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VERIFICATION OF CORE-FUEL INVENTORY OF A FAST CRITICAL FACILITY BY MONITORING REACTOR PHYSICS PARAMETERS

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On the safeguards problem, a technical feasibility was studied for experimentally verifying core-fuel inventory of a fast critical facility. The FCA Assembly VIII-1 with plutonium-fueled test zone was used for this purpose. Six loading patterns were chosen in the verification experiment to simulate the diversion of Pu-fuel from the core. The Pu-fuel removed from the core was about 3.5 ~ 5.8 kg. Verification techniques are based on the monitoring of small changes in fission rates and β/ℓ caused by the diversion of some amount of Pu-fuel. The fission rates were measured by a fission chamber technique with a hundred ^{239}Pu fission chambers located in the core region and multi-chamber scanning electronics, while β/ℓ values were measured by power noise analysis with two herium-3 chambers.

The verification experiment indicates that the fission rates and β/ℓ monitor well follow the quantities of plutonium removed from the core. It is concluded that the verification of core-fuel inventory is feasible by using the present monitoring method.

Keywords : Safeguards, Core-Fuel Inventory, Verification, Fast Critical Facility, Pu-Fuel, Removal, Monitor, Fission Chambers, β/ℓ, Power Noise Analysis.

炉物理パラメータの監視による高速炉臨界実験装置の炉心燃料インベントリーの検証

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（1982年10月13日受理）

保障措置の問題に関して，高速炉臨界実験装置の炉心装荷燃料インベントリーを実験的に検証するための技術的可能性を検討した。本目的のために，プルトニウム燃料装荷の試験領域を有するＦＣＡ Ⅷ－１集合体を使用した。プルトニウム燃料の転用を模擬する６種の装荷様式を選び，検証試験に供した。炉心から移動したプルトニウム燃料は約3.5～5.8 kgである。検証法は，プルトニウム燃料を移動した事により生ずる核分裂率とβ/ℓの変化を監視する事に依っている。核分裂率は，炉心内に設置した100個の^{239}Pu核分裂計数管と多計数管掃引装置を用いた核分裂計数管法により測定し，一方，β/ℓは２個のヘリウム－３計数管を用いた出力炉雑音解析法により測定した。

検証実験の結果，核分裂率及びβ/ℓ監視システムは炉心からの移動プルトニウム量を正しく検知している。以上から，本監視システムの使用により炉心装荷燃料インベントリーの検証が可能であるとの結論を得た。

Contents

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1. Introduction

Core inventory monitor that may predict the removal of SNM from the core by monitoring changes in various reactor physics parameters, has been proposed as an advanced safeguards instrument with a realtime inventory verification capability. Regarding safeguards standpoint, procedure using the core inventory monitor has been reported elsewhere(1). JAERI research program of this core inventory verification technique includes;

(1) Theoretical sensitivity analysis for the SNM removal from the core region,

(2) Experimental demonstration of this technique.

(3) Development of the technique as a routine safeguards tool.

In addition to the JAERI research program a research agreement has been provided to prove that the technique is to be reliable and adequate to the objective and criteria for the IAEA safeguards.

The present report describes an experimental demonstration on core-fuel inventory verification by the use of technique for reactor physics parameter monitoring.

2. FCA Assembly* VIII-1

The assembly FCA VIII-1 was built for demonstrating the technical feasibility of core inventory verification by monitoring reactor physics parameters. The reference configuration of FCA VIII-1 is shown in Figs. 1 and 2. As usual at FCA, zone loading configuration is adopted for FCA VIII-1 assembly. The height for core is about 90cm. The drawer makeup patterns for the reference configuration are shown in Fig.3 and Fig.4. The as-build critical mass is about 47kg of U^{235} and 104kg of Pu-fissile.

Since FCA VIII-1 was built as the initial assembly for core inventory monitor, very frequent changes of core configurations were expected to take place in order to realize various modes of fuel removal from the core region under the constraint condition of the constant multiplication factor. Therefore, the assembly size of FCA VIII-1 was chosen to be not so large as to be built using all fuel inventory at FCA.

In the core region of the assembly VIII-1, about 100 fission chambers are built-in. The fission chambers used for the measurement are parallel plate type as shown in Fig.5. The outer dimension of the chamber is

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* The term "Assembly" used to be comprehensive expression of a system built at FCA for experiments whose configuration includes core, blanket, reflector, shield and so forth depending on the purpose of experiment.

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51mm x 51mm x 9.5mm thick. About 150μg of plutonium dioxide is coated on the electrode and the working voltage is about 300V. These fission chambers are loaded in the fuel drawers for providing instrumented drawers. Interstitially between fuel cells, five fission chambers can be loaded per instrumented drawer. A typical instrumented drawer is shown in Fig. 6.

As seen in Fig.*7a* and *7b*, the void space of 1/4" wide x 1" hight is provided along inside instrumented drawer for accomodating signal cables to a head amplifier located at the end of the drawer. Signals necessary for controlling fission chamber counting and for interrogation of various functions are fed into the head amplifier through Computor Aided Measurement and Control (CAMAC) interface from the computer FACOM-U/200. The locations of the instrumented drawers in the assembly VIII-1, are shown in Figs.1 and 2 as MCSS Drawer.

The two sets of He^3 neutron counters used for measuring β/ℓ by means of the cross correlation technique are also loaded in the assembly VIII-1 and the locations of the He^3 counters are shown in Fig.1.

The main purpose of the assembly VIII-1 are as follow;

(1) to demonstrate technical feasibility for detecting the removal of significant quantity of SNM from the core region by monitoring the fission rate spatial distribution and the value of β/ℓ when the multiplication is held constant,

(2) to examine reliability, reproducibility and vulnerability of instrumentations for safeguards purpose and impacts on the proper purposes of the facility.

3. Removal Pattern of SNM from Core

When a certain amount of nuclear material is removed from the reference core, reactivity will decrease. Then such removal will easily be detected as an change in the multiplication factor, i.e. the change of control rod critical position. For example, one plutonium fuel plate (2" x 2" x 1/16", about 32gr of fissile plutonium) removed from the core center turns out the change of the CR#1 control rod position about 10mm that is equivalent to $10^{-2}\%\Delta k/k$, as seen in Appendix A.

When the significant amount of SNM is removed from the reference configuration, therefore, it is necessary to compensate the reactivity loss by means of a certain manner in order to hold the criticality of the assembly. For compensating reactivity loss due to fuel removal from the core region, polyethylene and carbon are added to the core in assembly VIII-1. However such compensation is not so easy because the space available in the fuel drawer and physical

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characteristics of material to be added to the core are constrained. Furthermore, reactor physics properties of hydrogeneous material have not been well known in the fast reactor cores, so that it is difficult to predict the compensation drawer makeup pattern only by means of analysis. Therefore the drawer patterns used to compensate the removal of the fuel drawer "T" in Fig.3 from the core are empirically determined by the measurement of a drawer reactivity worth and these are shown in Fig.8 and Fig.9.

Replacing some T-type fuel drawers in the core with PD6 or PD4-type drawers, six different cores shown in Fig.10, 11, 12, 13, 14 and 15 are used to simulate removal of plutonium from the core. The amount of plutonium removal from the core in each case is summarized in Table 1.

4. Measurement of Distortion in Fission Rate Spatial Distribution due to Removal of Fuel

As mentioned in the section 2, about 100 plate type fission chambers have been built in the core region for about three months of the all period of the assembly VIII-1. Prior to the measurement of the distortion in fission rate spatial distribution due to a removal of fuel from the core, the stability of whole counting system has been checked. The drift of a pre-set discrimination level of counting system including the head and main amplifiers has been measured for about two months and the result is given in Table 2. Even through, the drift is about 3%, the error of fission rate counting is less than 0.4%.The ratios of two independent measurements of fission rate spatial distributions in the same reference core are given in Table 3.

The ratios of fission rate spatial distributions measured in the core PD6-10C to those measured in the reference core are given in Table 4. Such ratios in the cores PD4-18A and PD4-16R are also given in Tables 5 and 6. It is interesting that the effect of the CR#1 control rod withdrawal necessary to adjust criticality in the core PD4-16R is clearly seen in the fission rates measured at the drawer position 14 in Table 6.

The measured total counts per each fission chamber vary from several thousands to several ten thousands depending on the location of fission chamber. The time necessary for measuring fission rates distribution at 100 differents positions is about 30 min.

5. Measurement of β/ℓ

In principle, the value of β/ℓ can be measured by two different techniques, pulse neutron technique and power noise analysis. Since the pulse neutron

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5. Measurement of β/ℓ

In principle, the value of β/ℓ can be measured by two different techniques, pulse neutron technique and power noise analysis. Since the pulse neutron

technique has shown to be effective method for the safeguards purpose at SPECTR critical facility in USSR(2), main effect at FCA has been concentrated to examine the noise analysis technique for the safeguards application. While difficulty to measure the absolute β/ℓ value with high accuracy, it is obvious that advantages of the power noise analysis technique are (1) it is less expensive with regard to instrumentation and set up, (2) it is so cheap that panoramic frequency instrumentation can be manufactured to obtain visual real-time display of the measured results.

