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PART II

COMMISSION OF THE EUROPEAN COMMUNITIES

COLLECTRONS, SELF-POWERED NEUTRON FLUX DETECTORS

Part II: Irradiation tests and calibration in Ispra-1

by

R.P. DEBEIR, M. GRIN and O. SIMONI

1972

Joint Nuclear Research Centre
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ABSTRACT

Collectrons are self-powered neutron flux detectors based on the activation of short life beta source by neutron flux itself. The first part of this report was devoted to the description of the devices, and to the computation of their theoretical sensitivity with particular reference to some correcting factors as neutron self-shielding and β self-absorption. The second part deals with the behaviour of the collectrons in normal working conditions. During a series of irradiation tests the following points have been examined : calibration of various β emitters and comparison with theoretical values; study of the wiring and background compensation; relative influence of thermal and epithermal flux on the output current of the detectors. The calibration values obtained are in very good agreement with theoretical computations. In annex is given an analysis of the equivalent electrical circuit of a collectron.

KEYWORDS

NEUTRON DETECTION	CALIBRATION
NEUTRON FLUX	PERFORMANCE
EMISSION	CURRENTS
BETA PARTICLES	ERRORS

CONTENTS

1. INTRODUCTION *)

Collectrons or self-powered neutron flux detectors, are β emitters largely employed to measure neutron flux.

An irradiation program has been developped in order to control, in normal conditions of utilization, the behaviour of such detectors, to calibrate their sensitivity and to compare the measurements with theoretical evaluations [1].

The following items have been studied :

- calibration of various emitters; comparison with theoretical values,

- importance of the wiring; study of the background compensation,

- relative influence of thermal and epithermal flux on the output signal of collectrons,

- importance of the insulation resistance of collectrons, its evolution in working conditions.

This program has been run during four successive irradiations in the ISPRA-1 reactor of the Common Research Center of EURATOM.

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*) Manuscript received on January 5, 1972

2. EXPERIMENTAL DEVICES

The rig of irradiation which contains collectrons is set in a standard thimble of aluminium which is then introduced either in the central channel or in a peripheral channel of the reactor (Fig. 1).
On Fig. 2 is schematically indicated the disposition of rig and thimble in the reactor (case of a peripheral channel). The thimble filled with an inert gaz (helium or azote), ensures the isolation of the rig from heavy water.

The rig itself is shown on Fig. 3 : it comports essentially :

a) a shielded plug (15)
b) a hanging tube (13)
c) the collectron-holder (8) + (3)
d) a tube containing flux monitors (1).

2.1. Shielded plug

It consists of a stainless steel tube containing a mixture of resin and lead balls (approximate density 5 g/cm^3) and fitted with a cadmium shield in its lower part. An helicoidal tube containing the thermocouples connecting cables passes through the plug : it is sealed with resin to insure the tightness to the filling gas which is introduced through the tube (24). The plug is fitted to the thimble by a bayonet joint, two O-rings ensuring the tightness (10).
At the lower part of the plug is set a holder for the thermocouples and collectrons connectors.

