Oktober 1974 KFK 2088

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Projekt Schneller Brüter

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Gesellschaft für Kernforschung mbH., Karlsruhe

Paper presented at the SMORN 1 EACRP Specialist Meeting on Reactor Noise, Rome, Italy, October 21-25, 1974

Abstract

To determine the response of a neutron detector to local perturbations in a typical fast breeder reactor detailed numerical calculations of space-dependent source transfer functions were performed for the German prototype reactor SNR 300. The small local reactivity perturbations considered here were replaced by a neutron source modulation for simplicity reasons. The source transfer function was obtained from the Laplace transform of the time-dependent inhomogeneous diffusion equation. The 26 groups KFK-INR cross section set and one-dimensional cylinder geometry were used for the numerical solution of the diffusion equation in the frequency domain.

The detector was treated as an integral part of the reactor. The detector materials B-10, U-235 and Pu-239 were chosen for comparison. The positions of source and detector were independently varied within the core and blanket of the reactor.

From the space-dependent transfer function of the reactor-detector system and the general theory, relating power spectral densities of neutron detector signals and reactivity perturbations for the point reactor model, the neutron instrumentation requirements for detecting local perturbations in a fast reactor were deduced. It was found that in the present class of fast breeder prototype reactors no in-core neutron detectors will be needed for a continuous inspection using noise analysis techniques to detect local perturbations.

Überlegungen zur Neutronenflußinstrumentierung für die Überwachung von Leistungsreaktoren mit Hilfe der Rauschanalyse

Zusammenfassung

Um den Einfluß einer lokalen Störung auf das Signal eines Neutronendetektors in einem typischen schnellen Brutreaktor zu bestimmen, wurden für den SNR3oo detaillierte numerische Berechnungen der ortsabhängigen Quellübertragungsfunktion durchgeführt. Die hier interessierenden lokalen Reaktivitätsstörungen sind so klein, daß sie durch eine entsprechende Quellmodulation ersetzt werden können. Die Übertragungsfunktion wurde näherungsweise aus der zeitabhängigen inhomogenen Diffusionsgleichung durch Laplace-Transformation und Reihenentwicklung berechnet. Die numerischen Rechnungen erfolgten in eindimensionaler Zylindergeometrie mit 26 Energiegruppen.

Der Neutronendetektor wurde als integraler Bestandteil des Reaktors behandelt. Zum Vergleich wurden Detektoren mit B-1o, U-235 und Pu-239 betrachtet. Die Positionen des Detektors und der Neutronenquelle wurden unabhängig voneinander im Core- und Blanketbereich variiert.

Aus der ortsabhängigen Übertragungsfunktion des Reaktor-Detektor-Systems und der Punktreaktortheorie des Leistungsrauschens wurden Aussagen über die für den Nachweis lokaler Reaktivitätsstörungen erforderliche Neutroneninstrumentierung gewonnen. Es zeigte sich insbesondere, daß zur kontinuierlichen Überwachung auf lokale Reaktivitätsstörungen in den gegenwärtig im Bau oder in der Planung befindlichen Brüterprototypen keine Neutronendetektoren innerhalb des Cores erforderlich sind.

1. Introduction

Noise analysis at power reactors presently has two major objectives: first, to investigate the capabilities of this technique to extract dynamics information on the reactor from the various fluctuating signals available during normal operating conditions; and second, to develop a diagnostics tool for malfunction detection indicating developing failures at an early stage in order to reduce shut-down times and costs for repairs, and to increase safety and availability of the nuclear power plant.

Most of the work in this field reported in the literature is of a more or less empirical nature. The measured power spectra are complex and only partly understood. Only in some cases have the reactivity driving forces for reactor power noise been identified qualitatively. On the other hand, for anomaly or malfunction detection by neutron noise analysis one needs precise information on the reactivity effect of local faults such as excessive fuel or control rod vibrations, partial blockage of cooling channels, or boiling of the coolant in a sub-assembly, as well as quantitative relations between a given reactivity perturbation at a certain position in a large power reactor and the neutron flux fluctuations at the position of a neutron detector.

In the past, noise measurements at power reactors have been performed with the standard neutron instrumentation for reactor control. Such instrumentation is usually not designed for noise analysis measurements. Due to limited bandwith, to high hum and noise in the electronic networks, noise measurements at power reactors are difficult to perform. The investigation of the possibilities of noise and correlation analysis techniques with respect to malfunction monitoring is often seriously limited. Limitations may also be caused by the low sensitivity of the out-of-core neutron detectors.

In large power reactors some decoupling of the neutron flux in different core regions has to be taken into account. Therefore out-of-core detectors are in general not or not equally sensitive to local reactivity pertur-

bations at all positions in the core. Only those perturbations which have a sufficiently large influence on the neutron flux at the detector position can be measured.

The amplitude of the neutron flux fluctuations at one position, i.e. the detector position, caused by a reactivity perturbation at a different position in the reactor is determined by the space-dependent reactivity transfer function. Therefore the transfer function can be used to estimate the sensitivity of a neutron detector necessary to detect local reactivity perturbations by measuring the power spectral density of the detector signal. Also optimum detector positions or configurations, if more than one detector is needed, can be found in this way. Furthermore, by integrating the detector into the reactor one can account for the effects of space-dependent neutron energy spectra on the efficiency of detectors with different neutron sensitive materials.

This work is part of the investigations on the use of noise analysis techniques for detecting boiling of the coolant in an LMFBR [1, 2]. Boiling of the sodium in an LMFBR fuel element has been extensively investigated at many places because of its safety implications. The fault conditions of sodium boiling are therefore well-known and its reactivity effect can be calculated for different positions of the boiling fuel element.

To clarify what extent of neutron instrumentation would be needed for monitoring a fast breeder reactor with respect to sodium boiling the space-dependent transfer function of the German prototype reactor SNR 300 has been studied in detail. Since only very small local reactivity perturbations are considered in this study, the perturbations were replaced by an equivalent neutron source modulation (δ-shaped pulse), allowing the application of an existing computer code for the calculation of the source transfer function.

For the SNR reactor it was found that the out-of-core neutron chambers of the normal reactor instrumentation will be sufficient for detection

of gross boiling in a fuel element. This is an important result because no in-core neutron detectors can be used in this reactor.

2. General Premises for Detecting Malfunctions by Monitoring Power Spectral Densities

The auto power spectral density (APSD) of a signal from a neutron detector placed in a power reactor which is perturbed by a reactivity driving function $\rho(\omega)$ is given [3] by

$$APSD(\omega) = W\,\overline{q^2}\,F + W^2\,\overline{q}^2\,FD/H(\omega)/^2 + W^2\,\overline{q}^2\,F^2/H(\omega)/^2\,P(\omega) \qquad (1)$$

where

W	detector efficiency in counts per fission
F	total fission rate
q	electric charge per neutron detected
$\overline{q^2}/\overline{q}^2$	$= R \approx 1.2$ (Bennet factor)
D	$\approx$ o.8 Diven factor
$H(\omega)$	reactor transfer function
$P(\omega)$	power spectral density of $\rho(\omega)$

In the APSD three contributions from different noise sources can be distinquished. The first term on the right hand side of equ. (1) describes the white noise due to the statistical properties of the detection process. It is observed in the APSD only. In cross power spectral densities (CPSD) of two detectors this term is not present. However, it influences the accuracy of both types of measurements [4,5,6]. It has been shown [7] that the minimum detector sensitivity necessary for proper measurements of power spectral densities in the two-detector experiment can be by a factor of 1o lower than in the one-detector experiment.

The second contribution to the APSD, called zero power noise, is a consequence of the branching of fission chains. It is negligible in power reactors. It is much smaller than the detection noise because of its second order dependence on the detector efficiency W which is very low in power reactors.

