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THE EXPERIMENTAL RESULTS FROM CRISTO

QUALIFICATION OF THE PREDICTED CRITICALITY OF FUEL STORAGES

C. GOLINELLI(1) - A. DARRAUD(2) - P. MARSAULT(2)

(1) DEPARTEMENT DES REACTEURS A EAU
CEN-CADARACHE

(2) FRAMATOME

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I - INTRODUCTION -

The CRISTO (CRIticité des STOckages) experiment, a joint programme between FRAMATOME and C.E.A. (Commissariat à l'Energie Atomique) was conducted during the first half of 1978 in the critical facility EOLE.

The high level of the French nuclear plant construction leads to an important need for fuel storage facilities for fresh and burnt fuel elements. The electricity utilities want to use the maximal available storage volume. The effective multiplication factor is calculated with computer codes, validated for the reactor type lattices. The purpose of CRISTO is to extend the qualification of these tools to overmoderated and poisonned lattices and special cases (low density voided moderation) required by the Safety Commissions.

In the first stage, we performed experiments on more common reactor lattices :

- fuel pins with a regular square pitch (homogeneous lattice)
- water spaced fuel elements (heterogeneous lattice).

In the second stage, we worked on the new subjects :

- fuel element surrounded by stainless steel plates
- square lattices moderated by an hydrogeneous material.

The first run enabled us to define the future experiments : fuel elements surrounded by strong absorbing plates, and flooded in various hydrogen density solid material. Those experiments are planned for the beginning of 1980.

2 - CRISTO EXPERIMENT PRINCIPLE -

The C.E.A. Light Water Reactor Department (DRE) owns the critical facility EOLE located at the Cadarache Center.

Different types of experiments for liquid moderated lattices are performed in this reactor.

This experiment is based on the study of a test zone surrounded by a driver zone with a variable number of fuel plates which enables us to obtain an overall critical core.

The multiplication factor of the zone may be lower or greater than 1.

It is a technique complementary to the subcritical ones : pulsed neutron, source multiplication ...

With CRISTO we can use the common means to obtain different neutronics parameters :

- reaction rates with foils, Mn, U238 capture and U235 fission) and with fission chambers (U235 - U238 - Pu239)
- reactivity variations corresponding to different driver zone loadings.

We can compare the experimental and calculated results in order to study the influence of :

- theoretical calculation methods (transport, diffusion)
- space, energy and azimuthal discretization
- data library evaluations.

Moreover by introducing the neutronic concept of equivalence between two multiplying media, it is possible to obtain the infinite multiplicative factor for any arrangement or fuel elements experimentally.

The substitution of one part of a medium by another does not modify the neutron balance, providing the different terms of balance are the same.

The PWR fuel element lattices (heteregeneous lattices) are compared to regular fuel pin lattices using the same fuel pins in both cases (homogeneous lattices).

To obtain the same neutron balance the water of the regular lattice is boricated to compensate the reduction in water capture due to the spectrum change.

The k∞ factor can be written the terms of the neutron balance.

$$k_\infty = \frac{\text{production}}{\text{absorption}} = \frac{N_5 \nu_5 \sigma_{f5} + N_8 \nu_8 \sigma_{f8}}{N_5 \sigma_{F5} + N_5 \sigma_{C5} + N_8 \sigma_{f8} + N_8 \sigma_{C8} + N_{H_2 0} \sigma_{H_2 0} + N_B \sigma_B + \Sigma \text{ structure}}$$

The following quantities are defined as :

$$I_{\frac{8}{5}} = \frac{N_8}{N_5} \cdot \frac{\sigma_{f8}}{\sigma_{f5}} \qquad \text{(measurable)}$$

$$\alpha_5 = \frac{\sigma_{C5}}{\sigma_{f5}} \qquad \text{(known with a good approximation)}$$

$$\gamma_8 = \frac{N_8}{N_5} \frac{\sigma_{C8}}{\sigma_{f5}} \qquad \text{(measurable)}$$

$$\delta_{H_2 0} = \frac{N_{H_2 0}}{N_5} \frac{\sigma_{H_2 0}}{\sigma_{f5}} + \frac{N_B}{N_5} \frac{\sigma_B}{\sigma_{f5}}$$

.../...

$$\Sigma = \frac{\Sigma \text{ structure}}{N_5 \sigma_{f5}}$$

k_∞ becomes :

$$k_\infty = \frac{\nu_5 (1 + \nu_8/\nu_5 \cdot I_{8/5})}{1 + \alpha_5 + \gamma_8 + I_{8/5} + \delta_{H_2O} + \Sigma}$$

The different parameter ranges which vary only very shightly.

$\nu_5 = 2{,}42$ $\nu_8 = 2{,}83$ $\alpha_5 = 0.18$

$I_{8/5} = 0.02$ $\Sigma = 0.01$

Only γ_8 and δ_{H_2O} are variable with the configuration.

If both k_∞ are the same, the neutron balance is obtained providing $\gamma_8 + \delta_{H_2O}$ is constant.

We can thus determinate a homogeneous configuration which equivalent to a heterogeneous configuration by varing the pitch and the concentration of boric acid.

The k_∞ of this regular lattice (close to 1) is deduced from the buckling measurements obtained by reaction rate mapping and from the calculated worth of the migration area.

The test zone and the driver zone spectrum are not rigourously matched ; this effect must be calculated correct its influence on the reactivity worth and on the power distribution for every configuration.

3 - DESCRIPTION OF THE EXPERIMENT -

3-1 : Brief description of the EOLE reactor

EOLE is a zero power reactor located at the Cadarache Center. It was built in 1965 to study the liquid moderated reactor. In recent years, only light water is used.

The more various critical assemblies can be studied. The fuel is put on a table and the criticality is obtained by rising the light water level.

For the CRISTO experiments, an assembly was designed with two zones using two independant water circuits.

The fuel always was completely submerged. The upper reflector is 25 cm thick.

3-2 : Experimental zone with PWR fuel elements

Except for the height (500 mm), the 3% enriched fuel pins were the same as those of the standard PWR 17x17 fuel elements used in French plants (see table 1).

Fuel arrays 14x14 locations with the same pitch (1.26 cm) as in the 17x17 fuel assemblies were used in the heteregeneous cases and with 16 guide tubes (or water holes).

The size of the interassembly gap may very from 0 to 20 mm. Two gaps were studied during the CRISTO 1 campaign : 8.078 cm and 10.26 cm.

The choice of the two gaps was determinated by the theoretical k_{∞}. The small gave a value greater than 1 and the largest gave a value less than 1.

The central element is comparable with an element of the storage in infinite medium. The three other elements were "exploded", and were therefore used as a buffer for the central one. In practice 16 modules were constructed corresponding to a quarter of fuel element (Figure 1).

Stainless steel plates 2 mm or 4 mm thick may be used absorbers between the fuel elements. The plates were just against the edge cells.

This experimental zone was closed in an aluminium vessel (2 mm thick) which separated the experimental zone from the driver core.

