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Dragon Project Report

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PROPOSALS FOR TRANSFER FUNCTION MEASUREMENTS ON THE DRAGON REACTOR EXPERIMENT

[redacted]

by

J. REBER

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ABSTRACT

This report contains details of the reactor physics information available from transfer function measurements. The experiments considered are the reactivity to flux transfer function at different power levels and the inlet to outlet helium temperature transfer function. Different methods of their measurement are described and discussed with respect to their relationship to the irradiation programme and their experimental usefulness.

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ON THE DRAGON REACTOR EXPERIMENT

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1. INTRODUCTION

The transfer function, which describes the time behaviour of a system in terms of a frequency spectrum, is very useful in two respects: first, the transfer function in itself as a criterion on stability, and second its application in determining some of the physical parameters which govern the reactor kinetics. The analysis of the transfer function in that second respect is part of the physics experiments on the Dragon Reactor Experiment, which are described in another report [1].

The transfer function normally used in reactor kinetics is the one with reactivity as input and neutron flux as output, but it also looks promising to use other parameters. A thermal experiment with inlet temperature or mass flow as input and outlet temperature as output could give better access to thermal parameters [2, 3]. (See Fig. 1.)

This report describes the information to be obtained from the analysis of transfer functions, some methods of their measurement and discusses their application in the light of their relationship to the irradiation programme, which will have priority in the experiments in the Dragon Reactor.

2. INFORMATION AVAILABLE FROM TRANSFER FUNCTION MEASUREMENTS

The general procedure is to set up the parameters of interest in a mathematical model and then to fit this to the measured transfer function. The reactivity flux transfer function depends in its high frequency region mainly upon the mean prompt neutron lifetime, in its low frequency region upon the delayed neutrons and the various thermal feedback effects.

A purely thermal transfer function can be used to confirm the heat transfer calculations and gives an estimate of the fuel element temperature independently of the thermocouples in the fuel elements.

2.1 Reactivity

If a control rod is sinusoidally oscillated about the critical position with small amplitude, then the output signal will be:-

$$\frac{\Delta N_o}{N_o} = \left|F(\omega)\right| \; \Delta\rho_o$$

where

ΔN_o = neutron flux variations

N_o = steady mean flux level

$|F(\omega)|$ = amplitude of transfer function

$\Delta\rho_o$ = reactivity oscillation by control rod movement.

If a set of calculated $|F(\omega)|$ are combined with a measured set of $\frac{\Delta N_o}{N_o}$ a set of values is found for the reactivity of the section of control rod oscillated. Using the control rod reactivity displacement curve obtained by other techniques, (e.g. period measurements) the worth of the whole rod, relative to the reactivity of the section oscillated, can be found [4].

This measurement will be quite useful to obtain the control rod worth at power, where period measurements look impossible.

2.2 Mean Prompt Neutron Lifetime and Delayed Neutron Data

The zero energy transfer function for reactivity used on Zenith experiments and for Dragon calculations [4] is as follows:-

$$|F(\omega)| = \left[\left(\beta_{eff}\ \omega^2 \sum_i \frac{a_i}{\lambda_i^{\,2} + \omega^2}\right)^2 + \left(\omega l + \beta_{eff}\ \omega \sum_i \frac{a_i\ \lambda_i}{\omega^2 + \lambda_i^{\,2}}\right)^2\right]^{-\frac{1}{2}}$$

$$tg\ \phi = \frac{1 + \beta_{eff} \sum_i \frac{\lambda_i\ a_i}{\lambda_i^{\,2} + \omega^2}}{\omega\ \beta_{eff} \sum_i \frac{a_i}{\lambda_i^{\,2} + \omega^2}}$$

where

l = prompt neutron lifetime

a_i, λ_i = relative concentrations and decay constants of the delayed neutron precursors

β_{eff} = effective delayed neutron fraction.

Fig. 2 shows $|F(\omega)|$ calculated for the Dragon Reactor in a double logarithmic scale. If one approximates the curve by the straight lines

$$|F_1| = \frac{\lambda'}{\beta^2_{eff}\,\omega} \quad \text{(1 group delayed neutrons)}$$

$$|F_1| = \frac{1}{\beta^2_{eff}\,\omega \sum_i \frac{a_i}{\lambda_i}} \quad \text{(6 groups delayed neutrons)}$$

for small ω

$$|F_2| = \frac{1}{\beta_{eff}} \qquad \text{medium } \omega$$

$$|F_3| = \frac{1}{\omega l} \qquad \text{high } \omega$$

one gets two intersections at the frequencies

$$\omega_1 = \frac{\lambda'}{\beta_{eff}} = \frac{1}{\beta_{eff} \sum_i \frac{a_i}{\lambda_i}} = \frac{1}{\sum_i \frac{\beta_i}{\lambda_i}} \quad \text{and} \quad \omega_2 = \frac{\beta_{eff}}{l}$$

The parameters obtained by a fitting process from the transfer function are ω_1 and ω_2 or, instead of ω_1 the ratios $\frac{\beta_i}{\lambda_i}$ for i = 1, 2, ... 6. Which of these is determined depends on the accuracy and frequency resolution of the measured transfer function, but we know from Zenith results [4] that the delayed neutron data given by Keepin [5] used in this model of transfer function gives satisfactory results. With these data and a measured ω_1 we will get an estimate of β_{eff} which can otherwise only be measured by irradiation experiments. ω_2 together with a knowledge of β_{eff} yields the mean neutron lifetime l.

