AECL-5833

ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

FLUX DISTRIBUTION MEASUREMENTS IN THE BRUCE A UNIT 1 REACTOR

by

A. OKAZAKI, D.A. KETTNER and V.K. MOHINDRA

Chalk River Nuclear Laboratories

Chalk River, Ontario

July 1977

ATOMIC ENERGY OF CANADA LIMITED

FLUX DISTRIBUTION MEASUREMENTS IN THE BRUCE A UNIT 1 REACTOR

by

A. Okazaki*, D.A. Kettner* and V.K. Mohindra+

*Reactor Physics Branch
Chalk River Nuclear Laboratories

+Reactor Physics Branch
Power Projects, Sheridan Park

Reactor Physics Branch
Chalk River Nuclear Laboratories
Chalk River, Ontario

July 1977

AECL-5833

Mesures de distribution de flux dans le réacteur de

l'unité 1 de Bruce A

par

A. Okazaki*, D.A. Kettner* et V.K. Mohindra†

Résumé

Des mesures de distribution de flux ont été effectuées par l'activation d'un fil de cuivre au cours de la mise en service à faible puissance du réacteur de l'unité 1 de la central nucléaire Bruce A de Ontario Hydro. La distribution a été mesurée le long d'un diamètre près des plans médians axiaux et horizontaux du coeur du réacteur. La distribution de l'activité le long du fil de cuivre a été mesurée par des dispositifs de balayage de fil munis de détecteurs au NaI. Les expériences ont été effectuées pour cinq configurations de mécanismes de contrôle de la réactivité.

*Reactor Physics Branch
L'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River

†Reactor Physics Branch
L'Energie Atomique du Canada, Limitée
Groupe électronucléaire

L'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River
Chalk River, Ontario

Juillet 1977

AECL-5833

FLUX DISTRIBUTION MEASUREMENTS IN THE BRUCE A UNIT 1 REACTOR

by

A. Okazaki*, D.A. Kettner* and V.K. Mohindra+

ABSTRACT

Flux distribution measurements were made by copper wire activation during low power commissioning of the Unit 1 reactor of the Bruce A Generating Station of Ontario Hydro. The distribution was measured along one diameter near the axial and horizontal midplanes of the reactor core. The activity distribution along the copper wire was measured by wire scanners with NaI detectors. The experiments were made for five configurations of reactivity control mechanisms.

* Reactor Physics Branch
Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories

+ Reactor Physics Branch
Atomic Energy of Canada Limited
Power Projects

Reactor Physics Branch
Chalk River Nuclear Laboratories
Chalk River, Ontario

July 1977

AECL-5833

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	IRRADIATION OF WIRES	1
	2.1 Location of Wires	1
	2.2 Experimental Details	2
	2.3 Irradiation Procedure	3
3.	MEASUREMENT OF WIRE ACTIVITY	4
	3.1 Counting System	4
	3.2 Relationship of Flux to Activity	5
	3.3 Calibration of Counters	6
4.	RESULTS	8
	4.1 Distributions	8
	4.2 Discussion of Plots	8
	4.3 Distribution in Reflector	9
5.	SUMMARY	9
6.	ACKNOWLEDGMENTS	10
7.	REFERENCES	10

LIST OF TABLES

Table 1:	Reactor and Irradiation Conditions	11
Table 2:	Factors Relating Activity to Integrated Flux	12

LIST OF FIGURES

Figure 1:	The locations and designations of the reactivity control devices.	13
Figure 2:	The location of the horizontal flux monitor site NFM1 looking from the north side of the reactor.	14

List of Figures Cont'd.

		Page
Figure 3:	The cross section of the reactor viewed from the east face. The central 216 channels each contain 2 depleted fuel bundles.	15
Figure 4:	Wire holder assembly.	16
Figure 5:	General layout in the reactor vault.	17
Figure 6:	Wire scanner	18
Figure 7:	Top view of counter showing: (1) collimator slot, (2) lateral guides, (3) vertical guides.	19
Figure 8:	Cross section of counter.	20
Figure 9:	Flux distribution for the reference core	21
Figure 10:	Flux distribution with 28 shutoff ords inserted. The upper curve from -88 cm has been multiplies by a factor of 10.	22
Figure 11:	Flux distribution with 3 booster rods inserted.	23
Figure 12:	Flux distribution with 15 booster rods inserted.	24
Figure 13:	Flux distribution with control absorbers CA3 and CA4 50% inserted.	25
Figure 14:	Experiment 1 flux distribution in the reflector.	26
Figure 15:	Experiment 2 flux distribution in the reflector.	27
Figure 16:	Experiment 3 flux distribution in the reflector.	28
Figure 17:	Experiment 4 flux distribution in the reflector.	29
Figure 18:	Experiment 5 flux distribution in the reflector.	30

FLUX DISTRIBUTION MEASUREMENTS IN THE BRUCE A UNIT 1 REACTOR

INTRODUCTION

1. Flux distribution measurements were made in the Bruce A Unit 1 reactor during the low power commissioning period to provide information, which can be used to check the methods of calculation of the power distribution.

Unit 1 is the second of the four 750 MWe CANDU-PHW reactors of the Ontario Hydro Bruce A Generating Station. These are heavy water moderated and natural uranium fuelled with horizontal pressure tube fuel channels cooled by pressurized heavy water. There are a number of reactivity control devices including: 14 zone control compartments, which can be filled with light water and are used for spatial control; 4 control absorbers; 16 booster rods to provide additional reactivity to compensate for Xe^{135} transients; and 30 shutoff rods which are part of the first shutdown system. The locations of these reactivity control devices is shown in Figure 1.

The flux distribution was measured by activation of a copper wire, a method used previously in the Gentilly-1 and Pickering A Unit 2 reactors(1,2). While it would have been desirable to have flux distributions in several axial and radial directions, the measurements were restricted to one diameter close to the horizontal and axial midplanes. Measurements were made for five different configurations of reactivity control devices.

IRRADIATION OF WIRES

2 Location of Wires

2.1 The neutron flux distribution measurement was made with a copper wire inserted in a vacant horizontal flux detector tube (NFM1) whose location is shown in Figures 2 and 3. This tube, which normally houses a self-powered detector, has a closed end and extends from the north side of the reactor through to within a few cm of the calandria wall on the south side. It is perpendicular to the fuel channels and is in the moderator midway between two rows of fuel channels. The lattice pitch is 28.575 cm.

2.2 Experimental Details

The location and accessibility of the site made the insertion and the withdrawal of the copper wire an interesting feature of the experiments. Among the requirements were:

1) The copper wire had to be mounted in a holder and kept stretched during activation.
2) The holder assembly had to be flexible enough to allow withdrawal and insertion of the copper wire within limited space and time.
3) The material of the holder assembly had to be such that it caused minimum radiation exposure problems after irradiation.

The copper wire holder assembly and other hardware used in the experiments were designed by the Reactivity Mechanism Branch of Atomic Energy of Canada Limited, Power Projects. The specially designed wire holder assembly was made of two parts: the "wire holder" (8.5 m in length) and an extension handle (3.6 m). The two were coupled together by means of a flexible spring. The wire holder assembly, shown in Fig. 4 was made of aluminum tubing with an outer diameter of 12.7 mm and a wall thickness of 0.89 mm. The copper wire was kept stretched during the irradiation with clamps in Zircaloy end pieces at both ends of the aluminum tube. A thin plastic sheath was heat shrunk on to the whole assembly to avoid leaving traces of aluminum in the flux detector tube, which could result from friction between the aluminum holder and Zircaloy tube.

A general layout of the space available on the north side of the reactor is shown in Fig. 5. The distance between the front end of the NFM1 detector tube and the wall on the north side was only 5.97 m. The total required length of the wire holder and the handle was 12.8 m (about 8.3 m to completely scan the core and reflector on the north side, 3.2 m in the shield tank, and the rest in NFM1 housing, etc.).

2.3 Irradiation Procedure

The copper wire was mounted in the wire holder and the aluminum handle was screwed on to the wire holder. Three persons were required to move the assembly in and out of the reactor. A wooden template shown in Fig. 5 helped to guide the movement of the assembly in and out of the core.

Each copper wire was irradiated for a period of 25 to 30 minutes. After irradiation the whole assembly was withdrawn and left in the reactor building for about 20 minutes to let the short-lived 2.24 minute half-life Al^{28} activity decay. The aluminum wire holder assembly while coming out of the core was very radioactive. Therefore, to ensure minimum radiation exposure to personnel, the handling procedures were well organized and rehearsed beforehand. After the cooling period the copper wire was taken out of the aluminum wire holder and wound lightly on specially designed wooden spools and shipped to the Chalk River Nuclear Laboratories (CRNL) for counting.

The insertion and withdrawal time of the copper wire was kept to a minimum and varied between 15 to 25 seconds. This time is short compared with the total irradiation time of 25 to 30 minutes.

The copper wire was 99.8% Cu with 0.1% Ag and 0.1% other impurities. The impurity level is low and its activity at the time of the wire gamma activity measurements will be small compared with that of copper. The diameter was measured at 30 cm intervals over the length of a 36 metre piece from the same spool of copper wire used in these flux distribution measurements. The average diameter and standard deviation were 0.997 ± 0.003 mm with a range of 0.991 to 1.006 mm.

The flux distributions were measured for the five different reactor configurations listed below.

1) Reference case.
2) 28 shutoff rods inserted.
3) 3 booster rods inserted.
4) 15 booster rods inserted.
5) CA3 and CA4 50% inserted.

These configurations were selected in such a way that the resulting flux changes could be detected by the copper wire. Table 1 lists the reactor conditions for each of the experimental measurements. The table also lists the time of the start and the end of irradiation for each.

3 MEASUREMENT OF WIRE ACTIVITY

3.1 Counting System

The counting equipment to measure the 12.71 hour half-life Cu^{64} activity distribution along the wire was the same as that used previously for similar measurements in the Gentilly 1 and Pickering A Unit 2 reactors[1,2]. One of the two wire scanners used is shown in Fig. 6. Each scanner has a 51 mm diameter, 25.4 mm thick NaI scintillation detector mounted in a Pb shield. The wire passed over the 10 mm wide collimator shown in Figures 7 and 8. The copper wire was held in the scanner carriage, which was driven across the top of the detector by a rack and pinion whose pulsed drive motor was controlled by an automatic control unit. The vertical position of the wire above the collimator was fixed by two bar guides attached to the collimator and the lateral position by two pins on the shield lid. These guides are shown in Fig. 7.

To enable the activity to be measured to the end of the wire that was in the core, a 10 cm long larger diameter copper wire was brazed to the end of the irradiated wire. The wire was clamped in the carriage and the activity was measured over 124 cm in either 1.0005 or 2.0009 cm intervals. Then the carriage position was reset and the wire was unclamped, moved 124 cm, and reclamped to count the next section of wire. The activity was measured over a 900 cm length and included part of the wire beyond the calandria into the shield tank.

The discriminator level was set to count gamma rays with energy greater than 50 keV.

3.2 Relationship of Flux to Activity

The measured activities of all copper wires were corrected for background, which was small, and the resulting net activities were corrected for decay of the Cu^{64} back to the same zero time. The corrected activity is related to the neutron flux by

$$A = \frac{N\hat{\sigma}\phi}{\lambda} \left(1 - e^{-\lambda T}\right) \varepsilon e^{-\lambda t_{\lambda}} \qquad (1)$$

where
- A = corrected activity at zero time
- N = number of Cu^{63} atoms in the collimator
- $\hat{\sigma}$ = effective cross section of Cu^{63}
- λ = Cu^{64} decay constant
- T = duration of irradiation
- ε = counter efficiency
- t = time from end of irradiation to zero time.