With the 8.078 cm gap, it was necessary to complete the vessel with four aluminium plates (3 mm thick).

The experimental equipment was completed by pieces to receive the foils (Mn fixed on millar sheet).

3-3 : Experimental zone with regular lattice

Two kinds of experiments are conducted. The first was to obtain the equivalent homogeneous medium to the heterogeneous assemblies studied.

Two blaks were constructed : - 28 x 28 fuel rods
- 30 x 30 fuel rods

4 tie-rods were used to obtain a solid bundle.

The same fuel rods were used, the regular pitch was 1.86 cm.

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k_∞ is a function of the boric acid concentration. This concentration was adjusted to obtain the same critical size as the heteregeneous core. For every heterogeneous case we obtained the equivalent homogeneous one. The material buckling as a function of the boron concentration was directly obtained by fitting on the power distribution.

The second kind of experiments corresponded to the k_∞ evaluation of the low moderated pool storage.

3-4 : Experimental zone with regular lattice and polythene

A low density hydrogeneous moderator was obtained by building a block with polythene layers (10 mm thick), 28x28 holes were punched with a 18.6 mm regular square pitch. The fuel pins were housed in these holes. It was possible to obtain different densities of this hydrogeneous moderator in order to simulate a variation in the amount of water. The goal was to simulate the range of optimum moderating conditions, i.e : equivalent to a water density of about 0.1 to 0.2

3-5 : Driver zone

The driver zone was constituted with swimming pool reactor type fuel elements containing 21 plates of uranium-aluminium alloy (93 % enriched Uranium) interchangeable with aluminium plates, reflected by graphite blocks.

The 4 positionning grids were removable and could slide to define an experimental zone with a variable size.

4 - EXPERIMENTAL PROGRAMME -

4-1 : Homogeneous experimental zone (28x28 and 30x30 fuel rods)

The radial buckling were obtained by fitting an hyperbolic cosine function on the experimental radial reaction rate measurements.

This distribution was obtained by counting of the γ activities of UO2 foils. The sample was located between two pellets in the fuel pin. The disturbance was minimized because the foil was of the same nature as the fuel (figure 2).

The discrepancy obtained by this technique was less than 10^{-4} cm^2. This value corresponds to 0.3 % over the k_∞.

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The axial reactor rate distribution was obtained by using various fission chambers (U5, Pu9, U8). The chambers were removed axially and the axial buckling was given with excellent precision and the discrepancy was negligeable when compared to the radial value.

A map of the U8 capture was established for one case.

The boron concentration was known by chemical method.

The uncertainty was 3.10^{-6} $g.cm^3$.

The total buckling was : $B^2m = B^2ax + 2B^2$ rad.

Table 1 shows an exemple of fitting and the obtention of the uncorrected radial buckling. B^2_{rad} uncorrected = $1.32\ 10^{-3}$

However, it was necessary to introduce the correction of the inseparibility of the flux.

It was shown that the flux was not isotropic because the boundary conditions of the central zone didn't respect the separibility conditions.

The spatial distribution was disturbed and it was possible to veriry that the buckling was not the same on the perpendicular axis and on the diagonal straight.

This effect can be raised either by an experimental method (a complete power distribution for every fuel rods), or a calculationnal method. In CABRI I only the latter was possible.

The calculationnal schema is :

- a cell calculation. APOLLO code (B^2_m, k_∞).
- a diffusion calculation in infinite medium ($k_\infty = \nu\Sigma_f/\Sigma a$)
- a diffusion calculation with the real critical configuration (experimental zone + driver core + reflector)
- comparaison between $k_\infty = \frac{\nu\Sigma_f}{\Sigma_a}$ on the finite medium and $k_\infty = 1 + B^2M^2$

  B^2 obtained by fitting on the power distribution on this example, we obtained :

$$k_\infty \text{cell} = 1.00280 \qquad B^2_m\ \text{cell} = 8.9\ 10^{-5}\ cm^{-2}$$

$$k_\infty \text{diff neutron balance} = 1.00673$$

$$k_\infty \text{diff adjust XY axis} = 0.99798 \text{ with } M^2 = 31.31\ cm^2.$$

The adjusted k_∞ was substimated by 0.875 %.

The correction of the material buckling was + $2.8\ 10^{-4}\ cm^{-2}$.

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Hence, the corrected radial buckling was :

$$B^2_{rad\ corrected} = -\ 2.64\ 10^{-3} + 0.28\ 10^{-3} = -\ 2.36\ 10^{-4}\ cm$$

the uncertainty was 10^{-4} cm^{-2} over the measured buckling and 20 % over the correction :

$$\Delta B^2_{rad} = 1.1\ 10^{-4}\ cm^{-2}$$

Table 2 shows the corresponding axial Pu239 fission rate distribution. The final result for the axial buckling was :

$$B^2_z = 2.52.\ 10^{-3} \pm 0.0310\ cm^{-2}$$

The corrected material buckling was :

$$B^2_m = -\ 2.96\ 10^{-3} + 2.52\ 10^{-3} = +\ 1.6\ 10^{-4}\ cm^{-2}$$

$$\Delta B^2_m = 1.1\ 10^{-4}\ cm^{-2}$$

$$B^2_m = (+\ 1.6 \pm 1.1) 10^{-4}\ cm^{-2}$$

This term was converted in to k_∞ with introduction of the migration area ($31.31\ cm^2$).

$$k_\infty = 1 + M^2 B^2_m = 1.00500 \pm 0.00350$$

5 boricated configurations were studied : 639, 748, 758, 770, $847.10^{-6} g.cm^{-3}$ with $770.10^{-6} g.cm^{-3}$, the capture U8/fission U5 ratio and the I5/8 index were measured.

<u>Material buckling as a function of the boron concentration</u>

Boron concentration $10^{-6} g.cm^{-3}$	639	748	758	770	847
B^2_m uncorrected cm^{-2}	$1.11\ 10^{-3}$	$-1.2\ 10^{-4}$	$-2.9\ 10^{-4}$	$-3.7\ 10^{-4}$	$-1.14\ 10^{-3}$
B^2_m corrected cm^{-2}		$+1.6\ 10^{-4}$			
k_∞ uncorrected		0.9962			
k_∞ corrected		1.0050			
σ_{f5}/σ_{f8}				1120	
σ_{e8}/σ_{f5}				0.0997	

4-3 : Heterogeneous Cases

With the heterogeneous cases , the water was always unpoisoned. For each configuration the critical parameter was the number of the UAl plates.

The experimental data were completed with :
- axial fission rate distribution (U5 or Pu9, U8)
- radial distribution in the midplane of γ activities of the UO2 foils and of a complete traverse of Mn activation (figure 5)
- a map of the U8 capture.