5.1 Cross Correlation Technique

A reactor does not operate at a strictly steady state power level. What is implied is an mean power level with power fluctuation about this mean. The power fluctuation appears from fluctuations in various reactivity equivalent quantities in reactor through reactor transfer function. In zero power reactor, these fluctuations in reactivity equivalent quantities are random due to the stochastic nature of all neutron reaction cross sections. When the reactor power is measured two independent detectors X and Y, the cross power correlation function $\phi(\tau)_{xy}$ is defined using the notation in Fig.16 as follow,

$$\phi(\tau)_{xy} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x_i(t)\ y_i(t+\tau)d\tau \tag{1}$$

According to the theory of noise analysis(3), the power spectrum density $\phi(\omega)_{xy}$ is obtained by Fourier integral transformation of the cross correlation function $\phi(\tau)_{xy}$ as follow,

$$\phi(\omega)_{xy} = \int_{-\infty}^{\infty} \phi(\tau)_{xy} e^{j\omega\tau} d\tau \tag{2}$$

In case of the zero power reactor*, the power spectrum density $\phi(\omega)_{xy}$ is correlated with β/ℓ in the following equation,

$$\phi(\omega)_{xy} = A/(\omega^2 + (\beta - \rho)^2/\ell^2) \tag{3}$$

where A : constant
β : effective delayed neutron fraction
ρ : reactivity
ℓ : neutron life-time

In case of the just critical system, $\rho=0$ so that the break frequency ω_b of the cross power spectrum density is equal to β/ℓ.

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* "Zero power reactor" means a reactor operated at such low thermal power that thermal feed back mechanisms are negligible on the reactor transfer function.

5.2 Measurement of the Cross Power Spectrum Density

The block diagram of the instrumentations used for the noise analysis is shown in Fig.17. Reactor power fluctuation is measured by two independent He^3 neutron counters located in the blanket region as shown in Fig.1. Signals from He^3 counters are fed into an AC-coupling pre-amplifier whose T_r* = 10μsec and T_f** = 20μsec, then amplified by the main amplifier whose band-width is 1Hz - 100kHz. The amplified signals are fed into correlation analyzer KANOMAX model SAI-52A through the band-pass filter LOCKLAND model 852 (10Hz - 30kHz). The cross correlation function obtained by KANOMAX model SAI-42A is fed into Fourier transformer KANOMAX model SAI-470 for obtaining the cross power spectrum density.

These analyzers and display devices are shown in Fig.18 and a typical result of the cross power spectrum density displayed on the cathode ray tube is shown in Fig.19.

The digital values of cross power spectrum density are fed into a computer to calculate the break frequency ω_b using the least square fitting technique. The time necessary to measure the value of β/ℓ is about 10 minutes. The measured values of β/ℓ in each version of core are summarized in Table 7.

6. Concluding Remarks

A verification experiment on the core-fuel inventory monitoring was made by using the fission chamber technique and the power noise analysis on β/ℓ. The amounts of Pu-fuel removed from the core were about 3.5 ~ 5.8 kg. From the above experiment, several conclusion are drawn, as follows :

(1) It is shown that the fission chambers can effectively detect the changes in fission rates at diversion places in the core where masses of Pu-fuel are removed.

(2) The drift of a pre-set discrimination level of multi-chamber scanning system is very small and it is only 3% during a period of two months. Then, the results of fission counting rates are not significantly affected by such drift of the system.

(3) The β/ℓ is very sensitive to the variation of in-core plutonium. The experiment shows that the removal of ~ 3.5 kg - Pu gives 54% change to the β/ℓ values.

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* T_r = rise time of signal pulse
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Table 1 Types of core used to simulated removal of Pu

core version	No. of replaced drawers and their types	critical rod position *	amount of Pu in kg removed from core
Reference	———	CR1 = 176.5 CR2 = 0.0	0.0
PD6-6C	6 x PD6/T	CR1 = 222.0 CR2 = 0.0	3.46
PD6-10A	10 x PD6/T		5.76
PD6-10B	10 x PD6/T	CR1 = 183.0 CR2 = 0.0	5.76
PD6-10C	10 x PD6/T	CR1 = 223.2 CR2 = 0.0	5.76
PD4-18A	18 x PD4/T	CR1 = 143.7 CR2 = 0.0	5.18
PD4-16R	16 x PD4/T	CR1 = 600.0 CR2 = 21.0	4.68

* The FCA is a fuel follower type facility.
The control rod positions are represented as, o.o mm : full-in and 600 mm : full-out.

Table 2 Drift of Discrimination level in volt.

Date	MCSS counting channel				
	No.1	No.2	No.3	No.4	No.5
24-10-78	0.78	0.78	0.78	0.78	0.78
10-11-78	0.78	0.78	0.78	0.78	0.78
14-11-78	0.78	0.78	0.78	0.77	0.77
16-11-78	0.78	0.78	0.78	0.78	0.78
6-12-78	0.78	0.79	0.77	0.77	0.78
8-12-78	0.78	0.78	0.78	0.77	0.78
14-12-78	0.77	0.78	0.79	0.76	0.78
26-12-78	0.77	0.78	0.78	0.76	0.78

Table 3 Reproducibility of the spatial fission rate measurement for the reference core[*1] (no fuel removal from core region)

Drawer[* 2] position	Fission Chamber Position[*3]				comment
	1	2	3	4	
1	1.001	1.001	1.000	1.014	
2	1.001	0.998	1.010	0.990	
3	1.002	0.996	1.006	1.012	
4	1.005	1.001	1.001	1.014	
5	1.007	1.000	1.000	1.000	
6	1.003	1.004	1.009	1.010	
7	1.004	0.990	1.014	1.003	
8	1.001	1.008	0.992	1.007	
9	1.007	0.994	0.998	0.995	
10	0.998	1.001	1.005	1.000	
11	1.002	0.990	1.015	1.000	
12	1.005	1.001	1.002	0.988	
13	0.998	0.997	0.997	0.993	
14	1.003	1.000	0.990	1.015	
15	1.006	1.000	0.990	0.993	
16	1.004	0.995	0.993	1.002	
17	0.994	1.008	0.988	0.980	
18	1.018	1.010	1.006	1.000	
19	1.015	1.006	1.002	0.996	
20	1.003	1.006	0.993	0.993	

[* 1] The values in the table represent the ratio of spatial fission rates in 2nd runs to those in 1st run.

[* 2] For drawer position, see Fig.1 and Fig.2.

[* 3] For fission chamber position, see Figs.7a and 7b.

Table 4 Shift of spatial fission rates in the core of removal pattern PD6-10C from those in the reference core.

Drawer position*	Fission Chamber Position**				comment
	1	2	3	4	
1	1.21	1.24	1.21	1.18	
2	1.21	1.22	1.23	1.18	
3	1.21	1.21	1.25	1.19	
4	1.21	1.22	1.22	1.16	
5	0.98	0.99	1.00	1.00	
6	0.98	0.98	0.98	1.01	
7	0.98	1.00	1.00	1.01	
8	0.99	0.98	1.01	0.98	
9	0.98	0.99	0.99	0.98	
10	0.98	0.99	1.00	1.00	
11	0.98	0.97	1.01	0.97	
12	1.01	0.97	0.99	0.96	
13	1.24	1.23	1.21	1.16	
14	1.21	1.23	1.21	1.17	
15	1.22	1.22	1.24	1.17	
16	1.24	1.22	1.22	1.16	
17	0.98	0.98	0.99	1.00	
18	—	—	—	—	
19	1.00	0.99	1.00	0.99	
20	1.01	0.99	1.00	0.97	

* For Drawer Position, See Fig.1 and Fig.2

** For Fission Chamber Position, See Figs.7*a* and 7*b*

Table 5 Shift of spatial fission rates in the core of removal pattern PD4-18A from those in the reference core.

Drawer[*] position	Fission Chamber Position[**]				comment
	1	2	3	4	
1	1.22	1.20	1.19	1.16	
2	1.25	1.33	1.27	1.22	
3	1.21	1.19	1.19	1.16	
4	1.25	1.26	1.27	1.21	
5	1.02	1.01	1.03	1.02	
6	1.01	1.02	1.03	1.03	
7	1.01	1.02	1.01	1.03	
8	1.01	1.01	1.02	1.02	
9	1.02	1.01	1.01	1.02	
10	1.01	1.02	1.02	1.00	
11	1.02	1.01	1.02	1.01	
12	1.03	1.02	1.01	1.01	
13	1.25	1.27	1.27	1.21	
14	1.22	1.21	1.20	1.15	
15	1.26	1.26	1.28	1.21	
16	1.21	1.20	1.20	1.15	
17	1.02	1.00	1.00	1.03	
18	—	—	—	—	
19	1.02	1.02	1.02	1.00	
20	1.02	1.01	1.03	1.00	

[*] For Drawer Position, See Fig.1 and Fig.2

[**] For Fission Chamber Position, See Figs.7*a* and 7*b*

Table 6 Shift of spatial fission rates in the core of removal pattern PD4-16R from those in the reference core.

