REACTOR TRANSFER FUNCTION MEASUREMENT AT PARR
BY NEUTRON NOISE ANALYSIS

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Open loop reactor transfer functions were measured at PARR utilizing neutron noise analysis techniques. Noise analysis was preferred over external reactivity oscillations (Pile Oscillator) method as it is very simple and does not disturb the reactor and can be carried on-line. In reactor noise measurements the fluctuations in the current of an ex-core neutron ion chamber were measured and analyzed. The power spectral density of neutron noise was used to get an estimate of the reactor transfer function. The break frequency of transfer function plot was used to obtain important kinetic parameters of PARR such as neutron mean life time, $l$, and reactivity, $\rho$, which have not been measured in the reactor before. The effect of graphite thermal column on reactor kinetics was also determined by this method. Based on noise measurements a new method of absolute reactor power determination is proposed for the calibration of power monitoring channels of PARR since there is no such provision in the reactor at low power levels.

Two detector cross correlation measurements were also made to improve the accuracy of transfer function determination. It is shown that cross correlation technique does not require very high efficiency neutron detectors as is needed for auto power spectral density measurements.
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1. **INTRODUCTION**

The transfer function or frequency response measurements on nuclear reactors have been successfully made for the past several years. The technique is useful both for determining the stability characteristics as well as the extraction of important kinetic parameters of the reactor system, like

i) The parameter $\theta/\lambda$ for critical reactor which provides the value of prompt neutron mean life time, $\lambda$.

ii) The values of reactivity and shut-down margin in subcritical reactor systems.

iii) Determination of absolute power of the reactor in both critical and sub-critical states.

There are two well known methods for experimental determination of reactor transfer function. By sinusoidal reactivity oscillation (pile Oscillator) and by analysing inherent fluctuations in reactor power i.e. neutron noise analysis. Both these methods have their own merits and de merits. Some of the obvious advantages in obtaining the transfer function from reactor noise are as follows:

i) In noise analysis method the inherent reactivity fluctuation present in the reactor are used as the input excitation to the reactor. As no external reactivity perturbation is required the noise measurements can be carried on-line without disturbing the reactor. This is a distinct advantage over the oscillation technique in which the reactor has to be externally perturbed during the experiment.

ii) In sinusoidal oscillation method each frequency has to be excited seperately. As the reactor dynamic response is required upto frequencies of the order of a few hundred Hertz, the whole measuring time becomes quite large.
In fact the noise technique is so simple and direct that a frequency spectrum analyzer can be used to obtain a real time display of the reactor dynamic response or transfer function which could be monitored alongwith the other process parameters of the reactor.

A principal disadvantage of noise analysis is that this method does not provide direct information about the phase of the transfer function. As no systematic input to the reactor is applied the noise analysis can only give an estimate of the magnitude and frequency bandwidth of the reactor transfer function.

However, as will be explained later, the important kinetic parameters of the reactor can be obtained by noting the break frequency of the transfer function which is readily given by noise analysis method.

Another disadvantage of this method is that it is less accurate than the oscillator technique. However, the later drawback can be overcome by using two detector cross correlation technique which cancels the large background noise present in auto power spectral density measurements.

2. Reactor Noise Theory

A description of general noise theory has been presented in a previous report (1). This section deals with the formulation of zero power reactor noise.

In critical and sub-critical reactor systems the fluctuations in neutron density or reactor power arise primarily due to inherent reactivity fluctuation which occur due to the statistical nature of nuclear fission phenomenon. The effect of external reactivity sources such as coolant temperature, control rod movement etc. is neglected in zero power reactor noise. In such simple case the reactor system can be considered a single input-output system.

As the transfer function is meaningful in frequency domain, we can define the zero power or open loop reactor transfer function by the following diagram.
Fig 3.1. Block diagram for open loop reactor transfer function.

In above diagram, $H_o(w)$ is the open loop transfer function and $\rho(x)$ and $N(w)$ are the input reactivity and output neutron fluctuation respectively as a function of frequency, $\omega$.