Thus the neutron flux can be expressed as

$$\phi = \frac{A\, e^{\lambda t}}{N\hat{\sigma}\, \varepsilon \left(1 - e^{-\lambda T}\right)} \qquad (2)$$

The time integrated neutron flux is

$$\phi T = \frac{ATe^{\lambda t}}{N\hat{\sigma}\varepsilon(1 - e^{-\lambda T})} \qquad (3)$$

The above relations assume a step irradiation in a constant flux ϕ for time T.

3.3 Calibration of Counters

The two counters were calibrated by measuring the activities of copper wires irradiated in a known thermal neutron flux. Two pieces of copper wire from the same lot as used in the Bruce experiments were attached to a rotating lucite wheel in the thermal column of the NRU reactor. A cobalt wire (0.127 mm diameter) was also attached to the wheel. After the irradiation each copper wire was counted in both scanners. The Co^{60} activity of the cobalt wire was measured in another counting system, which was calibrated by counting a Co^{60} source of known disintegration rate.

From the measured Co^{60} activities the integrated flux was

$$\phi T = (1.695 \pm 0.02) \times 10^{13}\ n \cdot cm^{-2}$$

based on the following values:

$\sigma_0 (Co^{59})$ = 37.2 barns* (2200 m/s)

Co^{60} half-life = 5.272 years.

The irradiation time T, which is determined by the opening and closing of the thermal column gate, was 3600 ± 60 seconds and is not known as accurately as the integrated flux.

The results for the copper wires are summarized below, where A_0 is the count rate corrected to the end of irradiation. The correction for decay from the count zero time to the end of the irradiation was $e^{\lambda t}$ = 2.751.

---

* 1 barn = 10^{-28} m^{-2}

		Scanner 1	Scanner 2
A_0 (c/s)	Wire A	1027 $\pm$ 4	1018 $\pm$ 4
	Wire B	1018 $\pm$ 4	1015 $\pm$ 4
	Average	1023 $\pm$ 6	1017 $\pm$ 6
$N\sigma_0\varepsilon\lambda$		$1.705(\pm 0.010)\times10^{-10}$	$1.699(\pm 0.010)\times10^{-10}$

The count rates and hence the efficiencies of the two scanners are the same within the uncertainties in the measurements. From the measured copper wire activity, A_0 and integrated flux, ϕT, the constant product $N\sigma_0\varepsilon\lambda$ was obtained and is given in the above table. The Cu^{64} half-life assumed is 12.71 hours.

The relationship given in Equation (3) of the integrated neutron flux to the measured activity of the Bruce wires can be written

$$\phi T = A\left(\frac{1}{N\sigma_0\varepsilon\lambda}\right)\left(\frac{\sigma_0}{\hat{\sigma}}\right)\left(\frac{\lambda T e^{\lambda t}}{1-e^{-\lambda T}}\right) \qquad (4)$$

The ratio of the Cu^{63} absorption cross sections in the thermal column and at the wire location in the Bruce reactor $(\sigma_0/\hat{\sigma})$, is 0.990. Thus the integrated flux is given by

$$\phi T = 5.82 \times 10^9 \ A\left(\frac{\lambda T e^{\lambda t}}{1-e^{-\lambda T}}\right) \qquad (5)$$

where as noted before A is the measured activity corrected to the counting zero time.

4. RESULTS

4.1 Distributions

The measured activities of the copper wires irradiated in the Bruce reactor were corrected for decay back to the zero time for counting which was at 09:55 Dec. 22. The activity distributions along the wires are shown in Figures 9 - 13. The normalized activities, which are plotted, were obtained by multiplying the measured activities (A) by the factor given in the upper right hand corner of the figures.

The integrated flux and hence flux can be obtained from the measured activity (A) using Equation (5). The factors, which take into account the decay during irradiation and the time between the end of irradiation and count zero time are listed in Table 2.

The precise location of the end of the flux detector tube was not known. The distinct maxima and minima in the activity distributions are associated with the rows of fuel channels and were used to define the location of the copper wire. The reactor center line is midway between the 12th and 13th rows of fuel channels and all distances are referred to this center line. The distance of the center from the end of the wire was determined from the maxima and minima in the distributions of Experiments 1, 3 and 4 and was 397.5 $\pm$ 0.4 cm.

4.2 Discussion of Plots

a) Expt. 1: The flux distribution for this reference core is almost symmetric about the center line. The radial dishing is due to the two depleted UO_2 fuel bundles in each of the central 216 channels shown in Fig. 3. There are 13 fuel bundles in each channel. The depleted bundles are at positions 5 and 6 in half of the channels and at 8 and 9 in alternate channels.

b) Expt. 2: In this configuration all shutoff rods were in the core, except the two shutoff rods (SA15 and 24) furthest to the south. There is a very large flux tilt with the flux varying over two orders of magnitude.

c) Expt. 3: Three boosters (BA 2, 7 and 8) were inserted in the southeast corner and produced a flux tilt with the flux on the south side about twice as high as on the north side.

d) Expt. 4: All boosters were inserted except one (BA 1) located just north of the center line on the east side. (See Fig. 1.) The distribution is peaked a short distance south of the center line.

e) Expt. 5: Two control absorbers (CA 3 and CA 4) located on the center line were partially inserted and produce a minimum at the center.

4.3 Distribution in Reflector

The flux distribution in the heavy water reflector and into the shield tank on the north side are shown in Figures 14 - 18.

A straight line extrapolation of the points from 406 to 413 cm from the reactor center line goes to zero at an average distance of 416.7 cm. All extrapolations are within 1 cm of this average.

5. SUMMARY

Flux distributions were measured along one diameter near the horizontal and axial midplanes of the reactor core for five configurations of reactivity control mechanisms. These configurations were chosen to produce flux shape changes at the location of the copper wire. The strong side-to-side flux tilts and gradients provide a test for the methods of calculating power distributions.

The counters were calibrated and this allows the determination of the absolute thermal neutron flux at the copper wire location from the measured activities.

6. ACKNOWLEDGMENTS

This experiment was made possible by the co-operation and effort of groups at Power Projects, Chalk River Nuclear Laboratories and Ontario Hydro.

The authors would like to acknowledge the co-operation of Bruce Generating Station A staff, in particular R. Coutts, J.R. Enselmoz, and D. Phillips. A.M. Lopez, Phase B co-ordinator for Unit 1 and I.N. Daly of Ontario Hydro provided tireless help in organizing and arranging the experiments. A.A. Pasanen provided continuous encouragement and guidance throughout the planning of the experiments. O.A. Trojan made various helpful suggestions. The copper wire holder assembly and other hardware was designed by Lada Suler of the Reactivity Mechanism Branch of Power Projects. One of the authors (V.K. Mohindra), G. Kugler, M. Mamourian, E.S.Y. Tin, R. Robertson of Power Projects and A.M. Lopez and I.N. Daly took part in the actual experimental work at site. D.E. Wright of CRNL assisted in the processing of the counting data.

7. REFERENCES

1. A. Okazaki, D.H. Walker, M.H.M. Roshd, "Flux Distribution Measurements in the Gentilly Reactor", Atomic Energy of Canada Limited, Report AECL-3962 (July 1971).
2. A. Okazaki, M.H.M. Roshd, "Flux Distribution Measurements in the Pickering Unit 2 Reactor", Atomic Energy of Canada Limited, Report AECL-4131 (February 1972).

TABLE 1

REACTOR AND IRRADIATION CONDITIONS

NO.	EXPERIMENT	REACTOR POWER	AVERAGE ZONE LEVEL	AVERAGE MODERATOR TEMPERATURE °C	AVERAGE HEAT TRANSPORT TEMPERATURE °C	DATE	TIME		
							Copper Wire In	Copper Wire Out	Activation Time Min.
1	Nominal Fresh Core	1.0×10^{-4} FP	34.8%	37.7	41.4	Dec. 21/76	03:14	03:44	30
2	28 SOR Inserted	5.0×10^{-4} FP	17%	38.3	44.6	Dec. 21/76	15:17	15:42	25
3	3 Boosters (BA 2, 7, 8) Inserted	3.2×10^{-4} FP	69.2%	38.0	43.6	Dec. 22/76	05:47	06:13	26
4	15 Boosters Inserted (BA 1 out)	3.2×10^{-4} FP	65.5%	38.0	45.5	Dec. 22/76	14:49	15:17	28
5	CA 3 and CA 4 50% Inserted	3.2×10^{-4} FP	37.0%	38.0	43.8	Dec. 22/76	19:49	20:14	25

FP is Full Power

Moderator isotopic purity = 99.76 wt%

Coolant isotopic purity = 99.52 wt%

TABLE 2

FACTORS RELATING ACTIVITY TO INTEGRATED FLUX

EXPT.	IRRADIATION				$\left(\frac{\lambda T e^{\lambda t}}{1 - e^{-\lambda T}}\right)$	$\frac{\phi T}{A}$ (10^{10})
	DATE	IN	OUT	T (min)		
1	Dec. 21	03:14	03:44	30	5.258	3.060
2	Dec. 21	15:17	15:42	25	2.726	1.587
3	Dec. 22	05:47	06:13	26	1.238	0.721
4	Dec. 22	14:49	15:17	28	0.756	0.440
5	Dec. 22	19:49	20:14	25	0.576	0.335

Count zero time 09:55 December 22, 1976.