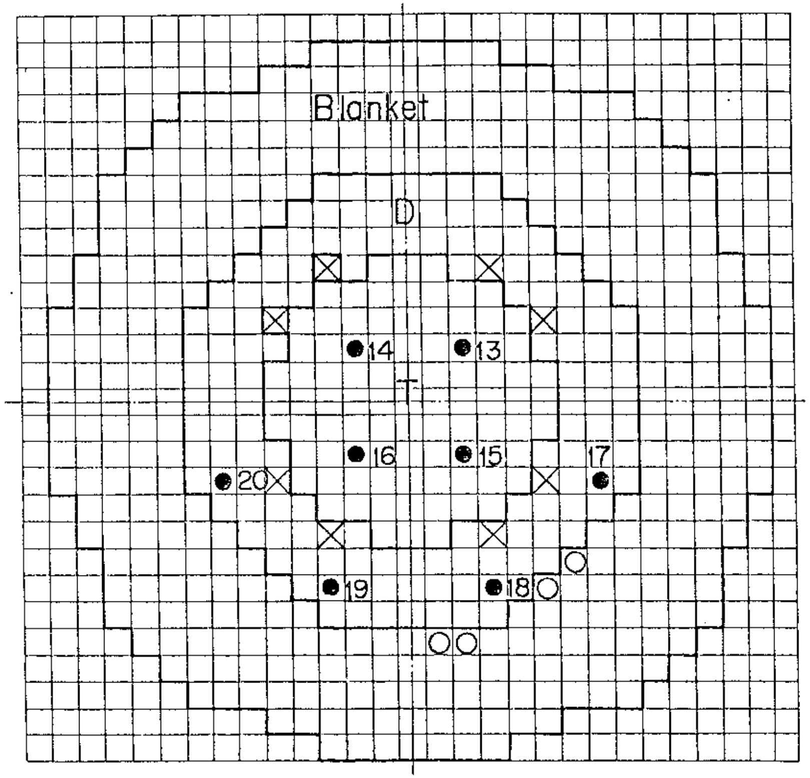
Drawer* position	Fission Chamber Position**				comment
	1	2	3	4	
1	1.02	1.03	1.01	1.02	
2	1.02	1.03	1.03	1.02	
3	1.02	1.03	1.02	1.02	
4	1.02	1.02	1.03	1.01	
5	1.02	1.01	1.03	1.03	
6	1.02	1.01	1.03	1.04	
7	1.02	1.01	1.01	1.04	
8	1.01	1.01	1.02	1.02	
9	1.02	1.01	1.02	1.02	
10	1.01	1.02	1.03	1.01	
11	0.99	1.01	1.02	1.00	
12	1.02	1.01	1.02	1.00	
13	1.02	1.00	1.02	1.00	
14	—	0.89	0.94	0.88	
15	1.02	1.00	1.01	1.01	
16	1.02	1.02	1.01	0.99	
17	1.02	1.02	1.02	1.02	
18	—	—	—	—	
19	1.01	1.01	1.01	1.01	
20	1.03	1.00	0.99	0.99	

* For Drawer Position, See Fig.1 and Fig.2

** For Fission Chamber Position, See Figs.7*a* and 7*b*

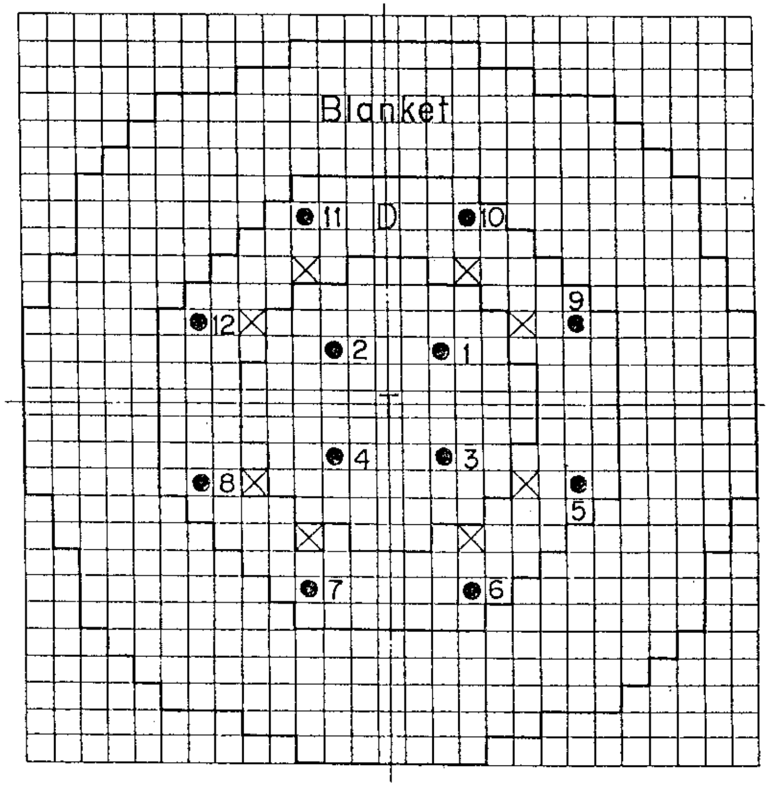
Table 7 Measured valves of β/ℓ

core version	amount of Pu removed in kg	β/ℓ in kHz
Reference	0.0	5.68
PD6-6C	3.46	3.29
PD6-10A	5.76	2.64
PD6-10B	5.76	3.07
PD6-10C	5.76	2.86
PD4-18A	5.18	3.81
PD4-16R	4.61	5.24



×	Safety Rod
☒	Control Rod # 1
●	MCSS Drawer (Multi-Chamber Scanning System)
○	He-3 Neutron counter

Fig. 1 FCA VIII-1 Assembly (Movable half)



×	Safety Rod
☒	Control Rod #2
●	MCSS Drawer (Multi-Chamber Scanning System)

Fig. 2 FCA VIII-1 Assembly (Fixed Half)

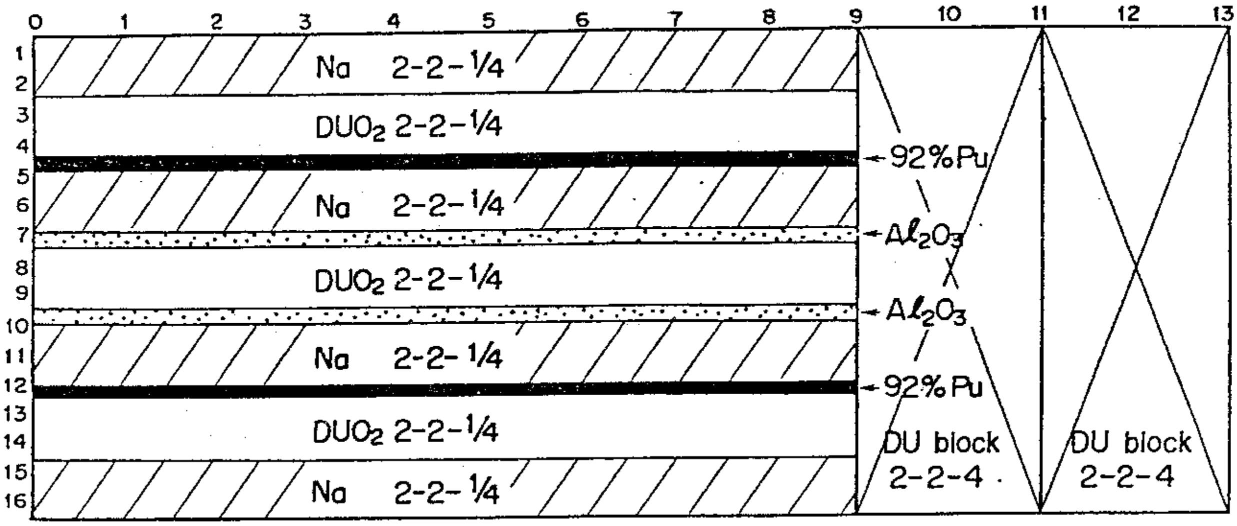


Fig. 3 Drawer Makeup Pattern for "T"

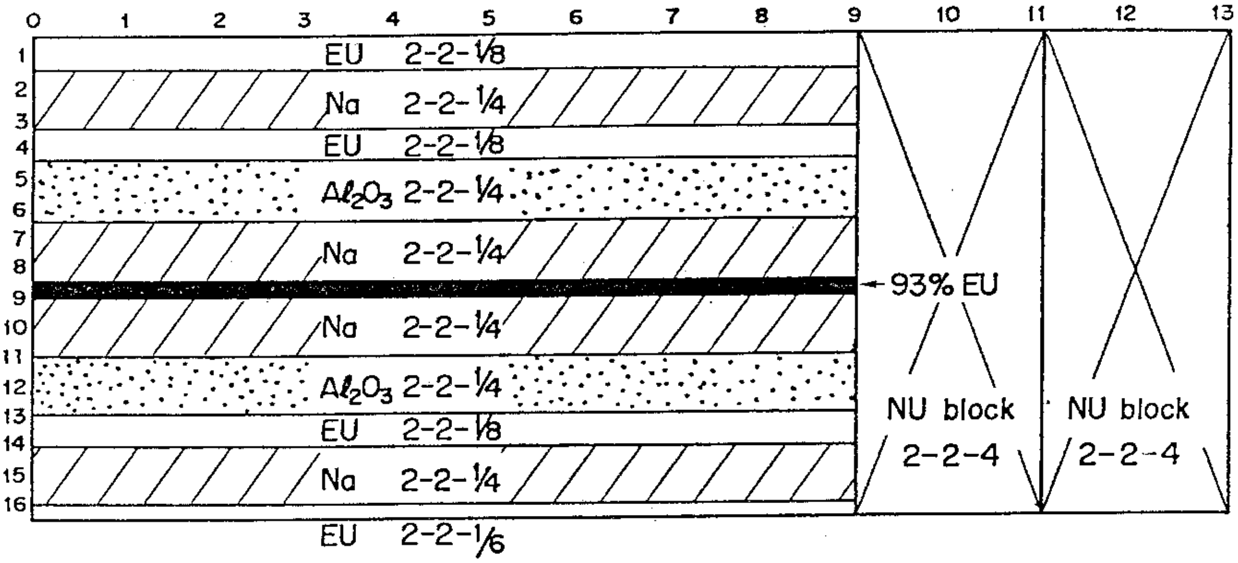


Fig. 4 Drawer Makeup Pattern for "D"

