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OPERATIONAL CONTROL ROD REACTIVITY WORTHS FROM OBSERVED HEAT GENERATION RATES

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I. Introduction

The reactivity difference associated with a reactor change can be simply related to the coincident changes in the neutron loss and generation rates[1]. Unfortunately, in many instances these rates are difficult to measure directly during high-level operation; thus reactivity values are normally found by other methods such as buckling calculations or low-level rising period measurements. However, with certain applicable control rod systems, it may be feasible to use heat generation rate in the rods as a measure of their reactivity-compensation effect.

The neutron absorption rate in the Hanford reactor control rods can be determined under equilibrium conditions (and without disturbing these conditions) from the heat transfer rate to the control rod coolant. This information, when combined with a measurement of the change in reactor leakage caused by rod insertion, allows the calculation of control rod strength.

II. Derivation of Reactivity Values From Neutron Production and Loss Rates

The multiplication factor of a reactor having two multiplying regions A and B may be expressed as

$$k = \frac{[k_\infty]_A \begin{bmatrix}\text{Fraction of neutron generation "N"}\\ \text{that is absorbed in A}\end{bmatrix}}{\begin{bmatrix}\text{Fraction of neutron generation "N"}\\ \text{that is produced in A}\end{bmatrix}}. \quad (1)$$

For a thermal reactor a more appropriate form is

$$k = \frac{[\eta\varepsilon f]_A \begin{bmatrix}\text{Fraction of neutron generation "N"}\\ \text{that is absorbed thermally in A}\end{bmatrix}}{\begin{bmatrix}\text{Fraction of neutron generation "N"}\\ \text{that is produced in A}\end{bmatrix}}, \quad (2)$$

$$= \frac{[\eta\varepsilon f]_A\,[1 - F_f - S_A - F_t - r_f - r_r - r_t - \alpha_B]_N}{(1-e_B)_N},$$

where:

$\eta\varepsilon f$ = neutrons produced per thermal absorption
F = fractional neutron leakage from reactor
S = fractional resonance absorption
r = fractional absorption in control rods
α = total fractional absorption in region
e_B = fractional neutron production in region B.
f, r and t denote fast, resonance and thermal neutron energies.

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[1] Gast, P. F. Methods of Calibrating Rods, HW-3-2581. June 4, 1945. (Declassified)

A change in reactivity is defined as

$$\Delta\rho = \frac{k_2 - k_1}{k_1 k_2} \qquad (3)$$

If $k_2 = k$ and $k_1 = k' = 1$, then from (2)

$$\Delta\rho = 1 - \frac{[\eta\epsilon f]_A[1 - F'_f - S'_A - F'_t - r'_f - r'_r - r'_t - \alpha'_B]\ (1-e_B)_N}{[\eta\epsilon f]_A[1 - F_f - S_A - F_t - r_f - r_r - r_t - \alpha_B]_N\ (1-e'_B)}\ ; \qquad (4)$$

The neutron generation subscripts have been omitted in the formulation of k' since $k' = 1$.

Usually it can be assumed that $[\eta\epsilon f]_A$ does not change if region A is not physically changed; therefore,

$$\Delta\rho = 1 - \frac{[1 - F'_f - S'_A - F'_t - r'_f - r'_r - r'_t - \alpha'_B]\ (1-e_B)_N}{[1 - F_f - S_A - F_t - r_f - r_r - r_t - \alpha_B]_N\ (1-e'_B)}. \qquad (5)$$

Equation (5) has been used to calculate the reactivity effects of single tube loading changes at the Hanford reactors. In such instances (i.e., Region A >> Region B) the changes in the leakage rate and resonance absorption rate in Region A are small and may be ignored; also, the neutron generation notation may be dropped with small error. The fractional neutron absorption α_B and α_B, may then be related to observed equilibrium fractional neutron generations (equal to the fractional power generation when all reactor fuel is uranium) e_B and e'_B. These relationships are $\alpha_B = e_B/k_{\infty B}$ and $\alpha'_B = e_B/k'_{\infty B}$.

For purposes of calculating the reactivity change on rod withdrawal, equation (5) may be written as

$$\Delta\rho = 1 - \frac{[1 - F'_f - S' - F'_t - r_f - r_r - r_t]}{[1 - F_f - S - F_t]}\ , \qquad (6)$$

where region "A" includes the entire reactor exclusive of the rods.