Interassembly gap (mm)	80.8	80.8	80.8	102.6
Stainless steel plate thickness (mm)	without	2	4	without
Axial buckling (cm^{-2})	$2.14\ 10^{-3}$	$2.12\ 10^{-3}$	$2.11\ 10^{-3}$	2.10^{-3}
Critical number of plates	529.0	636.3	660.9	669.3

The uncertainty for the critical number of plates is $\pm$ 0.2

4-4 : Experimental zone with polythene moderator

The $(CH^2)^n$ density was chosen as 144 $kg.cm^3$, which gave a moderation ratio slightly greater than the maximum. But the use an even lower density is anticipated for the next programme.

We filled one block of this polythene with pins representing an homogeneous medium. Two heterogeneous configurations were also simulated, by the simple removal of n x n arrays of fuel pins from the center of the cavity.

First, 10x10 fuel pins were removed, then 20x20 fuel pins. The criticality was adjusted by changing the number of fuel plates.

The experimental programme was completed by a map of Mn reaction rate. The foils were located in dummy rods. Special equipment was required to prevent some troubles with the local heterogeneity introduced by the foils.

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Number of fuel rods	Critical number of the UAl plates
0	612
376	671
668	551
756	541

5 - EXPERIMENTAL DATA AND INTERPRETATION -

Taking a migration of 31.31 cm^2, the k_∞ were deduced from the fitted material buckling. These values can be compared with the results of the cell calculations.

Homogeneous experimental zone					
Boron concentration mg/liter	639	748	758	770	847
Uncorrected evaluated k_∞	1.03475	0.9962	0.9909	0.9884	0.9643
Corrected k_∞ (see table 4)		1.0050			

The uncertainty on the measured values was 315 pcm on k_∞ and 3 mg/l on boron concentration which corresponds to 110 pcm. The total quadratic mean on k_∞ is 330 pcm.

In a first approximation, we admit the equivalence principle. If the experiments have the same critical size, the k_∞'s of the experimental zone are egal.

Whilst still waiting for the calculated result of the mismatching effect, we can give the worth of k_∞ without correction for the heterogeneous experimental zone.

Heterogeneous experimental zone				
Interelement space (mm)	80.8	80.8	80.8	102.6
Stainless steel plate thickness (mm)	without	2	4	without
Uncorrected evaluation k_∞ (Hambourg) /1/	1.0390	0.9992	0.9647	0.988

Two main corrections are possible :

- non-separibility effect over B_m^2
- mismatching effect between heterogeneous and homogeneous cases.

On the experiment with 27 mm thick S.S. plates the first correction gave : $k_\infty = 1.0080$ instead of 0.9992

The second effect must be calculated by comparison between two sets of calculations :

1/ The experimental size with a homogeneous configuration (boron configuration : 748 10^{-6} g.cm^{-3}), $k_{eff} = 1.01279$ for $k_\infty = 1{,}00347$

2/ The same critical size with a heterogeneous configuration where k_∞ is under and surestimated for the infinite medium

$$k_\infty = 1.06266 \rightarrow k_{eff} = 1.03328$$

$$k_\infty = 0.91330 \rightarrow k_{eff} = 0.98545$$

Hence, the linear function is deduced :

$$k_{eff} = 0.32023 \times k_\infty + 0.69298$$

With the same k_∞ (=1.00347), a difference Δk_{eff} is observed

$$\Delta k_{eff(HET-HOM)} = 1.01432 - 1.01279 = +153$$

In other words, if we have the same k_{eff} (=1.01279), the difference between the two k_∞'s is :

$$\Delta k_{\infty(HET-HOM)} = 0.99869 - 1.00347 = -478.10^{-5}$$

We deduce the value of k_∞ from the homogeneous medium by applying this last correction.

$$k_{\infty\ corrected} = 1.0080 - 0.00478 = 1.00322$$

The uncertainty is 340.10^{-5} over the matching effect :

$$k_\infty = 1.003 \pm 0.006$$

This interpretation is preliminary because all the calculation are not available present stage is :

- to reduce the difference between the testing k_∞ for the calculation of the matching effect and to obtain a best correction.
- to apply the method to the 3 other cases.

6 - FUTURE PROGRAMME -

An extension of the CRISTO experiment is planned for the beginning of 1980. This next programme is aimed at clarifying certain points, for example, first, the simulation of a variable low density of water between 0 and 1 g/cm^3, secondly, the realisation of a high capacity fuel storage.

This set of measurements will allow us to extend the qualification of codes and methods used in the future project of the storage facilities.

The precision will be bettered : firstly, by increasing the experimental points in the B_m^2 measurement (the expected limit is 4.10^{-5} cm^{-2} equivalent to $130\ 10^{-5}$ over k_∞) ; secondly by improving the calculation of the matching effect (200.10^{-5} over k_∞HET appears a possible goal).

If the both improvements are achieved, the uncertainty over the k_∞ of water pool storage will be 240.10^{-5}.

TABLE 1 - RADIAL POWER DISTRIBUTION (figure 2)

BORON COCENTRATION = $748 \pm 3\ 10^{-6}\ g.cm^{-3}$

E.W. traverse

x (cm)	measured activity M	adjusted activity A	$\frac{M - A}{A}$ %
0.93	1	1.0034	- 0.5
4.65	1.015	1.0064	0.8
8.37	1.021	1.0282	- 0.7
12.09	1.073	1.069	0.3
15.81	1.126	1.130	- 0.3
19.53	1.213	1.211	0.1

Adjusted function

$$y = 1.0023\ ch[3.66\ 10^{-2}\ (x - 2.1)]$$

N.S. traverse

x	measured activity
0.93	1
12.09	1.045
19.53	1.169

$$y = 0.996\ ch[3.61\ 10^{-2}(x - 3.45)]$$

$$B^2_{E.W} = 1.339\ 10^{-3}\ cm^{-2}$$

$$B^2_{NS} = 1.304\ 10^{-3}\ cm^{-2}$$

$$B^2_x = B^2_y = \frac{B^2_{EW} + B^2_{NS}}{2} = 1.32\ 10^{-3}\ cm^{-2}\ (\pm\ 0.02\ 10^{-3})$$