A very powerful tool of noise analysis in frequency domain is the function called power spectral density. By definition the auto power spectral density of a fluctuating signal is the power per unit frequency of that signal as a function of frequency. Mathematically the auto power spectral density of a function $x(w)$ is defined as the product of the function itself with its complex conjugate function, or

$$ G_x(w) = X^*(w)X(w) \quad (2.1) $$

where the asterisk stands for the complex conjugate function. In a similar way the cross power spectral density of two functions $X(w)$ and $Y(w)$ is given as.

$$ G_{XY}(w) = X^*(w)Y(w) \quad (2.2) $$

Thus, in Eq. 2.1, if we define $G(w)$ as the power spectral density function of input $\rho$ reactivity fluctuations and $G_N(w)$ as the power spectral density of output neutronic fluctuation, it follows that

$$ G_N(w) = |F_o(w)|^2G_P(w) \quad (2.3) $$

Eq. (2.3) establishes a relationship between the power spectral density of neutron noise and the reactor transfer function.

There are many causes of input reactivity fluctuation in a nuclear reactor in critical or sub-critical state. The most important being the randomness in the number of neutrons emitted per fission, $\nu$, which arises due to different fission cross-sections of various systems materials and their geometrical distribution in the reactor assembly. These reactivity fluctuations have large range...
of frequencies and can be considered as white noise (having constant magnitude over all frequencies). As the power spectral density of white noise is independent of frequency, the term $G_p(w)$ in Eq (2.3) can be considered a constant, $A$. Eq.(2.3) then becomes

$$G_N(w) = A |H_0(w)|^2$$  \hfill (2.4)

From Eq.(2.4) it follows that an estimate of reactor transfer function, $H_0(w)$, can be obtained directly from the power spectral density of neutron fluctuation, which can be measured experimentally in the reactor.

3. Derivation of Power Spectral Density of Reactor Noise

In this section a mathematical formulation of the neutron noise detected by a neutron detector in a reactor is presented and the power spectral density of the detector current will be derived.

As discussed earlier the inherent fluctuations in reactivity in a reactor can be considered white noise having large frequency bandwidths. The exact formulation of this reactivity noise taking into consideration all sources of reactivity perturbation is very involved and will not be attempted here. It can be shown that the power spectral density of such reactivity noise is given by the formula

$$G_p(w) = \frac{v_1}{n} \frac{-\nu^2 - \nu}{\epsilon}$$  \hfill (3.1)

where $G_p(w) = \text{power spectral density of reactivity noise}$

$n = \text{neutron mean life time in the reactor core.}$

$v = \text{average number of prompt neutrons emitted per fission.}$

$\epsilon = \text{detector efficiency}$

Since the reactor noise must be observed by some transducer to be meaningful, the process of neutron detection must be considered. This detection is commonly done by a neutron ion chamber that absorbs some of the neutrons in the reactor and produces an electrical signal or current. If $\epsilon$ is defined as the number of neutrons in the reactor, then the number of neutrons impinging on the detector per second is

$$N = \epsilon \frac{n}{1}$$  \hfill (3.2)
If $Q$ is the charge transferred per neutron absorbed, then the average current flowing through the detector is

$$\bar{I} = \epsilon Q \frac{n}{1}$$  (3.3)

Eq. (3.3) gives the value of the steady state current passing through the detector. Superimposed over this d.c. current will be the fluctuating current that arises in two ways.

i) The detector observes the fluctuation in neutron population in the reactor. These fluctuations are called correlated neutron noise as these represent the fluctuation in fission chain related neutron density. The correlated neutron current fluctuation is given in the same manner as Eq. (3.3) as

$$I_c(w) = \langle \epsilon Q \rangle n(w)$$  (3.4)

where $I_c(w)$ = frequency dependent correlated neutron current

$n(w)$ = correlated fluctuations in neutron population as a function of frequency.

Taking the power spectral densities of the correlated detector current and the neutron fluctuations in Eq. (3.4) gives (c.f. Eq. (2.1))

$$G_{I_c}(w) = \langle I_c^2(w) \rangle = \frac{\epsilon^2 Q^2}{1^2} \langle n^2(w), n(w) \rangle$$  (3.5)

or

$$G_{I_c}(w) = \frac{\epsilon^2 Q^2}{1^2} G_n(w)$$  (3.6)

where $G_n(w)$ is the power spectral density of neutron noise. Substituting the value of $G_n(w)$ from Eq. (2.3) gives

