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Absolute Power Measurement by Reactor Noise Analysis 〔Translation〕

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Absolute Power Measurement by Reactor Noise Analysis Translation *

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Experimental results are described on the measurement of absolute reactor power by reactor noise analysis. Reactor power is obtained by analyzing the power spectral density of out put current from detector located near a reactor core. Reactor power was measured in range from 50 mW to several hundreds watts and a effect of detector location appeared to be unimportant. Power measured by this method was smaller than power measured by the flux integral method by a factor 0.86. The power meter of JMTR was calibrated by this method before increasing power level. Thermal power was greater than power indicated by the power meter by a factor 1.12.

* previous JAERI-memo 4276 (1971) in Japanese

炉雑音解析による炉出力の測定*〔翻訳〕

大洗研究所材料試験炉部
中田　宏勝

炉雑音を解析して原子炉の出力が測定出来る事は多くの人々によって理論づけられ，国内をはじめ海外でも少なからず実験的に測定が試みられている。昨年本格的稼動に入ったＪＭＴＲでは５０ＭＷ出力上昇への目安として低出力で炉雑音解析を行ない出力計を較正し，熱出力との差が約１割と言う結果を得た。本報告ではそれに先立って行なったJMTRCでの確証実験，特に中性子束積分法による出力値との比較実験の結果及びいくつかの検討結果について述べ，更にＪＭＴＲの第１，第２運転サイクルで行なった出力計の較正及び熱出力との対比の結果を述べる。

* JAERI−memo 4276(1971)の英訳である。

CONTENTS

1. INTRODUCTION

Reactor noise is occured resulting the statistical behavior of neutrons and nuclear reactions. The reactor parameter, such as prompt neutron decay constant, β/ℓ, reactivity, ρ, and stability, can be measured by statistic analysis of neutron behavior. Reactor power is also absolutely measured by reactor noise analysis. For measureing reactor power absolutely at low power level, it is usually that many foils are inserted into active region of the reactor to measure a neutron flux distribution and to calculate a fission rate with fission cross-section (we call this method of reactor power measuring "foil activation" in this report). By reactor noise analysis reported in this paper, a reactor power will be obtained with less time and more simply than foil activation within suitable accuracy.

A method of reactor noise analysis is based on the fact that a relative fluctuation of reactor power is inversely proportional to a absolute reactor power. The theory of this relation has been clear by C.E. Cohn on the frequency domain.[1] It is also proven that a reactor power is absolutely measured by Rossi-α, which analyze neutron behavior in the time domain, as similarly as a prompt neutron decay constant or a subcriticality.[2] In this case, the power can't be measured in a thermal reactor, but in a fast reactor, because a prompt neutron life time is too long to separate each fission chain. Various author have reported results of reactor power measurement by reactor noise analysis in a thermal reactor.[3,4,5]

In JMTR (Japan Materials Testing Reactor, 50 MW), a reactor noise analysis for reactor power measurement has been developed to calibrate the reactor power meter at low power level. And in JMTRC (Nuclear mock up of JMTR), a reactor noise analysis has been recognized as a basic tool to estimate a power level.

In this paper, many results of experiment carried out in JMTRC and JMTR were reported. And a principle of analysis, method, and a short description of equipment used, were also described.

2. PRINCIPLE

A fluctuation of power meter of the reactor, which is criticaly, can be observed. A fluctuation of power meter is caused by three reasons, say,

i) instrument noise,

ii) detector noise, and

iii) reactor noise.

Instrument noise is rather smaller than others in a case of not so low detector current. Detector noise and reactor noise are independently each other, but each of them is proportional to detector current. A ratio of reactor noise to detector noise is varied mainly correspond to a position of detector in the reactor. A fluctuation of power meter, which detector is usually positioned far from the reactor core, is almost consist of a detector noise. A detector must be placed close to the reactor core to observe a reactor noise.

Reasons of reactor power fluctuation are divided into two category, they are inherent and exterior. Futher, inherent reasons are

1) random occurrence of nuclear reactions with neutrons, such as production, absorption and leakage, and

2) variation of neutrons released from a fission process, ν .

However, in a case of a reactor operated at high power, in addion to aboved inherent reasons, a reactor power is fluctuated by the mechanical vibration of reactor structures caused by coolant flow, fluctuations of temperature or density of coolant and some power feed-back effects. In a case of so-called zero power reactor, reasons of reactor power fluctuation are only inherent. Then some reactor constant including absolute reactor power can be obtained from analysis of reactor power fluctuation, reactor noise.

The priciple of absolute power measurement by reactor noise analysis is given as follow by C.E. Cohn.

The production, absorption, and leakage of neutrons in a reactor may be considered analogous to the random flow of electrons in a diode, because all of these processes obey the Poisson distribution. Therefore, the magnitude of the noise-equivalent source may be obtain from the Schottky formula,

$$\langle |I|^2 \rangle = 2 e^2 \overline{m} ,$$

where $\langle |I|^2 \rangle$ is the spectral density of the diode current noise, qi is the charge carried by each electrons, and $\overline{m}$ is the average number of electrons per second. For calculating the noise equivalent reactor source, the formula will appear in the form

$$\langle |So|^2 \rangle = 2 \sum_i qi^2 \, \overline{mi} . \qquad (1)$$

Here $\langle |So|^2 \rangle$ is the spectral density of the noise equivalent source, qi is the net number of neutrons produced in the occurrence of one nuclear reaction of type i, and $\overline{mi}$ is the average number of reactions of type i occurring per second in the reactor. The summation is taken over all possible types of nuclear reactions which may occur in the reactor. Absorption, production, and leakage are most important reactions. These reactions may be divided into two category; The one is productive and the other is non productive. Next table is made with this argument.