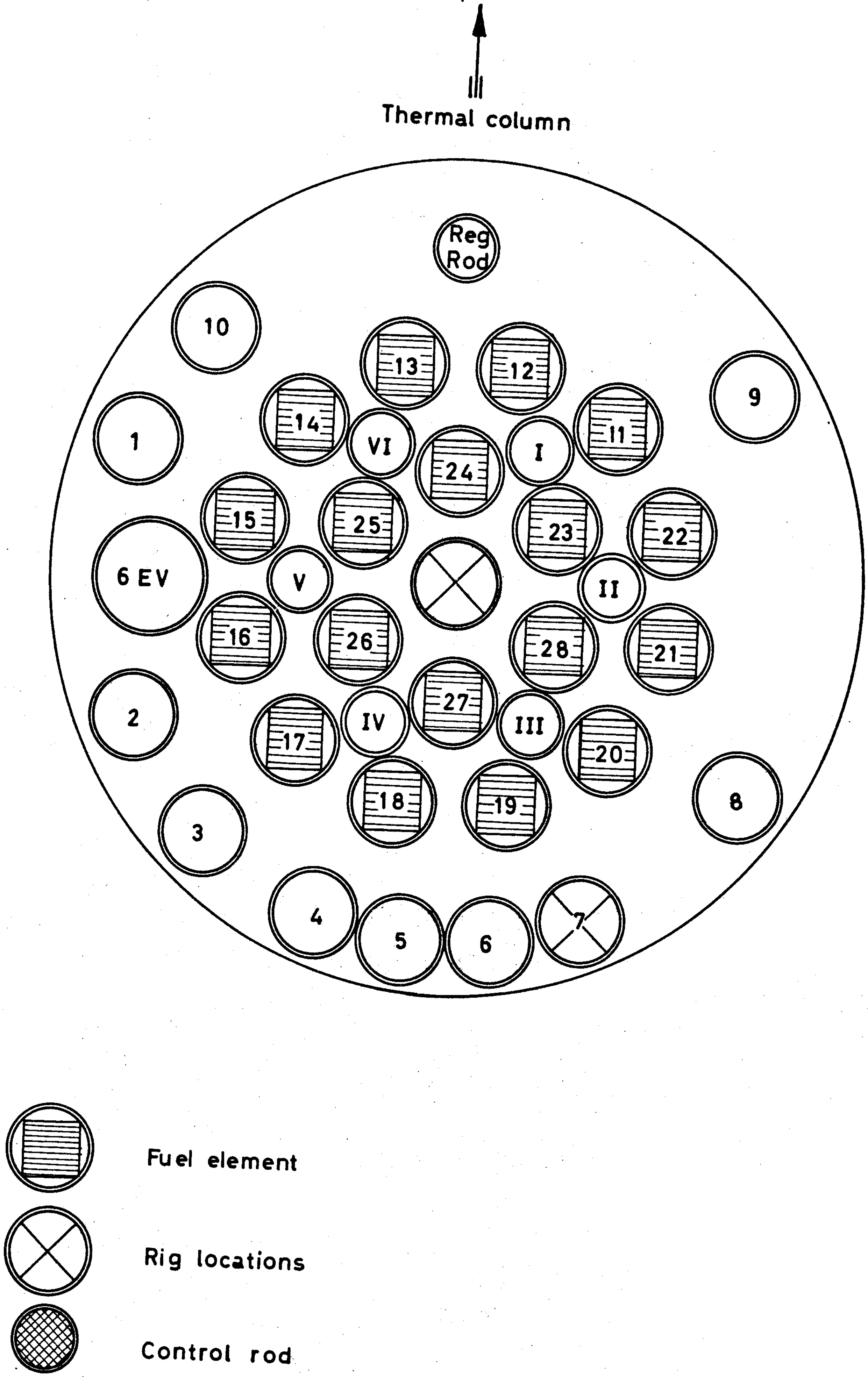


Fig.1 - Schematic core cross-section

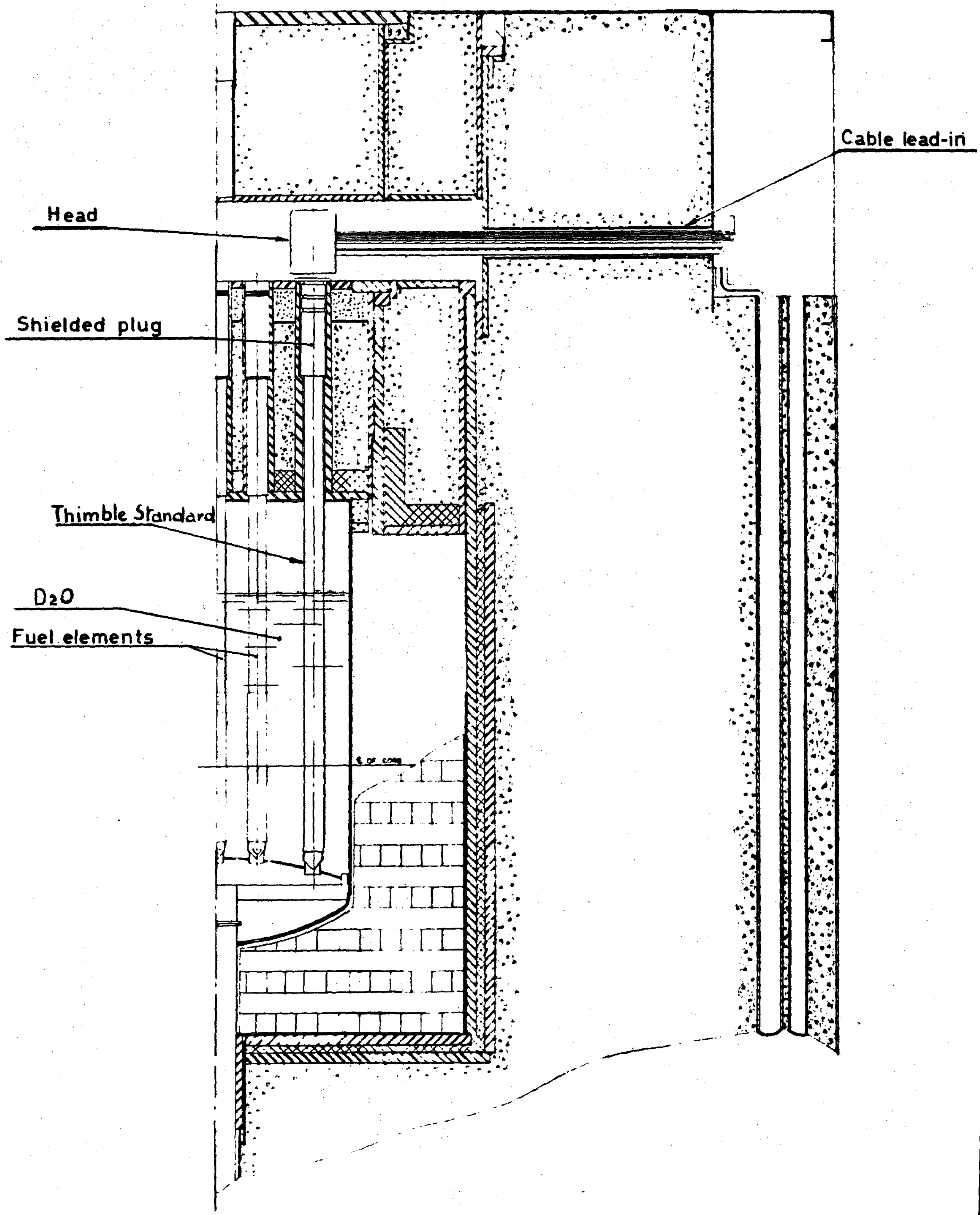


Fig.2 DISPOSITION OF THE RIG IN REACTOR

2.2. Hanging tube

It is an aluminium tube fitted by a pin (14) to the plug : a lower centering plate also acts as a support for the collectron-holder.

2.3. Collectron-holder

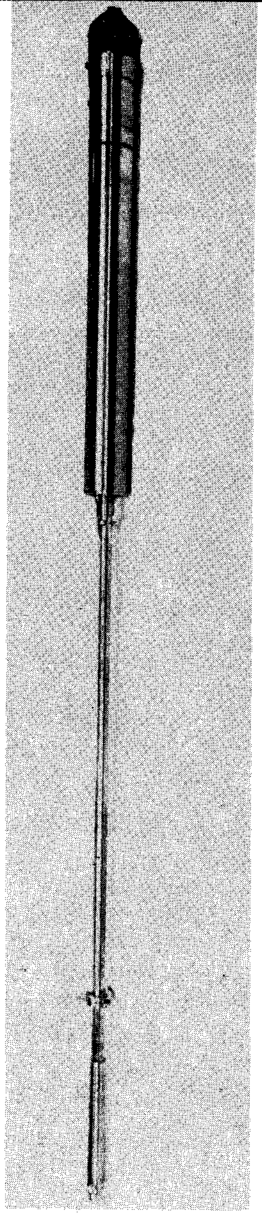
It is composed of 2 S.A.P. parts (Sintered Aluminium Powder choosen for its low cross-section and good mechanical resistance at high temperatures), which is raised to the testing temperature by γ heating. The middle part (8) is fitted to the hanging-tube by a plate : between the two plates is set a disc of alumina for thermal insulation.
The lower part (3) or collectron-holder, is an interchangeable piece whose shape and dimension vary according to the number and disposition of collectrons, thermocouples and monitors.
The holder shown in Fig. 3 was employed for the rig nr. 1. The tube containing the monitors (wires of AlCo 0.1%) is removable and allows recuperation and replacement during a test. Photographies (Fig. 4, 5 and 6) show the whole rig and the details of some constitutive parts.
With such a device, 4 irradiations of collectrons have been made [2, 3]. The dispositions of the collectrons during these various irradiation tests, with reference to the corresponding rig number, are indicated in Fig. 7.

3. THE ISPRA-1 REACTOR

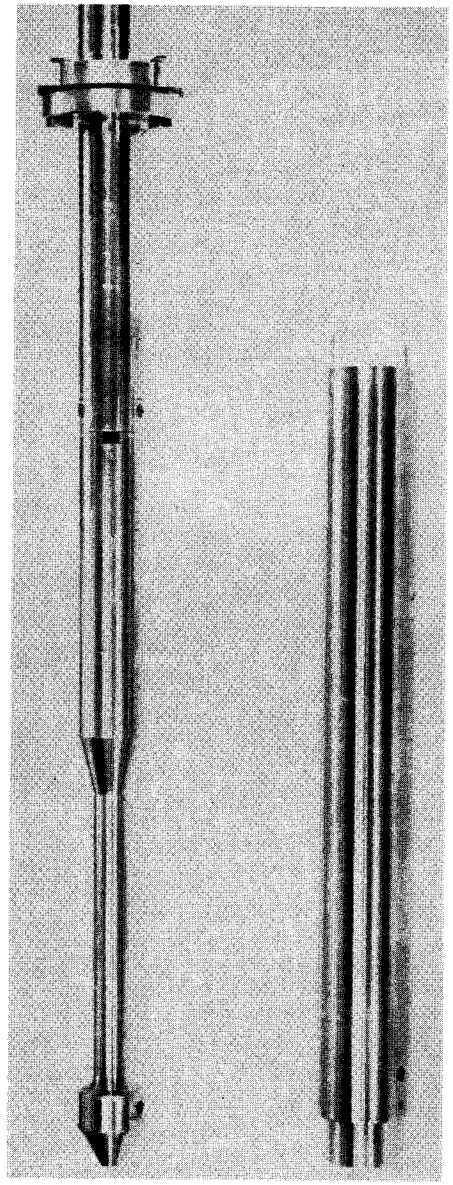
ISPRA-1 is an american reactor type C.P.5. Argonne with a maximum thermal flux of $10^{14} n.cm^{-2}.s^{-1}$. Fuel elements are of 90% enriched Uranium. The reactor is moderated and cooled with heavy water, its maximum power is 5 MW th. Figures 1 and 2 show schematically a cross-section and a longitudinal section of the reactor. The height of the core is 624.8 mm and Fig. 8 shows the axial distribution of the flux near the center line.

4. CALIBRATION OF THE COLLECTRONS. CONFRONTATION OF EXPERIMENTAL AND THEORETICAL VALUES

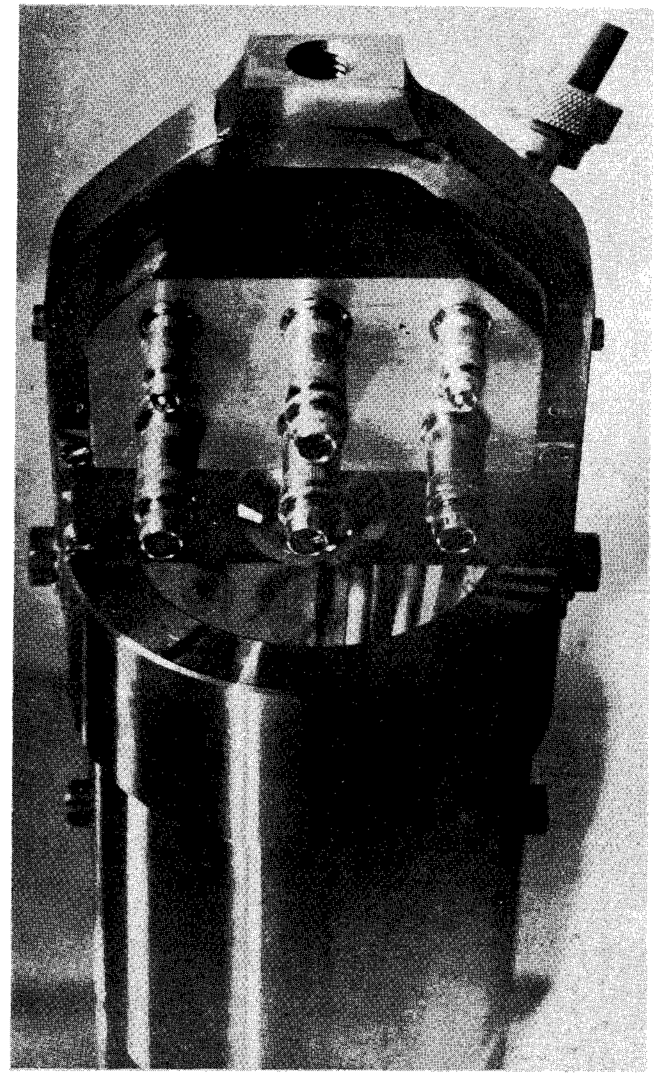
During 3 irradiations tests (RIG 1, RIG 3, RIG 4) collectrons with Rh, Ag and V emitters have been calibrated with respect to flux monitors wires of Al-Co 0.1% and Al-Ag 0.1%.
These irradiation tests were performed either in the central channel or in a peripheral channel of ISPRA-1 between Feb. 1967 and March 1969; repeated calibration tests were performed to set in evidence the reproducibility of the results.