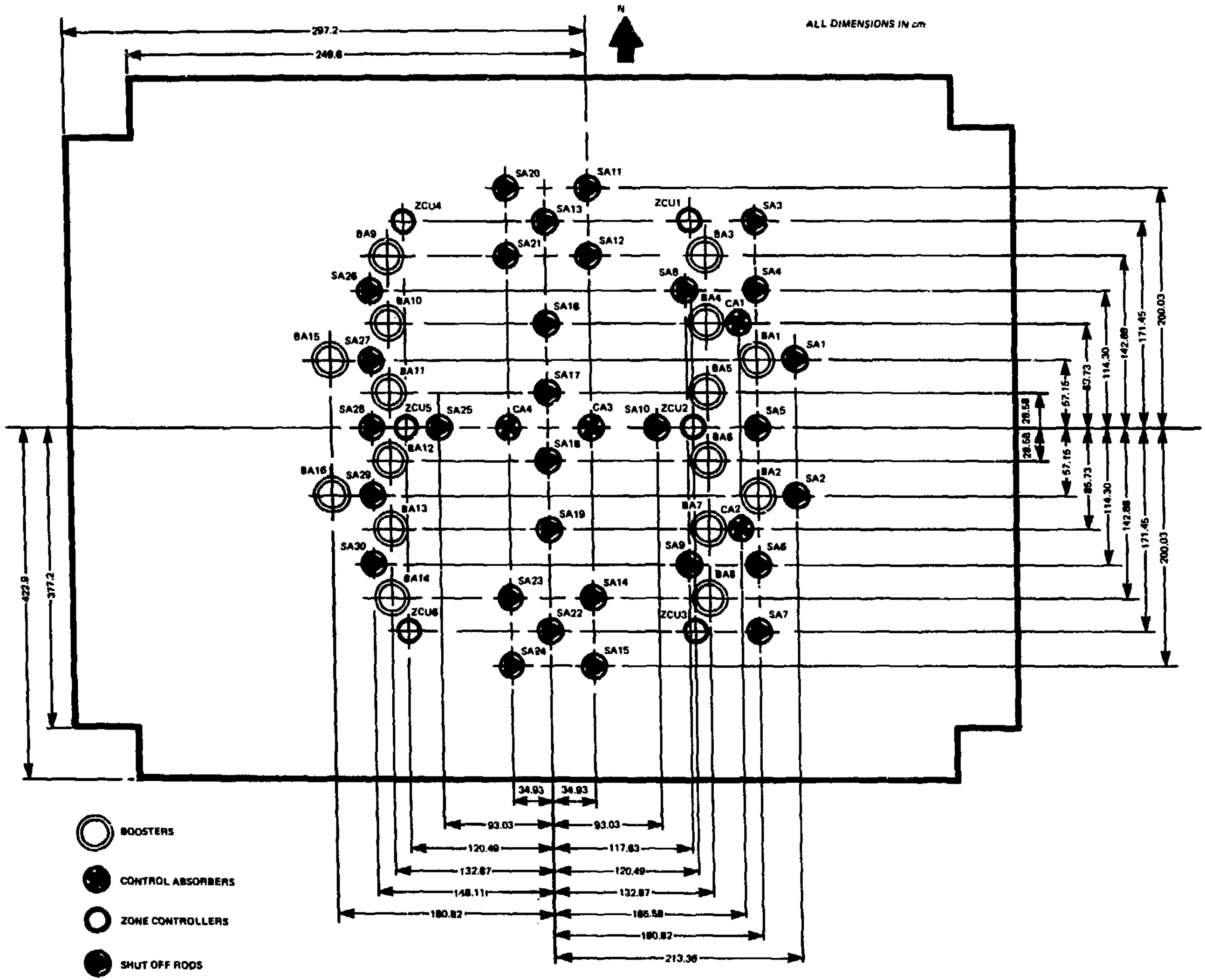

FIG. 1: The locations and designations of the reactivity control devices.

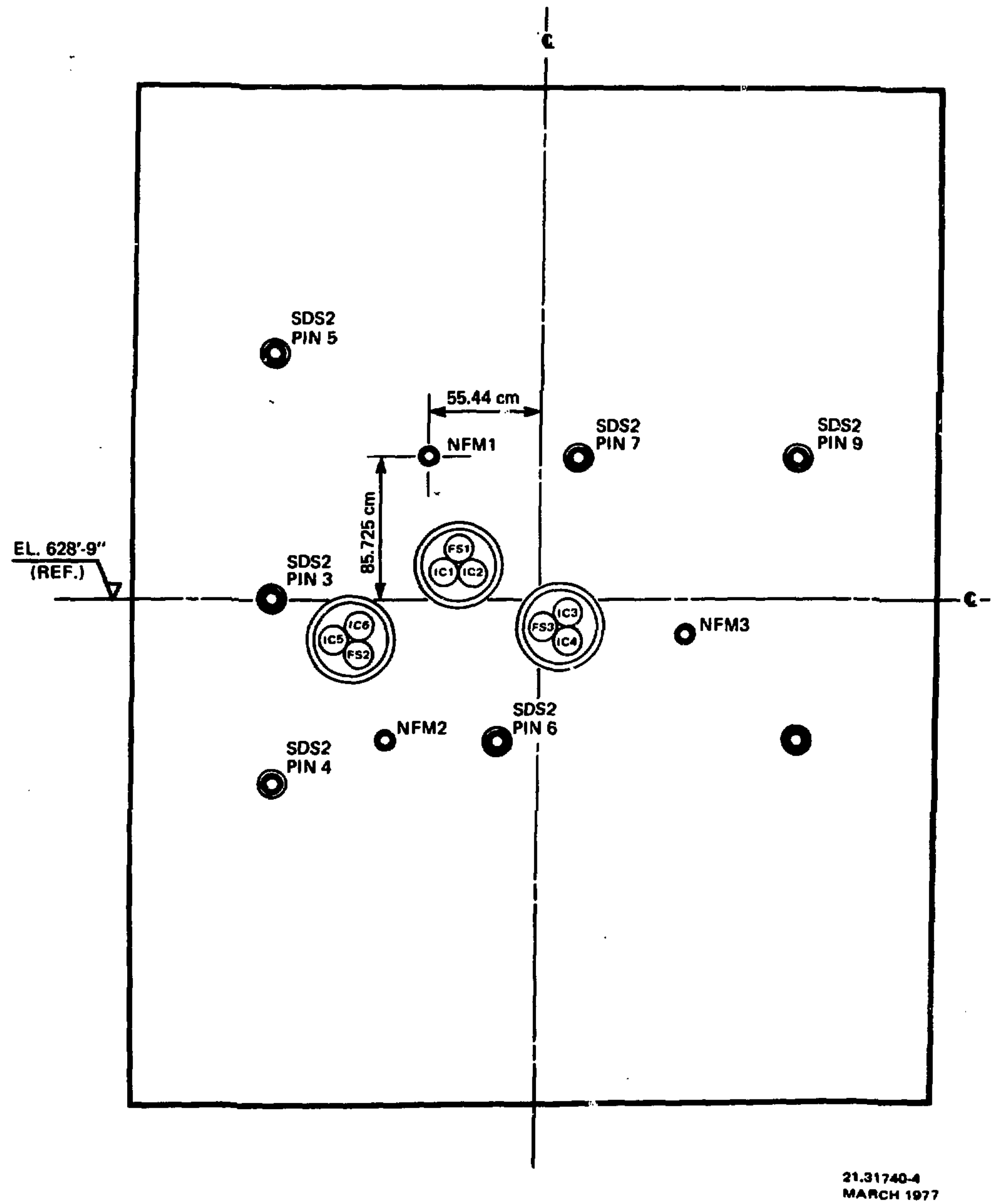

FIG. 2: The location of the horizontal flux monitor site NFM1 looking from the north side of the reactor. (The reference elevation 628' 9" = 191.64 m).

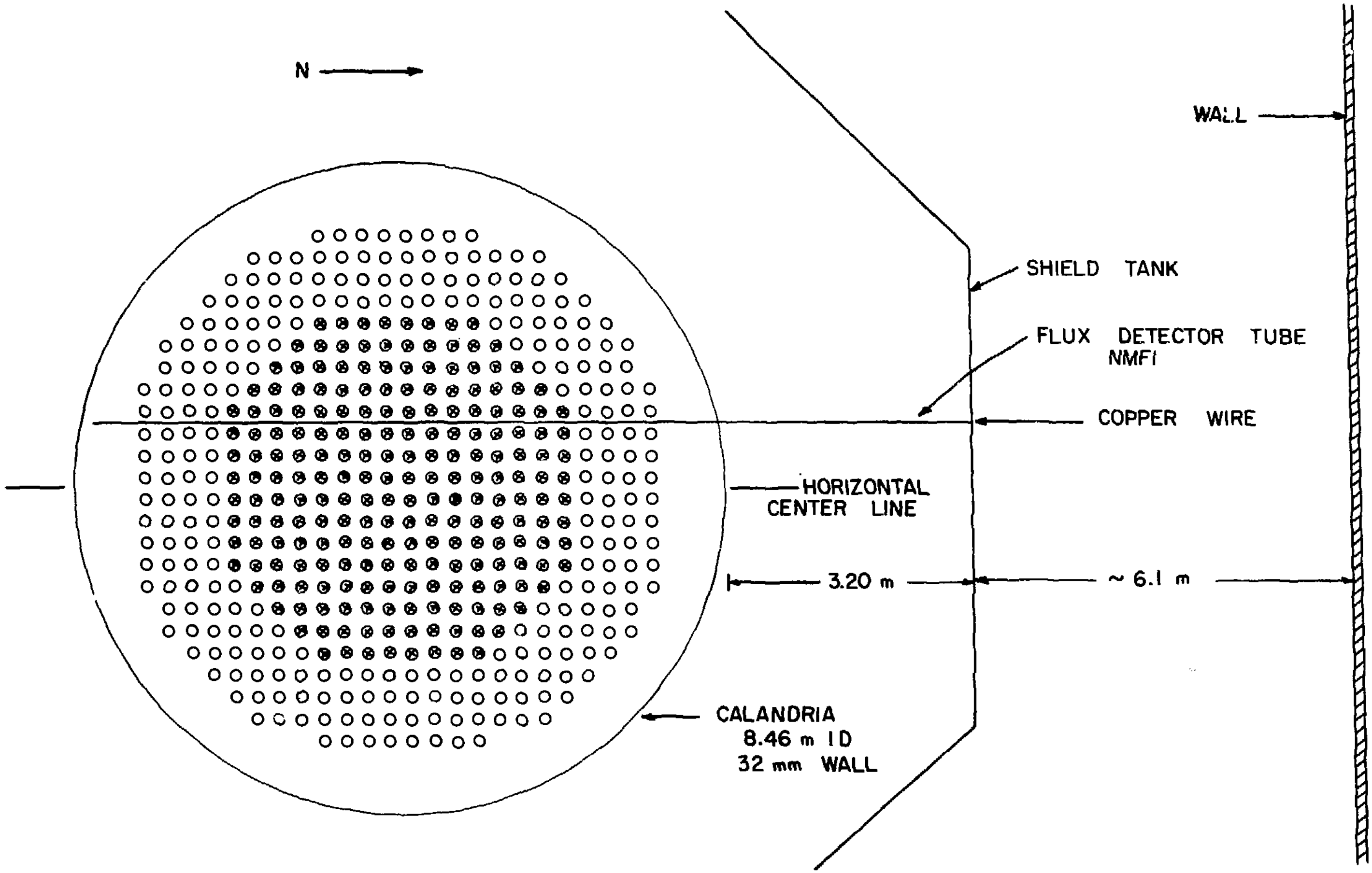

FIG. 3: The cross section of the reactor viewed from the east face. The central 216 channels each contain 2 depleted fuel bundles.