i	$\overline{mi}$	qi
productive (fission)	$\frac{N}{\ell} \frac{F}{A+F} P\nu$	$\nu - 1$
non-productive	$\frac{N}{\ell} \frac{A}{A+F}$	-1

In this table, N is the total number of neutrons in the reactor, ℓ is the prompt neutron lifetime, A is the macroscopic cross section for all nonproductive reactions, F is the macroscopic cross section for productive reaction, fission, and $P\nu$ is the probability that ν prompt neutrons will be produced in any one fission. Substituting the quantities in the above table into the equation (1), the following formula may be obtained,

$$\langle |So|^2 \rangle = \frac{2N}{\ell} \cdot \frac{\overline{\nu^2} - \overline{\nu}}{\overline{\nu}} \qquad (2)$$

The spectral density of the equivalent reactivity fluctuations may be obtained from the expression

$$\langle |\rho|^2 \rangle = \left(\frac{\ell}{N}\right)^2 \langle |So|^2 \rangle .$$

because a small reactivity fluctuation ρ can be looked upon as supplying to a critical reactor a source of strength $\rho N/\ell$ neutrons per second so long as the resulting fluctuation in N remains small. This yields

$$\langle|\rho|^2\rangle = \frac{2\ell}{N}\cdot\frac{\overline{\nu^2}-\overline{\nu}}{\overline{\nu}} \tag{3}$$

On the other hand, since $N/\overline{\nu}\ell$ is the number of fission occured in the reactor per second, the next relation may be written,

$$3.1\times10^{10}P = \frac{N}{\overline{\nu}\ell} \tag{4}$$

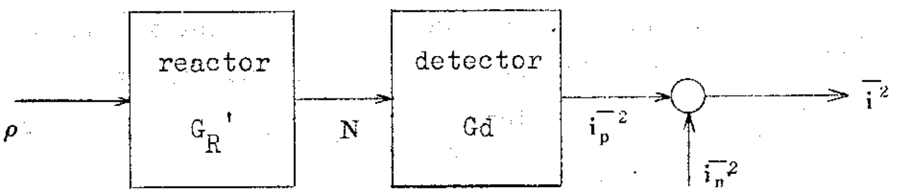
where P is the reactor power in watts. Combining equation (3) and (4) leads the final relation, that is,

$$\langle|\rho|^2\rangle = \frac{2}{3.1\times10^{10}P}\cdot\frac{\overline{\nu^2}-\overline{\nu}}{(\overline{\nu})^2} \tag{5}$$

Therefore, the reactor power, P , may be obtained from estimating value of reactivity fluctuation by reactor noise analysis.

3. DETECTION OF REACTOR NOISE

The reactivity fluctuation is detected as follows. The detecting system is shown in the next diagram.



Here G_R' is the transfer function of the reactor, Gd is the transfer function of the detector, $\overline{i_p^2}$ is the reactor noise component of the detector output, and $\overline{i_n^2}$ is the detector noise component. The total noise of the detector output, $\overline{i^2}$, is written by

$$\overline{i^2} = \overline{i_p^2} + \overline{i_n^2} \tag{6}$$

$\overline{i_p^2}$ includes the imformation of the reactor noise, that is, because a small reactivity fluctuation ρ can be looked upon as supplying to a critical reactor a source of strength $\rho N/\ell$ neutrons per second so long as the resulting fluctuation in N remains small. This yields

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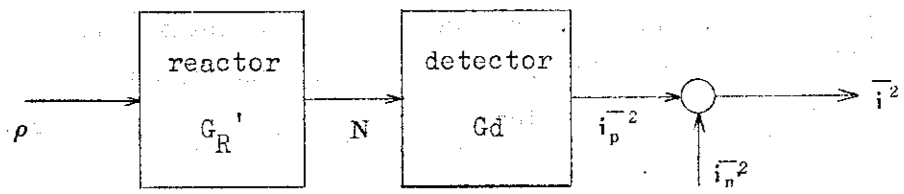

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$\overline{i_p^2}$ includes the imformation of the reactor noise, that is,

$$\overline{i_p^2} = |Gd|^2 \cdot <|N|^2>$$
$$= |Gd|^2 \cdot |G_R'|^2 \cdot <|\rho|^2> .$$

Let $|G_R|$ define the reactor transfer function divided by N , then $\overline{i_p^2}$ may be expressed by

$$\overline{i_p^2} = i_o^2 \cdot |G_R|^2 \cdot <|\rho|^2> , \quad (8)$$

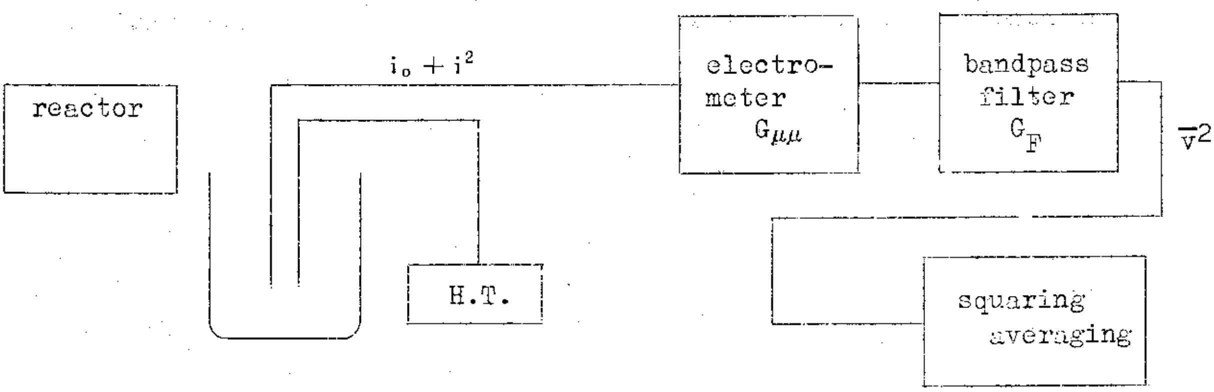
because the transfer function of the detector may be expressed by $|Gd| = i_o/N$ (i_o is the average detector output current). On the other hand, the detector noise component. $\overline{i_n^2}$, is written as follow by analogy with the Schottky formula on a diode,