$$B^2_{rad} = B^2_x + B^2_y = 2.64\ 10^{-3}\ cm^{-2}$$

TABLE 2 - AXIAL Pu 239 FISSION RATE DISTRIBUTION

	Height (cm)	Measured activity M	Adjusted Activity A	$\frac{M - A}{A}$	
	+ 19	0.538	0.532	- 1.1 %	
	+ 18	0.574	0.578	- 0.7 %	
	+ 17	0.611	0.619	- 1.2 %	
	16	0.656	0.657	- 0.1 %	
	15	0.692	0.694	- 0.3 %	
	14	0.727	0.729	- 0.3 %	validity limit
	13	0.764	0.762	+ 0.3	
	12	0.795	0.794	+ 0.1 %	
	11	0.819	0.823	- 0.5 %	
	10	0.850	0.851	- 0.1 %	
	9	0.874	0.876	- 0.2 %	
	8	0.895	0.900	- 0.6 %	
	7	0.924	0.920	+ 0.4 %	
	6	0.934	0.439	- 0.5 %	
	5	0.952	0.955	- 0.3 %	
	4	0.972	0.968	+ 0.4 %	
	3	0.974	0.980	- 0.6 %	
	2	0.990	0.989	+ 0.1 %	
	1	0.989	0.995	- 0.6 %	
midplan	0	0.996	0.999	- 0.3 %	
	- 1	1.000	1.000	0	
	- 2	0.997	0.999	- 0.2 %	
	- 3	0.990	0.995	- 0.3 %	
	- 4	0.981	0.989	- 0.8 %	
	- 5	0.989	0.980	+ 0.9 %	
	- 6	0.962	0.968	- 0.6 %	
	- 7	0.952	0.955	- 0.3 %	
	- 8	0.938	0.939	- 0.1 %	
	- 9	0.919	0.920	- 0.1 %	
	- 10	0.898	0.900	- 0.2 %	
	- 11	0.879	0.876	+ 0.3 %	
	- 12	0.849	0.851	- 0.2 %	
	- 13	0.817	0.823	- 0.7 %	
	- 14	0.788	0.794	- 0.8 %	
	- 15	0.765	0.762	+ 0.4 %	
	- 16	0.727	0.729	- 0.3 %	Validity limit
	- 17	0.689	0.694	- 0.7 %	
	- 18	0.652	0.657	- 0.8 %	
	- 19	0.609	0.619	- 1.5 %	

Adjusted function $y = a \cos /\frac{\pi}{H}(x-x_o)/$

$x_o = 1.0$ cm

$H = 62.56$ cm $\sigma = 0.16$ cm

R E F E R E N C E

/_1_/ CRISTO experiments for Fuel Storage Criticality Evaluations

A. DARRAUD - C. GOLINELLI - P. MARSAULT

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EXPERIMENTAL ZONE
HETEROGENEOUS MEDIUM