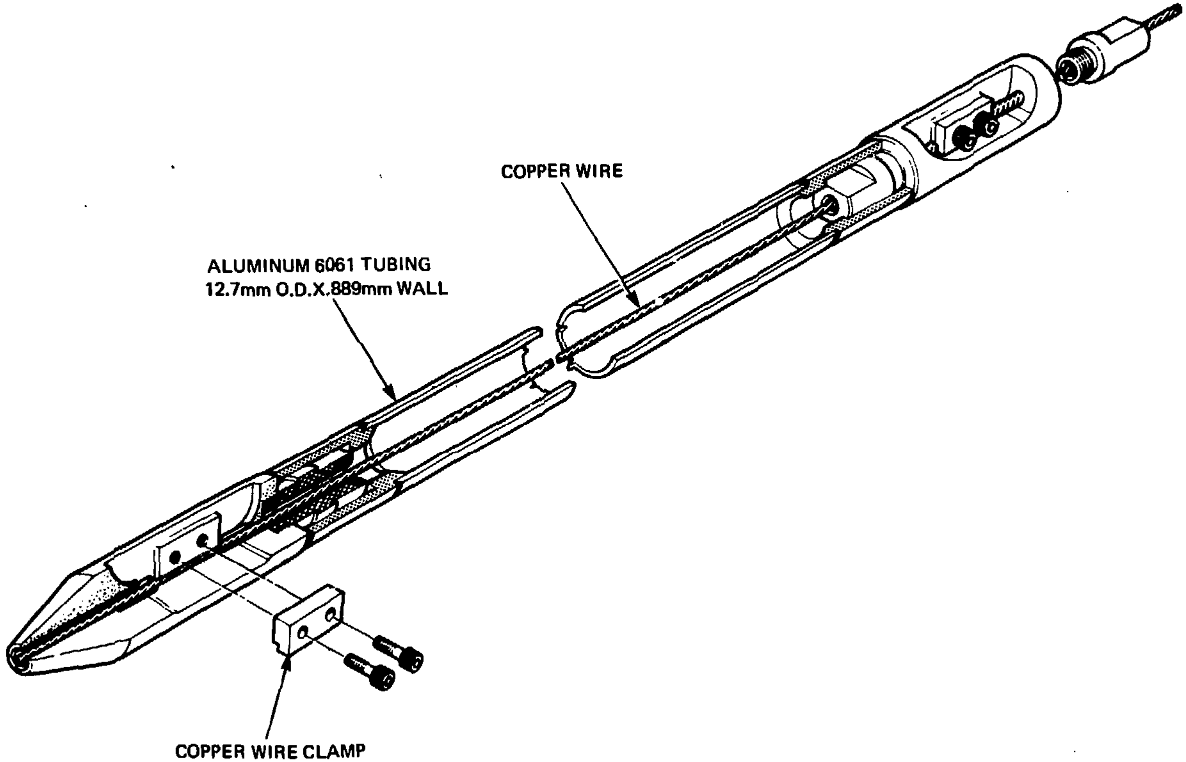

FIG. 4: Wire holder assembly.

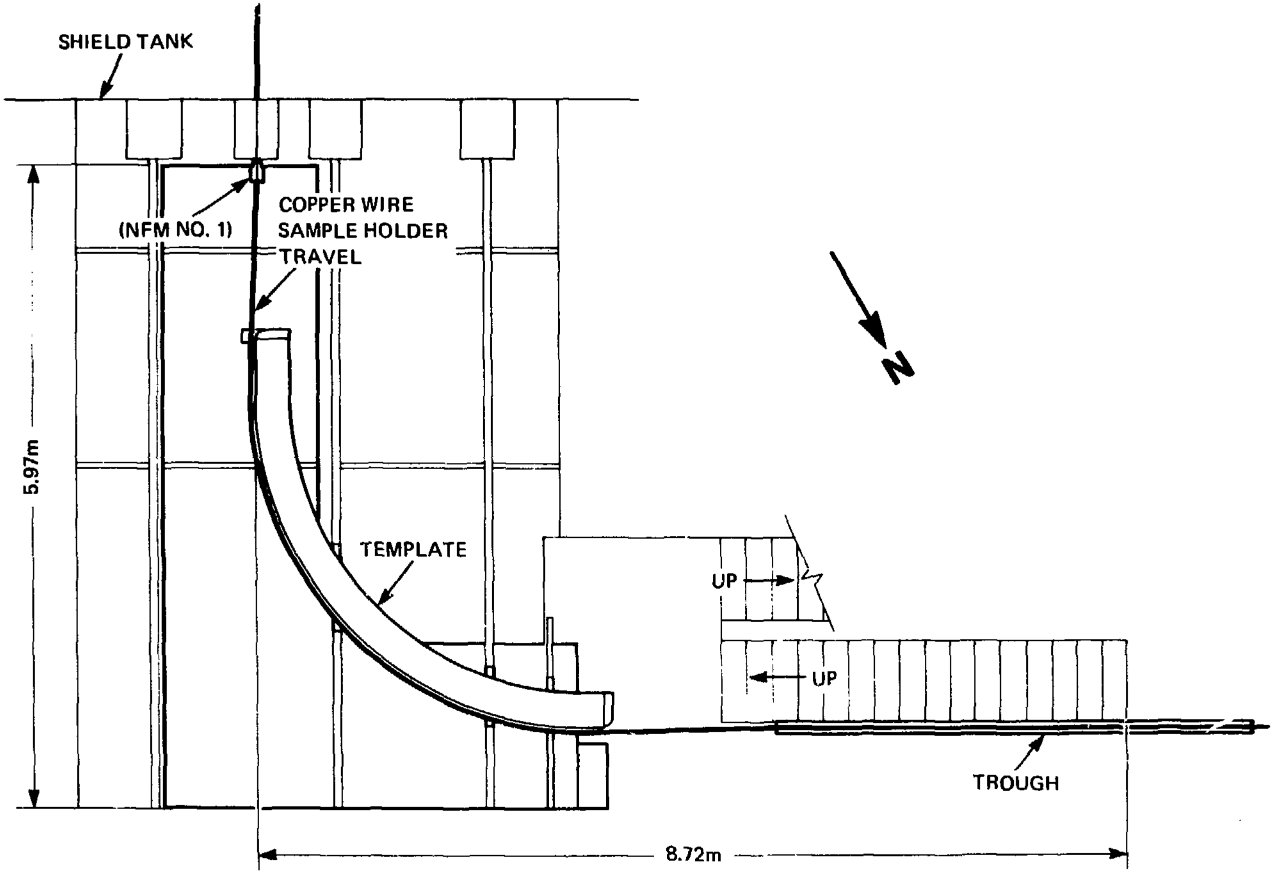

FIG. 5: General layout in the reactor vault.

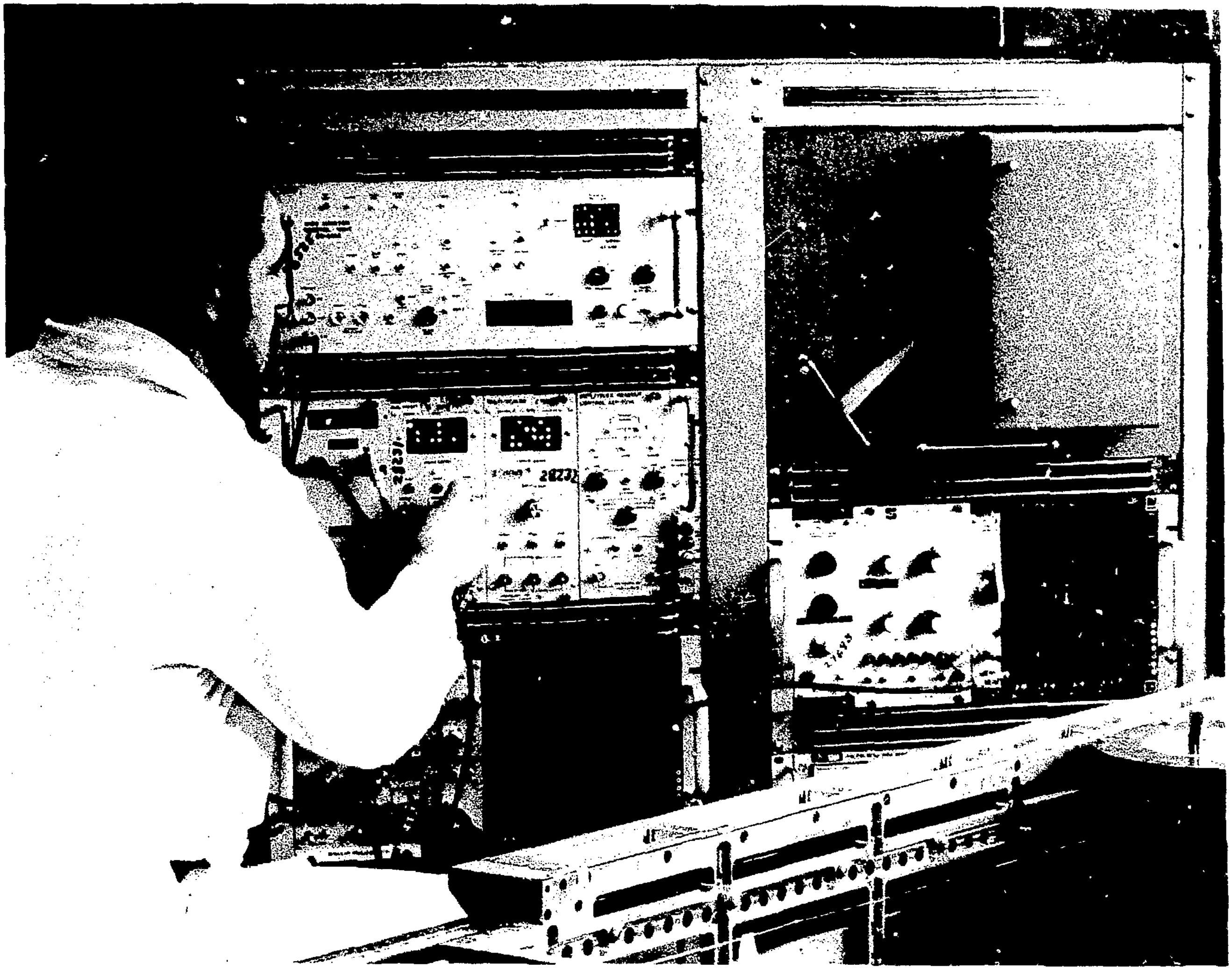

FIG. 6: Wire scanner.

