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AEEW - M 782

REACTIVITY MEASUREMENTS IN SGHW MOCK-UP CORES IN DIMPLE

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ABSTRACT

Prior to the commissioning of the SGHW prototype reactor a series of mock-up cores was studied in DIMPLE. Among the experiments carried out were measurements of reactivity using both divergent period and pulsed source techniques. This memo presents the results of these measurements, and compares them with theoretical predictions.

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June, 1967

W.9625

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1. Introduction

In the course of the SGHW mock-up experiment in DIMPLE (1) several cores were studied with different values of coolant composition and boron content of the moderator, and with certain perturbations introduced. The reactivity changes due to these differences have been measured, and are compared with predictions made using the two-group code AIMAZ (2).

Using the measured values of the moderator height coefficient of reactivity, $\frac{dp}{dH}$, reactivity changes are inferred from changes in critical height or critical axial buckling. The height coefficient was measured by both the divergent period technique and the pulsed source technique, and the results are compared with AIMAZ predictions. It is shown that AIMAZ consistently overestimates these measured height coefficients.

2. Period Measurements of $\frac{dp}{dH}$

For each core the flux doubling time of the reactor was measured as a function of the excess moderator height above the critical height. Theoretical reactivity scales were used to relate the reactor period to the excess reactivity, from which the value of $\frac{dp}{dH}$ was calculated. In general at least four divergences were carried out in each core, with periods in the region 20 secs - 40 secs.

The reactivity versus doubling time scales were calculated using the programme DONUT (5), with delayed neutron weighting factors and prompt neutron lifetime determined for each core by AIMAZ. Since the reactivity scale is directly dependent on the value of β_{eff}, any error in the initial delayed neutron parameters fed into DONUT will appear as an error in $\frac{dp}{dH}$. The calculation of β_{eff} takes into account both the smaller leakage of delayed neutrons as compared with prompt neutrons and their lower probability of causing fast fission in U238 (6). In the present system these two effects tend to cancel, giving a nett effect of about 2% with a variation of less than 1% over the range of interest. In this study the nett effect has been assumed to be constant.

For purposes of comparison, values of $H^3 \frac{dp}{dH}$ are calculated, since on one group theory this quantity is independent of axial buckling.

The predominant error in the measurement of $\frac{dp}{dH}$ is due to uncertainty in the doubling height, which was approximately 1-2 cms, and could be measured to $\pm$ 0.02 cms. The resulting error in $\frac{dp}{dH}$ is approximately $\pm$ 1.5%. The extrapolated height of each core was known to $\pm$ 0.5 cms, giving an error in H^3 of approximately $\pm$ 1% and in $H^3 \frac{dp}{dH}$ of approximately $\pm$ 2%.

The results are given in Table 2.1.

TABLE 2.1

Values of $\frac{dp}{dH}$ from Period Measurements

Core	Critical height for period m'ment cms	ΔH* cms	Extrapolated height, H cms	$\frac{dp}{dH}$ % cm^{-1}	$H^3 \frac{dp}{dH}$ x 10^{-3} cm^2
SGM1	137.26	6.81	144.07 ± .5	0.133	3.98 ± .07
SGM2	139.47	6.43	145.90 ± .5	0.135	4.19 ± .08
SGM3	144.69	6.15	150.84 ± .5	0.133	4.56 ± .08
SGM3/R	141.61	5.73	147.34 ± .5	0.147	4.70 ± .08
SGM5	161.75	5.92	167.67 ± .5	0.0942	4.44 ± .08
SGM6	201.17	4.77	205.94 ± .5	0.0534	4.66 ± .08
SGM7	245.80	4.19	249.99 ± .5	0.0286	4.47 ± .07
SGM9	238.67	4.49	243.16 ± .5	0.0305	4.38 ± .07
SGM10	230.29	5.54	235.83 ± .5	0.0315	4.13 ± .07
SGM11	191.00	5.16	196.16 ± .5	0.0530	4.00 ± .07
SGM11a	204.20	4.27	208.47 ± .5	0.0510	4.62 ± .08
SGM12	173.14	3.59	176.73 ± .5	0.0734	4.05 ± .07
SGM13	185.13	3.88	189.01 ± .5	0.0686	4.63 ± .08

* ΔH is the difference between critical height and extrapolated height as determined from axial scan measurements.