This equation can then be expressed in terms of non-loss probabilities. F_f, S and F_t can be related to p, P_f and P_t as defined by the equation $k = \eta\epsilon f p P_f P_t$. These relationships are:

$$\begin{aligned} F_f &= 1 - P_f \\ S &= P_f(1 - p) \\ F_t &= pP_f(1 - P_t) \end{aligned} \qquad (7)$$

Similar non-loss probabilities can be defined when the rods are inserted.

$$P'_f = 1 - \frac{\text{number of fast neutrons leaking out of reactor}}{\text{number of fast neutrons born in reactor}}$$

$$= 1 - F'_f,$$

$$p' = 1 - \frac{\text{number of resonance neutrons captured outside the rods}}{\text{number of neutrons attaining resonance energy in reactor}} \qquad (8)$$

$$= 1 - \frac{S'}{1 - F'_f - r_f},$$

$$P'_t = 1 - \frac{\text{number of thermal neutrons leaking out of reactor}}{\text{number of thermal neutrons born in reactor}}$$

$$= 1 - \frac{F'_t}{1 - F'_f - r_f - S' - r_r}$$

Substitution of equations (7) and (8) into (6) gives

$$\Delta\rho = \frac{1}{pP_tP_f} \left[pP_tP_f + r_t + P'_t r_r + p'P'_t r_f - p'P'_tP'_f\right] \qquad (9)$$

III. Application of Method to Hanford Control Rods

When inserted in the reactor, the Hanford reactor control rods lie in horizontal channels penetrating the graphite moderator stack (see Figure 1). Under normal equilibrium conditions the control rod coolant absorbs heat that comes from four sources: (1) the higher temperature graphite surrounding the rod, (2) absorption of reactor gammas in the rod, (3) thermalization of fast neutrons in the rod coolant, and (4) neutron absorption in the rod. In order to determine the neutron absorption rate in the rod (4) and thus the fraction of all neutrons generated that are absorbed in the rods ($R = r_f + r_r + r_t$), it is necessary to establish the magnitude of contributions (1), (2) and (3).

The control rod heating by the graphite stack was derived from data taken during a shutdown from equilibrium as summarized in Figure (2). The shutdown rate was rapid in comparison to the cooling time of the graphite stack. This made it possible to observe the decay of the graphite heating effect (residual gamma heating constituted a small correction) and to back-extrapolate these data to find the equilibrium effect. Heating by the graphite was found to contribute about 25 per cent of the total rod heat during steady-state high-level operation.

The equilibrium gamma heating effect, quantity (2), and the neutron thermalization effect, quantity (3), were estimated from theoretical values of the reactor gamma field and fast neutron flux, respectively. Combined, quantities (2) and (3) constituted about seven per cent of the total rod heating.

R, the fraction of all neutrons generated that were absorbed in the rods was then calculated from

$$R = (r_f + r_r + r_t) = \frac{\left[\begin{matrix}\text{Fraction of rod heating} \\ \text{from neutron capture}\end{matrix}\right]\left[\dfrac{\text{Total power concentrated in rods}}{\text{Total reactor power}}\right]}{\left[\dfrac{\text{Mev/neutron absorbed in rods}}{\text{Mev/fission}}\right]} \quad [\text{Neutrons/fission}] \qquad (10)$$

The specific energy release per control rod neutron absorption was found from information on the relative absorption rate in each rod material and the degree of attenuation by the rod for the attendant gammas generated. The first was found from a neutron transport calculation; the second was estimated from a gamma attenuation experiment outside the reactor. In this experiment a wire Co^{60} source was inserted in a sample rod section; an effective thickness, $\overline{X}$, was then found from the measured attenuation, $e^{-\mu\overline{X}}$.

For the Hanford reactors and other large, well-moderated reactors, two simplifications can be made in equation (9). First, r_f and r_r are small in comparison with r_t, and $P'_f \approx P'_t \approx 1$; thus the quantity $(p'P'_t r_f + P'_t r_r + r_t)$ very nearly equals the total neutron absorption fraction in the rods, R. Secondly, $p' \approx p$. The representation of the product $\frac{P'_f}{P_f}\frac{P'_t}{P_t}$ as the product $C_f C_t$ then reduces equation (9) to

$$\Delta\rho_{rods} = 1 + \frac{R}{pP_f P_t} - C_f C_t. \qquad (11)$$

For the Hanford reactor calculation, C_t was measured from thermal flux traverses. C_f was theoretically related to C_t through neutron diffusion calculations of the fast and thermal neutron flux distributions in the rods-in and rods-out states.