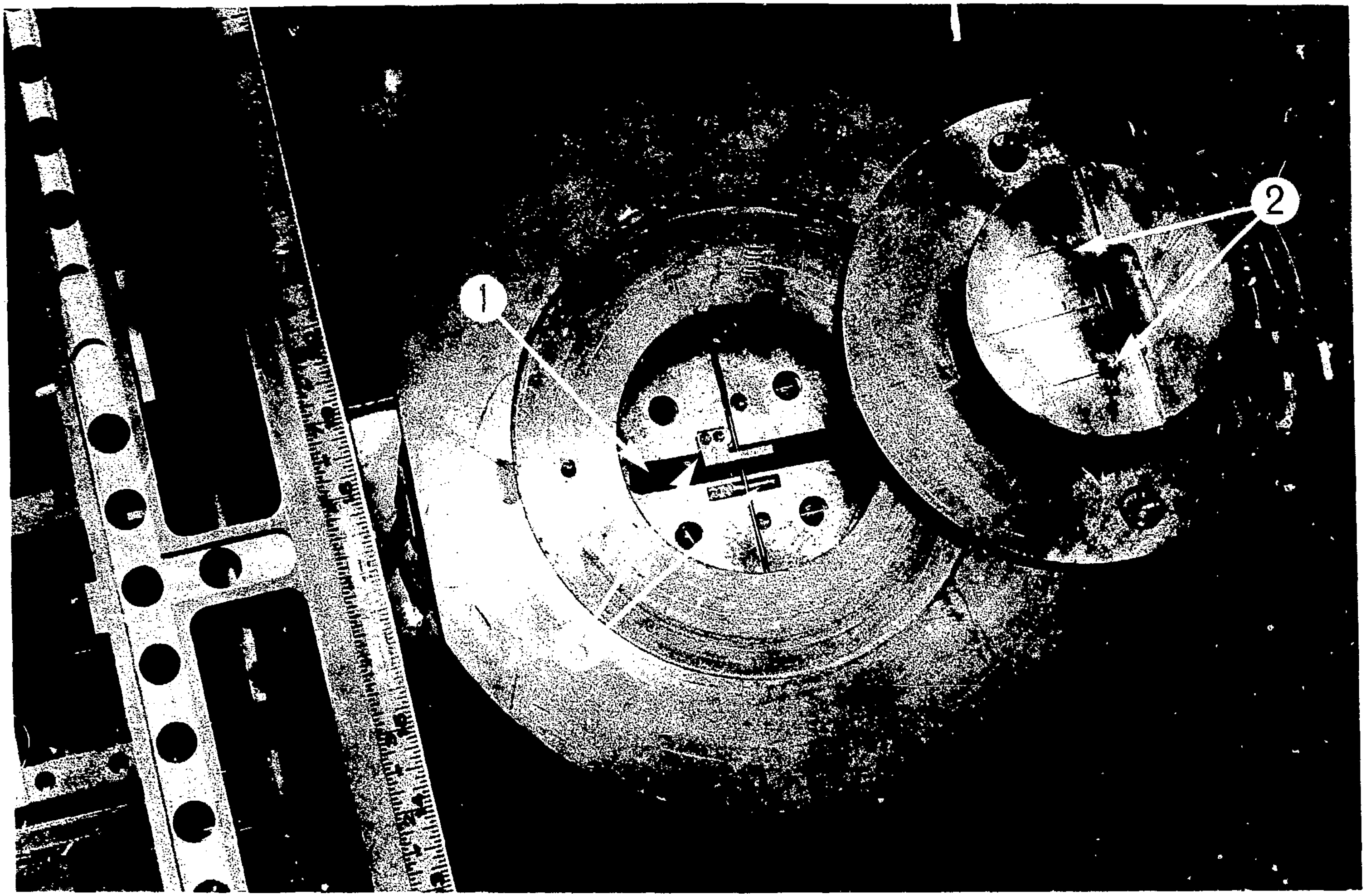

FIG. 7: Top view of counter showing (1) Collimator slot
(2) Lateral guides
(3) Vertical guides

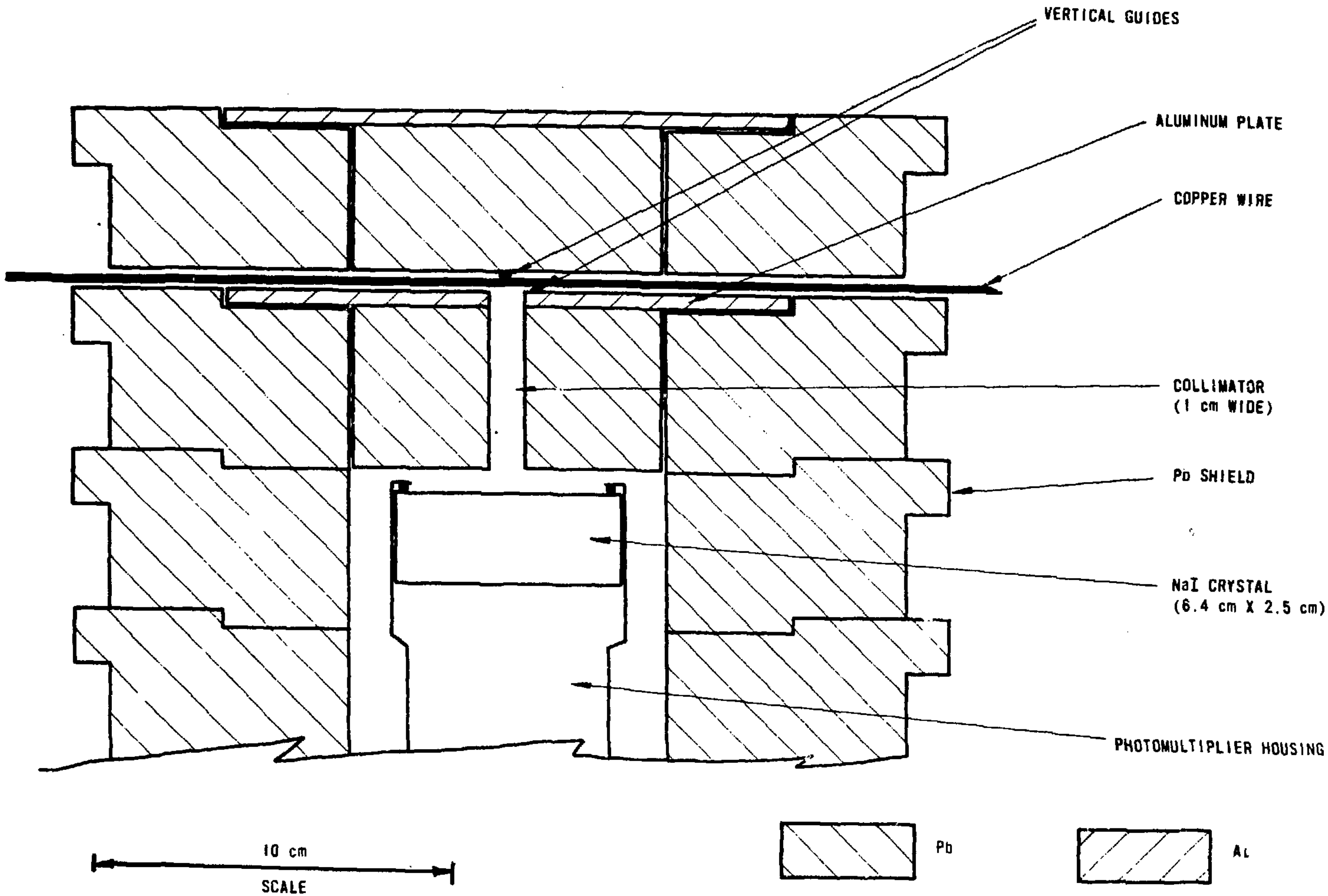

FIG. 8: Cross section of counter.

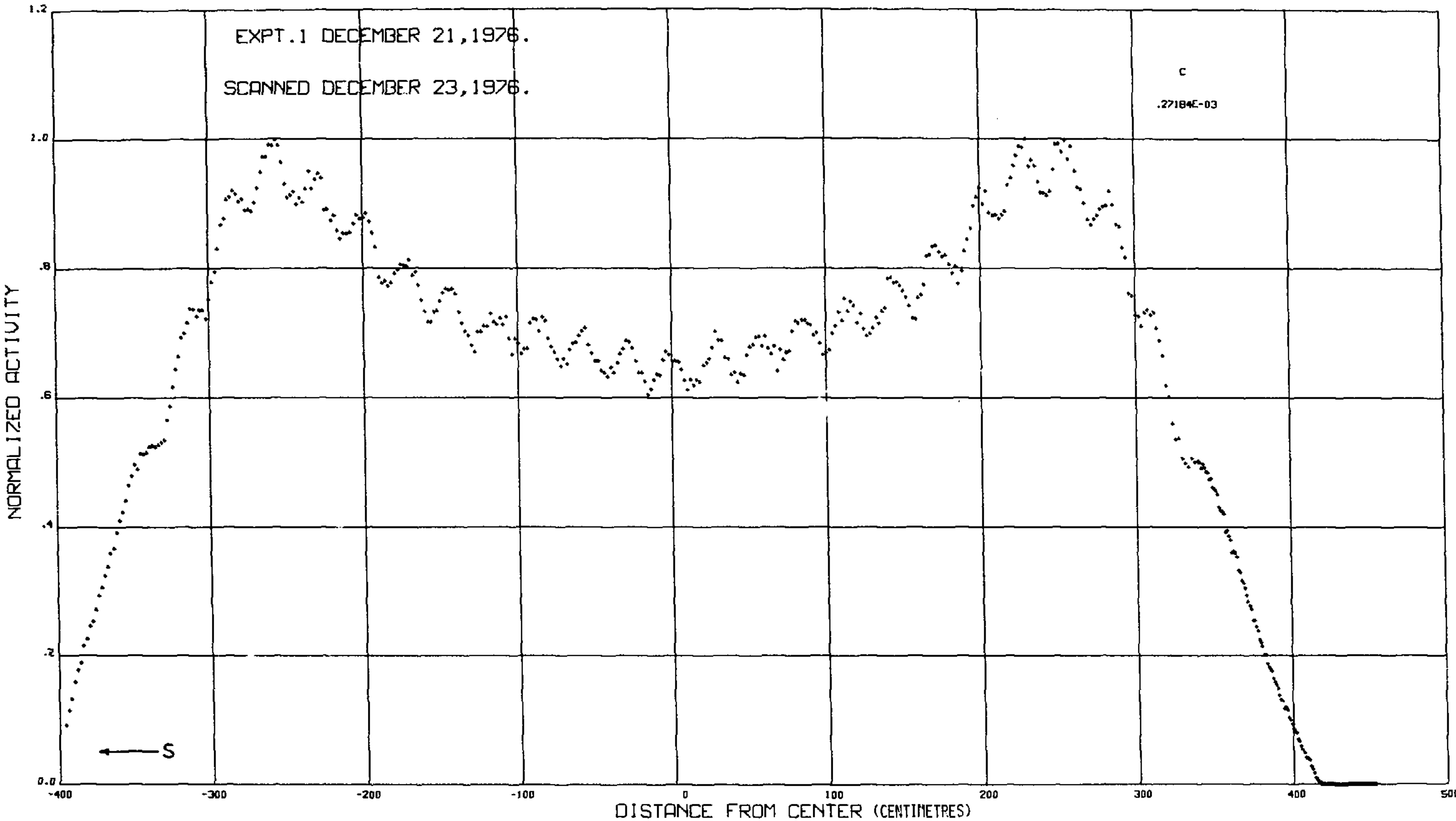

FIG. 9: Flux distribution for the reference core. The distance from the center is in centimetres.