The last expression in equ. (1) represents the power noise. Although depending on W^2 too, it is predominant at high reactor power because, in contrast to the two other terms, it is proportional to F^2. The power noise is caused by stochastic reactivity perturbations indirectly produced by turbulence and vibrations due to the forced coolant circulation at high mass flow rates. Also temperature fluctuations in the coolant, boiling of the coolant and cavitation may produce reactivity inputs to the reactor. A more detailed list of reactivity driving forces in power reactors is given in [8].

These reactivity perturbations may have specific frequency compositions according to the different mechanisms producing them. Changes in their intensity, frequency spectrum or amplitude distribution or the appearence of additional reactivity noise may indicate certain defects or malfunctions of the reactor or its components which might be recovered from analysis of the resulting neutron flux fluctuations measured by a neutron detector.

The relation between the power spectrum of the neutron flux fluctuations and the corresponding power spectrum of the reactivity perturbation is given by the reactor transfer function. Measuring the PSD of neutron detector signals therefore yields information which is contained in the driving forces or the transfer function. From the transfer function,in principle,overall dynamics information on the reactor including feedback and coupling effects, temperature coefficients, heat transfer and other parameters might be extracted. In the work reported here feedback and delayed neutrons have been neglected in the transfer function.

Due to the low pass characteristics of the transfer function the neutron flux fluctuations caused by high frequency perturbations may be attenuated.

Thus, their contribution to the power spectral density of a neutron detector signal can be reduced. Beyond the break frequency of the reactor the power spectral density due to reactivity perturbations may be completely covered by the detection noise contribution. Whether this happens or not, depends, besides the intensity of the perturbation, on the reactor power and detector efficiency.

Supposing that a single reactivity perturbation can be reliably detected if the corresponding power spectral density of the detector signal in a certain frequency range is at least of the same magnitude as the detection noise power spectral density, a general condition can be derived from equ. (1) for the detector sensitivity necessary to detect a reactivity perturbation:

$$W \geq \frac{1.2}{F \, |H(\omega)|^2 \, P(\omega)} \qquad (2)$$

From this relation the neutron detector requirements for surveillance of power reactors with respect to malfunctions or anomalies, based on power spectral density measurements, can be derived, provided the reactivity effect of the perturbation and the reactor transfer function are known. Conversely, one can calculate the sensitivity of the method, i.e. the minimum perturbation which could be detected against the background noise for a given reactor and neutron instrumentation. It should be pointed out here, that for cross power spectral density measurements the right hand side of (2) can be reduced by one order of magnitude.

In general, more than one reactivity perturbation will be present in a power reactor. The relevant part of equ. (1) then is generalized [9] to

$$APSD(\omega) = W \overline{q^2} \, F + W^2 \overline{q}^2 \, F^2 \, |H(\omega)|^2 \left[\sum_j P_j(\omega) + \sum_{\substack{j \\ j \neq k}} \sum_k P_{jk}(\omega) \right] \qquad (3)$$

with $P_j(\omega)$ APSD of driving function ρ_j

$P_{jk}(\omega)$ CPSD of driving functions ρ_j and ρ_k

If the individual driving forces are independent of each other, the last sum in equ. (3) disappears. Then a second condition for the possibility of detecting a distinct reactivity perturbation $\rho_k(\omega)$ in the power spectral density can be stated in a simple form:

$$P_k(\omega) \geq \sum_{j \neq k} P_j(\omega), \quad \omega_o \leq \omega \leq \omega_1 \tag{4}$$

which means that a reactivity perturbation can only be detected if there is a frequency interval $(\omega_o - \omega_1)$ in which it contributes significantly to the total reactivity noise. This frequency interval should be below the break frequency of the reactor to produce equivalent neutron flux fluctuations.

To determine the reactivity perturbations quantitatively, one has to know the transfer function. The same is true if the minimum detectable perturbation has to be estimated. The transfer function is of particular interest if local perturbations in a large reactor have to be investigated where the point reactor model cannot be applied a priori. Then the space-dependent transfer function has to be calculated.

3. Space-Dependent Transfer Functions

Equ. (1) has been derived from the point reactor model. The spatial dependence of the neutron flux is taken into account implicitly defining the detector efficiency in counts per fission in the whole reactor. By this definition the detector sensitivity becomes proportional to the neutron flux at the detector position. Therefore the detector efficiency is space-dependent. This follows directly from the identity

$$\overline{q}\, W\, F = S\, \phi\, (r, o) \tag{5}$$

for the mean value of the detector signal:

$$W = W(r) = \frac{S}{q} \cdot \frac{\phi\,(r,o)}{F} \tag{6}$$

with S detector sensitivity in A/nv

$\phi(r,o)$ stationary neutron flux at r (ω = o)

r detector position.

Consequently, the power spectral density is space-dependent too.

This treatment of space-dependent neutron noise is adequate when the neutron flux fluctuations caused by a source or reactivity perturbation are proportional to the stationary mean value of the flux at all positions in the reactor. Otherwise the space-dependent transfer function has to be used in equ. (1). Simultaneously, the detector sensitivity W must be replaced by the conventional sensitivity S according to equ. (5). One has to keep in mind that S and W also depend on the neutron energy spectrum. If the neutron spectrum in a reactor is space-dependent, S will be space-dependent too. The energy-dependence of the detector sensitivity was taken into account in the calculation of its spatial dependence to be described later.

The reactivity transfer function is defined as

$$H(r,\omega) = \frac{\phi(r,\omega)}{\phi(r,o)\ \rho(\omega)} \tag{7}$$

As already stated, the transfer function becomes spatially independent when the flux ratio in equ. (7) is independent of r for all frequencies. When local reactivity perturbations are considered, the transfer function in general will depend also on the position of the perturbation. This will not be taken into account explicitly in the following.

The frequency-dependent signal of a neutron detector caused by a reactivity perturbation $\rho(\omega)$ in a one-group approximation according to equ. (7) is

$$S\ \phi(r,\omega) = S\ \phi(r,o)\ H(r,\omega)\ \rho(\omega) \tag{8}$$

The same signal is obtained for a neutron source modulation $N(\omega)$ at the same position as the reactivity perturbation if

$$N(\omega) = \frac{\phi(r,o) \cdot \rho(\omega)}{\Lambda\, v} \tag{9}$$

is chosen, assuming the source transfer function defined as

$$H(r,\omega) = \frac{\phi(r,\omega)}{\Lambda v N(\omega)} \tag{1o}$$

is equal to the reactivity transfer function as in the point reactor model (v and Λ in equ. (9) and (1o) denote the neutron velocity and generation time respectively).

A local source modulation will be equivalent to a reactivity perturbation if the produced changes in the space- and energy-dependent neutron flux are identical in intensity, frequency and energy spectrum. Identical intensity and frequency spectrum are achieved by modulating the neutron source according to equ. (9). To eliminate energy effects approximately, the energy spectrum of the stationary flux at the source position is used for the source neutrons.

The detector response to the source modulation will be calculated for a unit charge released per detected neutron:

$$S/\bar{q}\ \phi(r,\omega) = S/\bar{q}\ \Lambda\, v\ N(\omega)\ H(r,\omega) \tag{11}$$

The true signal of a real detector is obtained by multiplying the results with the corresponding value of $\bar{q}$. For $N(\omega) \equiv 1$ the space-dependent transfer function of the reactor including the detector is obtained.