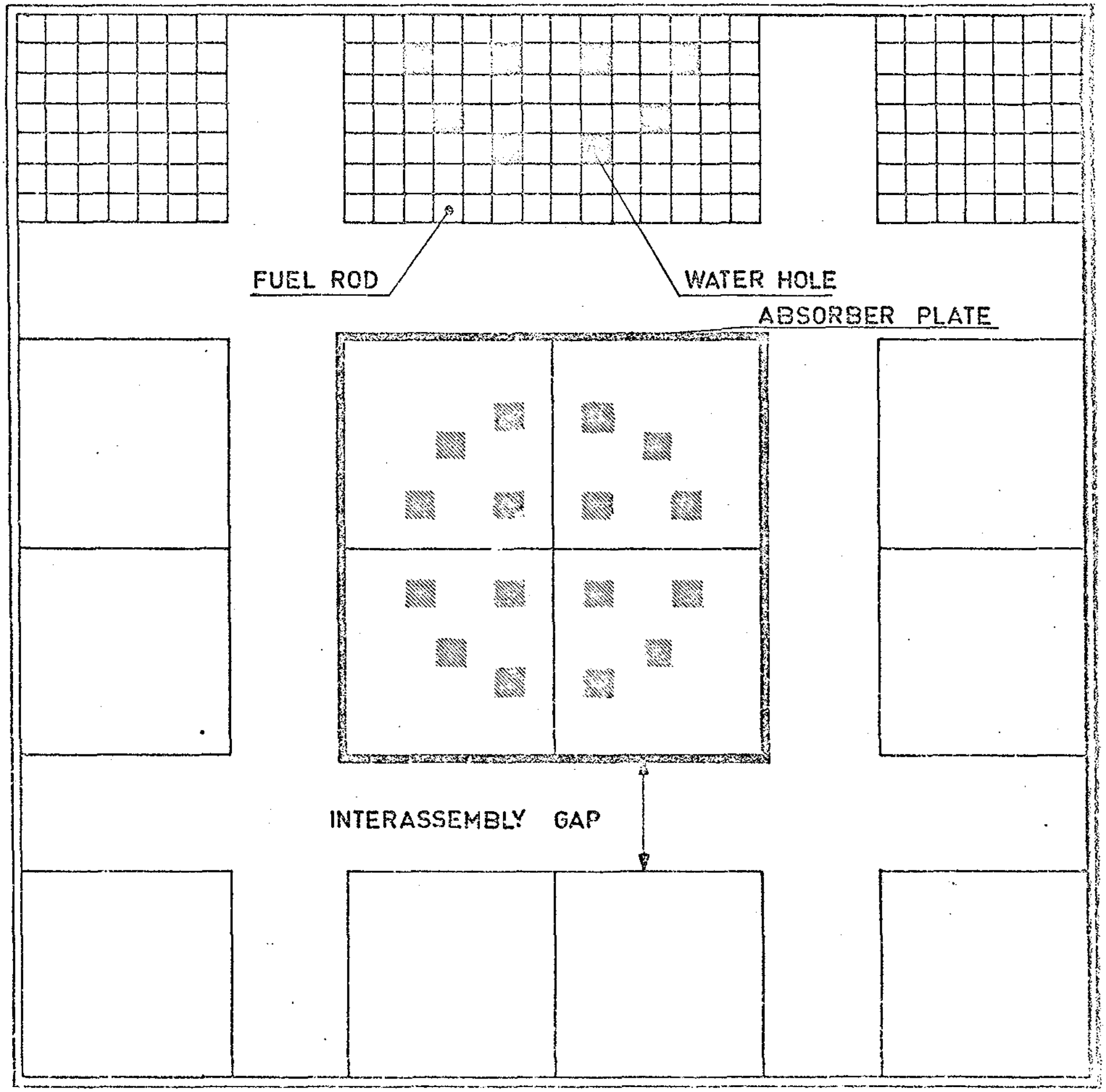

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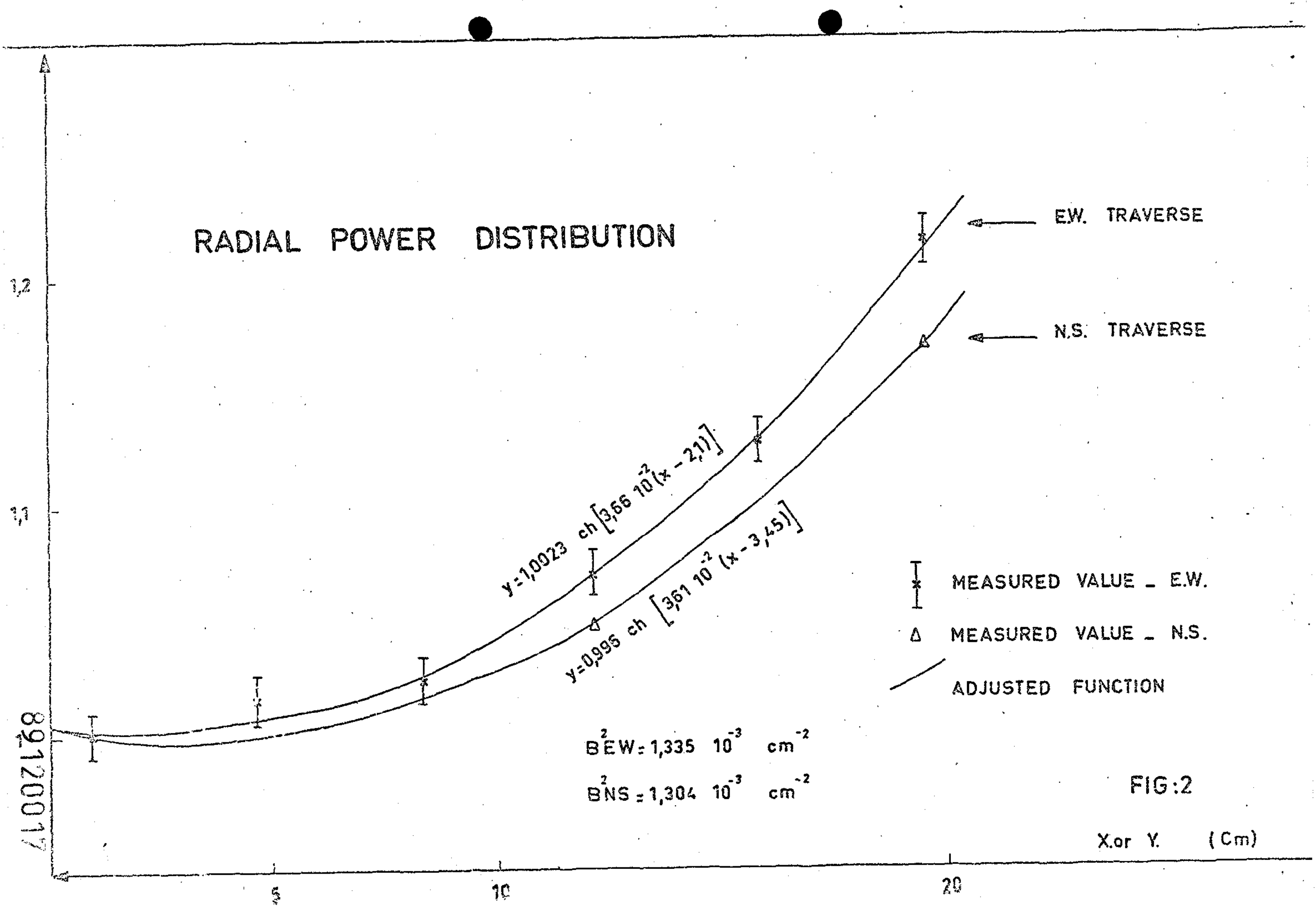
FIG 1



RADIAL POWER DISTRIBUTION
E.W. TRAVERSE
N.S. TRAVERSE
y=1,0023 ch[3,66 10^-2 (x-2,1)]
y=0,996 ch [3,61 10^-2 (x-3,45)]
MEASURED VALUE _ E.W.
MEASURED VALUE _ N.S.
ADJUSTED FUNCTION
B²EW = 1,335 10^-3 cm^-2
B²NS = 1,304 10^-3 cm^-2
X.or Y. (Cm)
1,2
1,1
5
10
20
8912001?