$$G_{I_c}(w) = \frac{\epsilon^2 Q^2}{1^2} G_p(w) \langle H_o(w) \rangle$$  (3.7)

and substituting the value of $G_p(w)$, the power spectral density of reactivity, from Eq. (3.1) gives

$$G_{I_c}(w) = \frac{\epsilon^2 Q^2}{n_1} \frac{\gamma^2 - \bar{\gamma}}{\bar{\gamma}} \langle H_o(w) \rangle^2$$  (3.8)
ii) The second component of ion chamber current fluctuations arises due
to the statistics of the detection process itself and it has no phase
relation (zero correlation) with the correlated neutron current $I_c$.
This current is analogous to the random current in an electronic diode
produced by individual arrival of electrons at the anode. The power
spectral density of the diode current noise is given by Schottkey
formula as (4).

$$G_I(w) = 2e^2 \bar{m}$$  \hspace{1cm} (3.9)

where $e = \text{electron charge.}$
and $\bar{m} = \text{average number of electrons flowing per second.}$
In the same way the power spectral density of detector current due to
uncorrelated detection noise is given by

$$G_{I_n}(w) = \langle I_n^2(w) \rangle = 2\epsilon^2 \frac{\epsilon_n}{1}$$  \hspace{1cm} (3.10)

Since these two noise components have no phase relation with each other
they can be added together, given the total current noise in the
neutron ion chamber output as

$$G_I(w) = G_{I_c}(w) + G_{I_n}(w)$$  \hspace{1cm} (3.11)

or from Eq. (3.8) and (3.10)

$$G_I(w) = \frac{2\epsilon^2 \epsilon_n}{1} + \frac{2\epsilon^2 \epsilon_n^2}{n} \frac{H_o(w)^2}{v}$$  \hspace{1cm} (3.12)

The reactivity transfer function of a critical reactor without delayed
neutron effect $H_o(w)$ is given by the relation (5)

$$H_o(w) = \frac{N(w)}{\rho (w)} = \frac{n/L}{jw+1/I} \left| \frac{H_o(w)^2}{v} \right|$$  \hspace{1cm} (for $\rho = 0$) \hspace{1cm} (3.13)

and Eq. (3.12) becomes

$$G_I(w) = \frac{2\epsilon^2 \epsilon_n}{1} + \frac{\epsilon^2}{\epsilon_n^2} \frac{v^2 - \bar{v}}{v}$$  \hspace{1cm} (3.14)

Eq. (3.14) gives a mathematical description of reactor noise
spectrum excluding the effect of external reactivity sources.
3.1 Extraction of Reactor Kinetic Parameters from Noise Spectrum

A more convenient form of Eq. (3.14) can be obtained by dividing the psd of current fluctuations by the square of mean (dc) detector current for a direct comparison with experimental noise spectrum. Such normalized power spectral density of neutron noise can be written as

$$G_{\text{norm}}(w) = \frac{G_r(w)}{I^2} = \frac{21}{\epsilon n} + \frac{21}{n} x \frac{v^{-2}}{v} x \frac{1}{w^{2} + \beta^2}$$

(3.15)

where the value of mean detector current $I$ has been obtained from Eq. (3.3).

As explained before, the first term of Eq. (3.15) represents the uncorrelated detection noise, while the second term is the true reactor noise. Note that the detection noise term is independent of frequency ($w$) and can be considered as white noise whereas the reactor noise term has the frequency behaviour of a low pass filter. This becomes apparent if we rewrite Eq. (3.15) as

$$G_{\text{norm}}(w) = \frac{A}{w^2 + \kappa^2} + B$$

(3.16)

where $A$ and $B$ are constants and $\kappa$ is the Rossi $-$ parameter given by the relation

$$\kappa = \frac{\beta - \rho}{c}$$

(3.17)

where $\rho = 0$, for above treatment as the reactor is in critical state.

The normalized psd of Eq. (3.16) can be plotted as a function of frequency as shown in Fig. 3.2

![Fig. 3.2: Plot of Power Spectral Density of Neutron Noise as a Function of Frequency.](image)
From Fig 3.2 we can arrive at an important conclusion. For value of frequency, \( w \), equal to \( \lambda \) the magnitude of \( G_{\text{norm}}(w) \) decreases to one half of its value at lower frequencies. In other words, the reactor noise spectrum has the half power point or break frequency at \( w = \lambda \). Recalling Eq. (3.17) for the value of \( \lambda \) one can write

\[
\omega_c = \lambda = \frac{\beta - \rho}{\eta}
\]  

(3.18)

Kinetic parameters of the reactor can therefore be obtained by simply noting the break frequency of the experimental power spectral density of neutron detector current in the reactor core.