<u>Fig. 4</u> : General
view of the RIG



<u>Fig. 5</u> : In-Pile section
Collectrons and
flux monitors
holders.



<u>Fig. 6</u> : Upper part of the RIG
with the connectors.

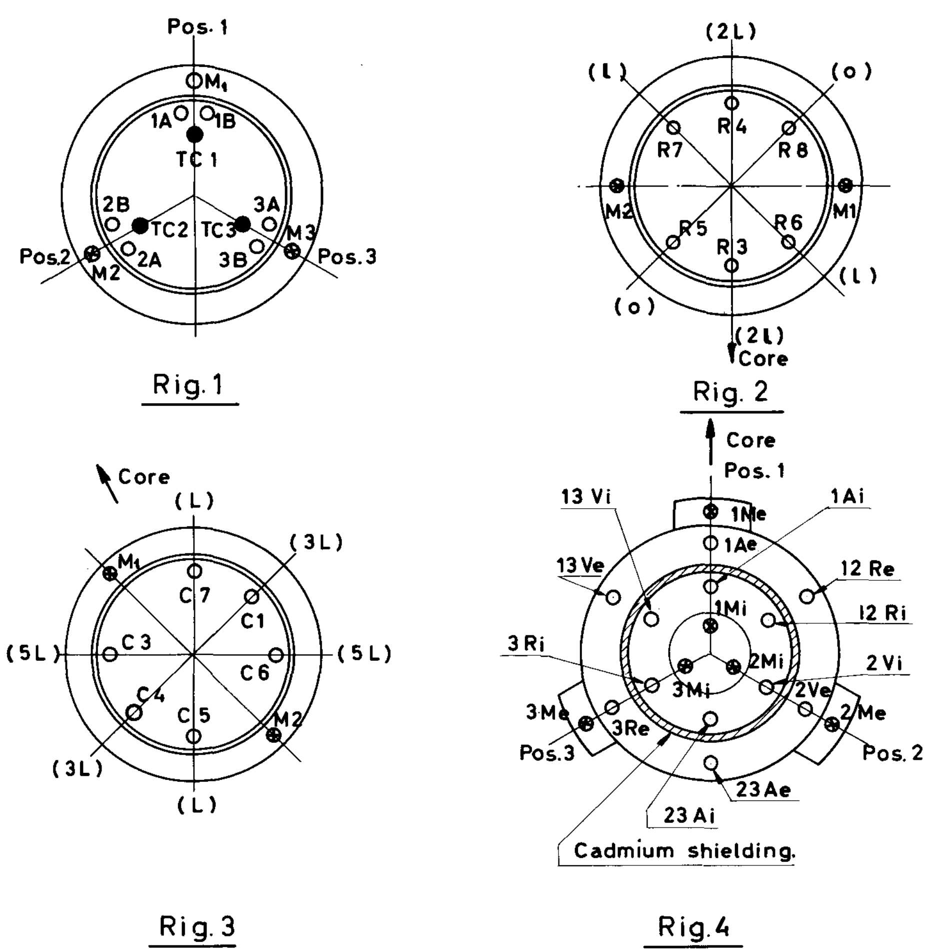


Fig. 7 - SCHEMATIC DISPOSITION OF THE COLLECTRONS IN THE VARIOUS RIGS.

- ● Thermocouple
- ⊗ Flux monitor
- ○ Collectron (A = silver, R = rhodium, V = vanadium)
- L connectingeable lengh
- l emitter lengh

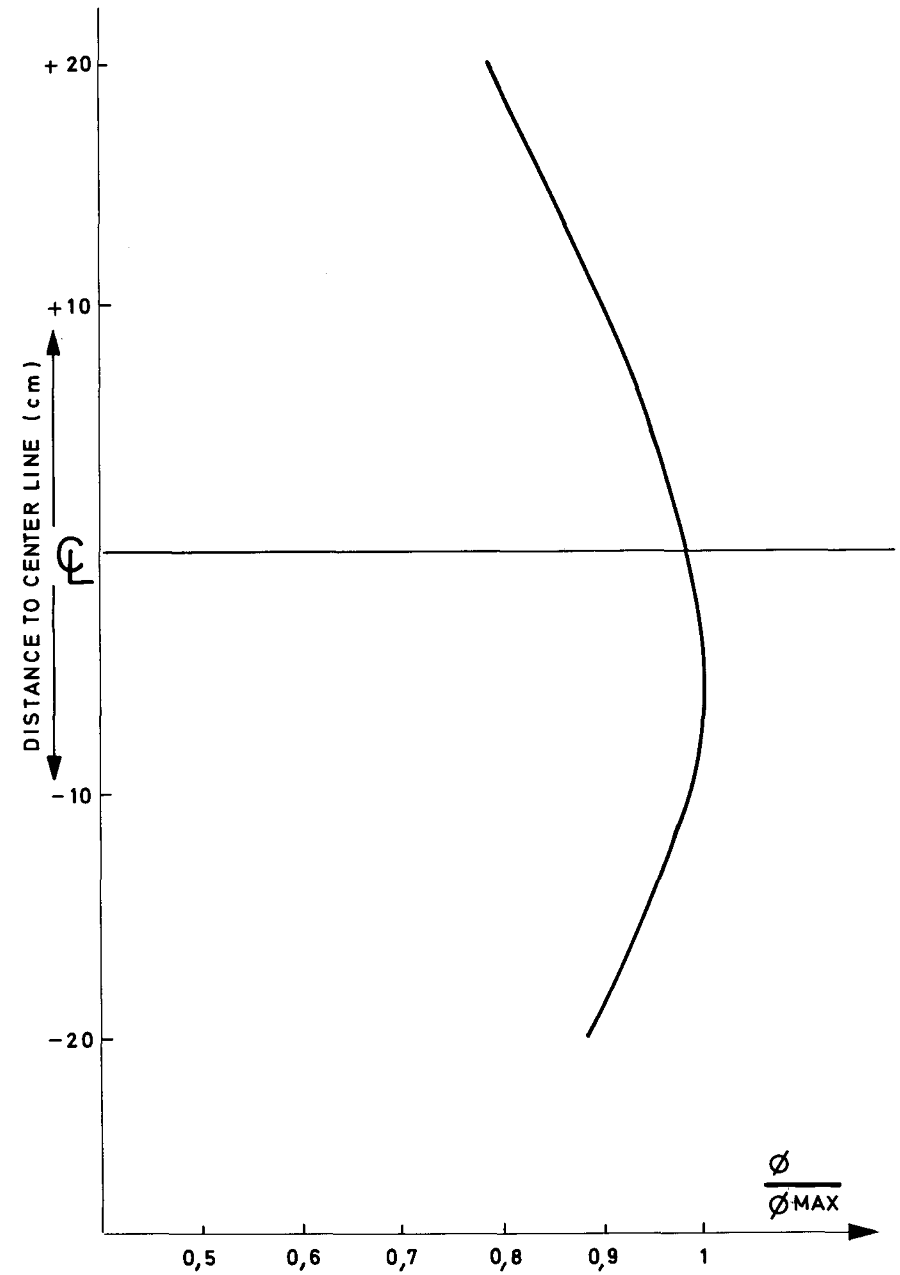


Fig.8 AXIAL FLUX DISTRIBUTION IN CHANNEL 7 NEAR CENTER-LINE.

4.1. Irradiation conditions

RIG.1

6 collectrons : 3 Rh and 3 Ag - diameter 0.5 mm
length 25 mm - sheath AISI 304 L - insulator Al_2O_3

43 days irradiation in the central channel corresponding to an integrated power of 4.939 MWh and 22 days, or 2.626 MWh, in the peripheral channel nr. 7.
temperature :
540°C to 585°C in the central channel
225°C in the peripheral channel.