2.3 Burn-up

If with increasing burn-up there is significant formation of a fuel with different delayed neutron data, this will be indicated in the transfer function.

It is assumed that the Dragon Reactor will start burning with 100% U-235 and end with 90% U-235 and 10% U-233 in the highest irradiated elements. The difference in the delayed neutron fraction of U-235 and U-233 is only about 10%. In the ideal case where all elements would get the same burn-up the shift in the total delayed neutron fraction would only be 1%, which is definitely too small to be measured with any accuracy. Therefore, U-233 formation in the Dragon core cannot be measured by means of the transfer function.

A more important burn-up effect will be the accumulation of fission product poisons, resulting in changed reactivity and, possibly, measurable changed temperature coefficients.

2.4 Thermal Data

There are two thermal parameters which are of greatest importance and can be evaluated from the transfer function: the temperature coefficients for reactivity changes with core temperature and the heat transfer coefficient from fuel rod to coolant. The first one causes, due to feedback, a change in the reactivity power transfer function at low frequencies and is described below in some detail. The second can be obtained from a purely thermal experiment by measuring the transfer function between inlet and outlet temperatures of coolant and is described in another report [2].

Fig. 1 shows the principle of the system on which we are measuring. In all our models it is assumed that the thermal attenuation of the heat exchanger is so great that its feedback can be neglected.

2.4.1 Temperature Coefficient of Reactivity

The total reactivity of a reactor under perturbation conditions is the sum of all independent reactivity changes. If $\Delta\rho_A$ is the reactivity applied to the system (e.g. by control rod movement) and $\Delta\rho_T$ is the reactivity effect of temperature, then the total reactivity change is given by the equation:-

$$\Delta\rho = \Delta\rho_A + \Delta\rho_T$$

Multiplying by $\frac{\phi^*}{\Delta\phi}$, where $\Delta\phi$ is the neutron flux variation and ϕ^* is the equilibrium flux,

$$\phi^* \frac{\Delta\rho}{\Delta\phi} = \phi^* \frac{\Delta\rho_A}{\Delta\phi} + \phi^* \frac{\Delta\rho_T}{\Delta\phi}$$

The reactivity/flux transfer function is defined as

$$F = \frac{1}{\phi^*} \cdot \frac{\Delta\phi}{\Delta\rho_A}$$

and at "zero power",

$$F_o = \frac{1}{\phi^*} \frac{\Delta\phi}{\Delta\rho}$$, since $\rho = \rho_A$ at zero power.

If we define also

$$L = \phi^* \frac{\Delta\rho_T}{\Delta\phi} ,$$

a flux/temperature reactivity transfer function, then

$$\frac{1}{F} = \frac{1}{F_o} - L$$

Since F_o is the conventional zero power transfer function in terms of neutron lifetime and delayed neutron behaviour, the behaviour of F at high power differs only through L. To determine temperature feedback it is only necessary, therefore, to determine the appropriate expression for L;

$$L = \phi^* \frac{\Delta \rho_T}{\Delta \phi}$$

In the calculations done so far, it has been assumed that flux and power are proportional, and that $\Delta\rho_T$ is the sum of effects of different temperatures; i.e.

$$\phi \; \alpha \; P$$

$$\Delta\rho_T = \sum_i \alpha_i \; \Delta T_i$$

where

P = power

α_i = temperature coefficient of reactivity for i:th temperature

ΔT_i = i:th temperature variation.

Therefore

$$L = P^* \sum_i \alpha_i \left(\frac{\Delta T_i}{\Delta P} \right)$$

The only remaining information now required is the behaviour of $\frac{\Delta T_i}{\Delta P}$ for every i.

The evaluation of $\frac{\Delta T_i}{\Delta P}$ will be illustrated using a simple model. The extension to a complicated model involves no new methods.

The model we consider consists of a fuel rod for which a one-temperature model is assumed, i.e. it is assumed that all the fuel rod heat capacity is concentrated at one point.

Considering the heat balance for a section of the fuel rod:

Heat absorbed in fuel rod = Heat produced in fuel rod –
– Heat removed by coolant

i.e.

$$C \frac{dT}{dt} = P - \lambda (T - \theta)$$

where

T = fuel rod temperature

t = time

P = power

θ = coolant temperature

C = heat capacity of fuel rod

λ = effective heat conductance from fuel rod to coolant.

To determine the effect of the coolant, we assume that the variation of θ is linear along the coolant channel. Thus, if θ is the value at the midpoint of the channel,

$$\theta = \frac{\theta_o + \theta_i}{2}$$

where

θ_o = outlet coolant temperature

θ_i = inlet coolant temperature

Assuming also that the heat transferred to the coolant at mid-channel is the average for the channel, and that the coolant heat capacity is not large,

$$\lambda (T - \theta) = WCp (\theta_o - \theta_i)$$

where

W = coolant mass flow

Cp = coolant specific heat

From the last two equations we obtain, eliminating θ_o

$$\theta = \frac{\lambda T + 2WCp\, \theta_i}{\lambda + 2WCp}$$

$$\lambda(T - \theta) = \frac{2 \lambda WCp}{\lambda + 2WCp} (T - \theta_i) = \lambda' (T - \theta_i) \text{ say.}$$

Therefore, the heat balance for the fuel rod is

$$C \frac{dT}{dt} = P - \lambda' (T - \theta_i)$$, which is now expressed in terms of inlet coolant temperature θ_i.