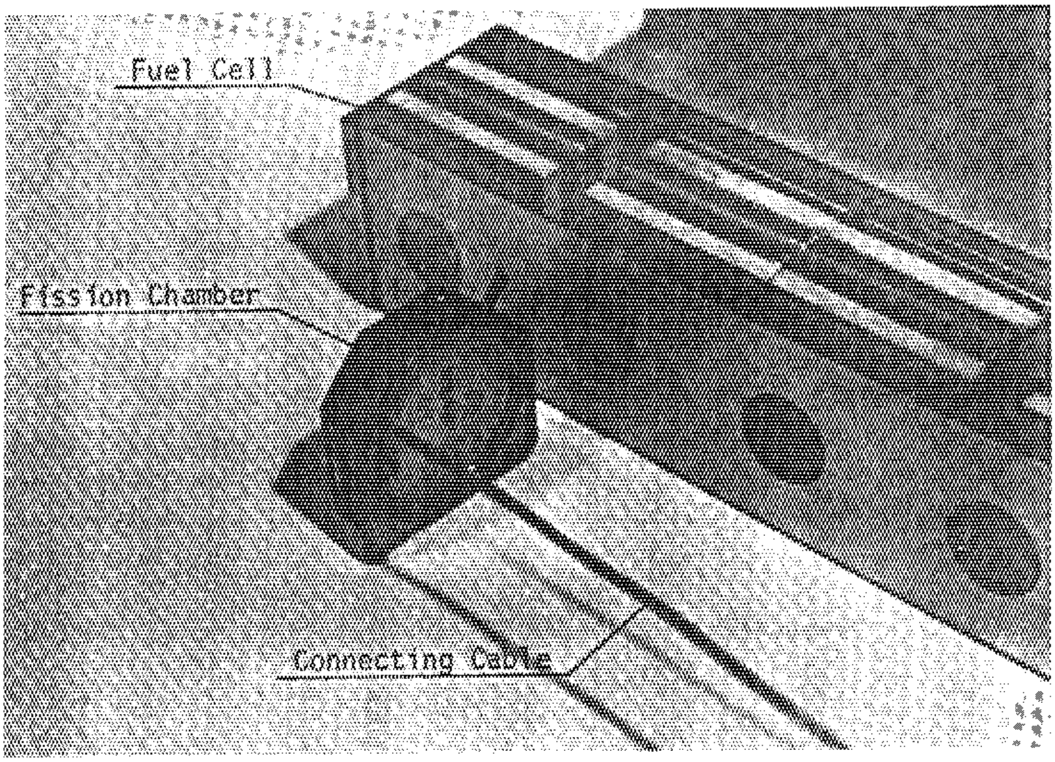


Fig. 5 Parallel Plate Type Fission Chamber

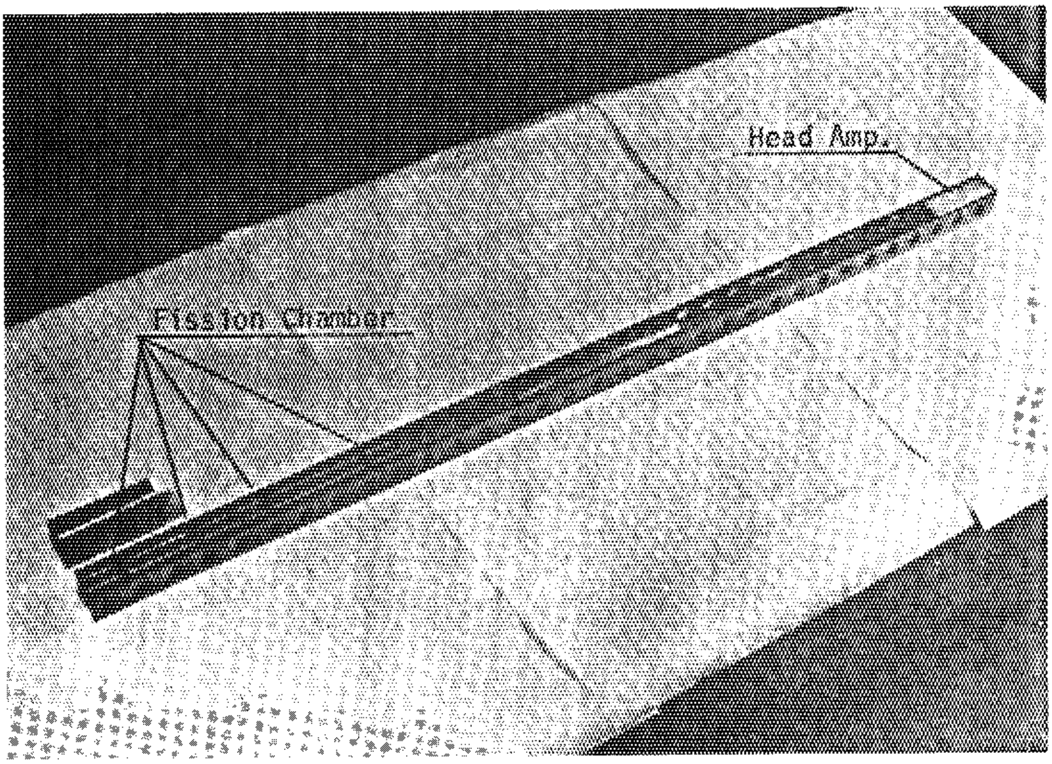


Fig. 6 Instrumented Fuel Drawer

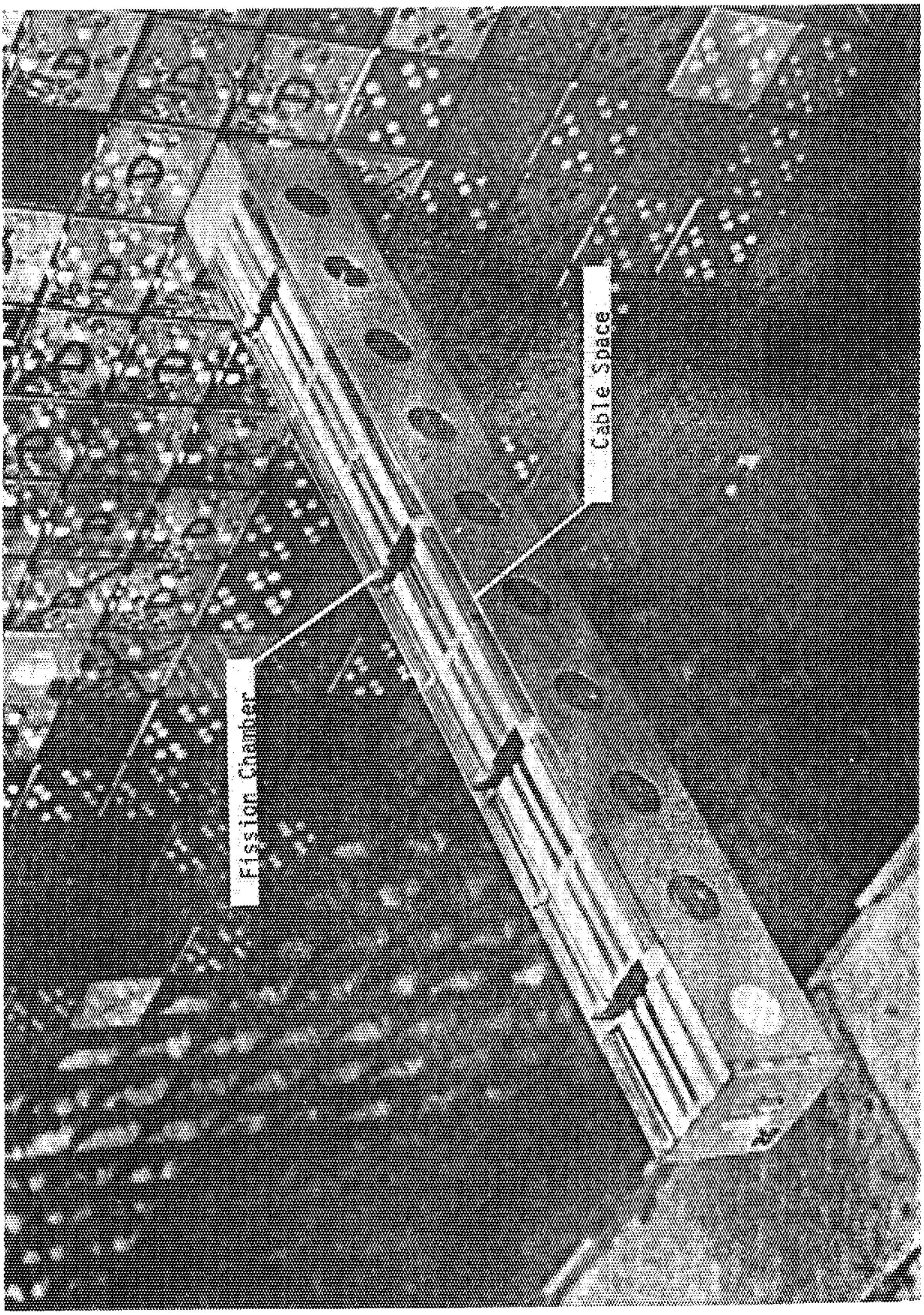
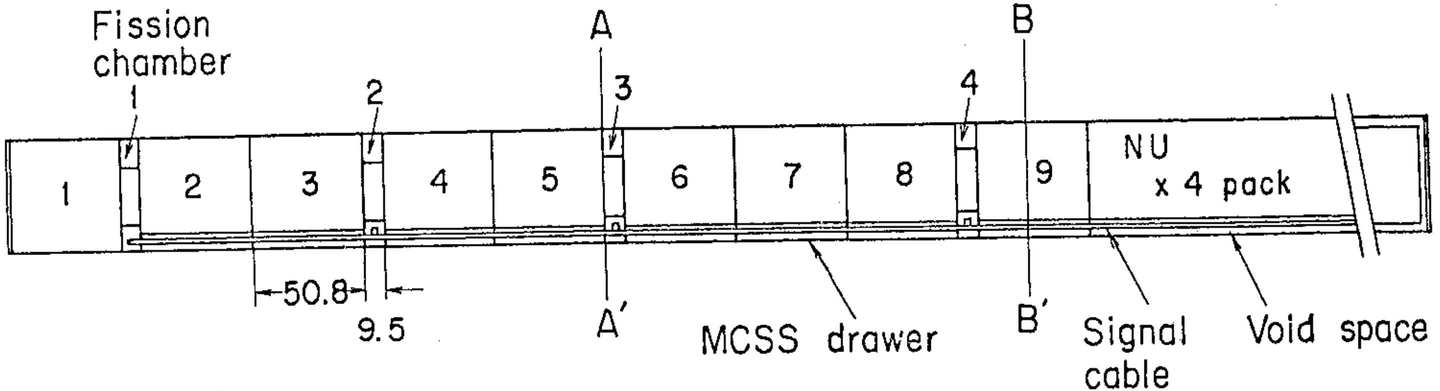