RIG.3

5 collectrons Ag - diameter 0.5 mm - length 50 mm
sheath AISI 304 l - insulator Al_2O_3.

duration of irradiation	:	52.3 days
integrated power	:	6.279 MWh
position	:	peripheral channel nr. 7
temperature	:	250°C

RIG.4

6 collectrons : 2 Ag, 2 Rh, 2 V - diameter 0.5 mm
length 100 mm - sheath AISI 304 L - insulator Al_2O_3

duration of irradiation	:	74.5 days
integrated power	:	8.942 MWh
position	:	peripheral channel nr. 7
temperature	:	430°C to 445°C.

	Central channel	Peripheral channel		
	RIG 1	RIG 1	RIG 3	RIG 4
$r\sqrt{\frac{T}{T_o}}$	0.050	0.030	0.026	0.043
r	0.045	0.027	0.025	0.038
Thermal flux $n.cm^{-2}.s^{-1}$	$7\ 10^{13}$	2 to 3 10^{12}		
Epithermal flux $\geq$ 0.51 ev $n.cm^{-2}.s^{-1}$	$5.9\ 10^{12}$	$1.1\ 10^{12}$		

TABLE 1 : Main irradiation data.

The moderator temperature (D_2O) varies from 42°C (inlet) to 50°C (outlet) : for the computation the mean value of 80°C was taken for the neutron temperature.

4.3. Experimental results

Some measurements were made with background compensation wiring, others were made without compensation : results of calibration tests are gathered in Table 2.

	Central channel	Peripheral channel		
		RIG 1	RIG 3	RIG 4
Rh non compensated	1.25	1.11		1.12
Ag non compensated compensated	0.59 0.65	0.47 0.51	0.45 0.51	0.48
Ag non compensated				0.047

TABLE 2 : Calibration values in $10^{-21}.A.n^{-1}$ for an emitter of 0.5 mm diameter and 10 mm long.

The values indicated are mean values obtained during various irradiation tests whose details are indicated in Annex 1.

Confrontation with theoretical predictions

Using the data previously determined [1] it is possible to calculate the theoretical value of the output current of a collectron in the conditions of the experience, that is to say with a neutron temperature of 80°C and a Westcott factor r of 0.045 in the central channel, then of 0.027 and 0.038 in the channel nr. 7.

The calculated values, obtained by application of the following formula, are indicated in Table 3.

$$I_S = K_1 \cdot K_2 \cdot N \cdot e \cdot \phi \cdot \bar{\sigma}$$

with

$$\bar{\sigma} = \sigma_o \cdot (g + r.s) \cdot \sqrt{\frac{\Pi}{4}} \cdot \sqrt{\frac{293.6}{273.6 + t}}$$

N : number of stable isotopes

ϕ : Westcott flux

e : electronic charge

K_1 : neutron flux depression factor [1]

K_2 : self absorption factor [1]

Emitter	σ_{20}	g_{80}	s_{80}	$\bar{\sigma}_{80}$		K_1	K_2	I_s $10^{-21}.A.n^{-1}$		
				Central	Periph.			Central	Peripheral	
									RIG 3	RIG 4
Rh	150.19	1.037	7.962	169.10	151.64	0.75	0.43	1.21	1.11	1.19
Ag	60	1.0071	15.5	82.52	69.01	0.90	0.11	0.56	0.47	0.52
V	4.5	1	0	3.63		0.99	0.62	0.053		

TABLE 3 : Theoretical values of the output of a collectron of 0.5 mm diameter and 10 mm long.

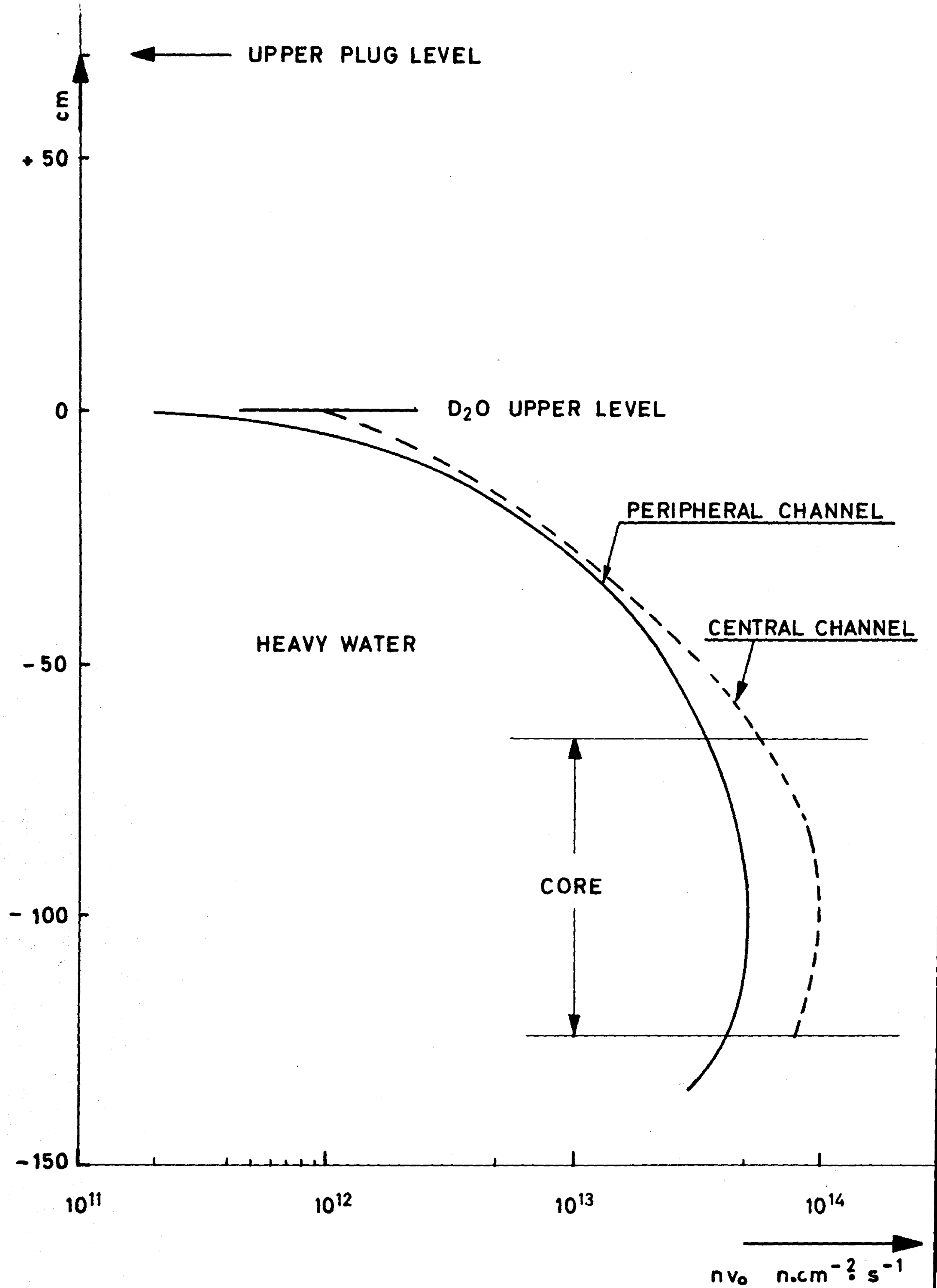


Fig.9 - AXIAL FLUX DISTRIBUTION UP TO D$_2$O LEVEL

The correlation between experimental and theoretical values is fairly good, specially with regard to RIG 1 and RIG 3. The discrepancies observed with RIG 4 can likely be attributed to the presence of a cadmium shield in the vicinity of the collectrons (see Fig. 7 and § 6).

5. COMPARISON OF COMPENSATING AND NON COMPENSATING WIRING

Series of measurements were made on collectrons fitted with mono-wire and two-wires connecting cables in order to determine the spurious currents due to the connecting cable and to test the validity of the compensating wiring.

In ISPRA-1 the length of cable under flux is of about 100 cm from which 30 cm in-core when the emitter is set on the center line of the reactor (Fig. 9). The total length of the connecting cable, up to the head of the RIG, is 300 cm (Fig. 2).

5.1. Working principle of the compensating wiring

A collectron with its connecting cable can be represented by the circuit diagram of Fig. 10 whose complete analysis has been developped in Annex 2.