Hanford reactor control system strength calculations by the above method showed close agreement with calibrations made by the "rising period" technique. Based on these comparisons, it is felt that control rod worths can be calculated by the discussed method to ±10 per cent accuracy under conditions in which the rod coolant temperature rise is at least 20°C.

IV. Conclusions

Control rod system reactivity worths can be determined with reasonable accuracy from estimates of the neutron absorption rate in the rods and evaluations of the change in reactor leakage rate on rod withdrawal. In the Hanford reactors these values may be found from measured control rod heat generation and reactor flux distribution data.

This calibration technique can also be applied to reactors without separate rod-cooling systems. The neutron absorption rate in the rods could be obtained from rod surface foil activation or activation of the rods themselves. The change in reactor leakage upon rod insertion could be found with theoretical determinations of the unperturbed flux distribution and the flux distribution after insertion of an equivalent control region.

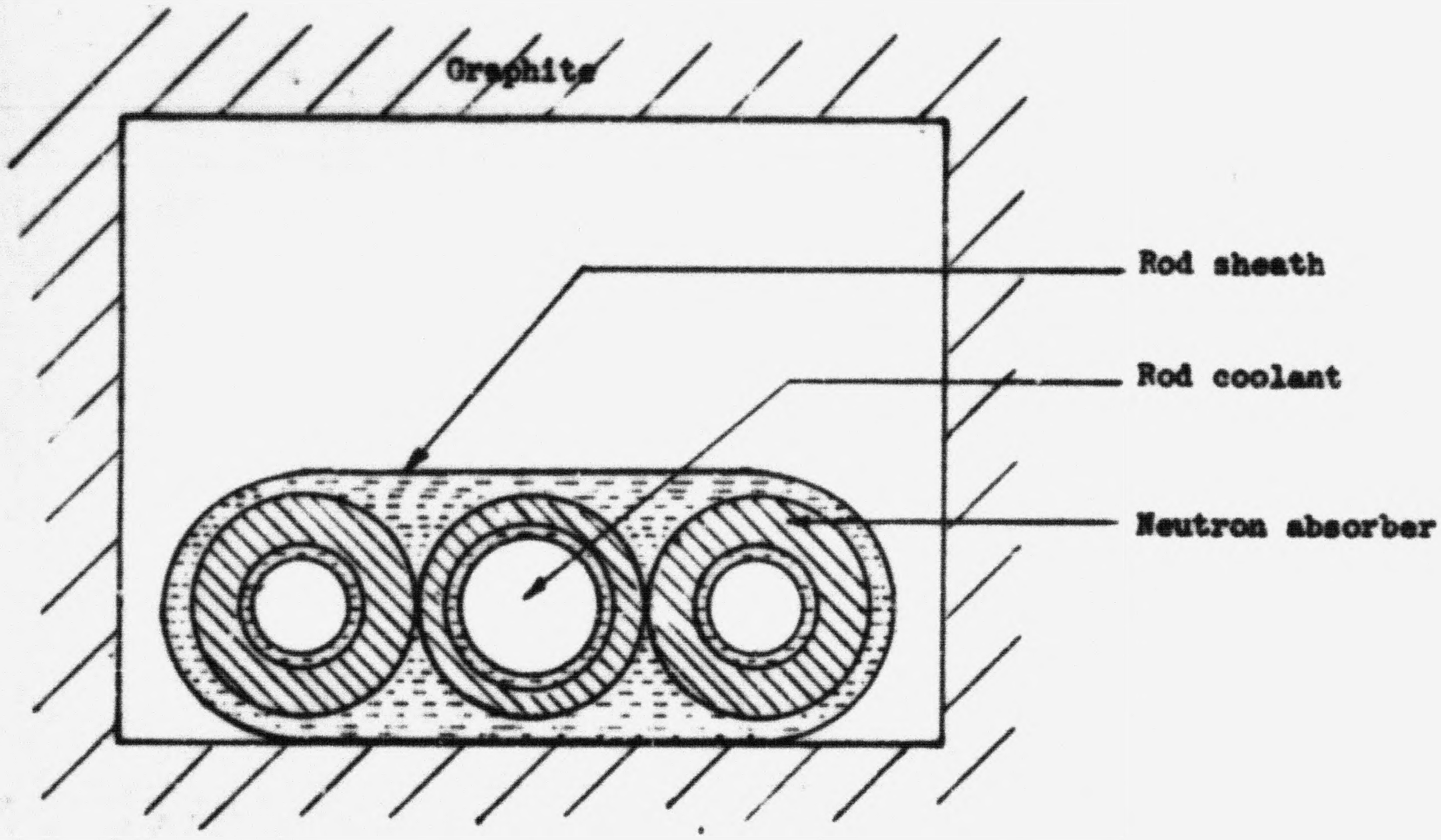

Figure 1

Cross Section of Inserted Control Rod

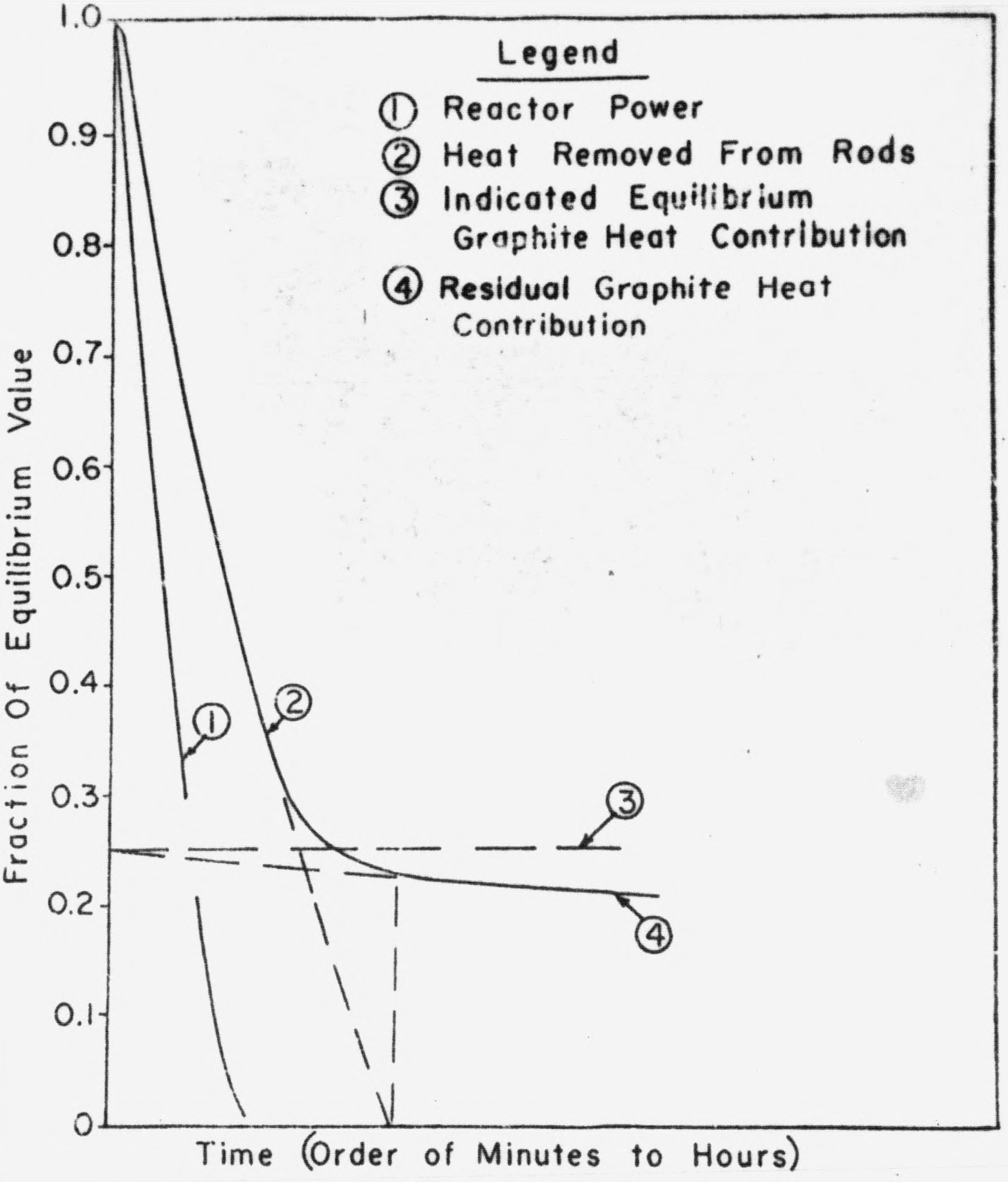

Figure 2

Determination Of Heat Transferred To Control Rods From Graphite