Assuming θ_i constant, we have

$$C \frac{d(\Delta T)}{dt} = \Delta P - \lambda' \Delta T$$

and for an oscillation of frequency ω,

$$\frac{\Delta T}{\Delta P} = \frac{1}{\lambda' + i\omega C}$$

If the temperature coefficient associated with ΔT is α, and no other temperatures have a reactivity effect,

$$L = \frac{\alpha P^*}{\lambda' + i\omega C}$$, which is a stabilising component if $\alpha < 0$.

The calculations, done on PACE, included four temperature points within the fuel rod.

L has a stabilising effect if

$R < 0$, $I > 0$ simultaneously, where R and I are the real and imaginary parts of L,

e.g.

$$L = \frac{\alpha P^*}{\lambda' + i\omega C} = \frac{\alpha P^*}{(\lambda')^2 + \omega^2 C^2} (\lambda' - i\omega C)$$, giving

$R < 0$ and $I > 0$ if $\alpha < 0$.

D.P. Report 75, Fig. 2.7.2 [6], illustrates this, where $\frac{1}{F}$ is plotted (real part plotted against imaginary part). Increasing power moves the transfer function downwards towards the right, i.e. $R < 0$, $I > 0$. In this figure one can also see the neutron lifetime break point at $\omega = 10$. Fig. 3 shows the same, but in a Bode diagram.

2.4.2 Heat Transfer Coefficient

As mentioned this experiment is described elsewhere [2] and, therefore, only a summary is given here.

The basis is the transfer function between inlet and outlet temperature. Assuming a thin fuel rod, no reflector effect and constant power, the mathematical model looks as follows:

$$F(j\omega) = \frac{\Delta T_o}{\Delta T_i} = \exp\left[-\frac{\lambda\,\omega_c\,\omega^2}{\omega^2+\omega_c^2} - j\omega\left(\tau + \frac{\lambda\,\omega_c^2}{\omega^2+\omega_c^2}\right)\right]$$

with $\lambda = \frac{mC_r}{WC_p}$

$$\omega_c = \frac{hS}{mC_r}$$

$$\tau = \frac{1}{V}$$

T_o, T_i	Outlet and inlet helium temperature
m	mass of fuel rod
C_r	specific heat of fuel rod
C_p	specific heat of helium
W	helium mass flow per rod
h	effective heat transfer coefficient (including conduction effect)
V	helium velocity

In Fig. 4, $F(j\omega)$ is plotted for different assumptions about fuel rod and reflector effect. The phase curve shows a peak where $\omega \approx \omega_c$. Because S, m and C_r are known with good accuracy the effective heat transfer coefficient h can be calculated from the measured ω_c. Knowing h, an estimate of the fuel rod temperature can be made, which is information of great importance if the fuel element thermocouples should fail.

3. METHODS OF MEASUREMENT

3.1 Oscillator Method

The most usual method in measuring a transfer function is to apply a sinusoidal signal at the input of the system under investigation and to determine the ratio of amplitudes and the phase lag between input and output signals. By variation of the input frequency the whole range of interest will be measured. In the Dragon case we shall oscillate a control rod for reactivity input, and possibly the circulator speed for mass flow variations and the primary heat exchanger by-pass valve for inlet temperature variations. At the moment only the rod oscillation experiment is definitely to be used. Regarding the other two experiments, the experimental feasibility and the safety aspects are not yet fully investigated. The output will in the first experiment be the neutron flux, and in the other two the helium outlet temperature. The generation of the input frequency and the computation of amplitude and phase at this frequency will be carried out using a transfer function analyser [7].

The accuracy of the transfer function depends upon the signal to noise ratio of output, the number of cycles measured and the performance of the transfer function analyser, but 1 or 2% should be feasible.

In our experiments the low frequency is limited by the transfer function analyser, the high frequency limit is set by the control rod drive. Because of the low high frequency limit of $\omega = 0.5\ s^{-1}$ we will not be able to use this method to measure the neutron lifetime which is expected to give a ω_2 of $10\ s^{-1}$.

3.2 Step Change

Another well known method, but less direct than the oscillator method, is the application of a sudden change in an input signal and the observation of the output. The Laplace transform of the output yields the transfer function. As in the oscillator experiment, one may move a rod or change mass flow or by-pass valve settings.

There are two types of input: either a single step change in increasing or decreasing direction, or a short impulse. The difference between the two lies at zero frequency. The first one does give and the second does not give, a permanent displacement of the working point.

The accuracy of the method will probably be limited by the speed of the input devices. Experiments on Zenith [8] showed an accuracy of 5% given by the speed of control rod movement. The statistical error introduced from counting was only 1%. The frequency interval of the transfer function from one measurement covers only about one decade. This method will mainly be used for reactivity measurements at zero energy.

3.3 Statistical Methods

A newer approach to the measurement of time behaviour is through the statistical analysis of input and output signals. The mathematical tool is the correlation of a signal either with itself - the auto correlation - or with another signal - the cross correlation. In the previous two methods the signals should be free from noise, a condition which is sometimes very restrictive. The statistical analysis by cross correlation gives a good separation from noise and therefore the signal to be measured can be buried in noise. The mathematical theory is given in several reports [9, with comprehensive references; 10] and is therefore omitted here. Only the most important results are summarised below.