4. Numerical Calculation of Space-Dependent Transfer Functions

The response of a reactor to a neutron source modulation N(r,t) can be obtained from the time-dependent diffusion equation

$$\Delta(r)\ \phi(r,t) + N(r,t) = \frac{1}{v}\frac{\partial\phi(r,t)}{\partial t} \qquad (12)$$

where $\Delta(r)$ is an operator accounting for production and loss of neutrons. The other symbols have the usual meaning. The one-group notation is used here as in the foregoing paragraph for simplicity. The actual calculations are performed with 26 energy groups using the KFK-INR cross section set [10].

Delayed neutrons are not included in equ. (12). To obtain the proper prompt-kinetic behaviour of the system the reactor was made 1 $ subcritical by reduction of the number of neutrons per fission to its prompt fraction.

The solution of equ. (12) for a δ-shaped neutron pulse $N(r,t) = N(r)\ \delta(t)$ represents the Greens function of the reactor. Its Fourier transform is the transfer function, i.e. the space- and frequency-dependent neutron flux normalized to the source spectrum.

Instead of solving equ. (12) we follow the procedure proposed in [11]. Accordingly, equ. (12) is Laplace transformed first and then approximately solved by expanding the transfer function in a Taylor series. The Laplace transform of equ. (12) for a δ-neutron pulse is

$$(\Delta(r) - \frac{s}{v})\ \phi(r,s) + N(r) = o \qquad (13)$$

with $s = p + i\,\omega$ Laplace variable.

Its approximate solution is

$$\phi(r,s) = \psi_o(r) + \psi_1(r)s + \psi_2(r)s^2 + \ldots \qquad (14)$$

The coefficients $\psi_j(r)$ in equ. (14) are the solutions of the following inhomogeneous stationary diffusion equations

$$\begin{aligned} \Delta(r)\ \psi_o(r) + N(r) &= o \\ \Delta(r)\ \psi_1(r) - \psi_o(r) &= o \\ \Delta(r)\ \psi_2(r) - \psi_1(r) &= o \end{aligned} \qquad (15)$$

It was shown in [11] that this method is superior to a modal approach with respect to convergence of the expansions. An additional advantage in our case is that the transfer function is obtained directly.

Any standard multigroup diffusion code can be used to calculate the coefficients $\psi_j(r)$. In this work a special computer code has been used which automatically calculates the $\psi_i(r)$ to a specified order and multiplies the results obtained for each energy group with the corresponding microscopic cross section of a specified detector material. The sum of these products over all energy groups represents the detector signal $[S/q\ \phi(r,\omega)]$ defined in equ. (11) for one energy group.

$$[\,S/q\ \phi(r,\omega)\,] = \sum_{k=1}^{26} \sigma(E_k)\ \phi(E_k,\ r,\ \omega) \qquad (16)$$

with

E_k group energies

$\sigma(E_k)$ group constants

$\phi(E_k,\ r,\ \omega)$ space- and energy-dependent neutron flux in energy group E_k from equ. (14).

The numerical results of equ. (16) are printed out for each mesh point and the frequencies ω as specified in the input data. For specified space points the whole transfer function is produced in printed and graphic form. The computer code is written for one-dimensional cylindrical geometry.

For fast reactors, due to the higher break frequency in the order of ω = 1ooo rad/sec, much higher frequencies have to be considered. The convergence in equ. (14) then would be very slow. Therefore the expansion was centered at some properly chosen frequencies in the range of interest instead of ω = o as in equ. (14). Then only expansions up to the second order were needed.

5. Results

Numerical calculations were performed for the German prototype breeder reactor SNR 3oo with Mark 1 core. As can be seen from the figures, it consists of two radial core regions surrounded by a thick blanket. Shim rods and followers at safety rod positions were included as special homogeneous cylindrical core zones.
The detector materials B-1o, U-235 and Pu-239 were simultaneously distributed over the whole core and blanket in low concentrations avoiding a significant change of the original material composition of the reactor. Source modulations were introduced at two positions, at the core center and at a distance of 6o cm from the center. The source strength was kept constant.

The space- and frequency-dependent detector signals obtained from equs. (14) to (16) with $N(\omega) \equiv 1$ are shown in Figs. 1 to 9 and Table I. These signals can be interpreted as space-dependent transfer functions of the reactor with integrated detector or as space- and frequency-dependent detector sensitivities. Frequencies are always given in rad/sec. Fig. 1 shows the relative sensitivity of the three detector materials. Obviously, the B-1o detector is superior to the fission detectors. From Fig. 2 and Table I it follows that the decrease of sensitivity with increasing distance from core center is the lowest for the B-1o detector. This is ascribed to the softening of the energy spectrum of the neutron field which is observed in the follower and blanket regions. In these regions the absorption rate is lower than in the core material.

In Fig. 3 and 4 the spatial dependence of the sensitivities of a B-1o detector for different frequencies are compared. It can be seen that the spatial dependence of the curves is the same for all frequencies up to $\omega = 1o^4$ and that the break frequency is between $1o^3$ and $1o^4$. Actually, a break frequency of $\frac{\beta}{l} = 7.5 \cdot 1o^3$ was found by independent calculations. The B-1o results for a source at the core center and for an eccentric source are compared in Fig. 5 and 6. The shape of the curves is essentially the same in both cases. The difference in magnitude is due to the difference in the importance of the source neutrons which is about a factor of two lower at the source 2 position than in the center of the core.

The influence of the neutron energy spectrum on the detector sensitivities is demonstrated in Figs. 7 and 8. In Fig. 7 the space-dependent detector signal (for $\omega = 1o$) is compared to the spatial distribution of the stationary neutron flux.

From equ. (16) it follows that the difference between the space-dependence of the neutron flux and the detector signal is only due to the space-dependence of the energy spectrum. For cross sections independent of the neutron energy the detector signal would be proportional to the total neutron flux $\phi(r,\omega)$.

Fig. 8 shows the ratio of the space-dependent sensitivity S to the sensitivity obtained for the energy spectrum at the core center,

$$K(r) = \frac{\left[S/q \ \phi(r,\omega) \right]}{\phi(r,o)} , \ 1 \leq \omega \leq 1ooo \qquad (17)$$

normalized to 1 at r = o. The detector sensitivity W used in noise analysis then changes according to equ. (6) in the following way

$$W'(r) = K(r) \ W(r) \sim K(r) \ \phi(r,o) \qquad (18)$$

The frequency-dependence of the results is shown in Fig. 9 for detectors with B-1o and U-235 at two radial positions and for two different positions of the neutron source. The curves represent the space-dependent transfer functions of reactor-detector systems. Up to the break frequency of the reactor there is no significant difference in shape between the space-dependent transfer functions and that obtained from the point reactor model. This result has been found earlier already [12] for a thermal reactor.

Beyond the break frequency some differences are observed. First of all, there is some higher mode contamination in the curve when the detector is near to the source. The higher mode contribution is rapidly decreasing with increasing distance between source and detector. Simultaneously the roll-off slope of the curves increases. These facts indicate that the space-dependent transfer function deviates from first-order low-pass characteristics, obtained in the point reactor model,to low pass characteristics of higher order. The order of the low pass is the higher the larger the distance between the perturbations and the point of observation is.

6. Conclusions

Although the work reported in this paper is not yet finished,the following conclusions are possible:

1. The source transfer functions of a fast reactor with neutron detector can be divided into two frequency regions with different space-dependent behaviour. The boundary frequency between the two regions is slightly higher than the break frequency of the reactor.

2. For the low frequency part of the transfer function the following statements can be made:

   2.1 There is no significant difference in the shape between the gain of the space-dependent fast reactor transfer function and the point reactor transfer function. The space- and frequency variables can be separated. Space-dependence is described by a space-dependent amplitude factor only.

2.2 The space-dependence of the amplitude factor is due to the space-dependent neutron energy spectrum.

2.3 Out-of-core detectors are equivalent to incore detectors if the lower amplitude factor can be compensated by larger mass of detector material.