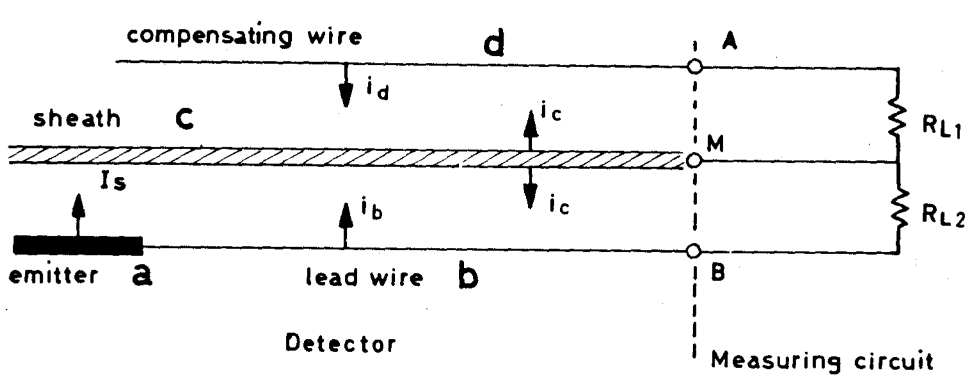


Fig. 10 : Electric circuit equivalent to a compensated collectron.

On the collectron 2 B were executed the following measurements :

V_{AM}, V_{BM}, V_{AB}

V_{AM} after removal of R_2 from the circuit

V_{BM} after removal of R_1 from the circuit

$R_1 = R_2 = 10.000\ \Omega$

The characteristics of the collectrons 2 B are indicated in Table 4 and the results obtained in Table 5.

Emitter	Silver : 0.5 mm d; 25 mm long
Connecting cable	Coaxial cable, MgO insulated, with 2 Ni wires, sheath AISI 304 L, 1 mm. o.d.

TABLE 4 : Characteristics of collectron 2 B.

Mode of wiring	Measured tension mV	Calculated tension (Annex 2) mV
Compensated with R_1 and R_2		
V_{AM}	- 0.122	
V_{BM}	- 1.050	
V_{AB}	- 1.172	
Non compensated with only R_1		
V_{AM}	+ 0.44	+ 0.403
Non compensated with only R_2		
V_{BM}	- 0.96	- 0.989

TABLE 5 : Influence of the compensating wiring.

5.2. Results

a) The very good correlation between measured and calculated values is a proof of the validity of the assumptions made in Annex 2.

b) The spurious current due to the connecting cable comes in substraction to the main current from the emitter.

c) In the considered conditions of geometry and irradiation it reaches 10 % of the main current.

d) Differences, previously observed (see § 4.3.) between compensated and non compensated collectrons, corroborate these results as shown by Table 6.

	Central channel	Channel nr. 7	
		RIG 1	RIG 3
Ag non compensated	0.59	0.47	0.45
Ag compensated	0.65	0.51	0.51

TABLE 6: Calibration values in $A.n^{-1}$ for an emitter of 0.5 mm diameter and 10 mm long.

5.3. Relative importance of sensitivity of the emitter and length of the connecting cable

During irradiation of RIG 2 were tested collectrons with two wires compensating cables and emitter lengthes of respectively 100 mm, 50 mm and 0 mm; emitter was Rhodium 0.5 mm diameter and systematic measurements with and without compensation were performed.

Spurious currents due to the connecting cables (without compensation) are respectively 1.8% and 0.85% for emitters of 50 mm and 100 mm. The ratio of the theoretical sensitivity of Rh and Ag beeing $\frac{1.11}{0.47} = 2.4$, these results confirm the preceeding ones but indicate that the spurious effect due to the connecting cable can be neglected when the length or sensitivity of the emitter becomes high.

5.4. Origin of the spurious currents

During irradiation of Rig 3 were tested collectrons with in-core connecting cable lengthes of L, 2L and 3L (see Fig. 8), exactly 270 mm, 530 mm and 790 mm : in all cases the emitter was Ag 0.5 mm diameter and 50 mm long.

The measured spurious currents is these conditions were 10.7, 12.6 and 11.2% of the total current : the order of magnitude is always the same, which is unacountable; moreover these values of about 10% are inconsistent with results indicated in § 5.1 relative to emitters with a sensitivity twice as low.

The only influence of the neutron flux on the connecting cable cannot take in account the spurious currents observed.

5.5. Conclusions

Connecting cables give rise to spurious currents whose origin is not ascertained but which can be neglected when the sensitivity of the emitter - type and (or) length-becomes sufficiently high. On the contrary it is possible to eliminate this secondary effect with a compensating wiring : it is recommended, in this case, to adopt a measuring device completely isolated from the mains to obtain reproducible values.

6. RELATIVE INFLUENCE OF THERMAL AND EPITHERMAL FLUX ON THE OUTPUT CURRENT

Neither rhodium nor silver are 1/v absorber and consequently they are sensitive to both thermal and epithermal flux, the limit between the 2 fields beeing arbitrary but normally fixed at 0.1 ev. Rhodium presents a pronounced resonnance peak for 1.25 ev ($\sigma_a = 4.8\ 10^3$ barn) and silver presents a very high resonnance peak for 5.12 ev ($1.25\ 10^4$ barn) followed between 10 ev and 100 ev by a succession of lower peaks (6 peaks from 100 to 600 barn).

Vanadium being a 1/v absorber is only sensitive to thermal flux but its poor sensitivity limits its applicability every time the flux is low or the emitter length short.

Sensitivity of rhodium and silver to epithermal flux is a limit for the calibration of collectrons realized from these emitters : indeed the flux distribution varies from one reactor to the other, from one position to the other in the same reactor and, to be strict, a calibration is only valid for the distribution existing at the time of the calibration.

The goal of the irradiation of Rig 4 was to determine the relative importance of thermal and epithermal flux on the output current of collectrons : two group of collectrons (Rh, Ag and V 0.5 mm diameter, 100 mm long) have been irradiated in the same conditions, one group being shielded with a 1 mm cadmium shield (see Fig. 7).

During this irradiation test, at the beginning of phase 2, two fuel elements were replaced in the near vicinity of the RIG.
Measurements performed during this test are summarized in Table 7.

Collectron	Output tension at the terminals of $R = 5.10^3\ \Omega$ 10^{-7} A		Contribution due to epithermal flux % total output	
	Phase 1	Phase 2	Phase 1	Phase 2
SILVER				
1 Ae	1.06	1.14	13.2	14.9
1 Ai	0.14	0.17		
23 Ae	0.84	0.91	14.2	17.6
23 Ai	0.12	0.16		
RHODIUM				
3 Re	2.0	2.13	9.5	11.2
3 Ri	0.19	0.24		
12 Re	2.35	2.49	9.4	11
12 Ri	0.22	0.27		
VANADIUM				
2 Ve	0.11	0.11	0	0
2 Vi	- 0.03	- 0.02		
13 Ve	0.09	0.10	0	0
13 Vi	- 0.03	- 0.03		

TABLE 7 : Relative influence of thermal and epithermal flux on output signal of collectrons.
i = internal to Cd shield
e = external to Cd shield

(see Fig. 7)

These results show that :

a - Vanadium, as foreseen, is completely shielded by cadmium : the residual negative signal is due to the connecting cables, the setting being not compensated.

b - The epithermal flux contribution is higher for Ag silver than for rhodium which corresponds to the relative importance of the resonnance peaks of these 2 materials.

The values of thermal and epithermal flux during this experiment (mean values for phase 1 plus phase 2) were determined by γ spectrometry of Co and Ag monitors; values obtained by activation measurements of Cobalt 60 and silver 110 are indicated in Table 8.

Flux monitor	Thermal flux $n.cm^{-2}.s^{-1}$	Epithermal flux $n.cm^{-2}.s^{-1}.(eV)^{-1}$ at 1 eV	Flux monitor
1 Me	$2.18\ 10^{13}$	$7.41\ 10^{11}$	1 Mi
2 Me	$1.87\ 10^{13}$	$6.94\ 10^{11}$	2 Mi
3 Me	$1.94\ 10^{13}$	$7.05\ 10^{11}$	3 Mi

TABLE 8 : Flux measurements during RIG 4 irradiation.

Values obtained present certainly some errors because of the compact configuration of the RIG where the external monitors are set closed to the cadmium shield.

7. EVOLUTION OF THE INSULATION RESISTANCE

The output signal of a collectron is normally measured at the terminals of a load resistance which must be high in order to obtain a sufficient tension, but must remain low in front of the insulation resistance of the collectron to limit leakage currents. The internal resistance value is then an important characteristic of collectron.

Radiation induced phenomena and temperature highly reduce the electrical resistivity of mineral insulators and it is necessary to obtain the best value insulation possible at the moment of fabrication of the collectron : high quality insulators must be employed and any trace of moisture avoided. The weldings must be free of porosities and the insulation resistance of a collectron must be stable after several days of stay in humid atmosphere.
In these conditions, typical values of the insulation resistance are indicated in Table 9.

Condition of measurement	Ri (M Ω)
In-laboratory measurement on a collectron with an emitter of 25 mm and a connecting cable of 300 cm. Measuring voltage 100 V dc.	$7\ 10^6$
Similar measurement on the same detector connected to a flexible leading cable (teflon insulated), 15 m long.	$1.3\ 10^5$

TABLE 9 : In-laboratory measurements of Ri.