### Uncorrelated Noise Error in Reactor Transfer Function Measurements

One major problem of frequency response determination of the reactor by noise analysis is a large detection noise component which is represented by the constant \( B \) at tail end of the noise spectrum curve of Fig. 3.2. As is evident from that figure, the term \( A/(w^2 + \alpha^2) \) must be considerably higher than \( B \) for an accurate determination of reactor break frequency. It may be noted that detection noise component of Eq. (3.15) decreases with an increase in detector efficiency. A higher efficiency of the neutron detector would therefore result in a considerable increase of correlated reactor noise over uncorrelated component. The criteria for minimum detector efficiency for meaningful transfer function or noise spectrum measurements can then be drawn from Eq. (3.15) as

\[
\epsilon_{\text{min}} > \frac{1}{\sqrt{2}w^2 - \eta^2} (w^2 L^2 + \beta^2)
\]

(3.19)

For \( ^{235}U \) system like PARR the minimum detector efficiency comes out to be

\[
\epsilon_{\text{min}} > 2 \times 10^{-5} \text{ counts/Fission (for } w \rightarrow 0) \]

(3.20)

Thus, for accurate experimental determination of reactor transfer function in PARR the detector efficiency must be much higher than the limiting value given by Eq. (3.20).
4. Two Detector Cross Correlation Measurements

As discussed in previous section the auto-power spectral density measurement of neutron noise imposes severe limitation on detector efficiency. Thus for accurate transfer function measurements the detector has to placed either in the reactor core or very near to it, a condition that can not be met in all reactors. In order to overcome this limitation and to improve the accuracy of transfer function measurements Seifritz et. al.\(^{(5)}\) proposed a new method in which the signals from two ex core neutron detectors were cross correlated and the cross power spectral density of the two detector signals was obtained. In this method the uncorrelated detection noise is cancelled in each detector current and the cross power spectral density comprises of the true neutron noise component only. This can be shown mathematically with the help of the similar block diagram as of Fig 4.1 for two detector systems.

\[ n(\omega) \rightarrow H_0(\omega) \rightarrow y_1(\omega) \]
\[ \rightarrow H_1(\omega) \rightarrow n_2(\omega) \]
\[ \rightarrow H_2(\omega) \rightarrow y_2(\omega) \]

In the system considered above the reactor output neutron noise is measured simultaneously with two neutron detectors having transfer functions \(H_1(\omega)\) and \(H_2(\omega)\) respectively. The detection noise component affecting the two detectors are \(n_1(\omega)\) and \(n_2(\omega)\) respectively. We can then write following input-output relations for the two detector outputs:

\[ y_1(\omega) = n_1(\omega) H_1(\omega) + p(\omega) H_0(\omega) \cdot R_0(\omega) \quad (4.6) \]
\[ y_2(\omega) = n_2(\omega) H_2(\omega) + p(\omega) H_0(\omega) \cdot R_0(\omega) \quad (4.7) \]

The cross power spectral density of the detector signals \(Y_1(\omega)\) and \(Y_2(\omega)\) is given by Eq. 2.2 as

\[ G_{Y_1 Y_2(\omega)} = Y_1^*(\omega) \cdot Y_2(\omega) \]
\[ = \left(n_1^*(\omega) H_1^*(\omega) + p^*(\omega) H_0^*(\omega) \cdot R_0^*(\omega) \right) \left(n_2(\omega) H_2(\omega) + H_0(\omega) \cdot R_0(\omega) \right) \]

\[ (4.8) \]