FIG:2

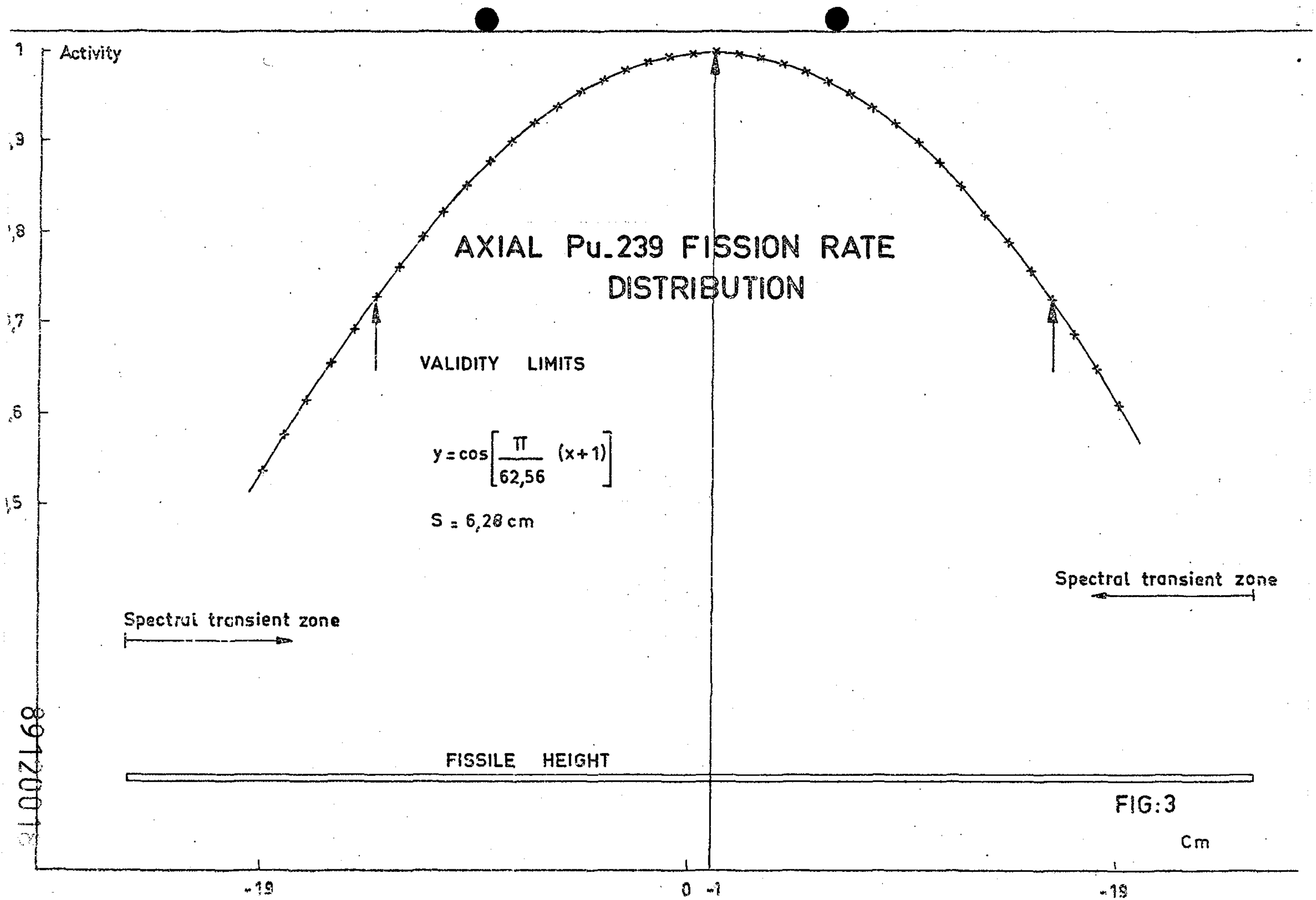
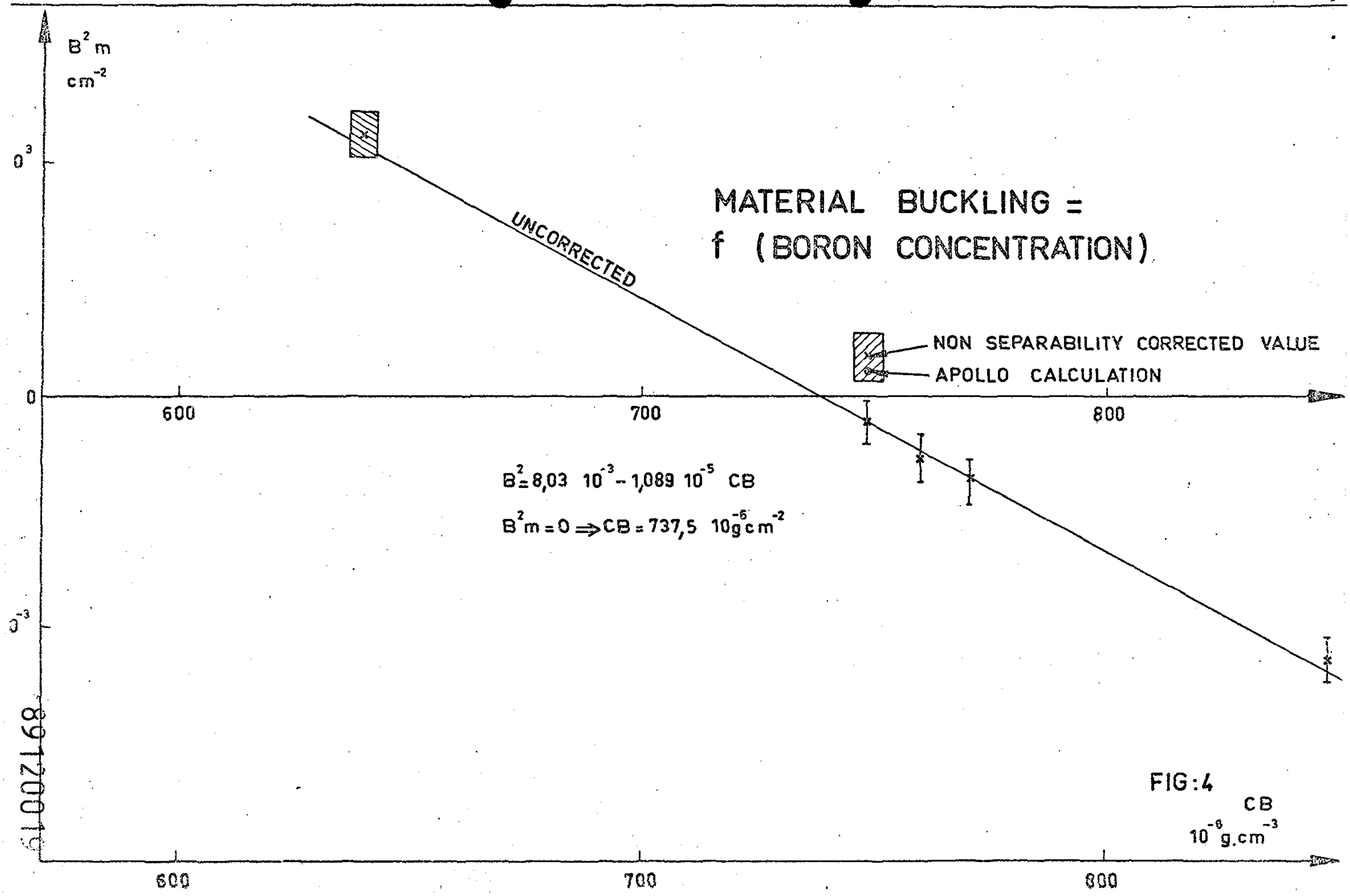
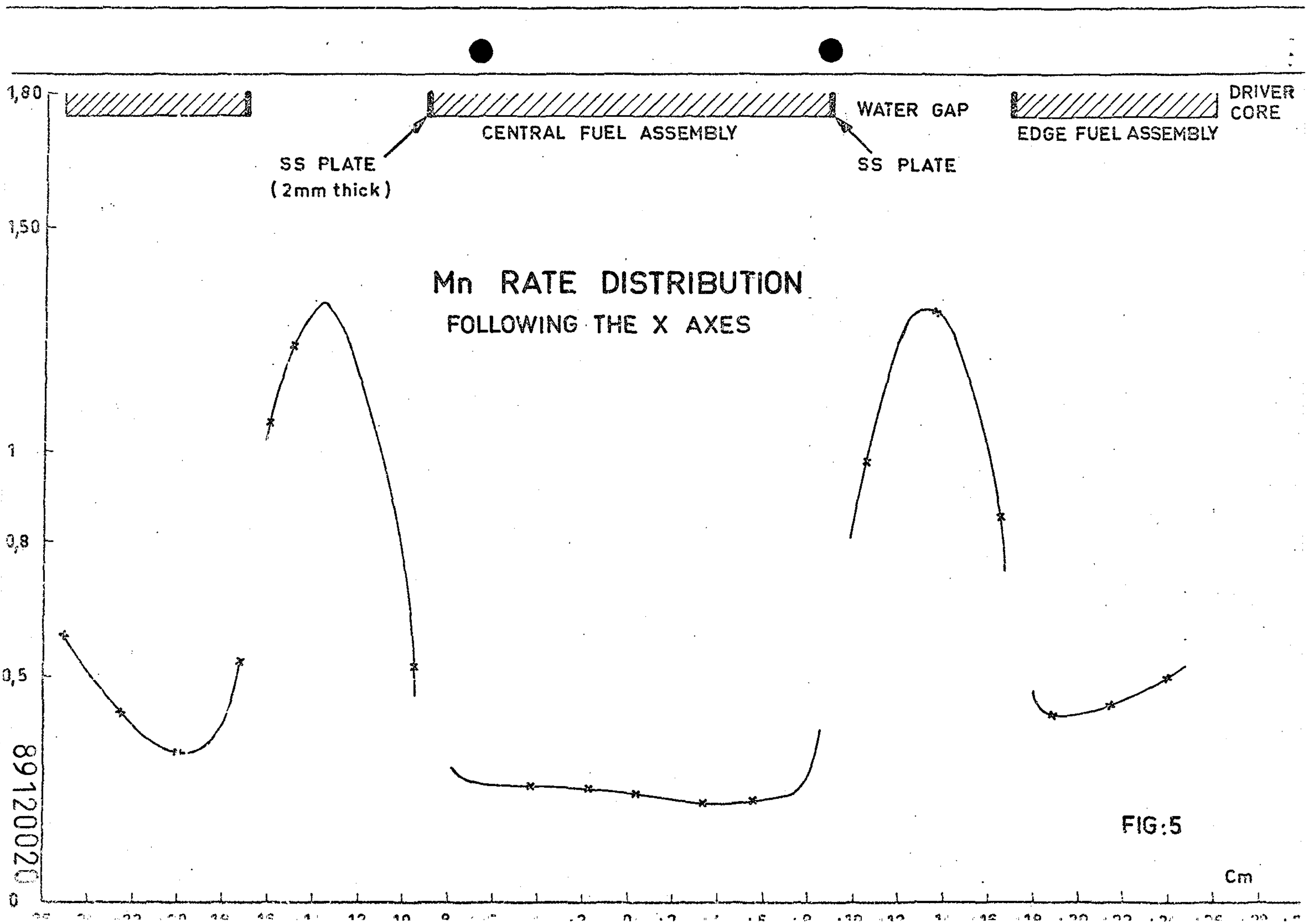