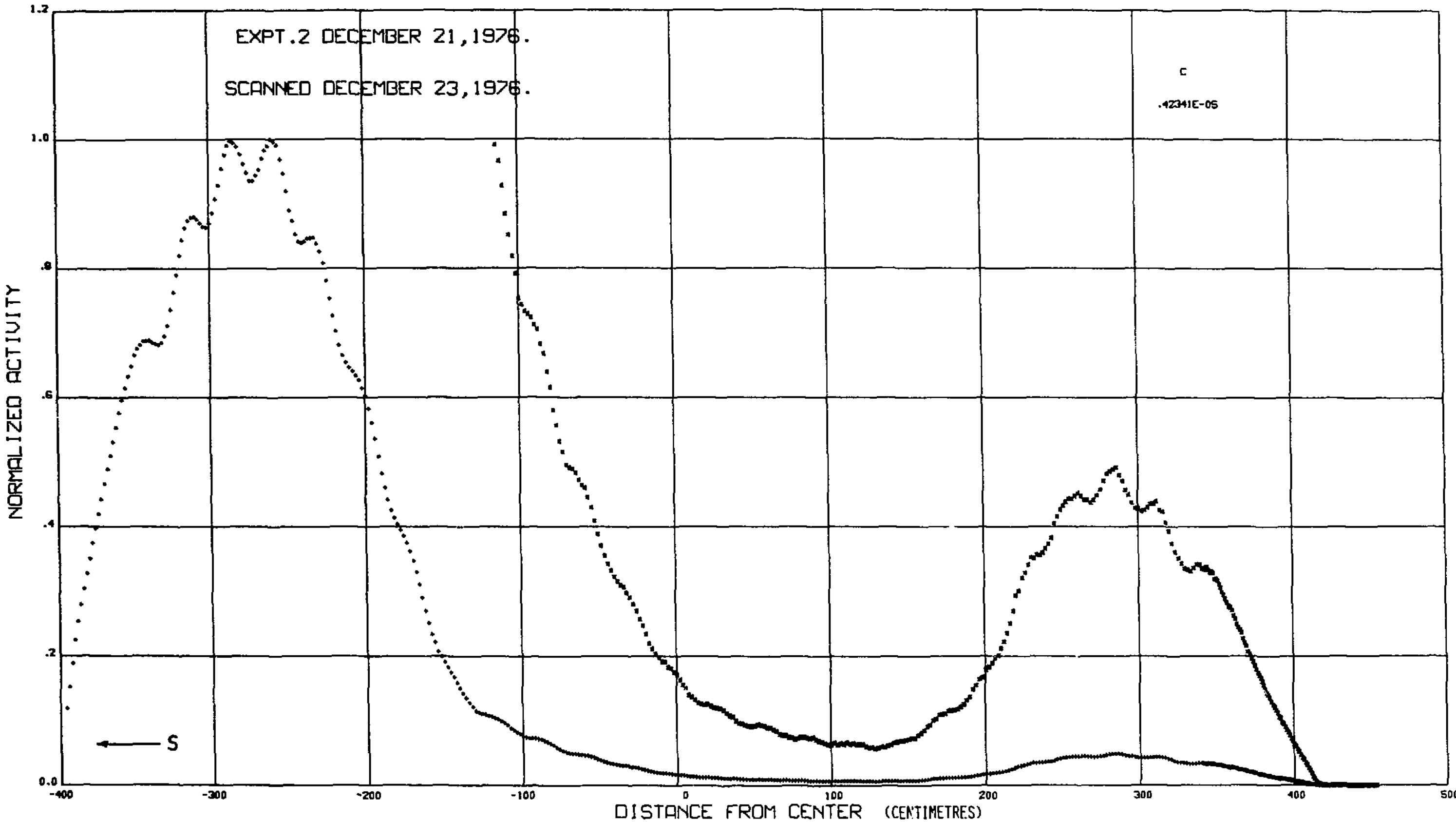

FIG. 10: Flux distribution with 28 shutoff rods inserted. The upper curve from -88 cm has been multiplied by a factor of 10. The distance from the center is in centimetres.

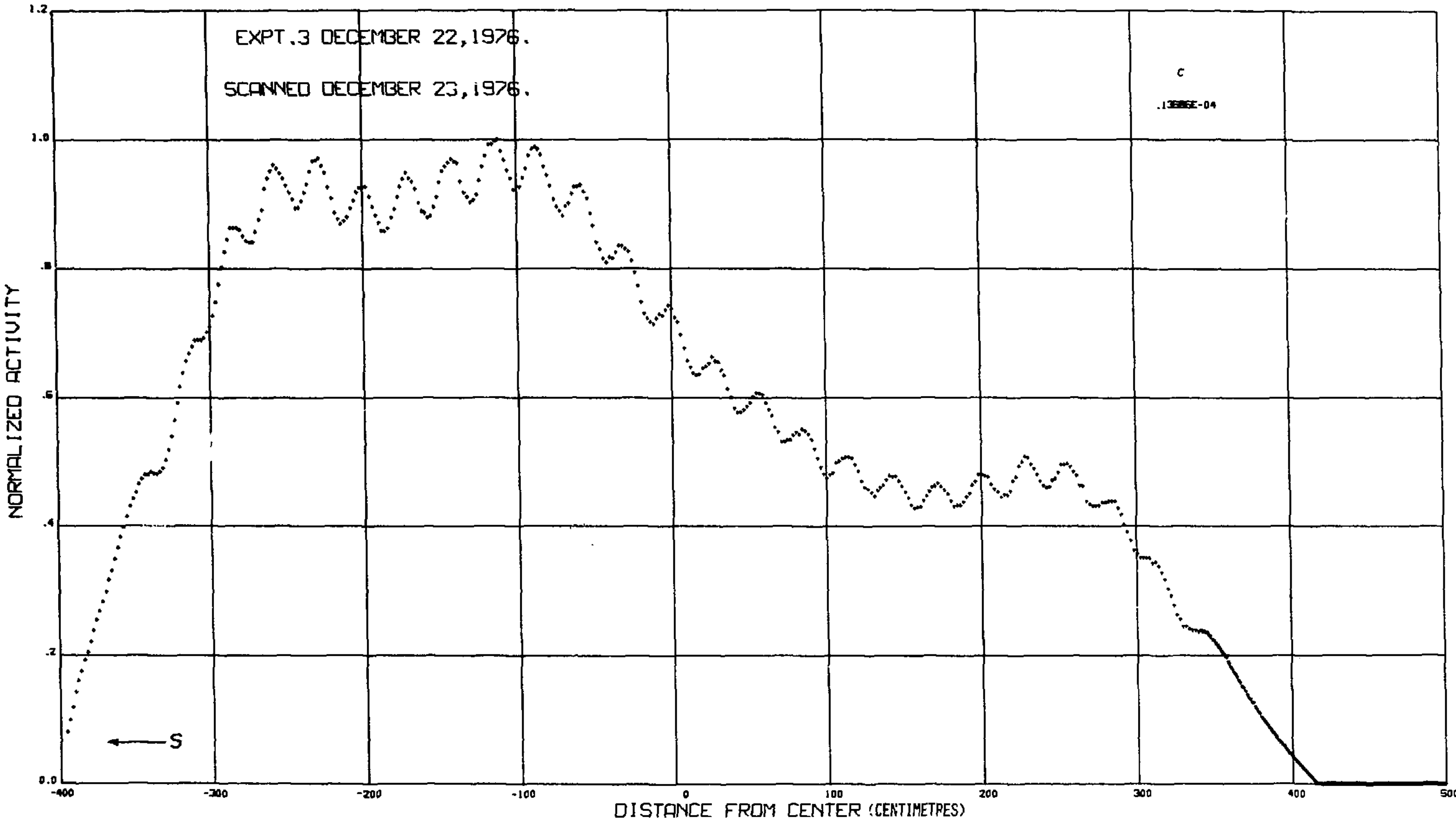

FIG. 11: Flux distribution with 3 booster rods inserted. The distance from the center is in centimetres.

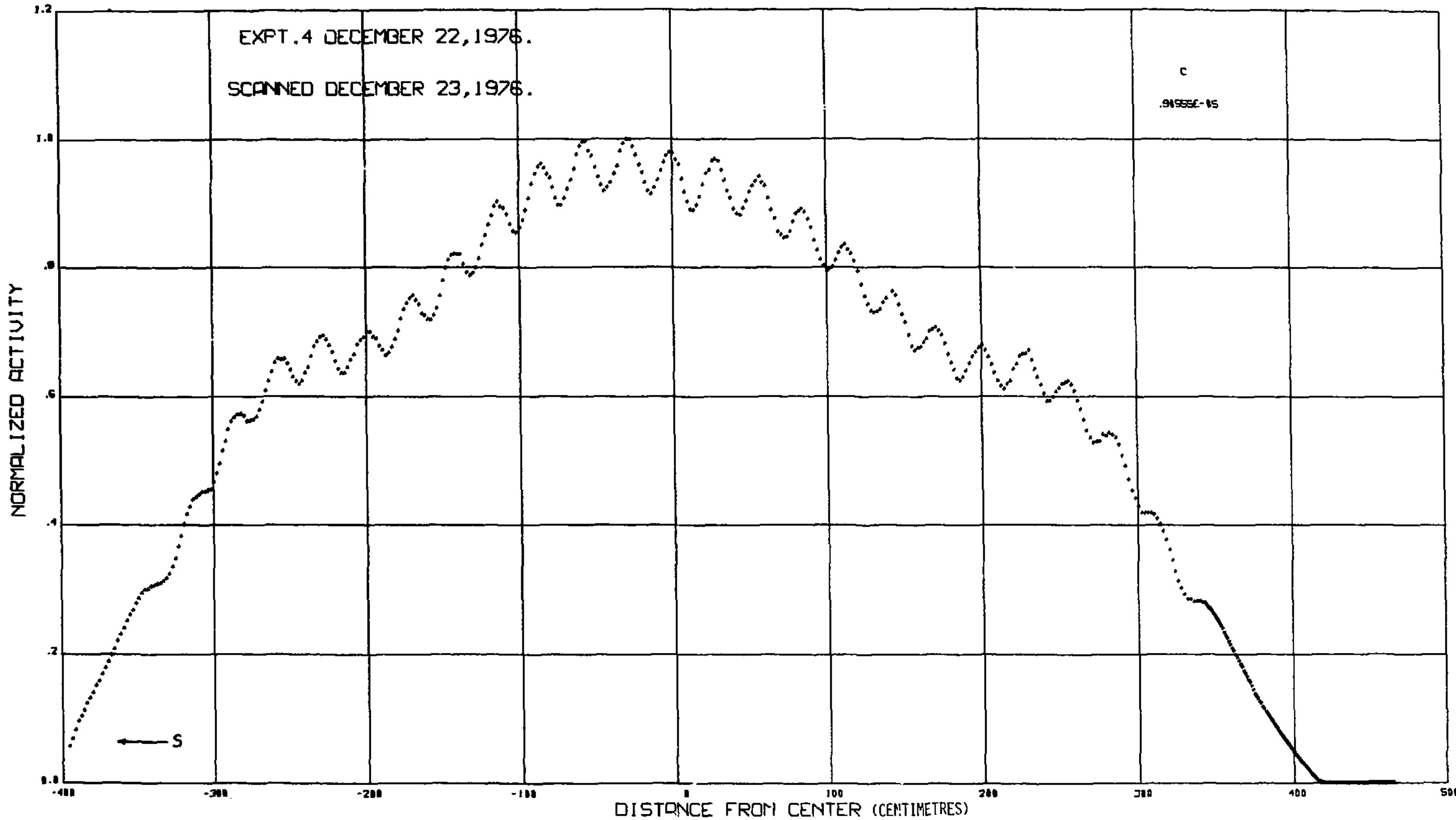

FIG. 12: Flux distribution with 15 booster rods inserted. The distance from the center is in centimetres.