The noise components \(n_1(\omega)\) and \(n_2(\omega)\) are local random fluctuations arising separately in the two detectors; as such these have no correlation either with each other or with the input reactivity noise as the three phenomena occur
independently of each other. In other words one can put
\[ \rho_1^*(w) \rho_2(w) = 0 \]
\[ \rho_1^*(w) \rho(w) = 0 \]
\[ \rho^*(w) \rho_2(w) = 0 \]
Eq. (4.8) can then be expanded to give
\[ G_{y_1 y_2}(w) = \rho^*(w) \rho(w) H_0^*(w) H_0(w) H_1^*(w) H_2(w) \]
or
\[ G_{y_1 y_2}(w) = G_0(w) \left| H_0(w) \right|^2 \left| H_1(w) \right|^2 (H_1(w) H_2(w)) \]
and from Eq. (2.3) one gets
\[ G_{y_1 y_2}(w) = G_N(w) \left| H_1(w) \right|^2 \]
Where \( G_N(w) \) is true correlated reactor noise spectrum described by the second term of Eq. (3.14). Usually, neutron ion chambers have transfer functions which are constant up to very high frequencies. \( H_1(w) \) can therefore be considered a constant and we can define an experimental cross spectral density function as
\[ G_{N}(w) = \frac{G_{y_1 y_2}(w)}{H_1^2(w)} \]
As is evident from Eq. (4.10) the experimental cross spectral density of two neutron detectors represents true reactor noise spectrum and is independent of the uncorrelated detection noise. The minimum detector efficiency criteria is no longer required in cross correlation experiments and accurate reactor noise spectra can be obtained even with low efficiency, ex-core detectors.

5. Experimental Measurements

The experimental arrangement for transfer function measurements is essentially the same as that described in a previous report (1) for high power noise measurements. A block diagram of various equipment used is shown in Fig. 5.1. A Centronic
The ion chamber was lowered at a place just adjacent to the reactor core for maximum efficiency. The neutron current signal from the ion chamber was fed to a Keithley model 410 micro-micro ammeter which converted the low level current into measurable voltage signal. The d.c. level of the ammeter output voltage was cutoff by passing the ammeter output through a high pass filter. This d.c. level was however noted for use in the calculation of normalized power spectral density. The fluctuating part of the ammeter voltage signal was amplified by a differential input band-pass amplifier; the differential input mode was used for common mode rejection of the unwanted noise in the signal.

The amplifier output was passed through antialiasing low pass filters in order to limit the band-width of the noise signal. The cut-off frequency of these low pass filters was set at 100 Hertz for all measurements. The filter output signal which was of the form of fluctuating analogue signal was recorded on the instrumentation tape recorder for off-line processing and analysis.

For cross spectral density measurements, one of the ion chambers (UIC) already installed near the reactor core for reactor operation was used along with the Centronic ion chamber. It was ensured that the entire measuring instrumentation had frequency pass band which extended well beyond the frequencies of interest in the neutron noise signals. In this way all signal frequency components were passed by the measuring instrumentation.

During all experimental measurements the reactor was maintained at a steady power level. Measurements were made at different power levels ranging from 50-400 watts. At these power levels the external reactivity perturbations were expected to be negligibly small especially as the reactor was operated without coolant flow. In some experiments the reactor was operated in both stall and open ends in order to observe the effect of graphite thermal column on neutron mean life time, $\tau$. 

The typical recording time for the noise measurements was about 30 minutes for auto power spectral density measurements and about 60 minutes for cross spectral density measurements. The relatively large measuring time for cross spectral density was necessitated by a large scatter of experimental data in the spectral density evaluation by the data processor.
In order to determine the magnitude of electronic noise in the measuring system for background subtraction, the same experimental arrangement as shown in Fig 5.1 (a) was used except that the ion chamber input to ammeter was disconnected and the input connector was grounded. In this way it was possible to measure the magnitude and frequency composition of the electronic noise present in all stages from input to output.

5. Processing of Experimental Data

The tape recorded analogue fluctuating signals were analysed on a digital fourier analyzer computer for evaluation of spectral density plots. The arrangement used for signal analysis is shown in Fig 5.1(b). The recorded signal was again passed through filtering network for proper shaping of the signal before feeding to the Fourier analyzer. The cut off frequency of low pass filter was still set at 100 Hz. Presence of large amount of 50 Hz line pick-up in the noise signal posed a problem but this was solved by writing a short subroutine in the computer program which erased the Fourier analysed data at 50 Hz frequency. Removing the separate ground loops in the experimental set up also reduced the line pick up by a large amount.