The correlation has the form

$$Cxy(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{+T} y(t + \tau) \cdot x(t)\, dt$$

where x(t) and y(t) are the time functions (e.g. input and output) to be correlated and $Cxy(\tau)$ the correlation function for a time lag τ. For $x(t) = y(t)$ $Cxy(\tau)$ becomes $Axx(\tau)$. $Cxy(\tau)$ is the cross correlation of $x(t)$ and $y(t)$, $Axx(\tau)$ is the auto correlation of $x(t)$.

According to Wiener's theorem, the Fourier transform of the correlation function yields the power spectrum of this correlation. In the case of the auto correlation function, the power spectrum becomes a real function and for the cross correlation function the power spectrum is a complex function of ω.

The transfer function is defined as the square root of the complex ratio of the power spectra of output and input. Therefore the transfer function becomes

$$F(j\omega) = \sqrt{\frac{\Phi xy(j\omega)}{\Phi xx(\omega)}}$$

where $\Phi xy(j\omega)$ is the crosspower spectrum of input and output and $\Phi xx(\omega)$ the power spectrum of the input.

The application of this to the transfer function measurement of a reactor is carried out as follows.

A random signal with suitable amplitude over the frequency range of interest is applied as input to the reactor. The output signal together with the input signal is fed either directly, or over an intermediate record, to a computer (analogue or digital) which computes the auto correlation of the input signal, the cross correlation of the output with input signal, makes the Fourier transform and delivers the transfer function in amplitude and phase.

This process may be simplified if certain conditions are fulfilled.

The most important simplification, which is quite often referred to in literature but for certain reasons not applicable to the Dragon work, is to use the inherent white noise of the chain reaction as reactivity input [11, 12, 13]. If there are no other fluctuations in reactivity such as from coolant flow, etc., the Fourier transform of the auto correlation function of the output signal equals the square of the modulus of the transfer function. A known additional signal affecting reactivity may be taken into account and the transfer function corrected for this, but detector noise in the output signal is another limitation. As the instantaneous input is not known because it is not measured there can be no distinction between pile noise and detector noise. To keep the noise resulting from the collection of neutrons in the flux measuring ion chamber small enough a minimum portion of all neutrons must reach the chamber [14].

The impossibility of having a big enough chamber inside the core of the Dragon Reactor and the noise resulting from fluctuations in coolant flow rules out this otherwise elegant method for application to the Dragon work.

There is another very promising simplification. A random analogue, reactivity input is difficult to realise although it has been done at least once [15]. It is said that it is possible to artificially generate random binary time series of amplitude ± a with a period T which have an auto correlation function very close to that of white noise correlated for infinite time [16]. The auto correlation function of white noise has a line at time lag zero (and at successive periodic times in the case of periodic noise) and is very nearly zero everywhere else. If a signal whose auto correlation function is a delta function, is applied to the input, the cross correlation will be the impulse response of the system.

Such an optional periodic binary noise is much easier to handle than analogue noise. It can be stored instead of being generated for each run and the transducer becomes simpler. Furthermore the multiplication in the computation of the cross correlation turns into a gating process, in analogue computation an important simplification. But most important is the fact that, provided the output signal to noise ratio is good, integration over the time interval T is equivalent to an infinite period of natural white noise. If the signal to noise ratio of the output signal is low the integration must take place over several whole periods T [17].

In the proposed thermal experiment with mass flow or inlet temperature variations as driving input it might be possible to use the noise of these parameters as input signal. The conditions are that the amplitude distribution in the frequency range of interest is satisfactory and that there is no correlation between the two signals. This will be checked by analysing the auto correlation and cross correlation of the two signals.

The weak point of the statistical method is the difficulty in obtaining accuracy. Because of the statistical nature of the process, a high number of samples must be taken and computed if good accuracy is to be realised. This gives long computing times and, at low frequencies also long times of measurement. The actual measurement and computing time required for a given accuracy depends upon a number of factors such as frequency resolution, frequency range, input signal, external noise, computing accuracy and so on. Quick overall measurements may give an accuracy of about ± 20% or even worse but for specific measurements it should be possible to bring this down to about 1%.

4. CO-ORDINATION WITH IRRADIATION PROGRAMME

As mentioned earlier experiments which would interrupt the irradiation programme should be avoided. Therefore the type of measurements which fits best into that programme will be chosen. This applies not only to the actual running parameters but also to shutdowns for the installation of equipment. Directly, only measurements on power will be affected, but because the zero energy measurements should be done within the commissioning period these experiments indirectly may be affected too. In the following only those interferences will be discussed which may arise from the method of measurement itself. Conflicting requirements on the operation conditions (power, temperatures, etc.) may also arise but these problems must be dealt with in the set-up of the actual operation programme.

4.1 Oscillator Method

The measurement of a transfer function by the oscillator method normally takes a long time but as also the irradiation programme consists of long runs at constant conditions this otherwise limiting feature is in that respect not embarrassing. The oscillation amplitude for rod oscillator experiments are kept quite small and should not affect the static operation point. The effect of continuous oscillation of variables on the strength and reliability of the fuel elements should however be kept in mind.

4.2 Step Change

A small change in the operating point may be tolerated for a short time but a full shutdown which does not coincide with a shutdown in the irradiation programme would be undesirable. Therefore this type of measurements will be restricted mainly to zero power measurements. Where it is essential that the mean operation point remains unchanged, the impulse method would be appropriate.

4.3 Statistical Methods

Of all the discussed methods, the statistical method causes by far the least interference with the operation conditions or even if the inherent noise at the selected input is used as driving signal - no interference at all. Because of its compatibility with other measurements this method is ideal provided the operation point remains constant over the whole period of measurements.