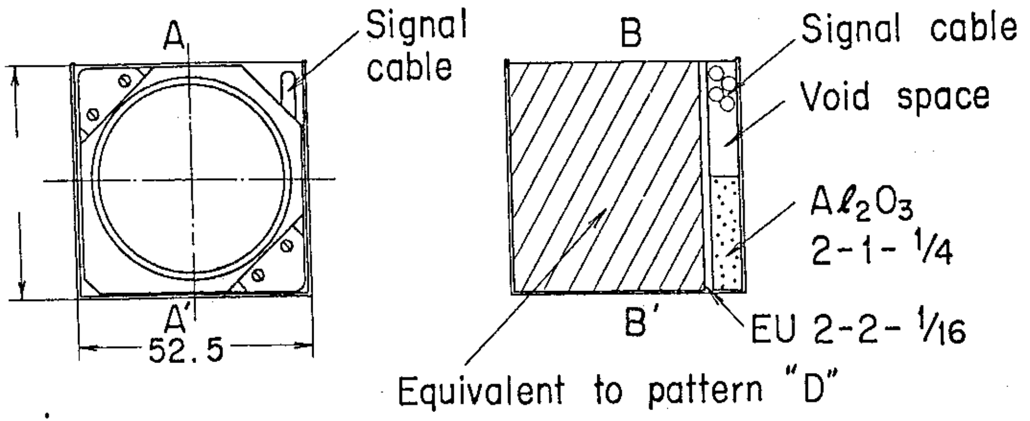


Fig. 7 a Instrumented Drawer Loading into FCA Matrix



Top view



Cross section view

Fig. 7b Fission chamber loading in MCSS drawer (dimensions in mm)

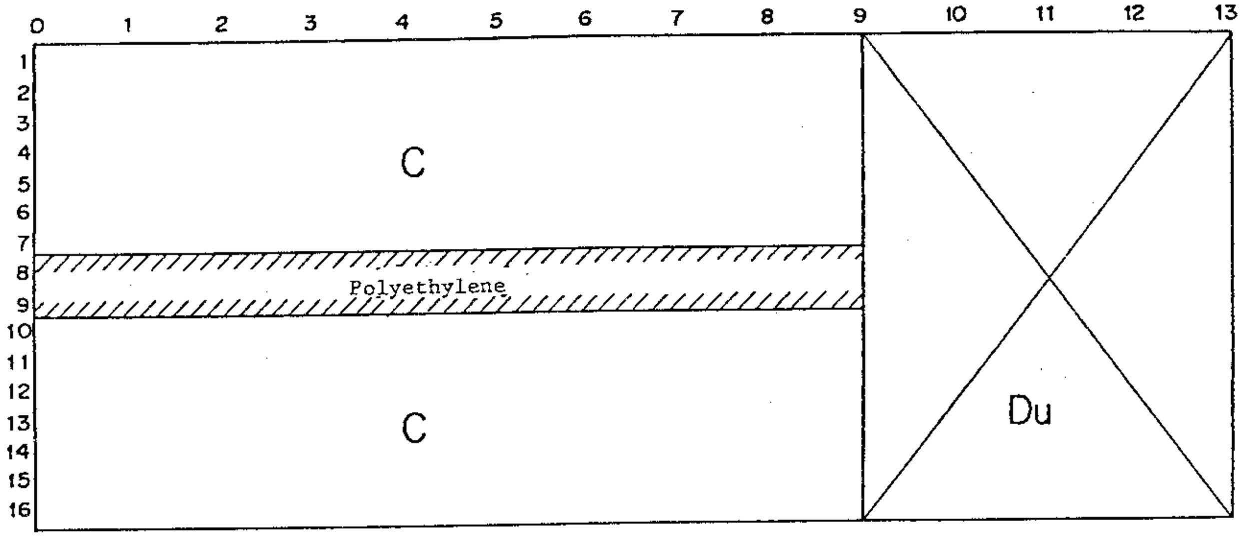


Fig. 8 Drawer Makeup Pattern for " PD-6"