$$\overline{i_n^2} = 2 q_o i_o , \quad (9)$$

where q_o is the average charge produced per neutron absorbed in the detector. Then, the total noise of the detector output is expressed

$$\overline{i^2} = \overline{i_p^2} + \overline{i_n^2}$$
$$= i_o^2 |G_R|^2 <|\rho|^2> + 2 q_o i_o$$
$$= i_o^2 |G_R|^2 \frac{2}{3.1 \times 10^{10} P} \frac{\overline{\nu^2} - \overline{\nu}}{(\overline{\nu})^2} + 2 q_o i_o . \quad (10)$$

The output of the detector is lead to the noise analyzer, which consists of electrometer, bandpass-filter, squaring-averaging circuit, and high voltage power supply for the detector. A typical arrangement of analyzer is shown in the next diagram.



The power of noise at the outlet of the bandpass filter is shown by

$$\overline{v}^2 = \int_0^\infty |G_F|^2 \cdot |G_{\mu\mu}|^2 \cdot \overline{i}^2 \, d_f . \tag{11}$$

Where G_F is the transfer function of the bandpass filter, and $G_{\mu\mu}$ is the transfer function of the electrometer. The squaring-averaging circuit is calibrated with noise signal known it's mean-square value. The output of the squaring-averaging circuit is converted to input by the calibration table previously obtained.

Substituting the quation (10) into the equation (11) the next relation may be obtained,

$$\overline{v^2} = \int_0^\infty |G_F|^2 \cdot |G_{\mu\mu}|^2 \cdot (i_o{}^2 \cdot |G_R|^2 \cdot \frac{2}{31 \times 10^{10} P} \frac{\overline{\nu^2} - \overline{\nu}}{(\overline{\nu})^2} + 2 q_o i_o) \, d_f \tag{12}$$

Because i_o, $\frac{2}{31 \times 10^{10} P}$, $\frac{\overline{\nu^2} - \overline{\nu}}{(\overline{\nu})^2}$, and $2 q_o i_o$ seem to be independent of frequency,

$$\overline{v}^2 = i_o{}^2 \cdot \frac{2}{3.1 \times 10^{10} P} \cdot \frac{\overline{\nu^2} - \overline{\nu}}{(\overline{\nu})^2} \int_0^\infty |G_F|^2 \cdot |G_{\mu\mu}|^2 \cdot |G_R|^2 \, d_f$$

$$+ 2 q_o i_o \int_0^\infty |G_F|^2 |G_{\mu\mu}|^2 \, d_f$$

Let $I_1 \equiv \int_0^\infty |G_F|^2 \cdot |G_{\mu\mu}|^2 \cdot |G_R|^2 \, d_f$

$$I_2 \equiv \int_0^\infty |G_F|^2 \cdot |G_{\mu\mu}|^2 \, d_f$$

Then the above equation may be rewritten as,

$$\overline{v}^2 = i_o^2 \frac{2}{3.1 \times 10^{10} P} \frac{\overline{\nu^2} - \overline{\nu}}{(\overline{\nu})^2} I_1 + 2 q_o i_o I_2 \tag{13}$$

The reactor power, P, then may be obtain from the next equation,

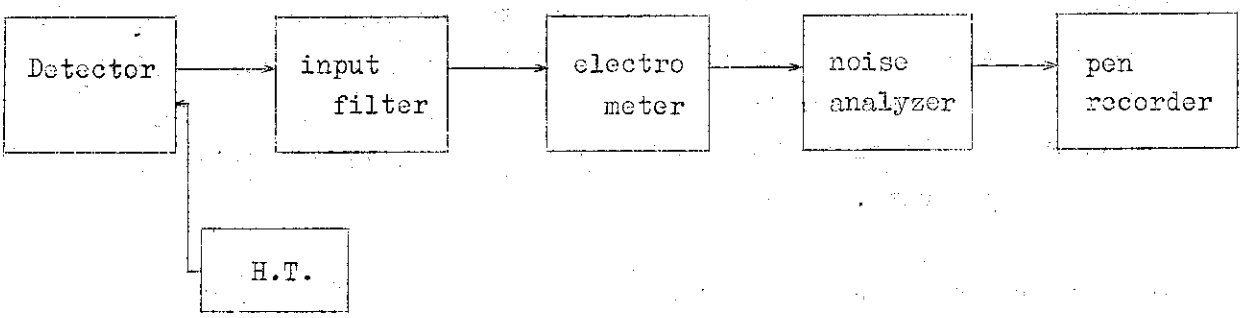
$$P = \frac{i_o{}^2 \frac{2}{3.1 \times 10^{10}} \frac{\overline{\nu^2} - \overline{\nu}}{(\overline{\nu})^2} I_1}{\overline{v}^2 - 2 q_o i_o I_2} \tag{14}$$