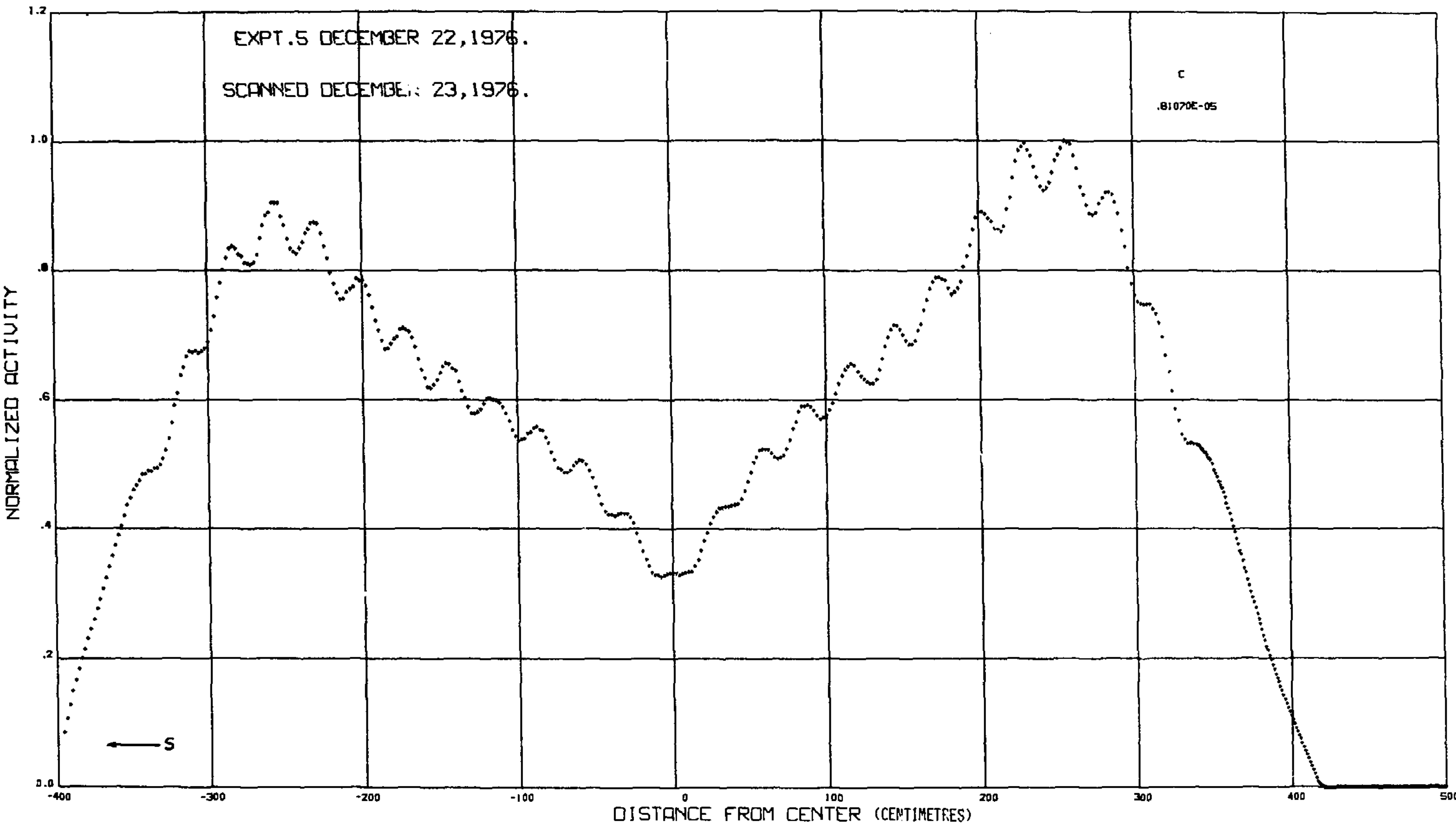

FIG. 13: Flux distribution with control absorbers CA3 and CA4 50% inserted.
The distance from the center is in centimetres.

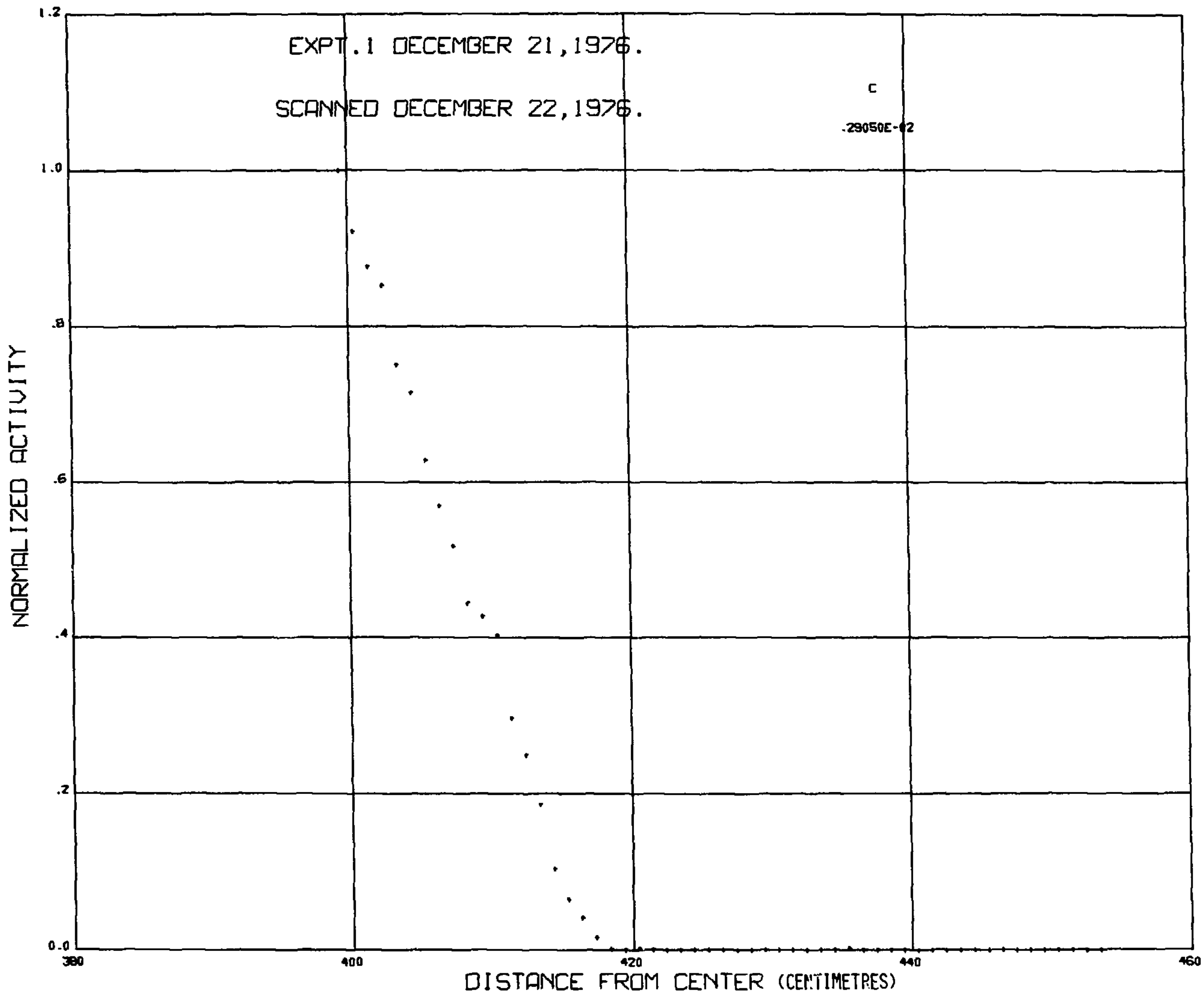

FIG. 14: Experiment 1 flux distribution in the reflector. The distance from the center is in centimetres.

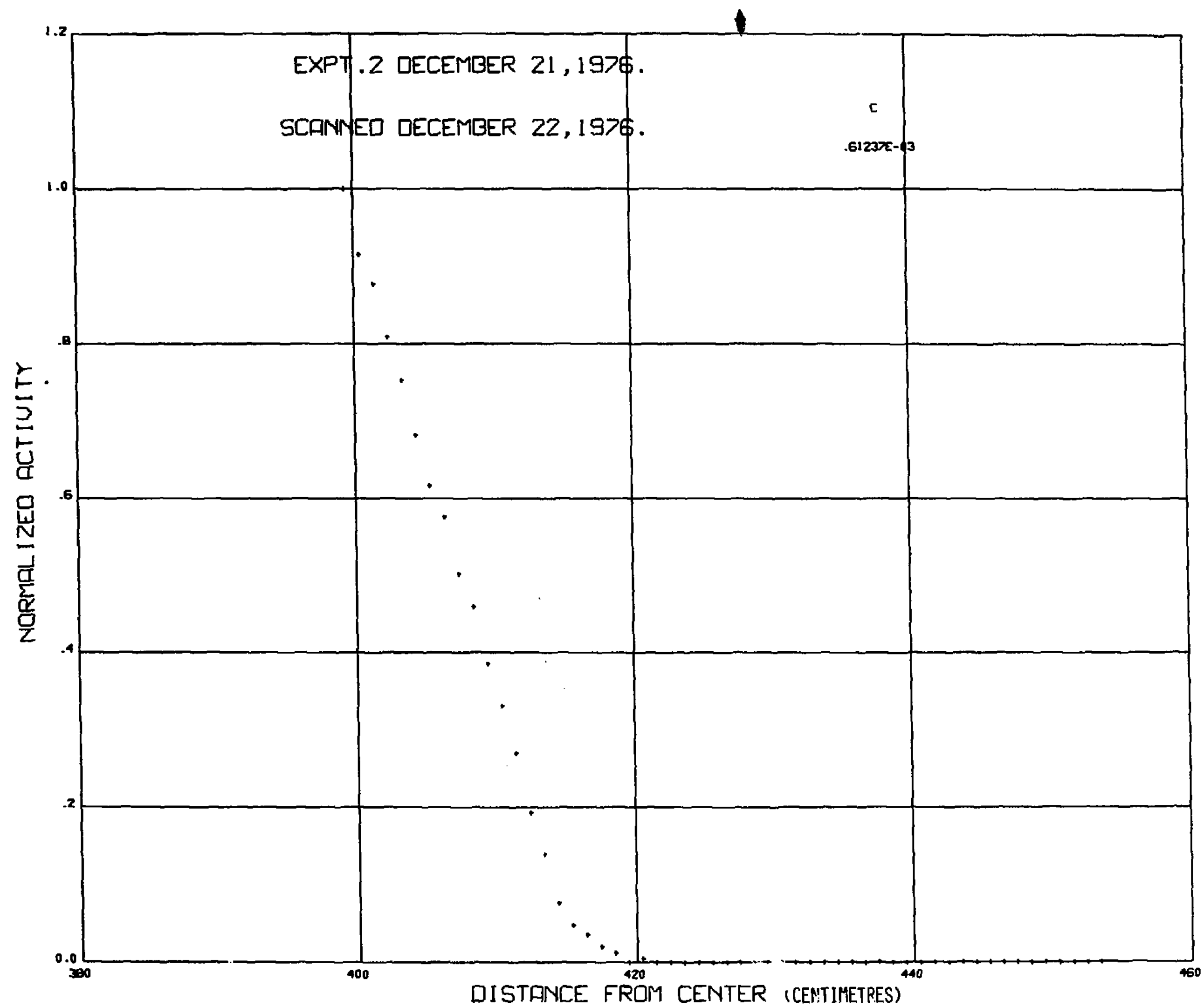

FIG. 15: Experiment 2 flux distribution in the reflector. The distance from the center is in centimetres.