Insulation measurement during operation is not directly possible because of the current produced by the collectron itself but an indirect measure is always possible :

if R_i = insulation resistance of the collectron

V_1 = measured tension at the terminals of a load resistance R_1

V_2 = measured tension at the terminals of a load resistance R_2.

it comes :

$$R_i = \frac{(V_2 - V_1) \quad (R_1 \cdot R_2)}{V_1 \cdot R_1 - V_2 \cdot R_2}$$

Measurements performed on collectrons of RIG 1 first in laboratory, afterwards in-situ before, during and after irradiation are gathered in Table 10. All values under irradiation are mean values resulting of daily measurements during 11 days irradiation.

The main effect is due to irradiation : values of 4 to 8 M Ω are currently obtained for in-pile collectrons at room temperature.

Considering these rather low values it is recommended to adopt for the load resistances values not exceeding 10.000 Ω to prevent shunting errors.

Collectron nr.	Insulation resistance (M Ω)			
	In-laboratory	In-situ		
		Before 1^{st} cycle	During irradiation	After irradiation
1 A	1.5 10^5	6 10^4	2.2	1.5 10^4
1 B	6 10^4	5 10^4	4.6	1.7 10^4
2 A	8.5 10^5	1 10^5	2.6	1.5 10^4
2 B	7 10^5	1.3 10^5	3.2	2.5 10^4
3 A	1 10^8	5.5 10^4	broken	
3 B	8 10^3	8 10^3	5.4	2.5 10^3
T^{re} (°C)	20		585	20
Reactor power MW		0	5	0

TABLE 10 : Evolution of insulation resistance of a collectron under working conditions.

8. CONCLUSIONS

Collectrons are very simple devices which are distinguished by their small size, low burn-up and simple construction.

The self generated signal, directly proportional to the neutron flux, can be measured as easily as those of a thermocouple.

Systematic irradiation tests have shown that :

a - There is a very good agreement between experimental calibration and theoretical assumptions. This point is specially important because of the impossibility to calibrate each detector before application.

b - The sensitivity of the collectrons is sufficiently high to use detectors of reduced dimensions (say 25 mm long for an overall diameter of 1.5 mm) well adapted for spot-checking of neutron flux.

c - The factor of quality of a collectron can be assimilated to the value of its insulation resistance which must be carefully controlled.

d - When it is not possible - for reasons of burn-up or (and) dimensions - to use detectors with high sensitivity it is recommended to employ a compensating wiring with two-wires connecting cables; in this case the measuring systems completely isolated from the mains are the best suited. Anyhow the longest emitter consistent with the foreseen application should be used; if necessary the low sensitivity detectors can be made in long lengthes and coiled to provide high sensitivity for a reduced bulkiness.

e - It must be born in mind that the collector of such a device can evidently collect electrons coming from other sources than the central β emitter : for example there should be at least 3 mm of water or equivalent mass between any aluminium and the detector otherwise the 2.87 MeV β from aluminium could generate spurious currents in the detector or connecting cable.

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ANNEX 1

DETAILS OF MEASUREMENTS PERFORMED

Collectron	Flux monitor	1^{st} cycle		2^{nd} cycle		3^{rd} cycle	
		I 10^{-7} A	$n\,v_o$ $10^{13} n.cm^{-2}.s^{-1}$	I	$n\,v_o$	I	$n\,v_o$
Ag2 B (n.c)	M_2	—	6.978	0.92	6.52 *	0.340	2.89
Ag2 B (c)		1.165		1.057		0.366	
Ag3 B (n.c)	M_3	1.06	6.953	0.977	6.52 *	0.364	3.10

* – supposed value. The value of monitor M_1 has been considered

n.c. – non compensating wiring

c – compensating wiring.

CALIBRATION VALUE (10^{-21} . A. n^{-1})

(emitter 0.5 mm diameter and 10 mm long)

Collectron	Central channel		Peripheral channel
	1^{st} cycle	2^{nd} cycle	3^{rd} cycle
Ag2B(n.c)		0.56	0.47
(c)	0.67	0.65	0.51
Ag3B(n.c)	0.60	0.60	0.47
Mean n.c	0.59		0.47
Mean c	0.66		0.51

Collectron l = 25 mm d = 0.5mm	Flux monitor	1st cycle		2nd cycle		3rd cycle	
		I 10^{-7} A	$n\,v_o$ 10^{13} n.cm^{-2}.s^{-1}	I	$n\,v_o$	I	$n\,v_o$
Rh 1 A(n.c)	M_1	1.998	6.965	1.980	6.52	0.763	2.78
Rh 1 B(n.c)	M_1	2.230	6.965	2.134	6.52	0.766	2.78
Rh 2 A(n.c)	M_2	2.182	6.978	2.066	6.52*	0.814	2.89

* supposed value - direct measurement not performed.

CALIBRATION VALUE (10^{-21} A . n^{-1})
(emitter 0.5 mm diameter and 10 mm long)

Collectron	Central channel		Peripheral channel
	1st cycle	2nd cycle	3rd cycle
Rh 1 A	1.15	1.21	1.10
Rh 1 B	1.28	1.31	1.10
Rh 2 A	1.25	1.27	1.13
Mean	1.25		1.11

Rh - RIG 1

Ag - RIG 3

A1 - 3

5 collectrons with Ag emitter 0.5 mm diameter and 50 mm long have been irradiated in peripheral channel Nr.7

Duration : 52.3 days

Integrated power : 6.279 MWh

Mean flux : $2.725.10^{13}.n.cm^{-2}.s^{-1}$.

		Reference number				
		5	7	4	1	3
I 10^{-7} A	c	0.698	0.701	0.694	0.700	0.720
	n.c	0.637	0.612	0.620	0.605	0.619
Calibration value 10^{-22} A.n^{-1}	c	0.51	0.51	0.51	0.51	0.53
	n.c	0.47	0.45	0.45	0.44	0.45

Values of I are mean values of 10 measurements; calibration values are referred to an emitter 0.5 mm diameter and 10 mm long.

Ag, Rh, V - RIG 4

6 collectrons Ag, Rh, V 0.5 mm diameter and 100 mm long have been irradiated in peripheral channel Nr. 7 during 74.5 days.

Collectron	Flux monitor	Flux n v_o $10^{13} n.cm^{-2}.s^{-1}$	I $10^{-7}. A. n^{-1}$ (0.5 mm, l=10mm)	Calibration value $A . n^{-1}$
1 Ae	1 Me	2.18	0.11	0.50
23 Ae	2 Me 3 Me	1.87 1.94 (1.90)	0.087	0.46
3 Re	3 Me	1.94	0.204	1.05
12 Re	1 Me 2 Me	2.18 1.87 (2.02)	0.242	1.19
2 Ve	2 Me	1.87	0.011	0.050
13 Ve	1 Me 3 Me	2.18 1.94 (2.06)	0.0093	0.045

Values of I are mean values of 20 measurements; calibration values are referred to an emitter of 0.5 mm diameter and 10 mm long.

ANNEX 2

ANALYSIS OF THE EQUIVALENT ELECTRICAL CIRCUIT OF A COLLECTRON

A. PHILIPPE

I. THE COLLECTRON AND ITS MEASURING CIRCUIT

Normally sheath and connecting wires contain always traces of β emitters (Manganese impurity is the most serious contribution) and under irradiation each constitutive element of an collectron will be the origin of a current (Fig. 1) :

To (a) will be associated the emission current Is

To (b) and (d), i_b and i_d

To (c), 2 i_c.

The capture probability by (d) of electrons coming from (a) and (b), and by (a) and (b) of electrons coming from (d) has not been considered.

When the load resistances are plugged-in the following currents will be established.

$|I|$ between (a) and (c)

$|i|$ between (d) and (c) and between (b) and (c)

If we can say that $|I|$ is directed from (a) to (c), it is impossible to assume "a priori" what would be the direction of $|i|$. A confrontation between experimental measurements and theoretical computation can only allow to distinguish between the two possibilities :

- Case a : i directed from (b) and (d) to (c)

- Case b : i directed from (c) to (b) and (d).