Before measuring the reactor power, the value of I_1, I_2, and q_o is must known. I_1 and I_2 may be calculated from $|G_R|$, $|G_{\mu\mu}|$ and $|G_R|$, which are measured or calculated. The q_o of the detector to be used may be measured by analysis of the output of the detector located near a neutron source, which emits neutrons steadily, such as Am-Be. In such a case, the reactor noise component in the equation (13) seems to be zero. Therefore, the q_0 may be calculated form the next relation,

$$q_0 = \frac{\overline{v^2}}{2\, i_0 I_2} \tag{15}$$

4. NOISE ANALYZER

The arrangement of measuring system is shown as following,



and the schematic diagram of analyzer and input filter are also shown in the Fig-1. The type WL-6377 manufactured by Westinghouse is used for detector. The time constant of the input filter is 10 seconds, so that the attenuation of the input filter for a signal, whose frequency is more than 1 H_Z , is negligible. The voltage drop across the by pass resistor is about 100V for maximum detector output and has no effect for a saturation characteristics of the detector. The band pass filter of the noise analyzer is a twin T type and it's selectivity, Q, is 10. A center frequency of the band pass filter is variable as discrete. A effective band width of a tunning type filter is shown as,

$$B = \frac{\pi}{2} \frac{f_0}{Q} . \tag{16}$$

A characteristic of the band pass filter at 4 H_Z center frequency is shown in Fig. 2. The diode type squaring circuit is calibrated with the noise signal known it's mean-square value. The time constant of the averaging-circuit is selected as 200 seconds. The statistical variation of the averaging circuit output is estimated with the next relation.

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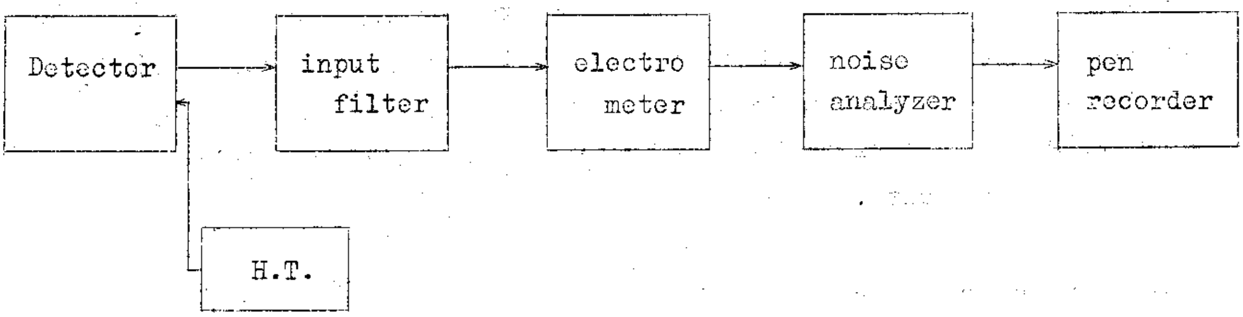

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where σ is a relative variation of the output, B is the band width of the band pass filter, and T is a time constant of the averaging-circuit. For the band pass filter of 4 H_Z, $\sigma = \pm 4.2$ %.

5. EXPERIMENTAL RESULTS

5.1 Measurement of detector noise

With 4 C_i Am-Be neutron source, the spectral power density of the detector output was measured at various output current and is shown in Fig.-3. The detector noise is clearly independent of frequency as discussed before and the value of q_0, average charge produced per neutron absorbed in the detector, was obtained as $(4.1 \pm 1.0) \times 10^{-15}$ coulomb. The break down frequency of the spectrum shown in Fig-3 corresponds to the rise-time of electrometer dependent on it's gain and a input capacity.

5.2 Measurement of reactor noise

The reactor noise of the JMTRC has been measured. The detector, which q_0 has been obtained as above was located near the fuel region. The spectral power density of reactor noise is shown in Fig-4. The detector noise component was subtracted from the spectral density measured to obtain the reactor noise. The reactor-noise to detector-noise ratio at 4 H_z, $\overline{i_p^2}/\overline{i_n^2}$ $(4H_z)$ was about 12. Using the spectral density of reactor noise correspond to 4 H_z, the reactor power was obtained as 0.89 Watts to be campared with the nominal reactor power of 1 Watts. And for 10 Watts, it was obtained as 7.6 Watts.

5.3 Effect of detector noise

Considering equation (10) again, it is clear that the reactor noise component is proportional to square of i_o and the detector noise component is proportional to i_o. That is to say the reactor-noise to detector-noise ratio, $\overline{i_p^2}/\overline{i_n^2}$ is proportional to i_o. To obtain high ratio, therefore, it is necessary that the detector is located near the reactor core. The next table shows that $\overline{i_p^2}/\overline{i_n^2}$ must be greater than one to obtain the correct power.

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i_o (A)	P (A)	$\overline{i_p^2}/\overline{i_n^2}$
1.7×10^{-7}	4.18	4.16
0.5×10^{-7}	4.42	1.14
1.7×10^{-8}	3.87	0.44
0.5×10^{-8}	—	—
1.7×10^{-9}	—	—

This measurement is carried out under the condition of constant reactor power. In a case of last two line in this table, the reactor noise component could not be calculated because the noise measured is nearly equal to the detector noise.