2.4 B-1o detectors are superior to fission detectors in detecting local perturbations.

3. For the high frequency part of the transfer functions the following conclusions can be made:

3.1 The shape of the gain is different from that of the point reactor transfer function and different at different positions.

3.2 For small distances between perturbation and detector more than one break frequency exists in the transfer function.

3.3 The roll-off slope increases with increasing distance between detector and perturbation.

4. The physical meaning of the observed properties of space-dependent transfer functions should be further investigated. Coupling effects would be emphasized more in reactors with smaller migration length or reactors of a more complicated geometrical configuration, i.e. thermal reactors or fast reactors with thermal drivers.

Acknowledgement

The author is much indebted to Mr. G. Arnecke, Mr. K. Böhnel and Dr. H.B. Stewart for providing the computer codes and for assistance in the numerical calculations.

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		Source at R = o			Source at R = 60 cm		
ω [rad/sec]	R [cm]	B-10	U-235	Pu-235	B-10	U-235	Pu-239
1	0	890	666	635	445	330	314
	121	72.0	33.6	28.5	37.4	17.4	14.
	% of R=0*	8.1	5.0	4.5	8.4	5.3	4.4
1000	0	789	591	564	393	292	277
	121	62.6	29.6	25.1	32.9	15.4	13.1
	% of R=0*	7.9	5.0	4.4	8.4	5.3	4.7

Table I Gain of Source Transfer Functions of Reactor-Detector Systems normalized to 10^{25} Detector Atoms (equ.16)

*) Stationary flux at R=121 0.6% of maximum flux at R=0

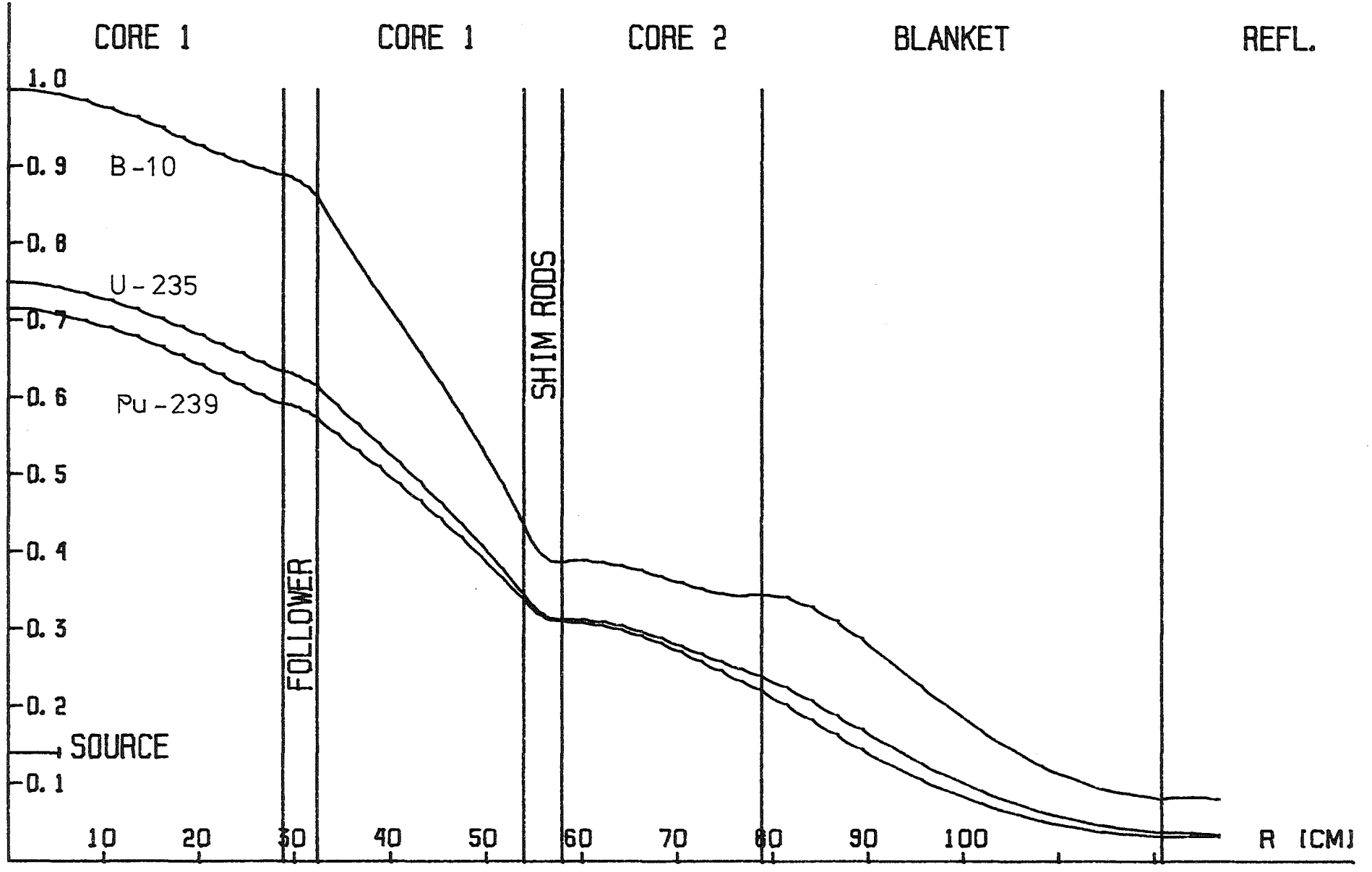


FIG. 1 RELATIVE DETECTOR SENSITIVITIES VERSUS DISTANCE FROM CORE CENTER (ω=10 RADIANS/SEC)