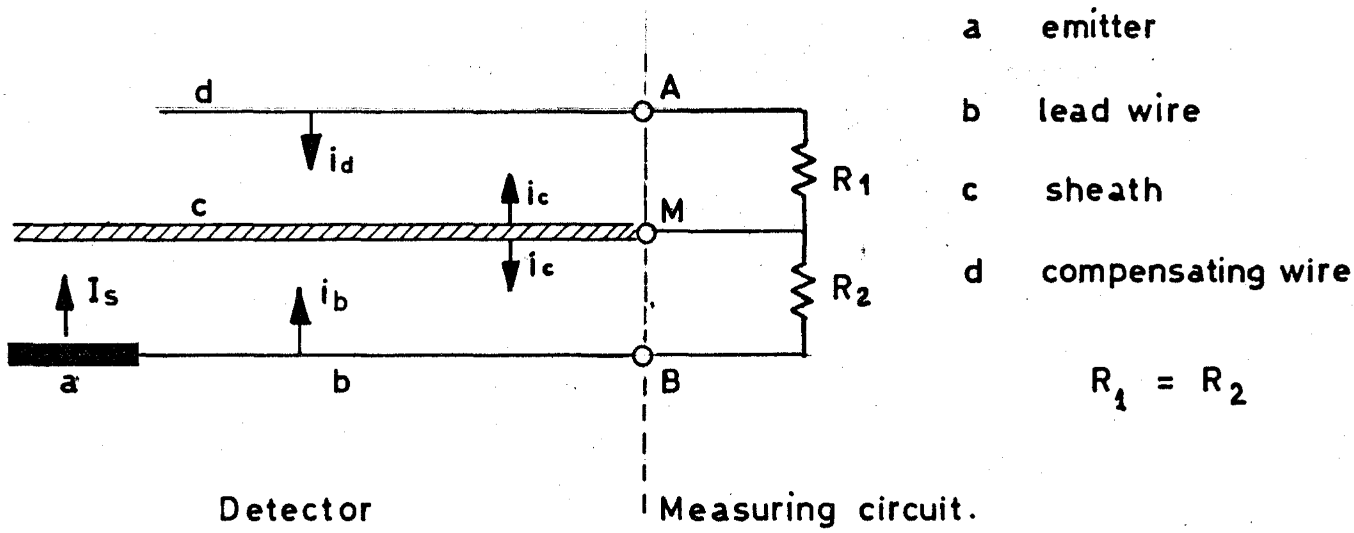
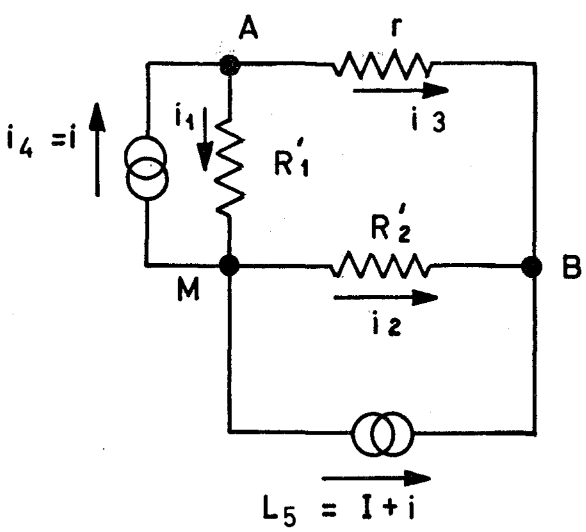
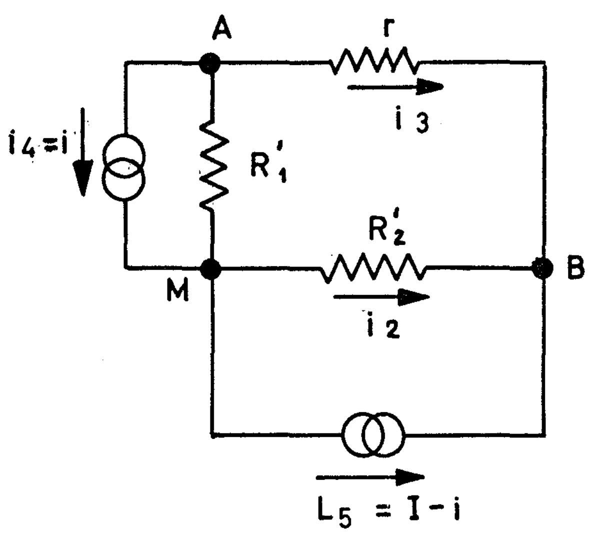


Fig.1 ELECTRICAL EQUIVALENT CIRCUIT OF A COLLECTRON WITH COMPENSATING WIRING





$$R_1' = \frac{r \cdot R_1}{r + R_1}$$

$$R_2' = \frac{r \cdot R_2}{r + R_2}$$

Fig. 2a **Fig. 2b**

II. EQUIVALENT ELECTRICAL CIRCUIT AND COMPUTATION OF THE TENSIONS AT THE TERMINALS OF R_1 AND R_2

II.1. Equivalent circuit

With r being value of the leakage resistance between :

- (c) and (d)
- (c) and (b) or (c) and (a)
- (d) and (b).

the electrical circuits corresponding to the cases a and b are represented on Fig. 2.

II.2. Computation of V_{AM}, V_{MB}, V_{AB}

II.2.1. Case a (Fig. 2a)

$$
\begin{bmatrix}
\left(\dfrac{1}{R'_1} + \dfrac{1}{r}\right) & -\dfrac{1}{r} \\[2em]
-\dfrac{1}{r} & \left(\dfrac{1}{R'_2} + \dfrac{1}{r}\right)
\end{bmatrix}
\begin{bmatrix}
- V_1 \\[2em]
+ V_2
\end{bmatrix}
+
\begin{bmatrix}
+ i_4 \\[2em]
+ i_5
\end{bmatrix}
= 0
$$

or :

$$
\left\{
\begin{aligned}
& - \left(\frac{1}{R'_1} + \frac{1}{r}\right) V_1 - \frac{1}{r} V_2 + i_4 = 0 \\
& + \frac{1}{r} V_1 + \left(\frac{1}{R'_2} + \frac{1}{r}\right) V_2 + i_5 = 0
\end{aligned}
\right.
\qquad (II.2.1)
$$

with :

$$V_1 = V_{AM} \quad ; \quad i_4 = i$$

$$V_2 = V_{BM} \quad ; \quad i_5 = I + i$$

$$V_3 = V_{AB} \quad ;$$

It comes from (II.2.1.)

$$V_1 = V_{AM} = \frac{i\left(\frac{1}{R'_2} + \frac{2}{r}\right) + I\left(\frac{1}{r}\right)}{\left(\frac{1}{R'_1} + \frac{1}{r}\right)\left(\frac{1}{R'_2} + \frac{1}{r}\right) - \left(\frac{1}{r}\right)^2} \qquad \text{(II.2.2.)}$$

$$V_2 = V_{BM} = \frac{-i\left(\frac{1}{R'_1} + \frac{2}{r}\right) - I\left(\frac{1}{R'_1} + \frac{1}{r}\right)}{\left(\frac{1}{R'_1} + \frac{1}{r}\right)\left(\frac{1}{R'_2} + \frac{1}{r}\right) - \left(\frac{1}{r}\right)^2} \qquad \text{(II.2.3.)}$$

$$V_3 = V_{AB} = V_1 + V_2 \qquad \text{(II.2.4.)}$$

II.2.1.1. $R'_1 = R'_2 = R'$ (case A see Fig. 3)

But as $r \gg R_1$ and R_2 it comes $R'_1 \neq R'_2 \neq R' \neq R_2 \neq R_1 \neq R$ and, after simplification, it can be derived from (II.2.2.), (II.2.3.) and (II.2.4.) :

$$V_1 = V_{AM} = Ri \qquad \text{(II.2.5.)}$$

$$V_2 = V_{BM} = -R(I + i) \qquad \text{(II.2.6.)}$$

$$V_3 = V_{AB} = -RI \qquad \text{(II.2.7.)}$$

II.2.1.2. $R_1 = \infty$ (case B, Fig. 3)

R'_1 can be assimilated to r and if $r \gg R_2$ it comes $R'_2 = R_2 = R$. In these conditions (II.2.3.) becomes :

$$V_2 = V_{BM} = -\frac{R}{2}(3i + 2I) \qquad \text{(II.2.8.)}$$

II.2.1.3. (case C, Fig. 3)