5.4 Effect of detector location

In the above discussion, the dynamics of reactor is treated as a one-point model. It may be correct that the space dependence of reactor dynamics is out of consideration in a case of our reactor, which core is very small. To observe the dependency of detector location on reactor noise analysis, the noise-signal from the detector located various position was analyzed. The next table shows the result of this observation.

detector location	i_o (A)	P (W)	$\overline{i_p^2}/\overline{i_n^2}$
A	1.36×10^{-6}	4.04	34.6
B	1.02×10^{-7}	3.97	2.61
C	0.95×10^{-7}	4.24	2.28

This observation was also carried out under the condition of constant reactor power. The detector location is illustrated in Fig-5. From this observation, it is clear that a effect of detector location is unimportant.

5.5 Limitation on power measurement

There is no limitation on reactor power measurement in principle. However, the sensitivity of the electrometer limits a lower power to be able to analyze, and further it is difficult to keep the reactor to be critical because it's large fluctuation at very low power. At high power, the voltage drop across the by pass resister of the input filter becomes very large so that the effect for a saturation characteristic of the detector can't be negligible, and the fluctuations of temperature or density of coolant cause another power fluctuation, where the principle equation (5) can't be applied.

According to our experiments, the power range to be able to analyze is from about 50mW up to several hundreds watts. Power in this range were obtained with relative variance of 2.4%.

5.6 Comparison with foil-activation

Reactor power measured by noise analysis were compared with that measured by foil-activation to testify the propriety of noise analysis method.

The distribution of thermal neutron flux have been measured with gold foils and copper tapes, and then the fission rate in the reactor, or reactor power, were calculated with fission cross-section of U-235 being corrected for the depletion effect of neutron flux on the fuel, the contribution of non-thermal fission effect, and so on.

Many comparisions were carried out in many core configurations of JMTRC and the results are shown in Table-1. The average ratio of power by noise analysis to that by foil activation, A/B in Table-1, is 0.86 with variance of 0.07. Considering the accuracy of power measured by foil-activation, the value of the ratio, 0.86, does not reject the reactor noise analysis as a mean of absolute reactor power measurement.

Table-1 Comparision with foil activation

No	by noise analysis A (W)	by foil activation B (W)	A/B
1	3.83	5.00	0.77
2	3.80	4.92	0.77
3	3.86	5.00	0.77
4	3.73	4.68	0.80
5	3.90	4.42	0.88
6	4.18	4.50	0.93
7	3.24	3.28	0.99
8	2.50	2.84	0.88
9	3.04	3.40	0.89
10	1.86	2.65	0.70
11	5.03	2.76	1.82
12	5.36	5.65	0.95
13	2.82	3.51	0.80
14	1.71	2.18	0.78
15	1.71	2.18	0.78
16	3.80	5.53	0.69
17	3.67	5.34	0.69
18	3.61	5.00	0.72
19	4.04	5.23	0.77
20	3.71	4.09	0.91

6. CALIBRATION OF POWER METER

The power meter of JMTR, which went to critical on March 1968, was calibrated by noise analysis before increasing power level. The neutron detectors of the power meter are located far from the reactor core, then, the extra neutron detector used in the experiments described above was inserted close to the reactor core for reactor noise analysis.

The signal from the extra detector was analyzed to obtain reactor power level just after the reactor went to critical. Subsequently, the sensitivity of the power meter was adjusted to indicate the power obtained by noise analysis.

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11	5.03	2.76	1.82
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The signal from the extra detector was analyzed to obtain reactor power level just after the reactor went to critical. Subsequently, the sensitivity of the power meter was adjusted to indicate the power obtained by noise analysis.

The reactor power was increased to the thermal output of 50MW step by step. At each step, the thermal output was calculated by $\Delta T \times Q$ after the system had reached to the thermal equilibrium, and was compared with the indication of the power meter. The thermal out put was greater than the indication of the power meter, which had been calibrated by noise analysis, by a factor of 1.12 ± 0.04. This inconsistency seems to be chiefly caused by the error of noise analysis. The gain of the noise analyzer and the reactor transfer function, and the value of the energy releared from a fission are expected as factors of the error of noise analysis, but not proven.

7. CONCLUSION

From the above experiments and discussions, the usefulness of reactor noise analysis on power measurement was proven. However, there are several problems such as

i) accuracy of power obtained, that is, the power obtained rather smaller than that obtained by foil-activation or thermal output,

ii) insertion of large neutron detector to a reactor core to detect reactor noise at high efficiency, and

iii) limitation of measurable power range up to several hundred watts.

The second of these problems seems to be overcome with the two-detector technique developed recently.[6]

8. REFERENCES

1. C. E. Cohn; A Simplified Theory of Pile Noise, N. S. E. 7, 472～475 (1960)
2. Iijima ; Basic consideration of Rossi-α, JAERI-memo 3217
3. R. Schröder; Bestimmung der Reaktorleistung mit Hilfe des Reaktorrauchens, NUKLEONIK 227～227 Band 4, Heft 5
4. V. E. Robin; Neutronenrauschanalyse in Verzögert kritischen Kern des FDR, ATOMKERNENERGIE 13 Jg. (1968) H.5

The reactor power was increased to the thermal output of 50MW step by step. At each step, the thermal output was calculated by $\triangle T \times Q$ after the system had reached to the thermal equilibrium, and was compared with the indication of the power meter. The thermal out put was greater than the indication of the power meter, which had been calibrated by noise analysis, by a factor of 1.12 ± 0.04. This inconsistency seems to be chiefly caused by the error of noise analysis. The gain of the noise analyzer and the reactor transfer function, and the value of the energy releared from a fission are expected as factors of the error of noise analysis, but not proven.