The sampling frequency of the analyzer had to be set at a value more than double the filter cut off frequency, as required by the aliasing criteria (1). With a filter frequency of 100 Hz, this set the sampling rate of the ADC at a minimum value of 200 Hz (5m sec). The number of data points (acquisition block size) used in the computer for analysis were 1024. These computer settings limited the minimum frequency resolution (Δ f) of two successive points in the frequency spectrum to be about 0.2 Hz, a resolution which is sufficiently high for an accurate measurement of neutron noise spectrum upto hundred Hertz frequencies.

6. Results and Discussion

In this section the normalized power spectral densities of neutron noise obtained for different reactor operating conditions will be discussed. The effect of background instrumentation noise on these spectra, as explained in Section 5.1, was found to be negligibly small even after maximum amplification of instrumentation
noise in the measuring circuit.

6.1 Experimental Power Spectral Density of Neutron Noise

The normalized power spectral density of neutron noise from an ex-core ion chamber is shown in Fig. 6.1 for two different detector locations and at a constant power level of 100 watts. The power spectra shown in Fig. 5.2 are obtained by dividing the psd of the detector current fluctuations by the square of mean detector current fluctuations, \( \frac{\Delta I}{I^2} \). In Fig. 6.1, the effect of detector efficiency on reactor noise spectrum, as explained in Section 4, is quite apparent. In the figure, curve-I represents the power spectral density when the detector is placed at a less efficient position about 20 cms away from the side of the reactor core. The resulting noise spectrum is that of white noise having constant magnitude for all frequencies. Apparently, due to distant position of ion chamber from the reactor core, the detector current fluctuations comprise entirely of uncorrelated detection noise. This is explained in Section 3.2.

The minimum detector efficiency expressed in Eq. (3.19) for meaningful transfer function measurement of PARR is

\[ \varepsilon_{\text{min}} \geq 2 \times 10^{-5} \text{ counts/fission} \]

The reactor power for experimental measurements of Fig. (6.1) is 250 watts and neutron ion chamber has a sensitivity of \( 4 \times 10^{-14} \) amperes/count/sec. The minimum chamber current therefore comes out to be

\[ i_{\text{min}} = 2 \times 10^{-5} \times 7.5 \times 10^{12} \times 4 \times 10^{-14} \]

or

\[ I_{\text{min}} = 6.0 \text{ micro amperes} \]

Thus, for a power level of 250 watts the output current of neutron ion chamber must be more than 6 micro-amperes for a meaningful measurement of reactor transfer function.

Curve-II of Fig. 6.1 is the power spectral density of chamber current when the detector is placed just adjacent to the reactor core in its most efficient position.
The ion chamber current at this position is 18.5 amperes which is three times higher than the minimum efficiency criteria. The resulting power spectral density is markedly different from that of curve-I and represents the true reactor transfer function as described by the first term of Eq. (14.4). The break frequency (half power point) of reactor noise spectrum comes out to be 18.2 Hertz, which is the value of $\sqrt{2\pi}$ expressed in Eq. (3.18). Recalling Eq. (4.5) one can write

$$f_b = \frac{\alpha}{2\pi} = \frac{\beta \cdot \rho}{2\pi \ell}$$

where $f_b$ is the experimentally determined break frequency.

As the reactor was just critical at the time of experiment (reactor power was constant), we can put $\rho = 0$

Also $f_b = 18.2$ Hertz

and $\beta = 0.0064$ for $^{235}\text{U}$ systems

The value of prompt neutron life time for PARR core in the stall comes out to be $\tau = 5.54 \times 10^{-5}$ sec.

This experimentally determined value of $\tau$ is in quite good arrangement with that supplied by AMF Atomic (6).

It may be noted that once the value of $\tau$ is determined for a particular core configuration it is expected to remain constant for different values of reactivity. The value of break frequency of reactor transfer function can therefore be used to determine the reactivity of the reactor in subcritical or supercritical states, in accordance with Eq. (4.5).