Activity
1
,9
,8
,7
,6
,5
AXIAL Pu-239 FISSION RATE DISTRIBUTION
VALIDITY LIMITS
$y = \cos\left[\frac{\pi}{62{,}56}(x+1)\right]$
S = 6,28 cm
Spectral transient zone
Spectral transient zone
FISSILE HEIGHT
Cm
-19
0
-1
-19

FIG:3



B² m
cm⁻²
0³
0
0⁻³
600
700
800
MATERIAL BUCKLING =
f (BORON CONCENTRATION)
UNCORRECTED
NON SEPARABILITY CORRECTED VALUE
APOLLO CALCULATION
$B^2 = 8,03\ 10^{-3} - 1,089\ 10^{-5}$ CB
$B^2 m = 0 \Rightarrow CB = 737,5\ 10^{-6} g\, cm^{-2}$
CB
10^{-6} g.cm^{-3}
600
700
800

FIG: 4



DRIVER CORE
WATER GAP
CENTRAL FUEL ASSEMBLY
EDGE FUEL ASSEMBLY
SS PLATE
(2mm thick)
SS PLATE
Mn RATE DISTRIBUTION
FOLLOWING THE X AXES
1,80
1,50
1
0,8
0,5
0
Cm

FIG:5

$\frac{\sigma c\,8}{\sigma f\,5}$ DISTRIBUTION

WATER GAP INTERASSEMBLY= 8.08 cm
WITHOUT S.S. PLATE

REFERENCE POINT
HARMONIE THERMAL COLUMN $\left[\frac{\sigma c\,8}{\sigma f\,5}\right]_{Th} = \frac{2{,}736\ b}{572{,}2\ b} = 0{,}00478$