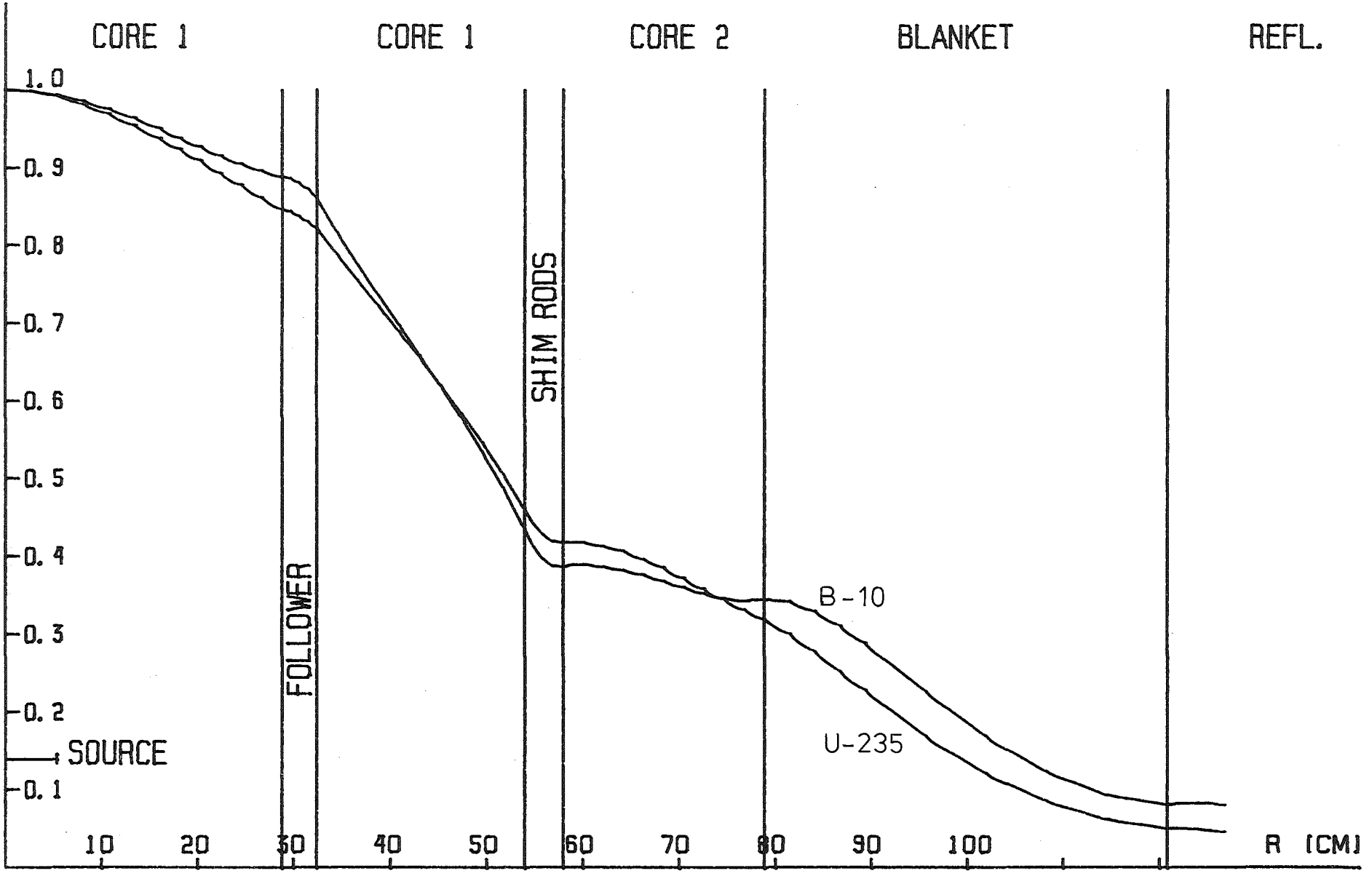


FIG. 2 NORMALIZED DETECTOR SENSITIVITIES VERSUS DISTANCE FROM CORE CENTER (ω=10 RADIANS/SEC)