R'_2 can be assimilated to r and if $r \gg R_1$ it comes $R'_1 = R_1 = R$. In these conditions (II.2.2.) becomes :

$$V_1 = V_{AM} = +\frac{R}{2}(3i + I) \qquad \text{(II.2.9.)}$$

II.2.2. Case b (Fig. 2b)

$$\begin{bmatrix} \left(\dfrac{1}{R'_1} + \dfrac{1}{r}\right) & +\dfrac{1}{r} \\ +\dfrac{1}{r} & \left(\dfrac{1}{R'_2} + \dfrac{1}{r}\right) \end{bmatrix} \begin{bmatrix} +V_1 \\ +V_2 \end{bmatrix} + \begin{bmatrix} +i_4 \\ +i_5 \end{bmatrix} = 0$$

or :

$$\begin{cases} \left(\dfrac{1}{R'_1} + \dfrac{1}{r}\right) V_1 + \left(\dfrac{1}{r}\right) V_2 + i_4 = 0 \\ \left(\dfrac{1}{r}\right) V_1 + \left(\dfrac{1}{R'_2} + \dfrac{1}{r}\right) V_2 + i_5 = 0 \end{cases} \qquad (II.2.10)$$

with

$$V_1 = V_{AM} \;;\quad i_4 = i$$

$$V_2 = V_{BM} \;;\quad i_5 = I - i$$

$$V_3 = V_{AB} \;;$$

It comes from (II.2.10).

$$V_1 = V_{AM} = \frac{-\, i \left(\frac{2}{r} + \frac{1}{R'_2} \right) + \left(\frac{1}{r} \right) I}{\left(\frac{1}{R'_1} + \frac{1}{r} \right) \left(\frac{1}{R'_2} + \frac{1}{r} \right) - \left(\frac{1}{r} \right)^2} \qquad \text{(II.2.11)}$$

$$V_2 = V_{BM} = \frac{+\, i \left(\frac{2}{r} + \frac{1}{R'_1} \right) - \left(\frac{1}{r} + \frac{1}{R'_1} \right) I}{\left(\frac{1}{R'_1} + \frac{1}{r} \right) \left(\frac{1}{R'_2} + \frac{1}{r} \right) - \left(\frac{1}{r} \right)^2} \qquad \text{(II.2.12)}$$

$$V_3 = V_1 + V_2 \qquad \text{(II.2.13)}$$

II.2.2.1 $\quad R'_1 = R'_2 = R'$

But as $r \gg R_1$ and R_2 it comes $R'_1 \# R'_2 \# R' \# R_2 \# R_1 \# R$

(II.2.11), (II.2.12), and (II.2.13) become :

$$V_1 = V_{AM} = - R_i \qquad \text{(II.2.14)}$$

$$V_2 = V_{BM} = - R\,(I - i) \qquad \text{(II.2.15)}$$

$$V_3 = V_{AB} = - R\,I \qquad \text{(II.2.16)}$$

II.2.2.2. $R_1 = \infty$

with the same assumptions as in II.2.1.2. it comes :

$$V_2 = V_{BM} = -\frac{R}{2}\,(2\,I - 3i) \qquad \text{(II.2.17)}$$

II.2.2.3. $R_2 = \infty$

with the same assumptions as in II.2.1.3. it comes :

$$V_1 = V_{AM} = +\frac{R}{2}\,(I - 3i) \qquad \text{(II.2.18)}$$

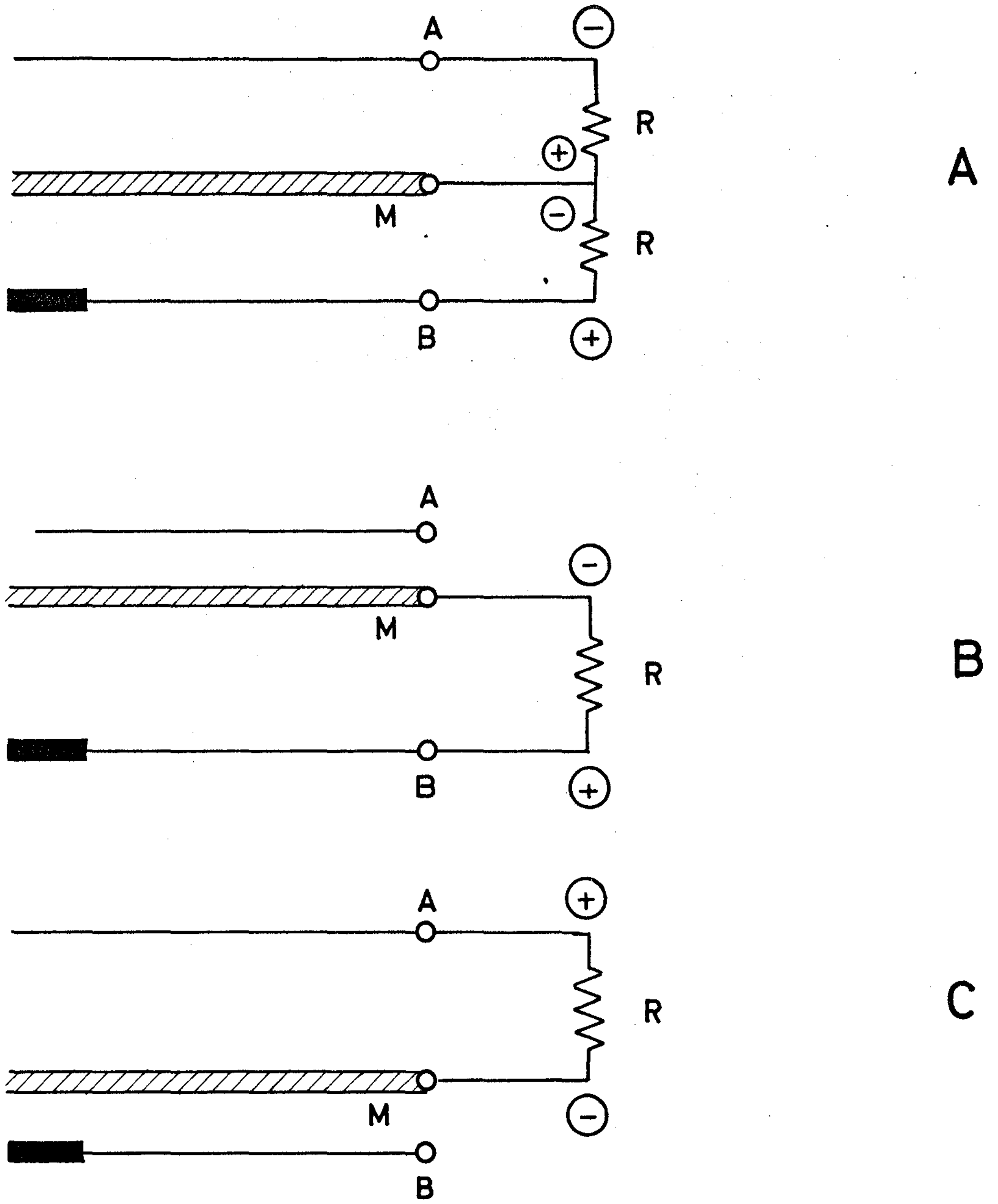


Fig.3-EXPERIMENTAL CHECKING OF COLLECTRONS VARIOUS CIRCUIT DIAGRAMS EXAMINED.

III. Choice and verification of the electrical circuit diagram

According to measurements on a collectron loaded by $R_1 = R_2 = 10\ K\Omega$, tensions V_{AM} and V_{MB} have the same direction along A M B (+ in B).

The only acceptable scheme is then the one of Fig. 2b.

Experimental checking

Case A (see Fig. 3 A)

$V_{AM} = - Ri$	measured value	- 0.122 mV
$V_{BM} = - R\ (I - i)$	" "	- 1.050 mV
$V_{AB} = - R\ I$	" "	- 1.172 mV

Case B (see Fig. 3 B)

$$V_{BM} = - \frac{R}{2}\ (2\ I - 3i) \qquad \text{measured value - 0.96 mV.}$$

Using the preceding values of Ri and RI it comes :

$$V_{BM} = - R\ I + \frac{3}{2}\ Ri = - 1.172 + \frac{3}{2}\ (0.122) = - 0.989\ \text{mV}$$

which verifies at $\simeq$ 2% the measured value of 0.96 mV.

Case C (see Fig. 3C)

$$V_{AM} = + \frac{R}{2} (I - 3i)$$ measured value + 0.44 mV

and, considering the measured values of case A it comes :

$$V_{AM} = \frac{1}{2} R I - \frac{3}{2} Ri = + \frac{1.172}{2} - \frac{3}{2} (0.122) = + 0.403 \text{ mV}$$

which verifies at ≃ 9% the measured value of + 0.44 mV.

Remarks

1. $$\frac{V_{AM}}{V_{AB}} = \frac{i}{I} = \frac{0.122}{0.172} = 0.104$$

$$i \# 10\% \, I$$

2. Between $V_{AB} = - R I$ (case A) and :

$V_{BM} = - \frac{R}{2} (2I - 3i)$ (case B) there is a difference of $\frac{3}{2} R_i$;

consequently the error made on the measurement of flux without compensation is :

$$\frac{3}{2} \left(0 . 104 \, I \right) = 15\% \, I.$$

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Alfred Nobel

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