

III.2.2 - Mesh size correction

The mesh size used is small : the small related correction is assumed to be, in relative value of the rod-worth, independant of the rod. It has been calculated on the PRE-RACINE central 280 cm² rod using the normal mesh (≈ 1/2") and a double mesh (≈ 1") calculation, by extrapolation to zero mesh size of Keff values with and without absorber.

III.2.3 - Axial streaming corrections

XY geometry has been choosen for the following reasons :

- coherence with design calculations,

- actual rod boundary representation,

- coherence of the whole program :
  - analysis will include multirod configurations where XY geometry is necessary
  - radial reaction rates have to be calculated with the exact radial geometry specialy near the rod.

It makes necessary an axial streaming correction which is easily calculated for single central rod configurations by 2D(RZ) and 1D(R) (with the same zones and groups dependant axial buckling than XY calculations) 6 energy groups calculations. For multirod configurations, 3D calculations test will be necessary.

III.3 - Other corrections

III.3.1 - Exact number of cells accounting

For cost reasons, only quarter of core calculations are run. This can lead to one or two peripheral cells difference with actual core. A Keff correction is applied to experimental results, using experimental calibrated peripheral cell value.

III.3.2 - Other corrections will be necessary for reaction rates measurements analysis

They will be presented and discussed with these results when available.

III.4 - ΔK analysis with ΔR measurements for rod worth

In previous rod worth experiments analysis, we had assumed that the (E-C)/C values on ΔR could directly be used for transposition to ΔK uncertainties of design calculations. In fact the (E-C)/C value on ΔK at reference core size with Na follower would be the right one. For large rod worth, as it is the case for central rods in RACINE and PRE-RACINE, core size variations are important and induce large variations of rod worth. It is not obvious that (E-C)/C values are ΔR and ΔK can be used as equivalent.

In the present analysis, the ΔK way has been choosen (including use of subcritical measurements in RACINE experiments). It means that :

- for PRE-RACINE ΔR rod worth measurements, a transposition to ΔK (E-C)/C values at reference core size can be assumed,

- a check of this assumption can be made in the RACINE central rod worth measurement : in that case both subcritical and critical ways are used.

In a first time we have tried the following assumption : for a given core and a given single central rod, measured and calculated Keff = f (core radius) curves are parallel straight lines.

In that case it can be written :

$$\left(\frac{E-C}{C}\right)_{\text{on rod worth}} \simeq \frac{\dfrac{\left(k_{E,b}^{b} - k_{E,ref}^{ref}\right) - \left(k_{C,b}^{b} - k_{C,ref}^{ref}\right)}{k_{C,b}^{b} \cdot k_{C,ref}^{b}}}{\rho_C}$$

where :

E means experimental value

C means calculated corrected value

b means with absorber inserted

b means with absorber critical experimental core size

ref. means without absorber

ref. means with reference experimental core size

III.5 - Available results : central rod worth (E-C)/C values

At the moment the status of the work is :

- central single rods worth measurements achieved and calculated results available
- reaction rates distributions with central rods analysis under progress
- multi-rod experiments planed for second mid of 82.

So further § of this paper are now restricted to central single rod worth. Table IV and V give calculated corrections and values, (E-C)/C values and uncertainties according to § III.4. Chapter IV introduces discussion on (E-C)/C analysis.

TABLE IV - Calculated ΔK/K values and corrections (in %) (Reference in k : Na follower situation)