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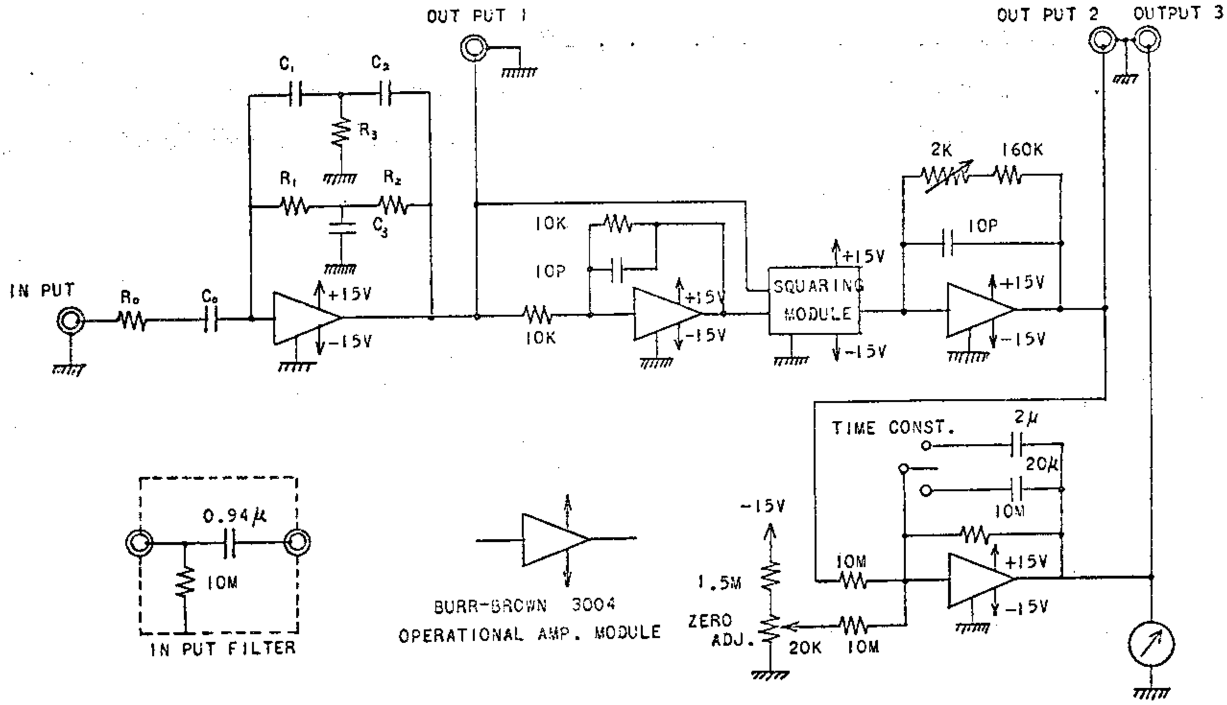