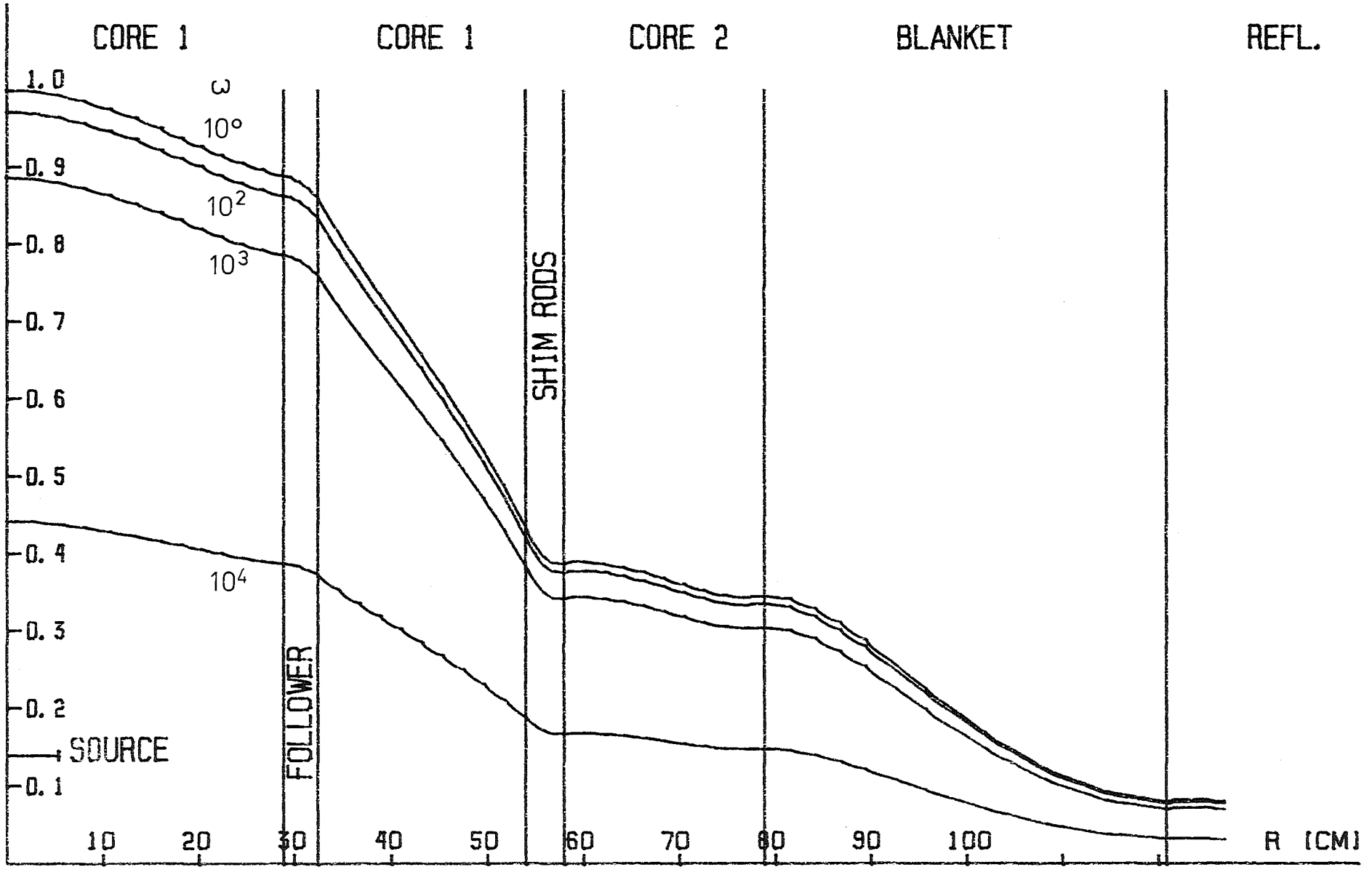


FIG. 3 RELATIVE SENSITIVITY OF A B-10 DETECTOR FOR DIFFERENT FREQUENCIES VERSUS DISTANCE FROM CENTER

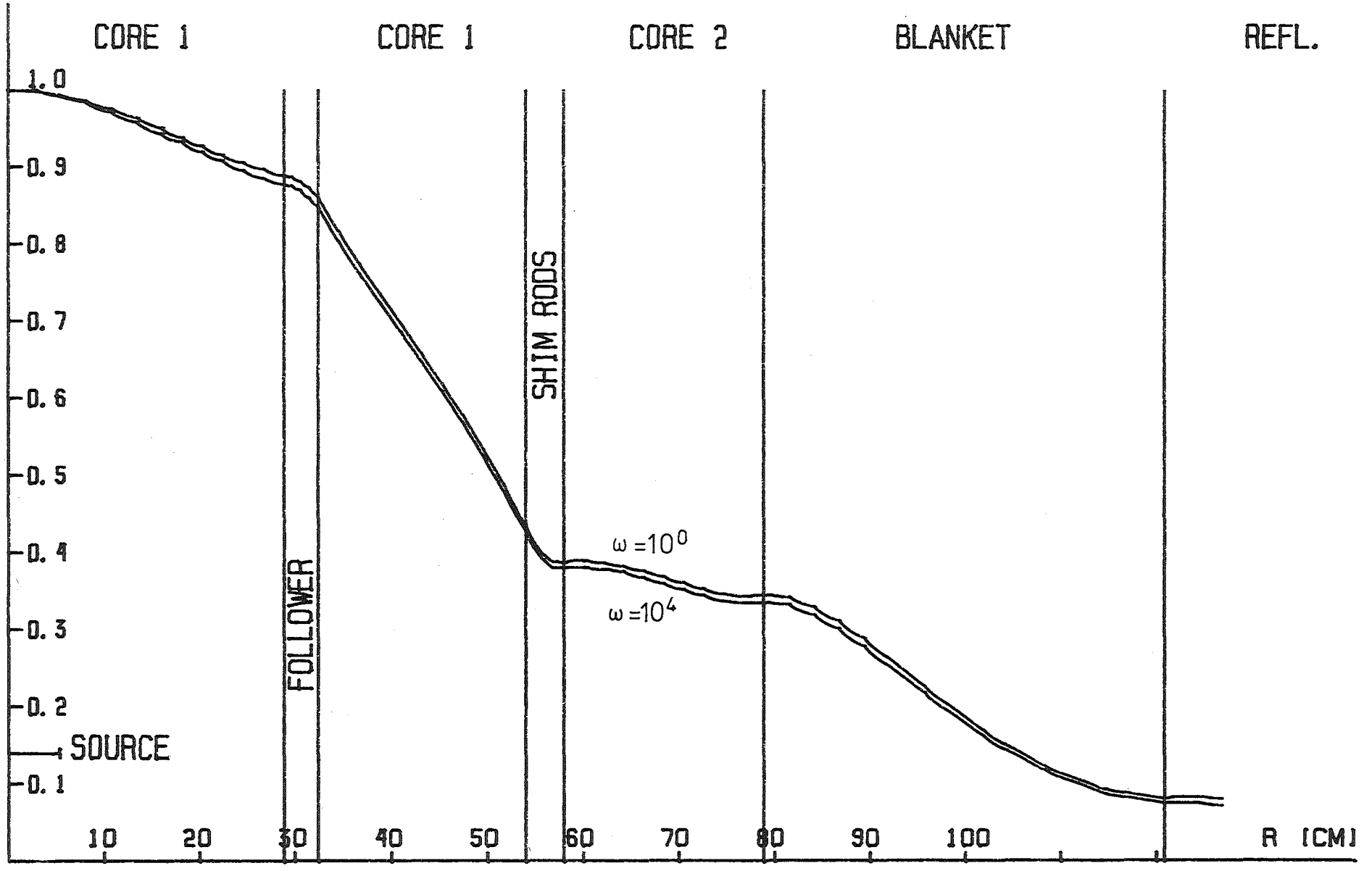


FIG. 4 NORMALIZED SENSITIVITY OF A B-10 DETECTOR FOR TWO FREQUENCIES VERSUS DISTANCE FROM CENTER

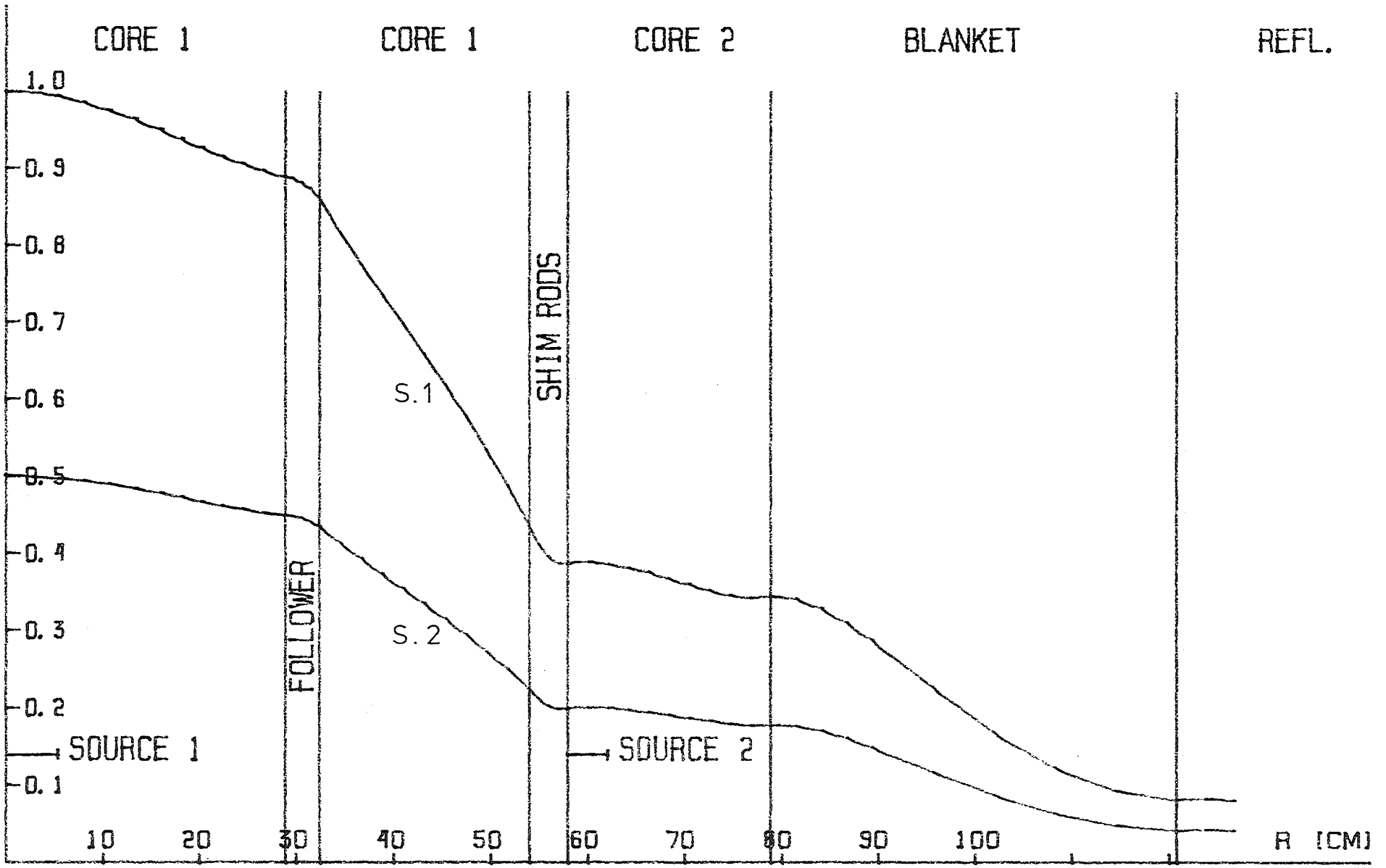