Rod			Reference core Size	IV 25 groups diffusion ΔK/K %	Calculated corrections %			Corrected ΔK/K %
n°	Size cm²	Boron enrichment			Mesh step	Axial Streaming	Transport *	
12	90	Nat.	PRE-RACINE clean core (without follower) experiment critical	- 4.68	- 0.5±0.2	0.5 ± 0.2	-11.4±1.0	- 4.15±0.07
13	90	47%	"	- 6.90	- 0.6±0.2	0.3 ± 0.2	- 9.6±1.0	- 6.22±0.10
14	90	90%	"	- 8.08	- 0.6±0.2	0.3 ± 0.2	-11.6±1.0	- 7.15±0.14
11	112	Nat.	"	- 5.11	- 0.6±0.2	0.5 ± 0.2	- 7.2±1.0	- 4.73±0.07
11	112	Nat.	PRE-RACINE with Na follower (112 cm²) experiment critical	- 4.88	- 0.8±0.2	0.5 ± 0.2	- 5.2±1.0	- 4.61±0.07
21	200	69% Hetero. Na	PRE-RACINE with Na follower (200 cm²) experiment critical	- 8.14	- 0.7±0.2	0.3 ± 0.2	- 7.5±1.0	- 7.50±0.11
22	200	69% Homog. Na	"	- 8.79	- 0.7±0.2	0.3 ± 0.2	- 7.7±1.0	- 8.08±0.12
22	200	69% Homog. Na	RACINE 1D with Na follower (200 cm²) experiment critical	- 2.88	- 0.5±0.2	0.2 ± 0.2	- 6.4±1.0	- 2.68±0.04
23	200	Nat. Homog. Na	"	- 2.11	- 0.5±0.2	0.0 ± 0.2	- 4.1±1.0	- 2.01±0.03

* For transport correction uncertainty see [4].

TABLE V - Experiment to calculation comparison

Rod N°	Rod Size cm²	Rod Boron enrichment	Calculated corrected ΔK/K %	$\frac{E-C}{C}$ %	COMMENTS	
12	98	Nat.	- 4.15 ± 0.07	- 1.3 ± 2.0	At PRE-RACINE reference clean core size (R_c = 55 cm)	
13	98	47%	- 6.22 ± 0,10	- 1.7 ± 2.0		
14	98	90%	- 7.15 ± 0.14	- 1.7 ± 2.1		
11	112	Nat.	- 4.73 ± 0.07	- 1.1 ± 2.0	All PRE-RACINE measurements ΔR ⟶ ΔK	
11	112	Nat.	- 4.61 ± 0.07	- 0.6 ± 2.0	At PRE-RACINE with Na follower core size	R_c = 56.5 cm
21	280	69% Hetero. Na	- 7.50 ± 0.11	- 6,5 ± 2.0		R_c = 58 cm
22	280	69% Homog. Na	- 8.08 ± 0.12	- 6.5 ± 2.0		R_c = 58 cm
22	280	69% Homog. Na	- 2.68 ± 0.04	- 7.8 ± 1.5	RACINE heterogeneous with Na follower	ΔR ⟶ ΔK R_c = 92 cm
22	280	69% Homog. Na	- 2.68 ± 0.04	- 9.7 ± 6.0		Subcritical R_c = 92 cm
23	280	Nat. Homog. Na	- 2.01 ± 0.03	- 7.4 ± 5.0		Subcritical R_c = 92 cm

IV - COMMENTS ON (E-C)/C VALUES

It can be seen on table V that the discrepancy between experiment and calculation, expressed in % of rod worth, can be considered as independant of rod worth at constant core size and rod geometry.

The general trend to over estimate rod worth can be precised by the following findings :

- over estimation seems to be slightly dependant of core size at constant rod geometry :

  ≈ 6.5% of a 280 cm^2 rod in a 60 cm radius core
  ≈ 8 % for the same rod in a 92 cm radius core

- over estimation is dependant of rod geometry :

  ≈ 1 to 2% for 110 cm^2 rods without Na
  ≈ 6.5 to 9% for 280 cm^2 rods of mixed Na/absorber composition

For this point, at the present stage, it cannot be said wether the effect is due to rod size, presence of sodium, or both. But comparison between rods 21 and 22 in PRE-RACINE indicates that relative position of sodium and absorber as no influence on the discrepancy.

Last, subcritical and critical measurements (analysed in ΔK) seem to be in good agreement.

V - CONCLUSION

At present, a ± 13% uncertainty is associated to all control rod design calculations |4|. In this value, the major contribution is due to the experiment to calculation comparison. In fact, starting from the results presented in this paper, a conservative value of ± 10% uncertainty (i.e. no bias factor) has been deduced, which is linearly combined with a ± 3% method uncertainty.

Since the ± 10% value is mainly coming from the 7 to 9% discrepancy observed on large mixed Na/absorber rods, a suplementary analysis effort should be made to explain and correct this discrepancy.

The next part of RACINE control rod program, shortly discribed in the paper, will give informations on rods interactions with same order of magnitude interaction factors than in power reactors. Accuracy on these calculated factors is the necessary complement of the single control rod studies.

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