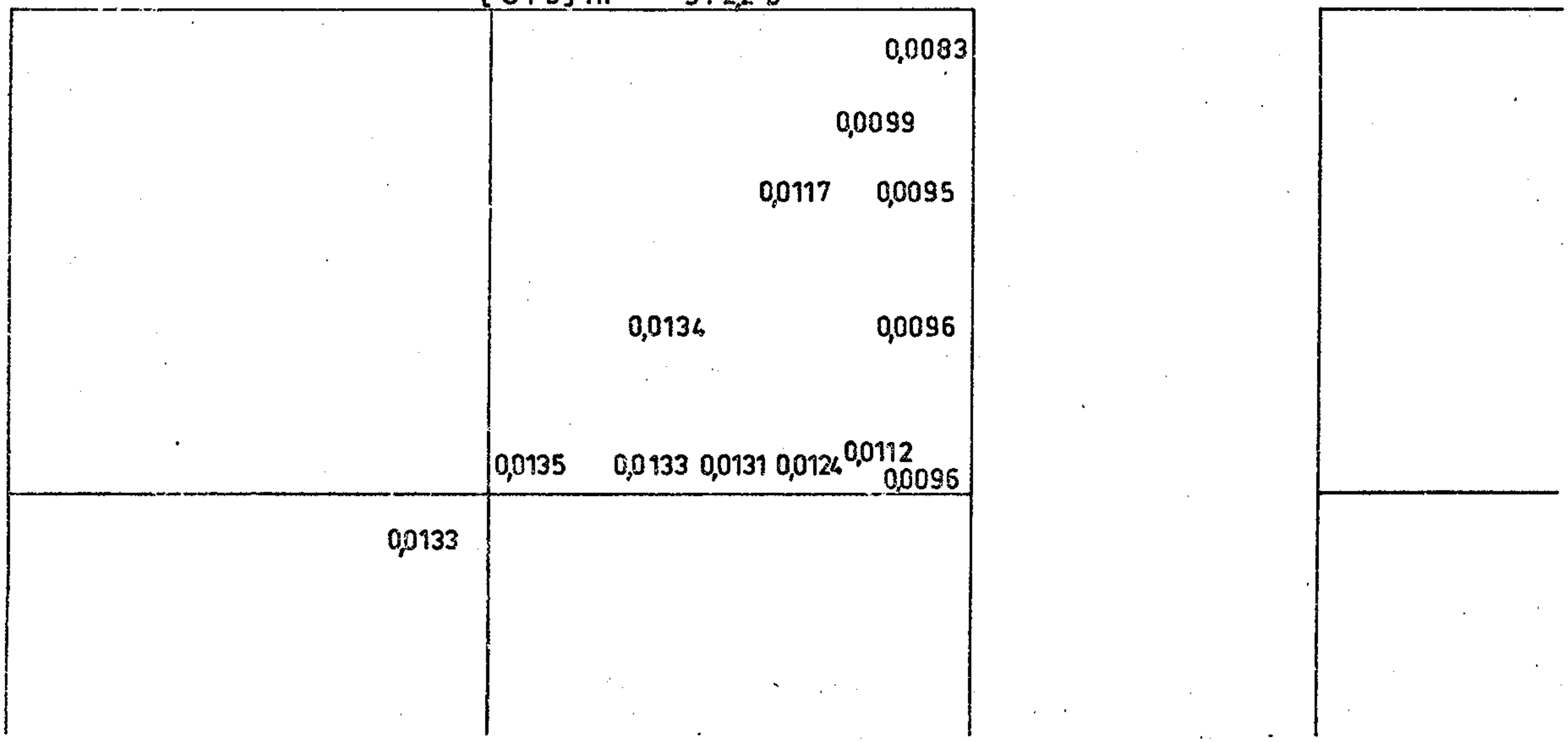


FIG: 6

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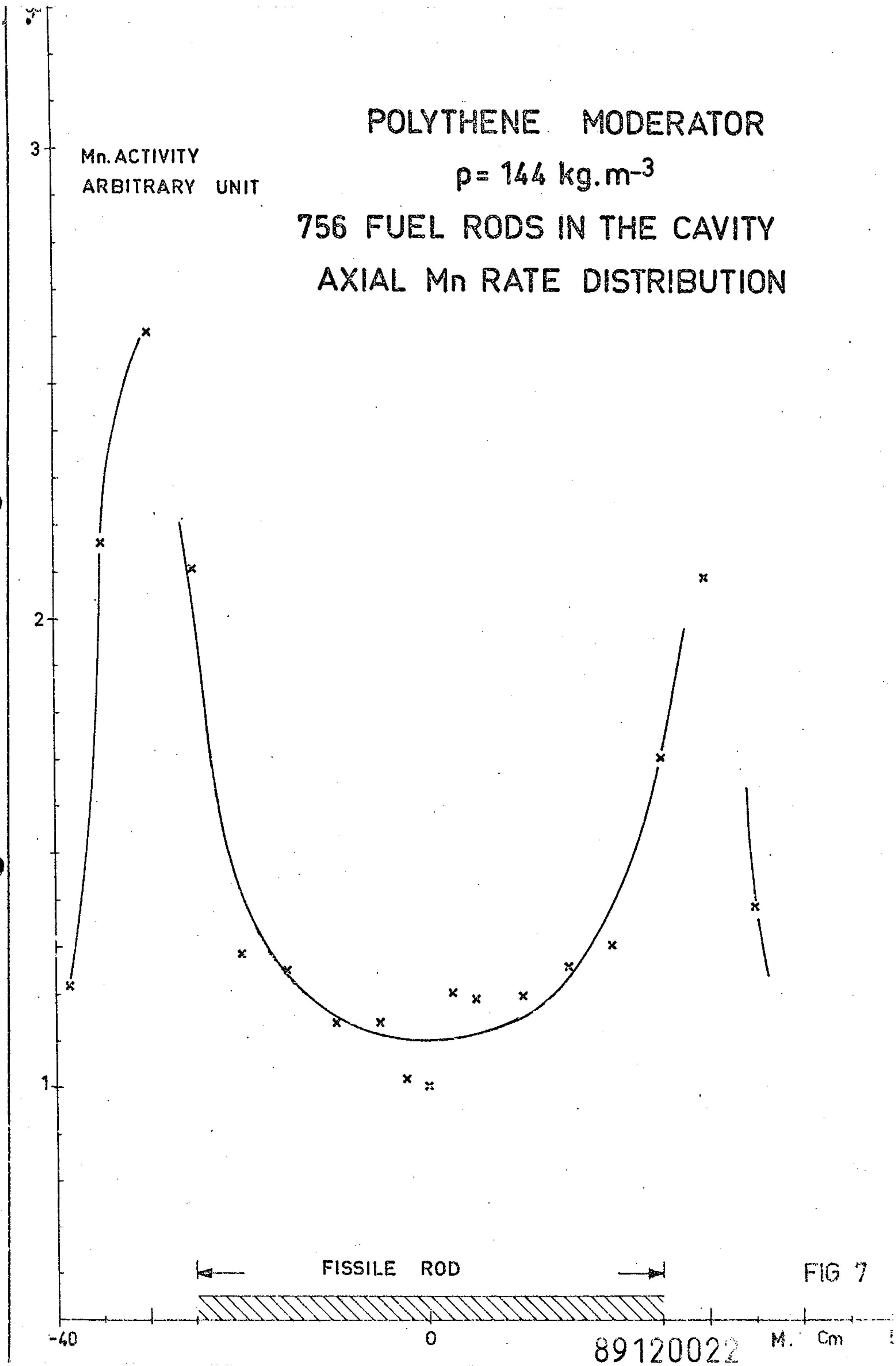

FIG 7

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RADIAL Mn RATE DISTRIBUTION

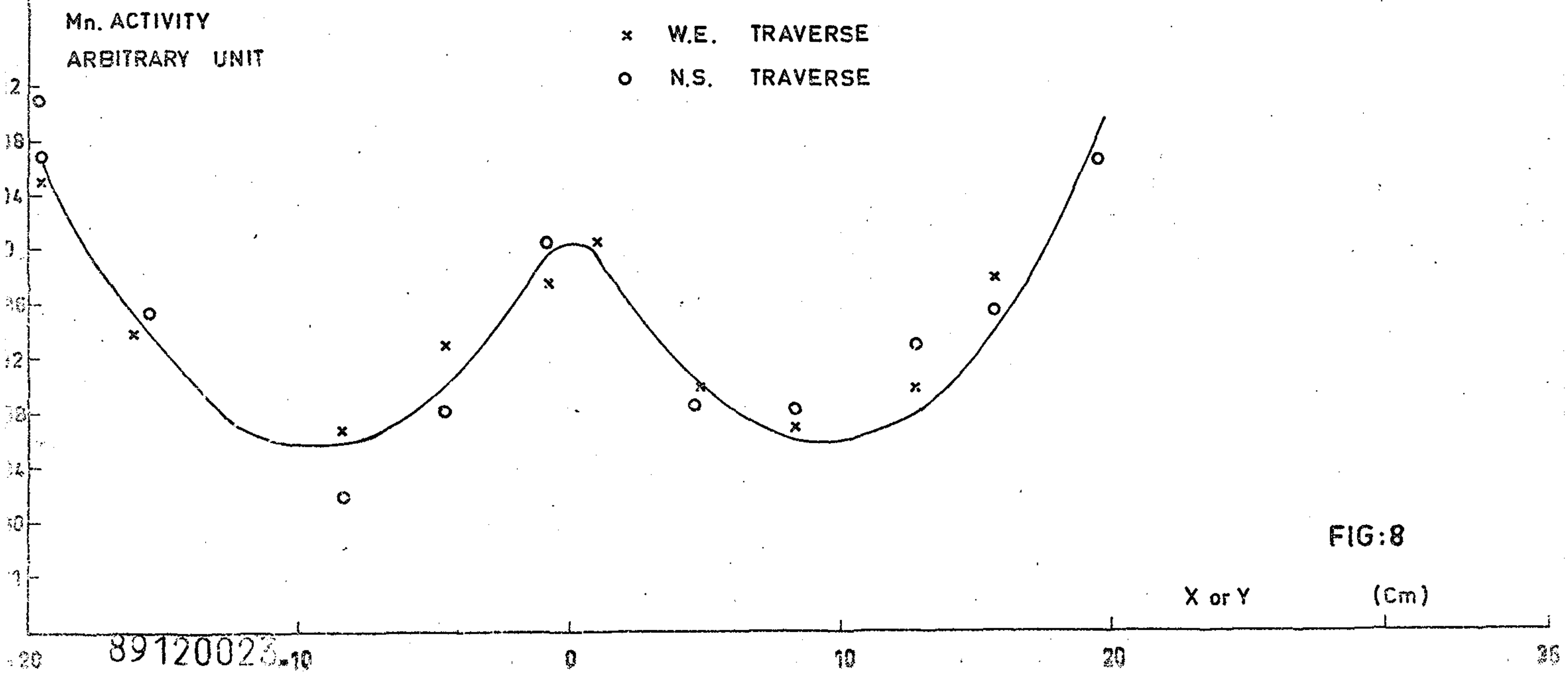

FIG:8

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