FIG. 5 RESPONSE OF A B-10 DETECTOR TO NEUTRON SOURCES AT DIFFERENT RADIAL POSITIONS

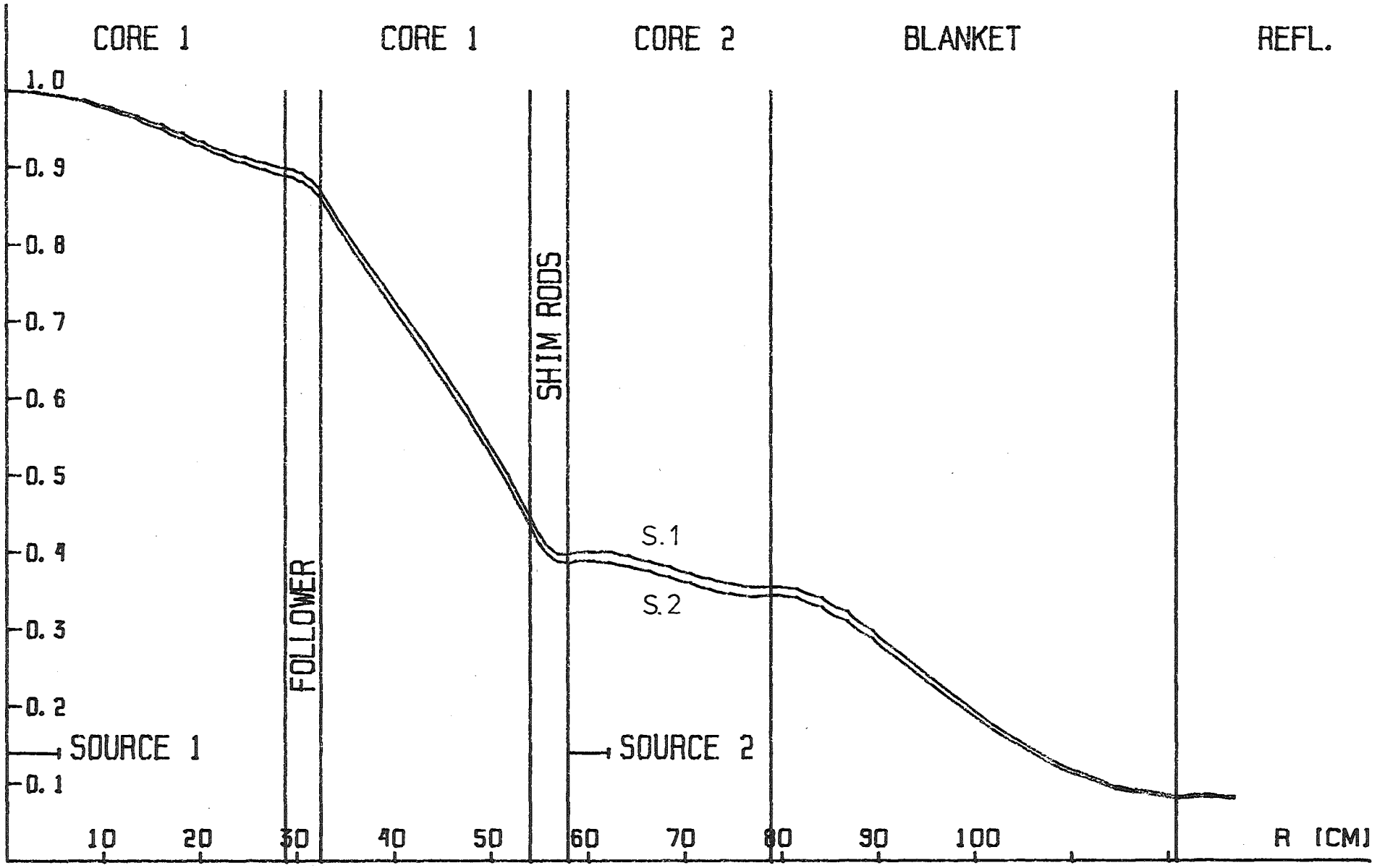


FIG. 6 NORMALIZED RESPONSE OF A B-10 DETECTOR TO NEUTRON SOURCES AT DIFFERENT RADIAL POSITIONS

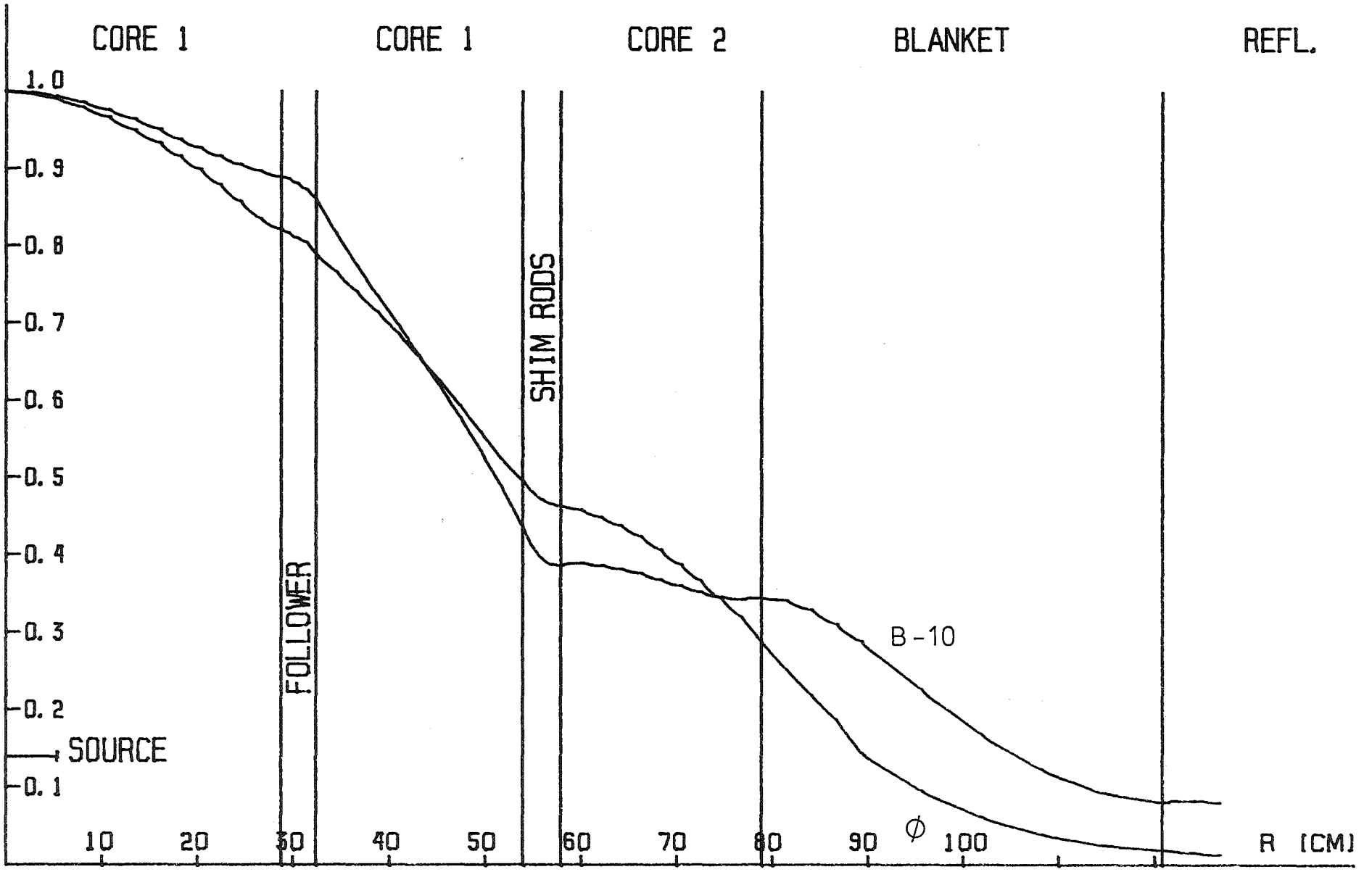


FIG. 7 NORMALIZED NEUTRON FLUX AND SENSITIVITY OF A B-10 DETECTOR VERSUS DISTANCE FROM CORE CENTER

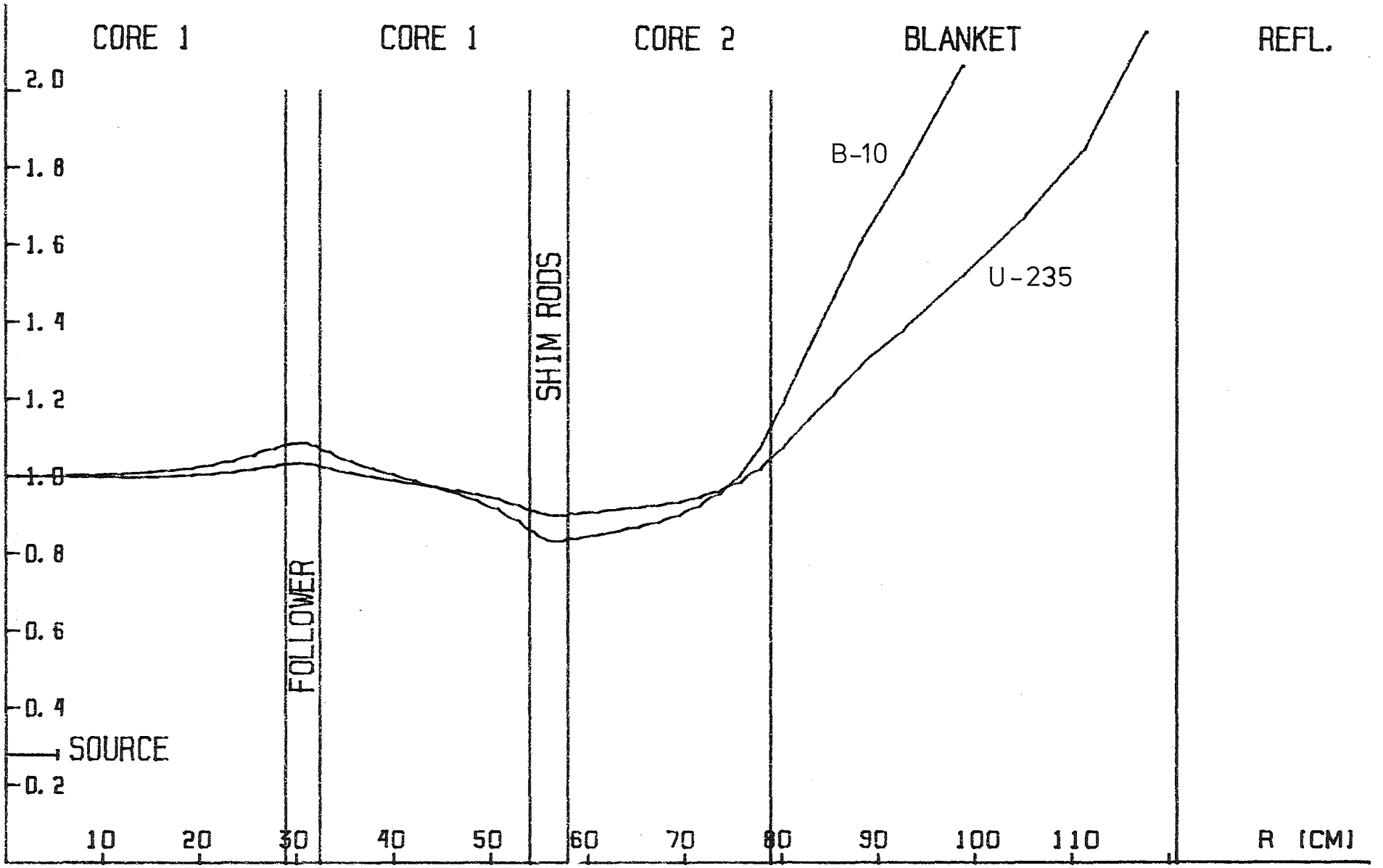