FIG. 1 SCHAMATIC DIAGRAM OF NOISE ANALYZER

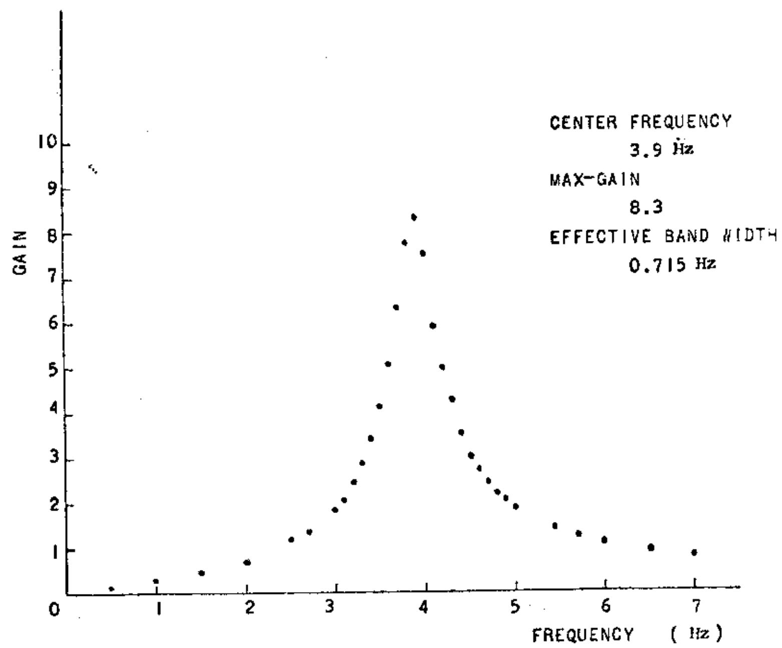

FIG.2 CHARACTERISTIC OF 4Hz BAND PASS FILTER

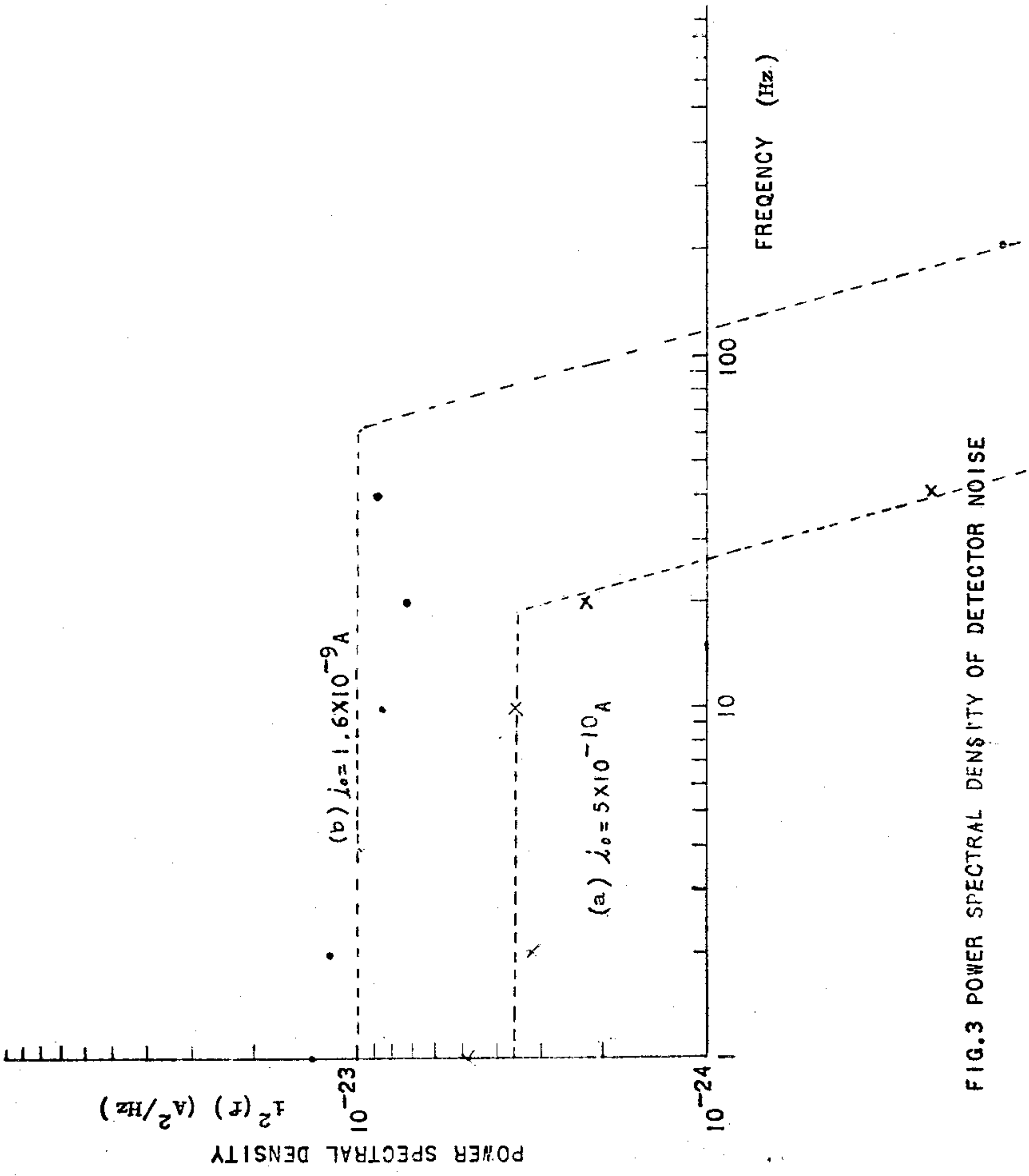