6.2 Effect of Graphite Thermal Column on Reactor Kinetics

In stall end position of the reactor core its one side is covered by a graphite thermal column. When the reactor is operated in open end the graphite is
replaced by water. In water the neutrons are thermalized in a shorter time as compared to graphite. Also the probability of neutron absorption is greater in water. As the neutron life time, $t$, is defined as the time interval between production and absorption of a neutron the value of $t$ will be smaller in open end as compared to the stall end. The reactor break frequency will also shift toward higher value in open end for the same value of reactivity. In order to determine the value of $t$ in open end experimental measurements were made with the reactor exactly critical in both stall and open ends. The resulting power spectral densities for the two cases are shown in Fig. 6.2. The break frequency of curve II comes out to be at 20 Hertz as compared to 18.2 Hz of curve-I giving the mean neutron life time as $5.09 \times 10^{-5}$ sec.

6.3 Cross Spectral Density

Fig. 6.3 shows the cross spectral density plot along with the psd, of individual detector signal of two neutron ion chamber. Both the detectors were placed at low efficiency position, away from the reactor core, and the power spectral densities of individual detector signals are expected to be those of uncorrelated noise, as is apparent from Fig. 6.3. The cross correlation of the two detector signals, however, eliminates the uncorrelated noise component and the cross spectral density plot of Fig. 6.3 depicts the true picture of reactor transfer function. The cross correlation method results in a significant improvement over single detector psd in that it is no longer necessary to place the detector in a position inside or very near to the reactor core. It may be pointed out that after the installation of reflector elements along the side of PARR core the PSD technique can not be used for transfer function measurements in future. Under the circumstances cross spectral density is the only method for providing the reactor transfer function information. One drawback of CPSD measurements, as evident from Fig. 6.3, is relatively large scatter in magnitude of the data points in the frequency spectrum.

This scatter in magnitude can only be improved by giving large collection time of detector signals which may extend upto 2 to 4 times than required for Psd measurements.

6.4 Absolute Reactor Power

The effect of reactor power on neutron power spectral density is shown in Fig. 6.4 for two power levels of 100 watts and 200 watts. Following facts are
evident from the figure.

1. The break frequency of the neutron noise spectrum remains constant for different power levels. This is expected as the reactivity of the reactor remains unchanged.

2. The magnitude of neutron noise spectrum varies almost proportionally with the reactor power. This is expected from the theory of reactor noise (Eq. 3.15) where the magnitude of normalized power spectral density is shown to be proportional to neutron density $n_n$. The observed proportionality of the neutron noise with reactor power is very significant as it provides a method for determination of absolute reactor power at low power levels. It may be noted that the magnitude of normalized power spectral density described by (Eq. 3.15) is independent of detector efficiency as it is already divided by the chamber mean current. As other kinetic parameter of Eq. (3.15) are expected to remain constant once the core geometry and materials are fixed, the magnitude of $psd$ is a function of number of neutron per second, which is nothing but the reactor power. This implies that as large as the minimum detector efficiency criteria is satisfied the magnitude of neutron $psd$ will indicate true reactor power which is not affected by a change in detector position and efficiency.

This is a very significant conclusion as it indicates that experimental determination of neutron power spectral density could be used for reactor power calibration of power monitoring channels of PARR at low power, something which is not possible otherwise in the reactor.

Some more detailed studies of neutron noise at various power levels are still required before adopting this method for reactor power calibration.
7. Conclusion

It has been shown that the neutron noise analysis technique offers a very simple and useful direct method for reactor transfer function determinations without any disturbance to the reactor system. Important reactor kinetic parameters have been obtained by this method. Further measurements will be made to use the magnitude of neutron noise for absolute power calibration of the reactor.
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FIG. 5.1 (a) - ON LINE NEUTRON NOISE MEASUREMENTS

FIG. 5.1 (b) - OFF LINE PROCESSING OF EXPERIMENTAL DATA
FIG. 6.1—EFFECT OF DETECTOR POSITION ON NEUTRON POWER SPECTRAL DENSITY
FIG. 6.2 - EFFECT OF THERMAL COLUMN ON NEUTRON POWER SPECTRAL DENSITY

CURVE I: REACTOR AT STALL END
CURVE II: REACTOR AT OPEN END
FIG. 6.3-COMPARISON OF CROSS POWER SPECTRAL DENSITY AND AUTO POWER SPECTRAL DENSITY AT REACTOR POWER 250 WATTS
FIG. 6.4—POWER SPECTRAL DENSITY OF NEUTRON NOISE AT DIFFERENT REACTOR POWER

CURVE I = 100 WATTS
CURVE II = 200 WATTS