5. EXPERIMENTAL USEFULNESS

All three methods have in common that signals well above the noise level, and also longer periods of measurement, increase the accuracy of the results. But there are differences in the way the time is used. In the oscillator experiment one frequency is measured subsequently to the other, each for a time long enough to filter out statistical fluctuations. A much more efficient use of time is made by the other two types of measurement. Both these experiments measure all frequencies simultanously. Because the step change is normally applied only once for each experiment its time of measurement is short and its accuracy therefore correspondingly low. The statistical measurement can be extended over any time, short or long and with signals at noise level or higher. This makes it the most versatile type of measurement. The possibility of working with very low amplitudes might also be profitable in cases where higher signals are not allowed for safety reasons or in cases of very non linear systems. But for high accuracy a long computing time is required. This, together with our lack of experience are at present its chief disadvantages.

The oscillator and step change methods are both well known. In addition there is operational experience from work on Zenith. For these reasons these methods of measurement will certainly be used, and the necessary instrumentation has been ordered. For the statistical methods the planning of actual measurements and instrumentation required has not yet been started. Therefore the main efforts will be concentrated on the oscillator and step change methods. However, the statistical methods have very promising aspects and measurements on other reactors have been reported to give such good results [18, 15], that these methods are of interest. It is hoped that independent measurements using statistical methods will be possible at some stage of the physics experiments.

Moreover, it is not known at present if oscillation of mass flow and inlet temperature will prove attractive from the stand point of reactor safety. If they do not, or if other difficulties should appear, these measurements would be an interesting field for the application of statistical methods.

6. ACKNOWLEDGMENT

Paragraph 2.4.1 and the results of Dragon calculations contained in the illustrations are contributed by Mr. J. P. H. Blake. His very helpful support for this report is gratefully acknowledged.

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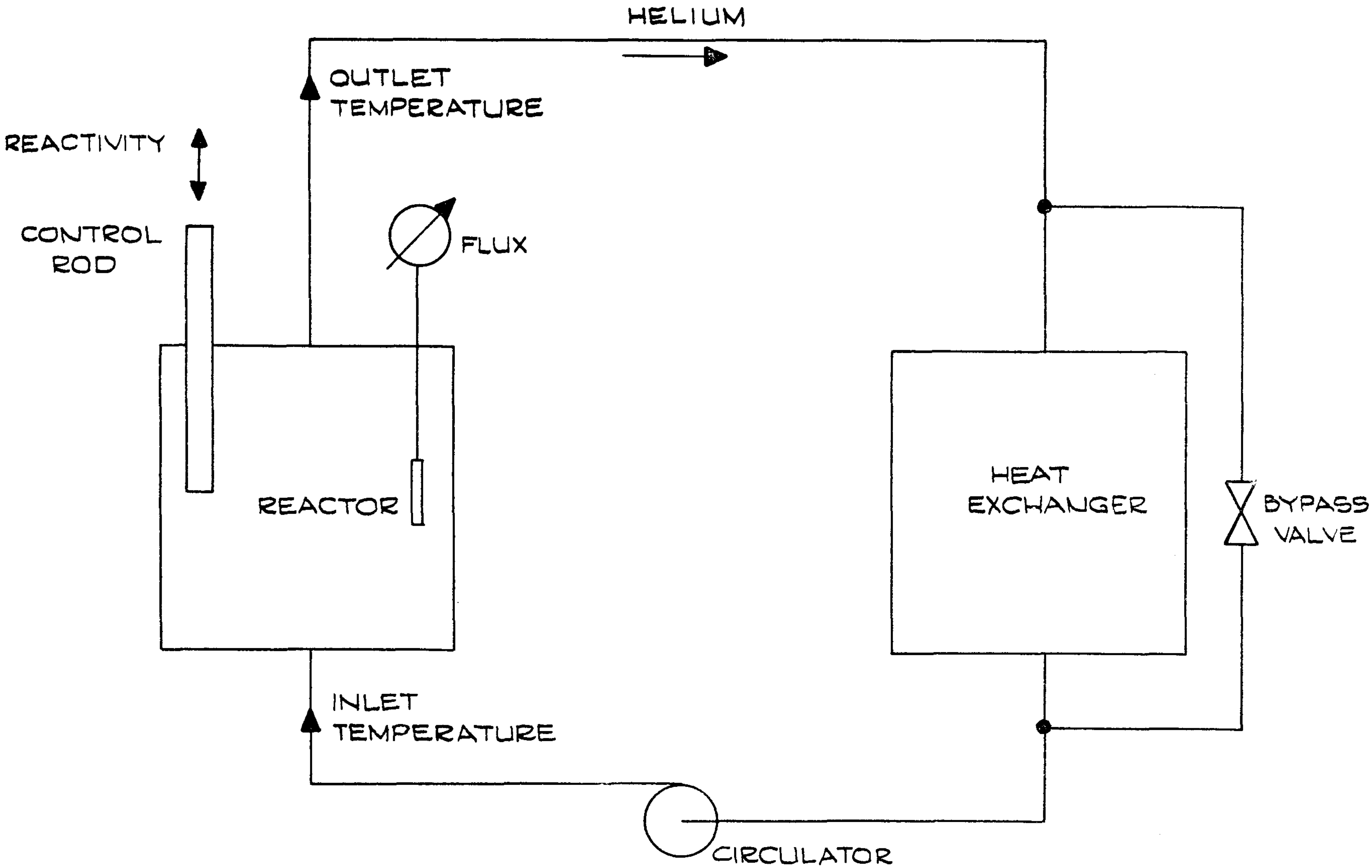

FIG. I PRINCIPLE OF REACTOR WITH PRIMARY CIRCUIT.