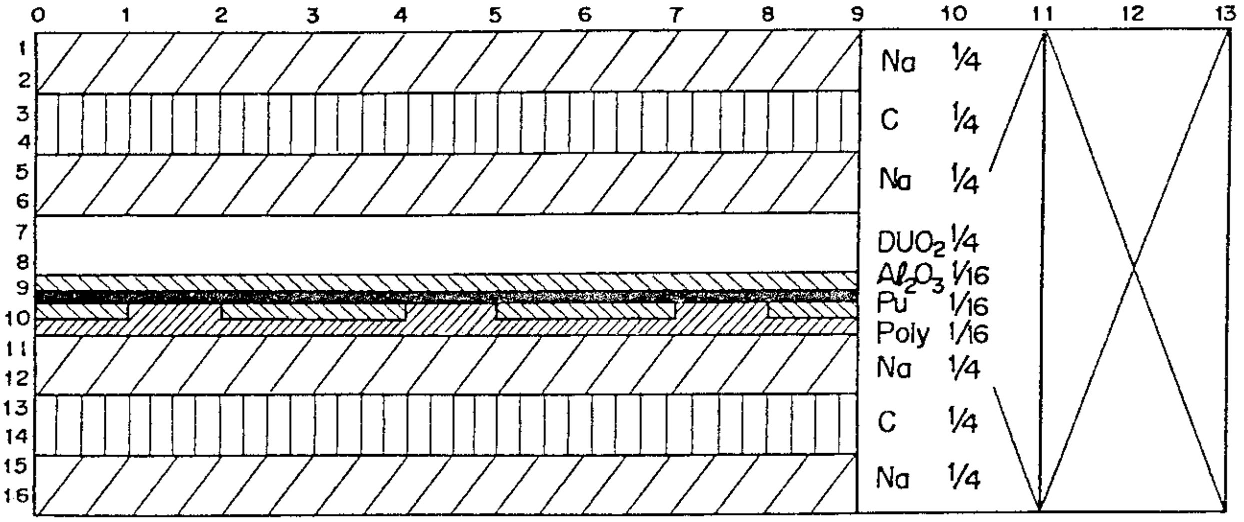
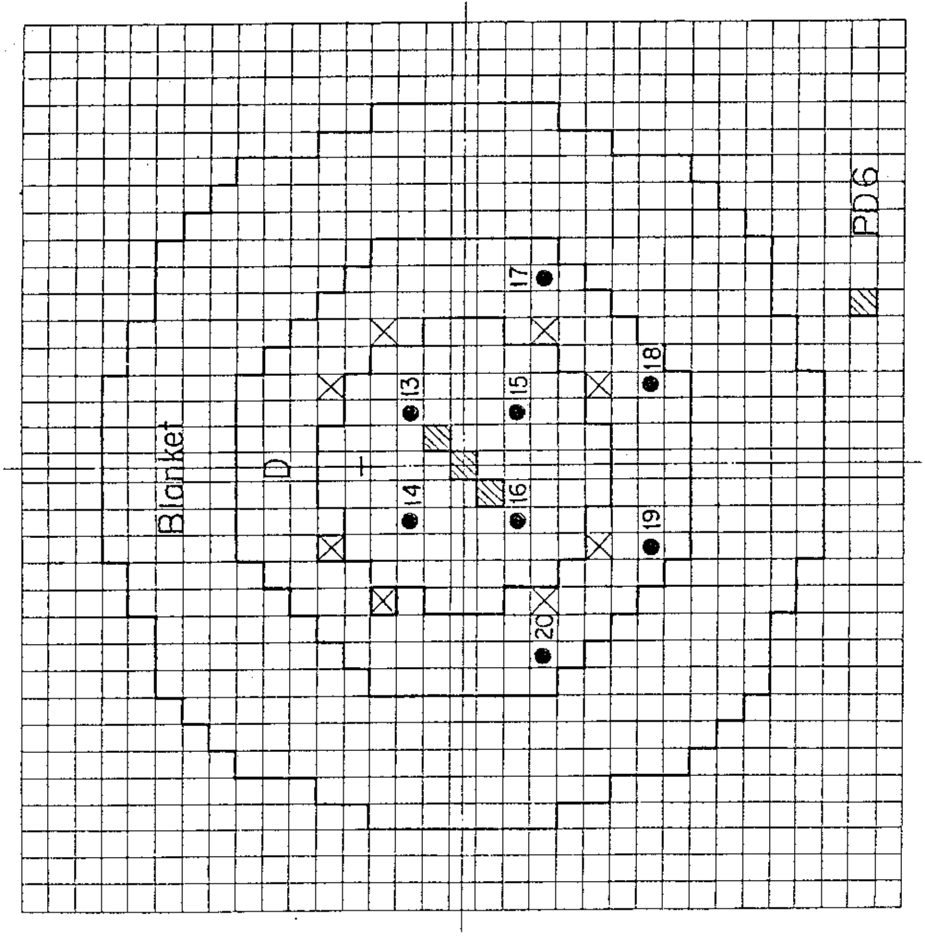
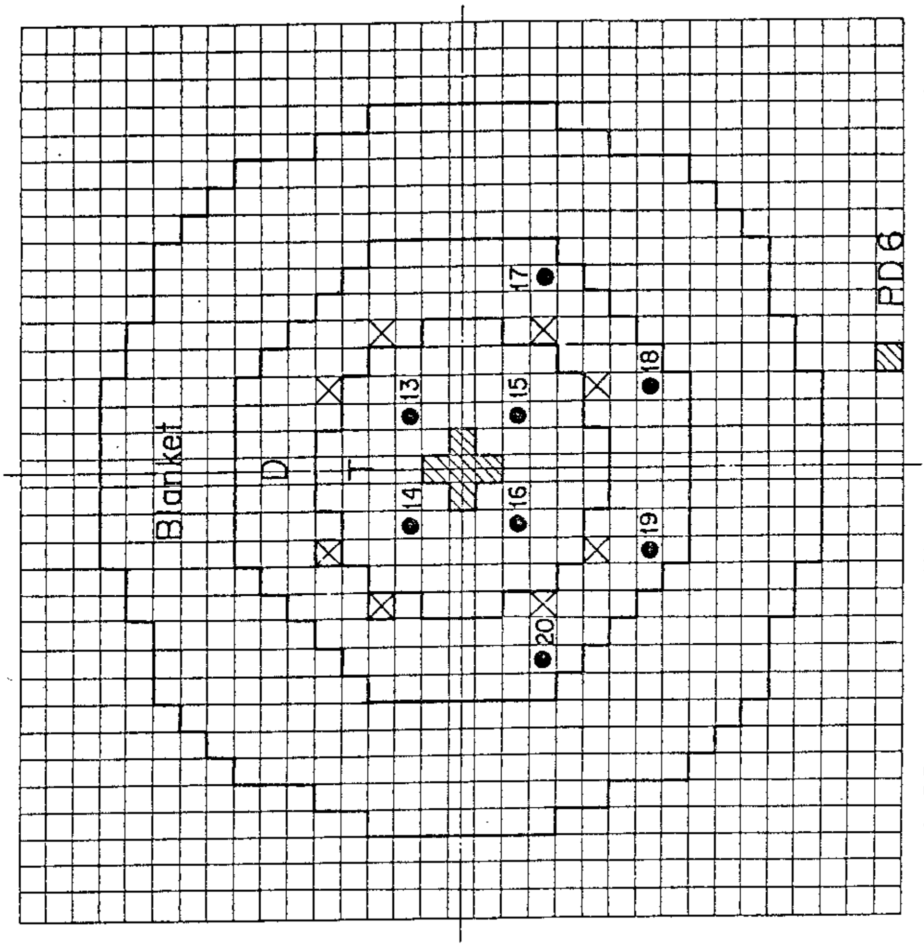


Fig. 9 Drawer Makeup Pattern for " PD-4"



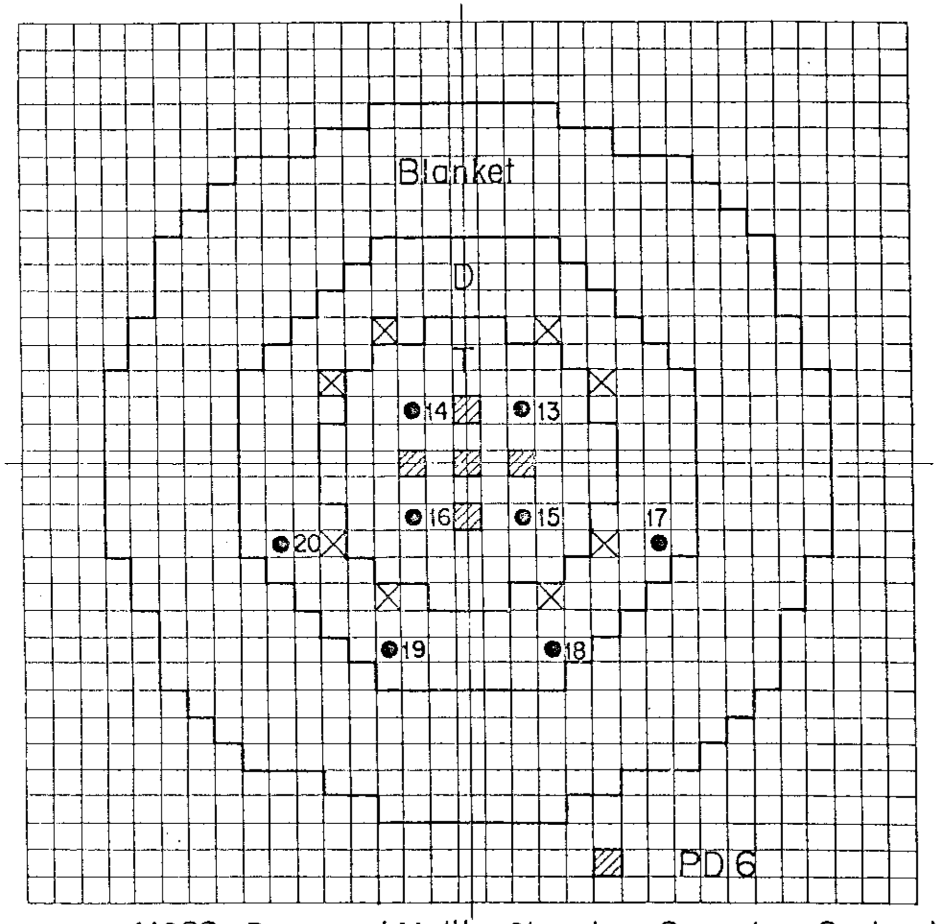
● MCSS Drawer (Multi-Chamber Scanning System)