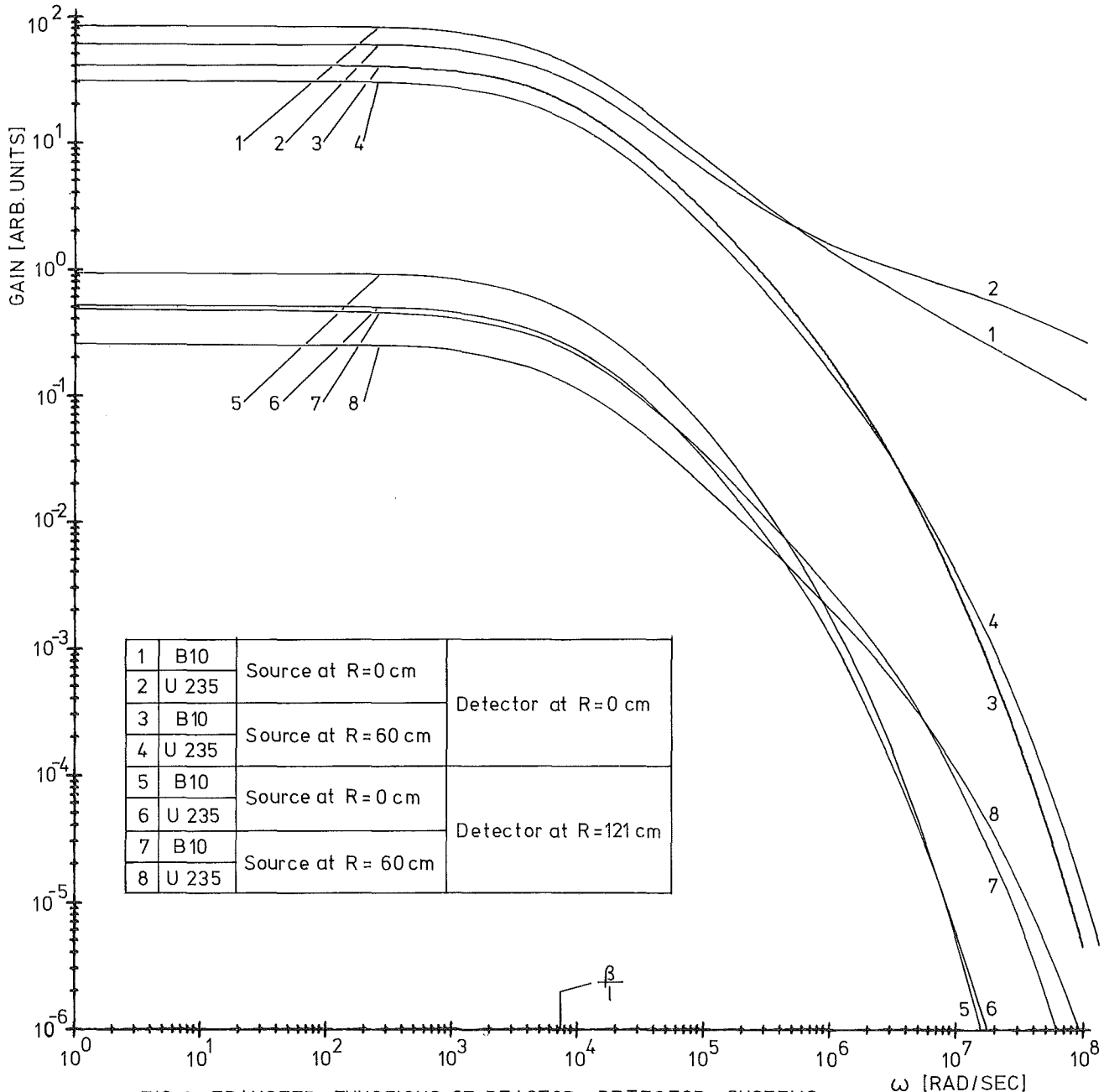


FIG. 8 INFLUENCE OF SPACE-DEPENDENT NEUTRON ENERGY SPECTRUM ON DETECTOR SENSITIVITY K(R)



1	B10	Source at R=0 cm	Detector at R=0 cm
2	U 235		
3	B10	Source at R=60 cm	
4	U 235		
5	B10	Source at R=0 cm	Detector at R=121 cm
6	U 235		
7	B10	Source at R= 60 cm	
8	U 235		

FIG.9 TRANSFER FUNCTIONS OF REACTOR-DETECTOR SYSTEMS