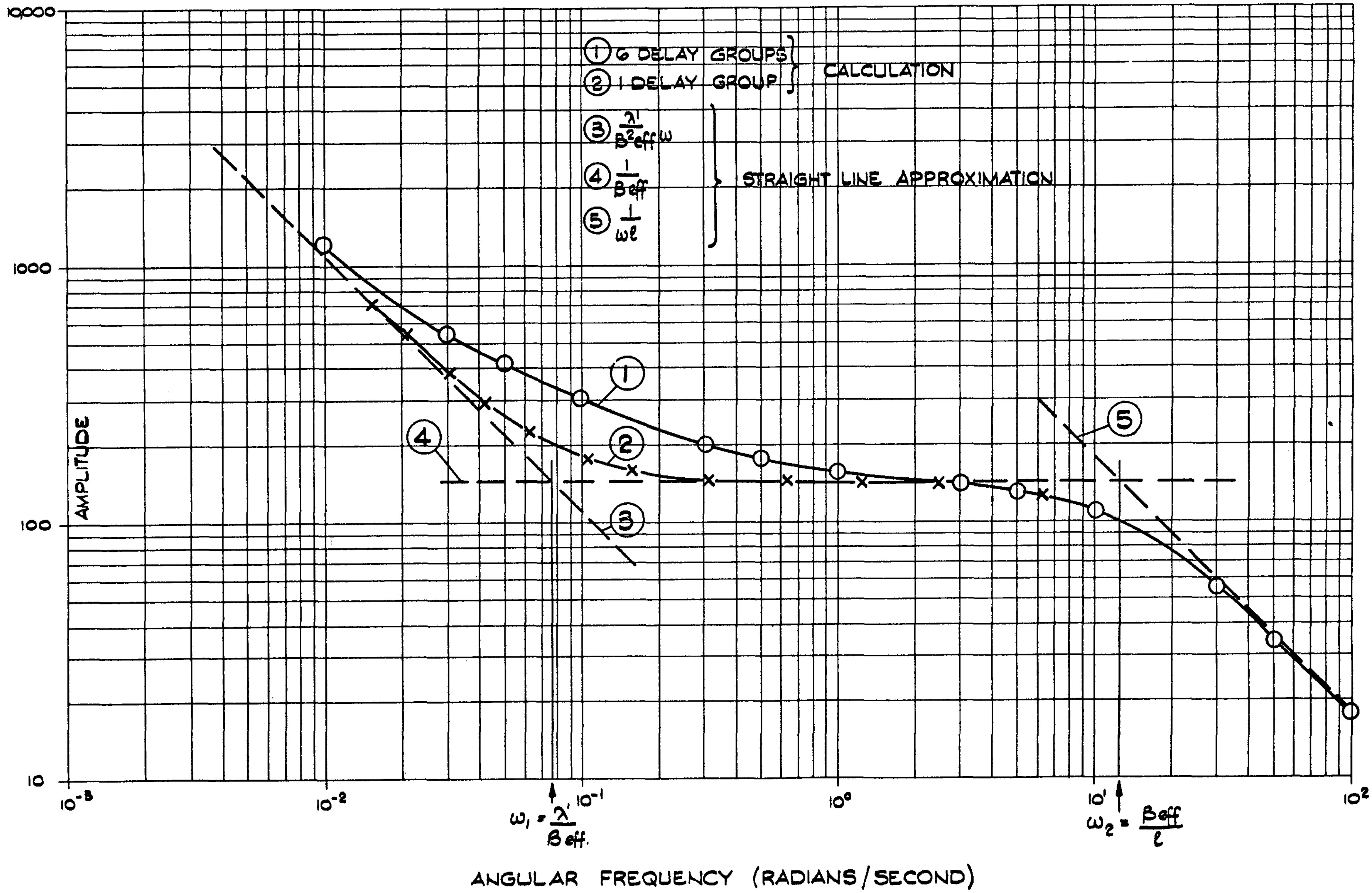

FIG. 2 ZERO ENERGY FLUX/REACTIVITY TRANSFER FUNCTION (AMPLITUDE)