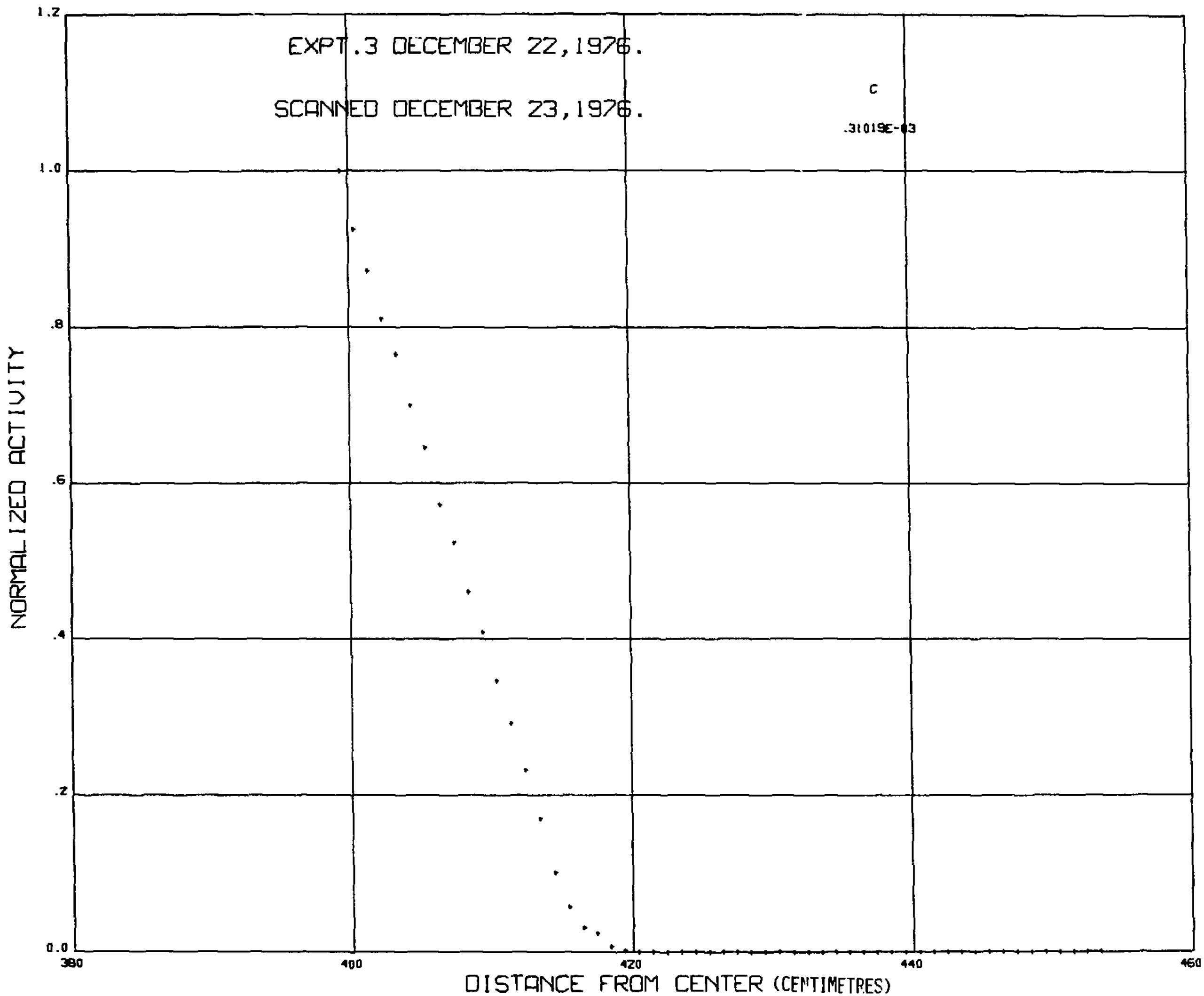

FIG. 16: Experiment 3 flux distribution in the reflector. The distance from the center is in centimetres.

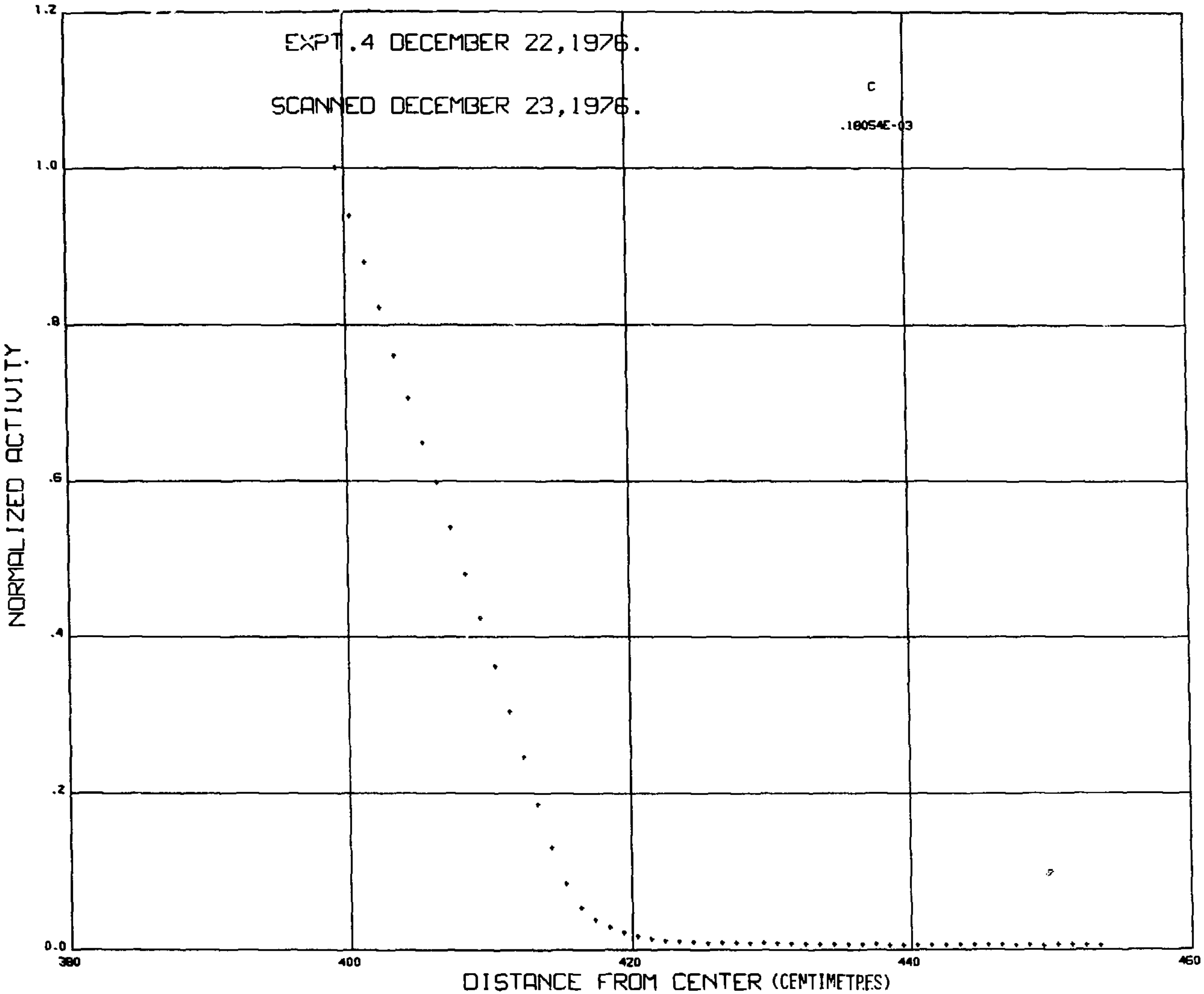

FIG. 17: Experiment 4 flux distribution in the reflector. The distance from the center is in centimetres.

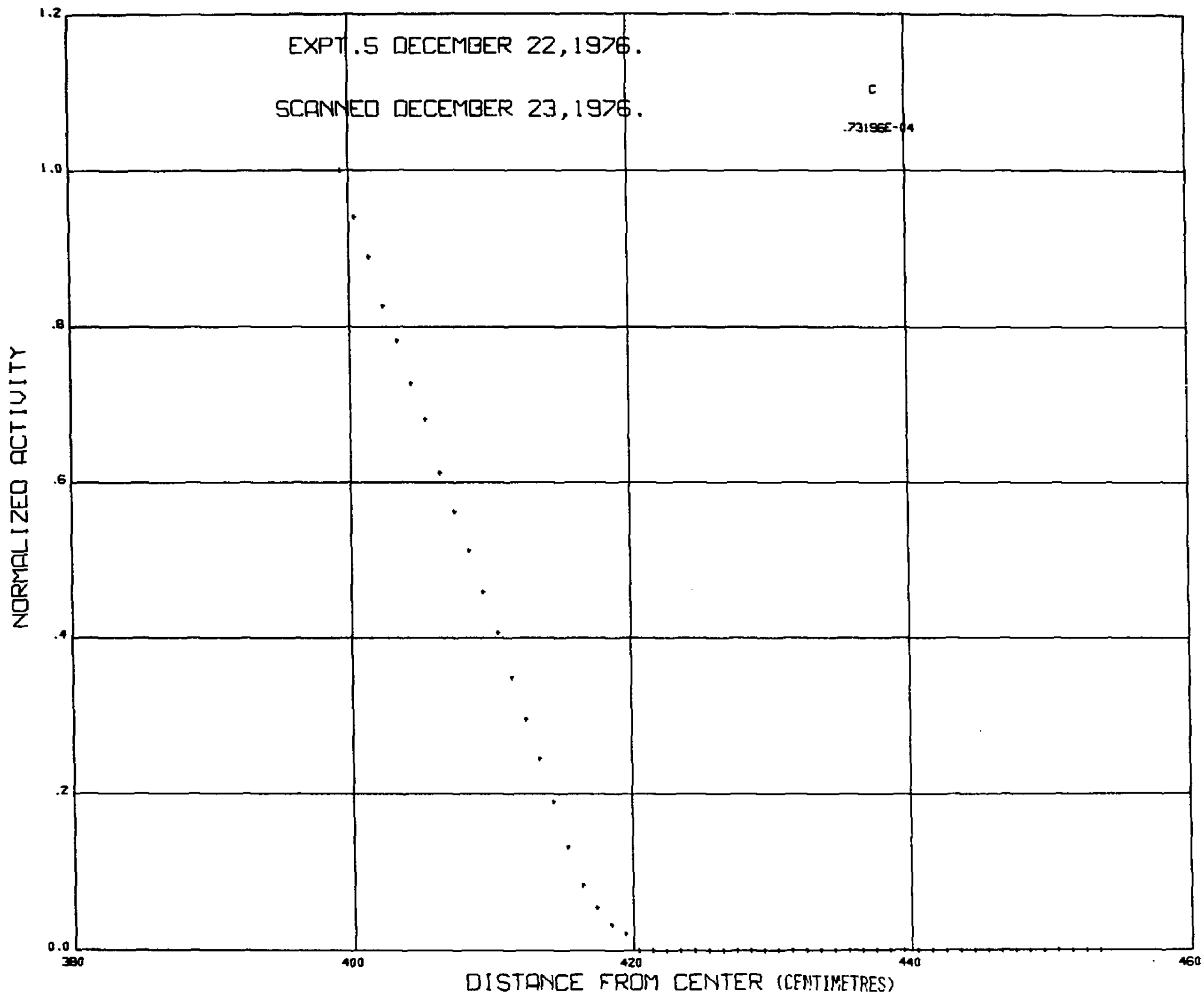

FIG. 18: Experiment 5 flux distribution in the reflector. The distance from the center is in centimetres.

The International Standard Serial Number

ISSN 0067–0367

has been assigned to this series of reports.

To identify individual documents in the series
we have assigned an AECL–number.

Please refer to the AECL–number when
requesting additional copies of this document
from

Scientific Document Distribution Office
Atomic Energy of Canada Limited
Chalk River, Ontario, Canada
K0J 1J0

Price $3.00 per copy

1293-77