Fig.10 Diversion Type PD6-6C



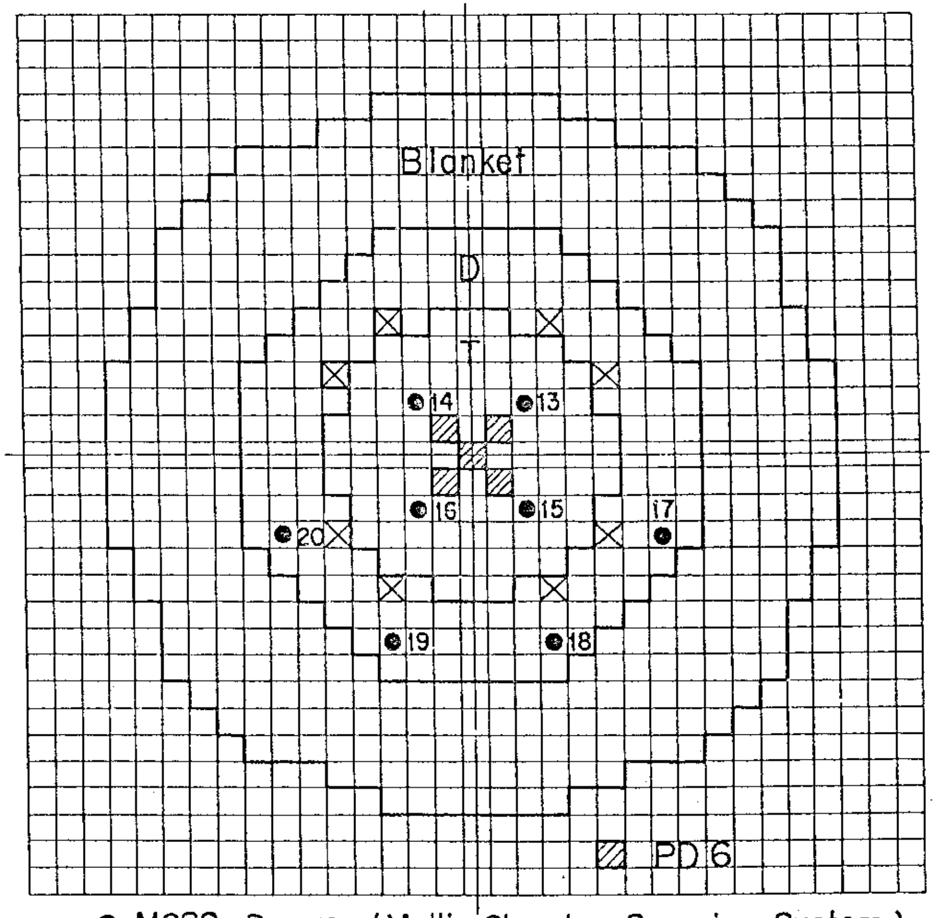
● MCSS Drawer (Multi-Chamber Scanning System)

Fig.11 Diversion Type PD6-10A



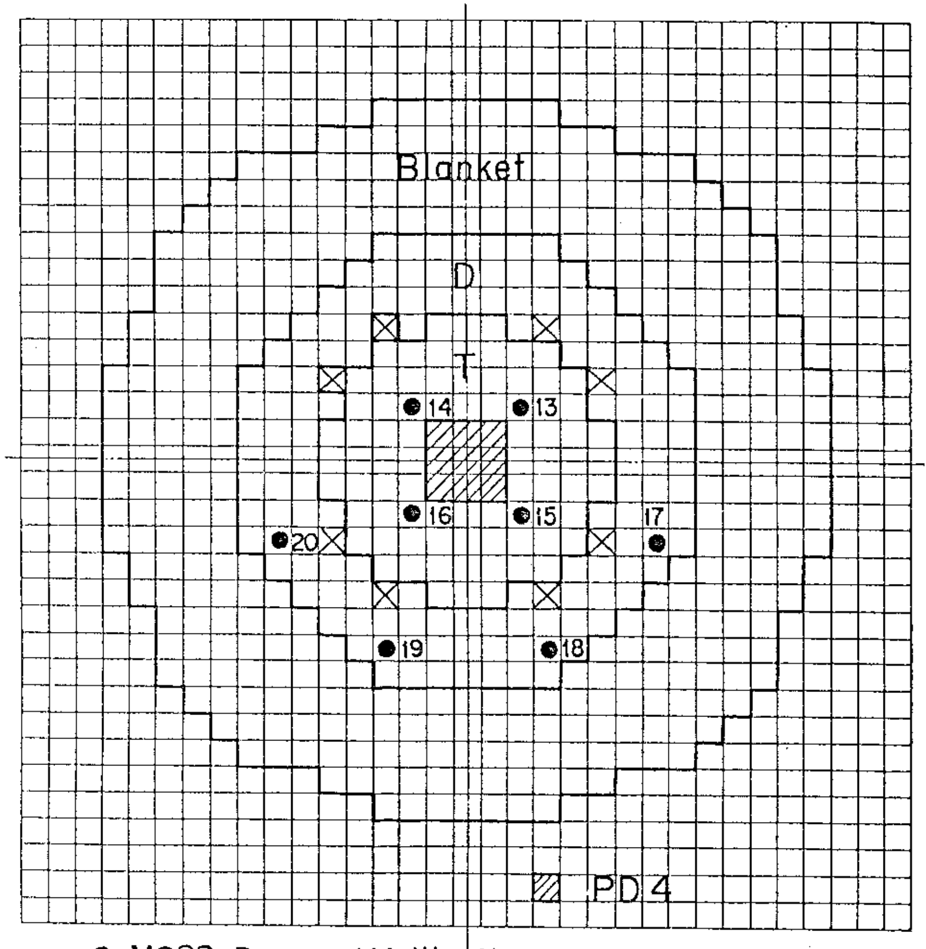
● MCSS Drawer (Multi-Chamber Scanning System)

Fig. 12 Diversion Type PD6-10B

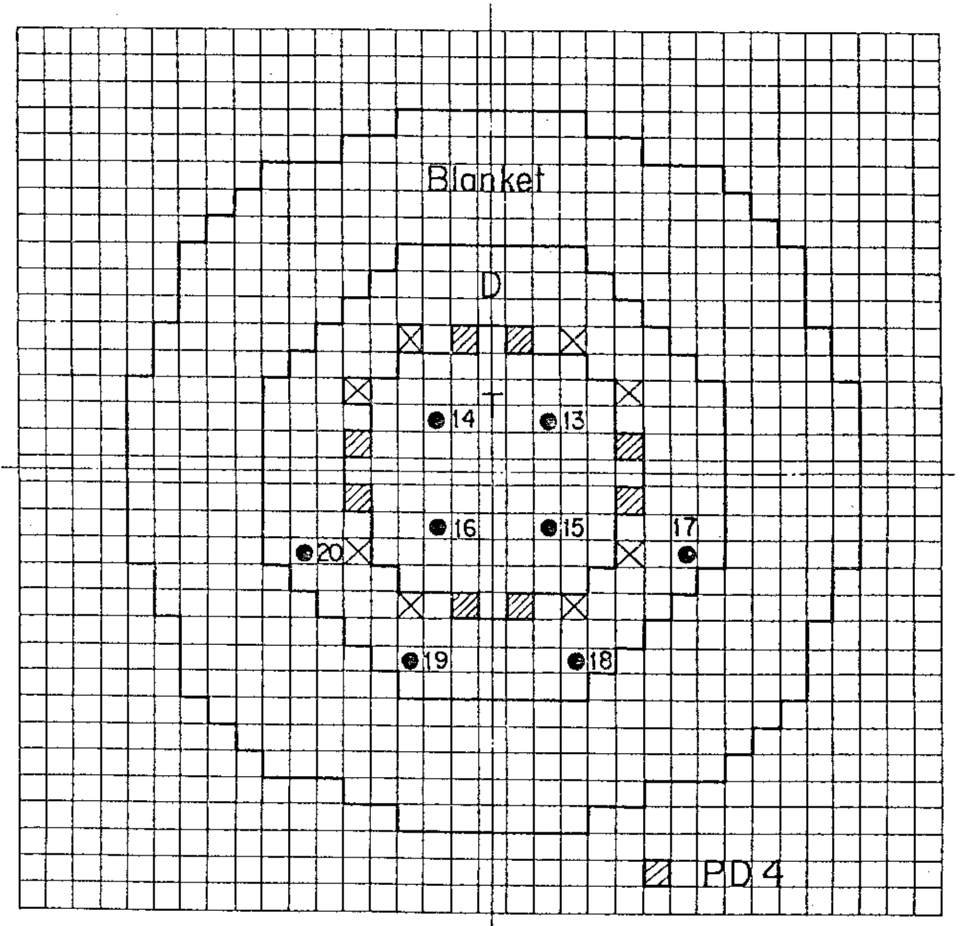


● MCSS Drawer (Multi-Chamber Scanning System)