FIG.3 POWER SPECTRAL DENSITY OF DETECTOR NOISE

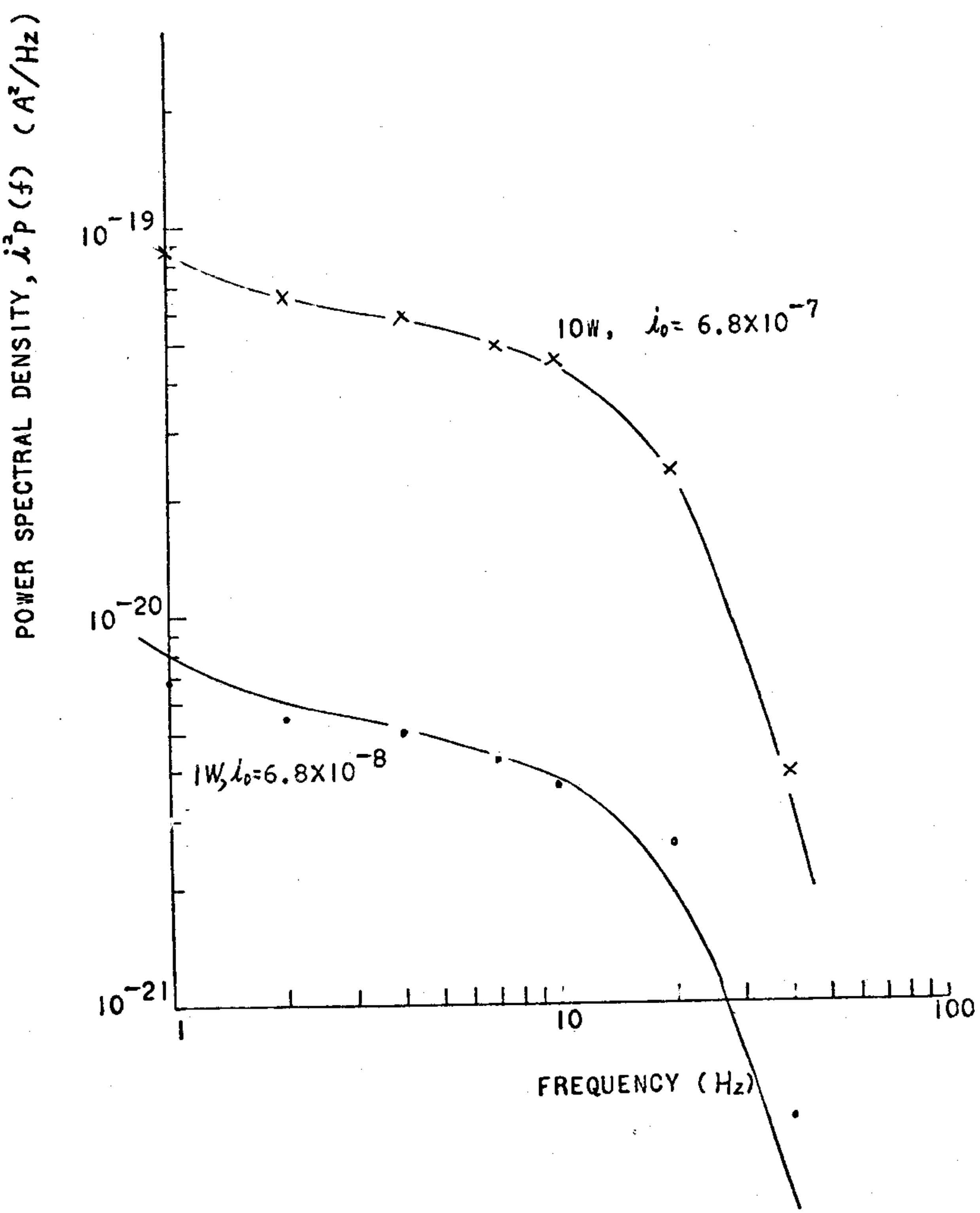

FIG.4 POWER SPECTRAL DENSITY OF REACTOR NOISE

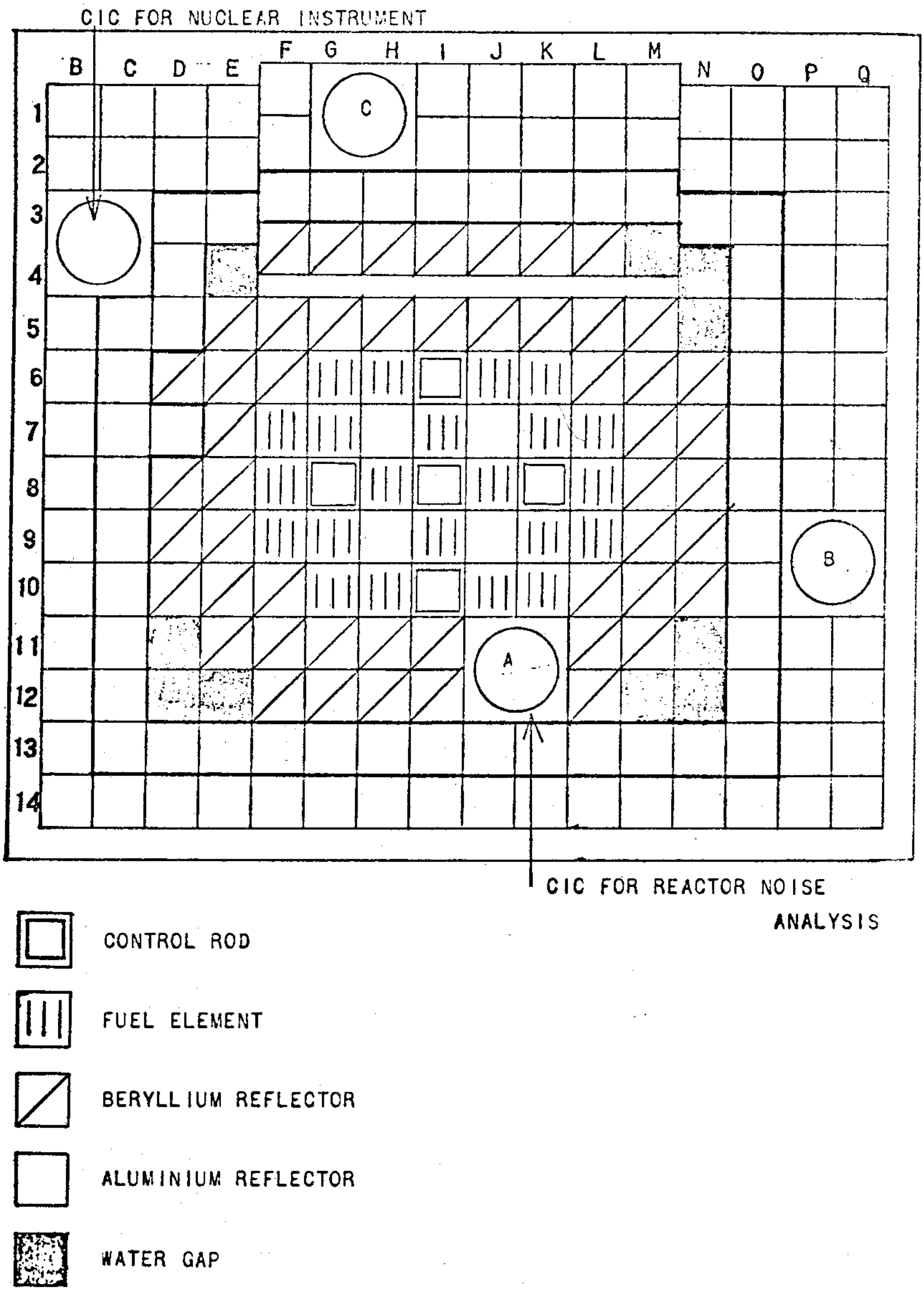

FIG.5 CORE CONFIGURATION OF JMTR