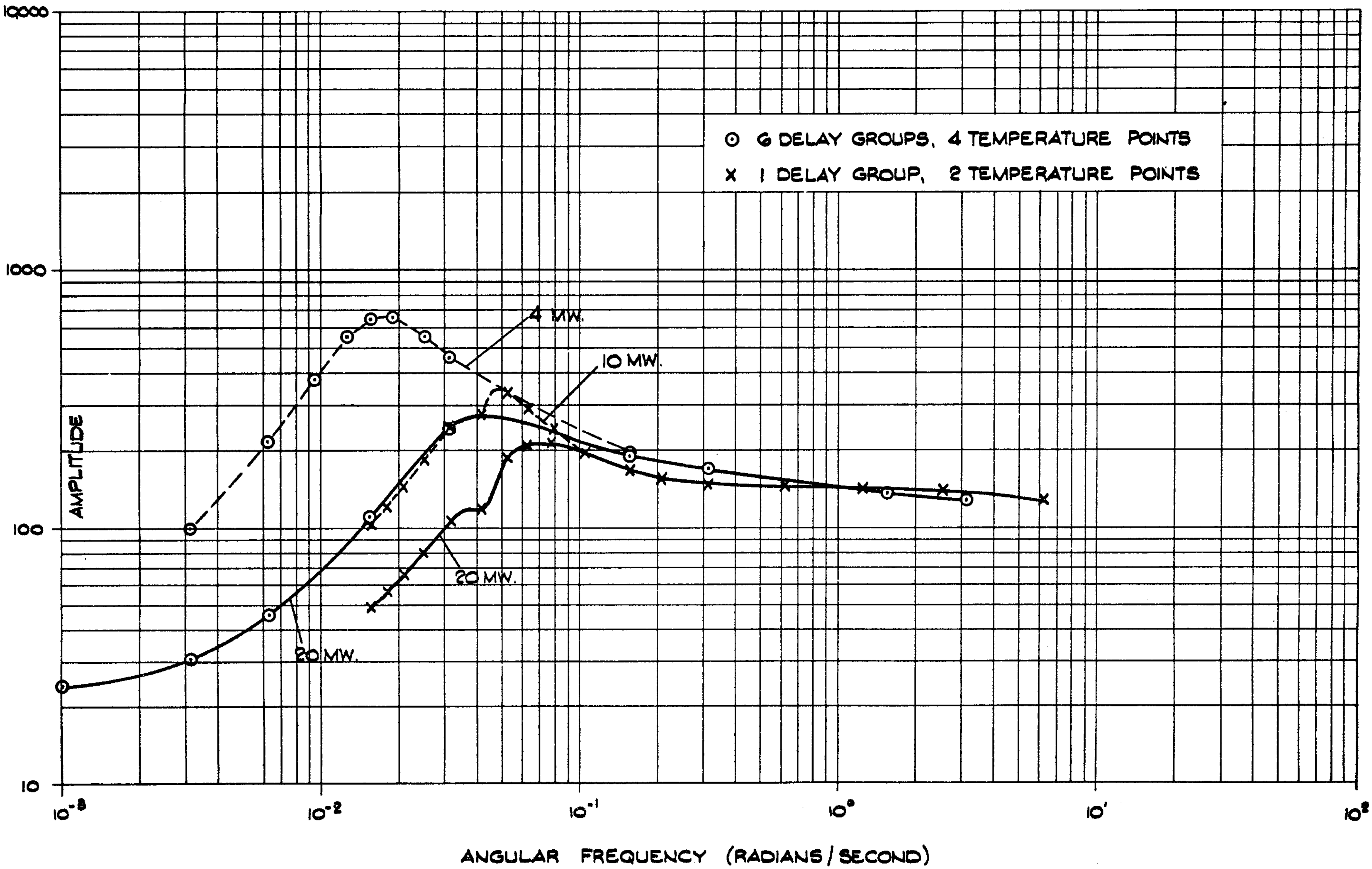

FIG. 3A FLUX/REACTIVITY TRANSFER FUNCTION AT DIFFERENT POWER LEVELS (AMPLITUDE)