Fig. 13 Diversion Type PD6-10C



● MCSS Drawer (Multi-Chamber Scanning System)
Fig. 14 Diversion Type PD4-18A



● MCSS Drawer Multi-Chamber Scanning System)
Fig. 15 Diversion Type PD4-16R

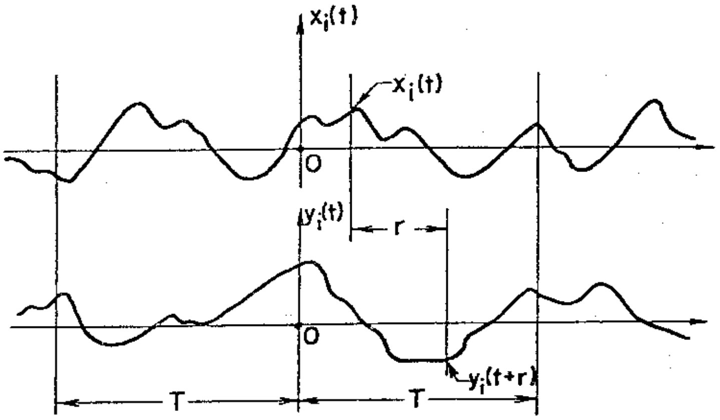


Fig. 16 Schematic showing reactor power trace by two detectors

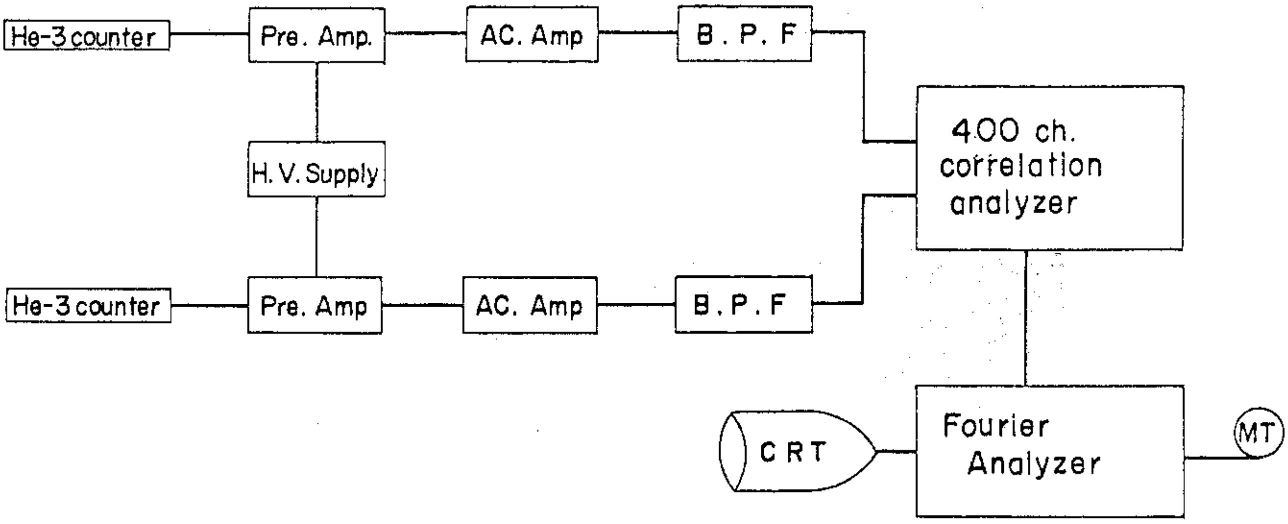


Fig. 17 Schematic Diagram of Noise Analysis System

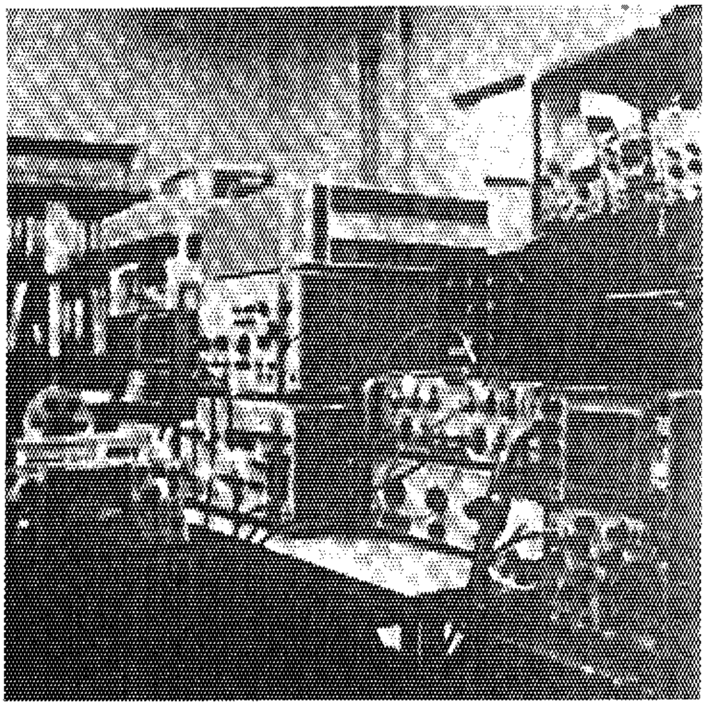
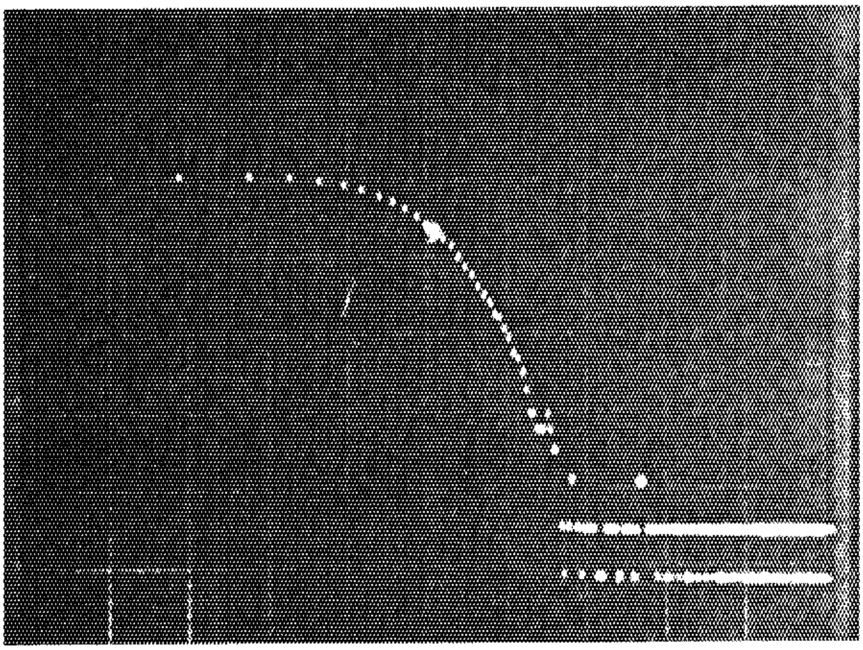


Fig. 18 Arrangement of B/ℓ Analyzer

PD6 - 6C 6w CROSS dt = 1×10^{-6} sec 30 kHz



6 kHz

Fig. 19 Cross Power Spectrum Density

Appendix A. Control rod worth

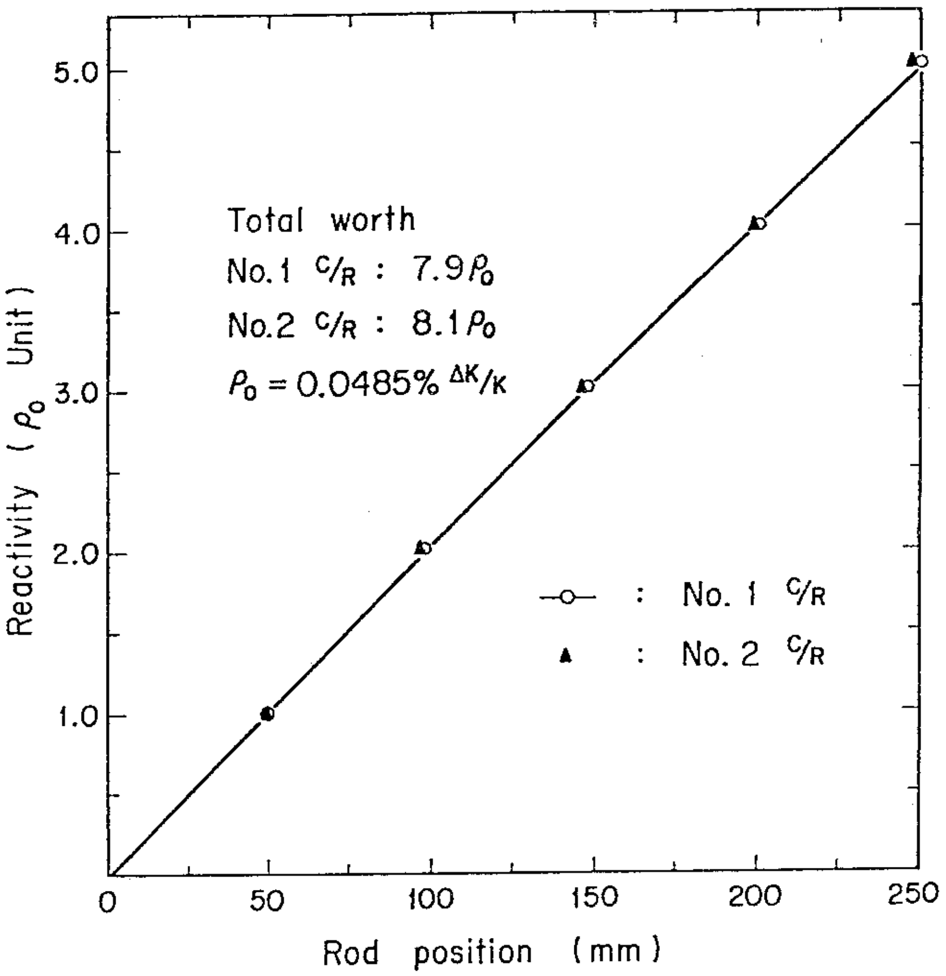


Fig. A-1 Calibration curve of control rods of Assembly Ⅷ-2 (MCSS)