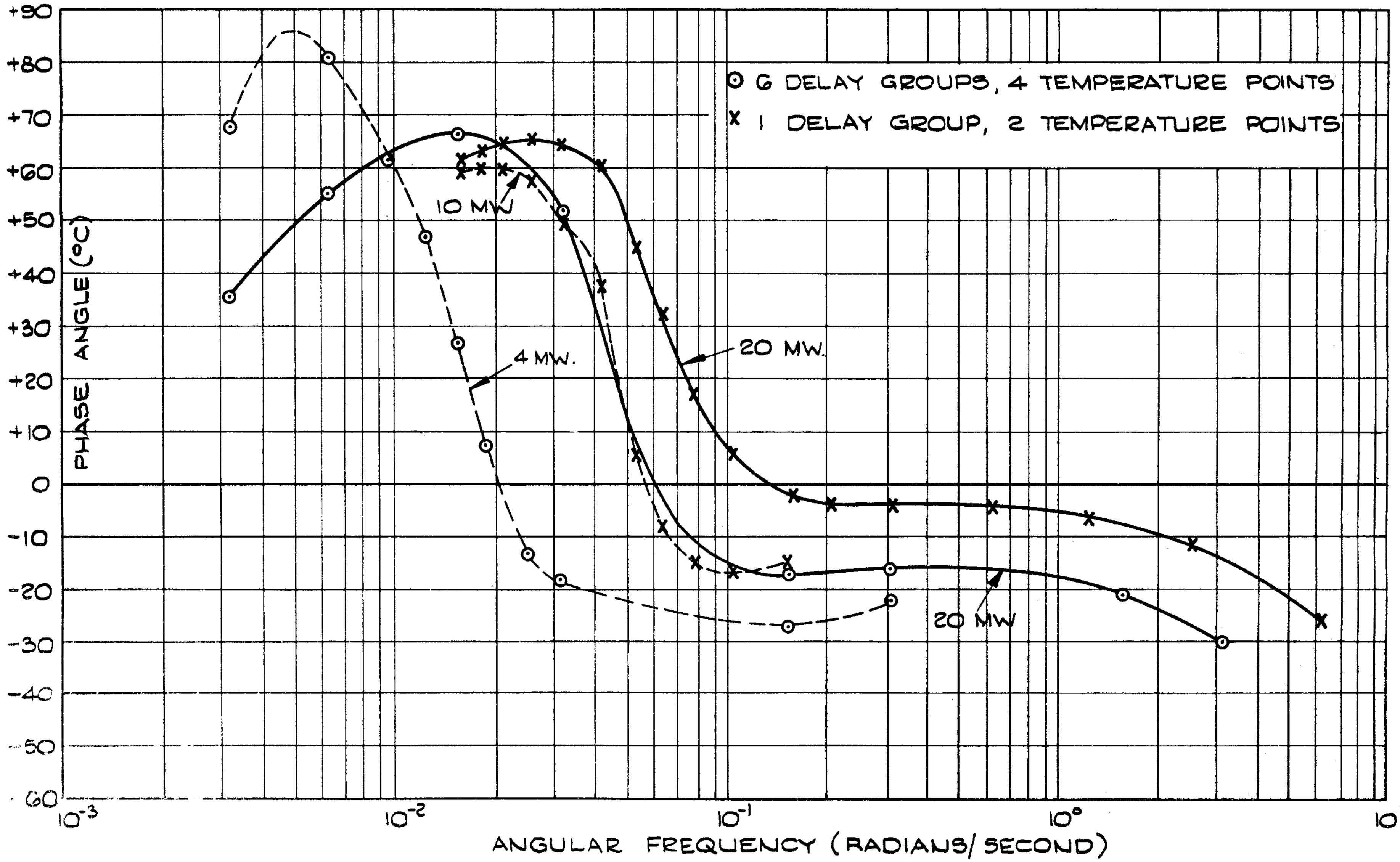

FIG. 3b FLUX/REACTIVITY TRANSFER FUNCTION AT DIFFERENT POWER LEVELS (PHASE)

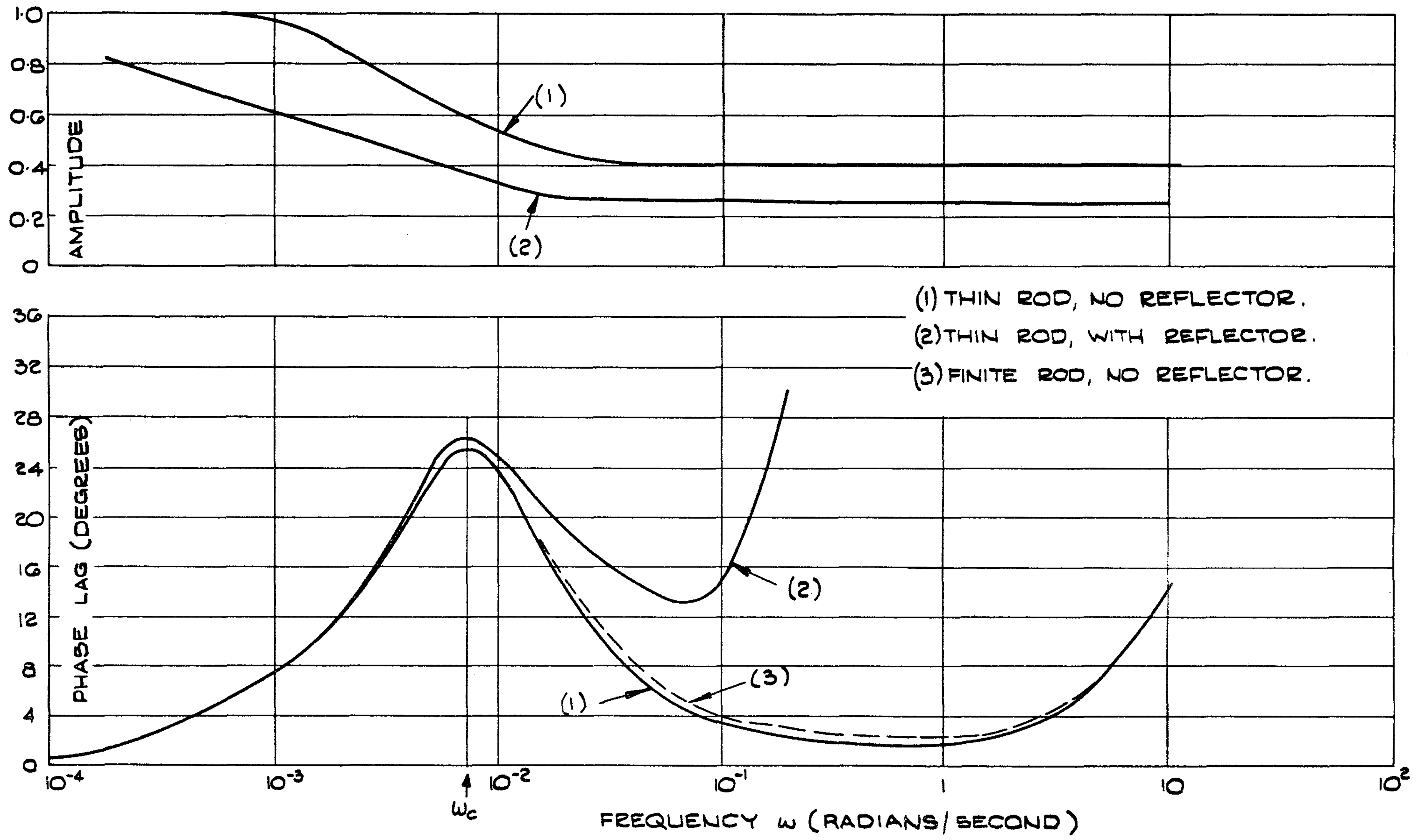

FIG. 4 THERMAL TRANSFER FUNCTION – GAS OUTLET / GAS INLET.