3. Pulsed Source Measurements of $\frac{dp}{dH}$

3.1 Basis of the Measurement

In each core the fundamental prompt neutron decay constant, α_o, was measured for a range of moderator heights below critical. The reactor was pulsed with neutrons at a repetition rate of approximately 1 sec^{-1}, and the decaying flux measured with a BF_3 chamber in the centre of the core. The neutron source was embedded in the graphite reflector beneath the core.

After the subtraction of the constant background an exponential function was fitted to the data from about three half lives after the pulse was given, and the decay constant, α_o, was determined.

Using one group theory it may be shown that

$$\alpha_o = \alpha_{oc} \left(1 - \frac{\rho}{\beta}\right)$$

where α_{oc} is the value of α_o at critical, and β is the effective delayed neutron fraction (3).

Since for systems close to critical

$$\rho = 1 - \frac{1}{k_{eff}}$$

and

$$k_{eff} = \frac{k_\infty}{1 + M^2B^2}$$

on one group theory and

$$B^2 = B_r^{\ 2} + \left(\frac{\pi}{H}\right)^2$$

it may be seen that

$$\alpha_o = a_1 + \frac{a_2}{H^2}$$

where a_1 and a_2 are constants.

Also,

$$H^3 \frac{dp}{dH} = -2 \frac{dp}{d\left(\frac{1}{H^2}\right)}$$

$$= -2 \frac{dp}{d\alpha_o} \frac{d\alpha_o}{d\left(\frac{1}{H^2}\right)}$$

$$= 2 \frac{\beta}{\alpha_{oc}} a_2$$

Having determined α_o at various values of moderator height, a straight line was fitted, using a least squares method, to a plot of α_o against $\frac{1}{H^2}$, where H is the extrapolated height. At large values of negative reactivity the relation between α_o and $\frac{1}{H^2}$ ceases to be linear, and points in this region were not included in the straight line fit. The fitting procedure gave values of α_{oc} and the slope a_2, so that the value of $H^3 \frac{dp}{dH}$ at critical could be calculated.

As with the period measurements, the value of $\frac{dp}{dH}$ determined is directly dependent on the delayed neutron fraction, β. This quantity was calculated for each core using weighting factors produced by ADMAZ.

The results are given in Table 3.1.

TABLE 3.1

Values of $\frac{dp}{dH}$ from Pulsed Source Measurements

Core	$\beta \times 10^2$	α_{oc} Sec^{-1}	$a_2 \times 10^{-5}$	$H^3 \frac{dp}{dH} \times 10^{-3}$ cm^2
SGM1	0.7063	26.5 ± 0.4	72.7 + 1.2	3.87 ± 0.09
SGM2	0.7105	27.1 ± 0.6	70.9 ± 0.9	3.72 ± 0.09
SGM3	0.7144	24.2 ± 0.2	76.3 ± 0.7	4.51 ± 0.06
SGM5	0.7124	24.6 ± 0.2	77.2 ± 0.4	4.47 ± 0.04
SGM6	0.7077	25.6 ± 0.3	79.9 ± 0.8	4.42 ± 0.07
SGM7	0.7079	30.7 ± 1.3	93.0 ± 4.4	4.29 ± 0.27
SGM9	0.7073	25.5 ± 0.3	82.2 ± 1.5	4.57 ± 0.10
SGM10	0.7118	23.6 ± 0.2	87.1 ± 0.8	5.27 ± 0.07
SGM11	0.7116	27.9 ± 0.3	77.5 ± 0.8	3.95 ± 0.06

3.2 Systematic Errors in Pulsed Source Measurements

The simple one group analysis of the pulsed source measurements makes two important assumptions, (a) that the prompt neutron generation time is independent of buckling, and (b) that delayed neutrons have no effect on the prompt neutron decay constant, α_o. The effect of these assumptions on the values of $\frac{dp}{dH}$ is discussed below.

3.2.1 Dependence of neutron generation time on axial buckling

On one group theory the prompt neutron lifetime is given by

$$l \doteq \frac{k_{eff}}{v\Sigma_a k_\infty}$$

so that the generation time, $\Lambda = 1/k_{eff}$, is independent of buckling.

The definition of the lifetime is

$$l = \frac{\text{number of neutrons in reactor}}{\text{rate of loss of neutrons}}$$

which on two group theory becomes

$$l = \frac{\frac{\phi_1}{v_1} + \frac{\phi_2}{v_2}}{\phi_1 \Sigma a_1 \left(1 + \frac{L_1^2 B^2}{1 - p}\right) + \phi_2 \Sigma a_2 \left(1 + L_2^2 B^2\right)}$$

In a well moderated thermal system such as that considered here, ϕ_2 and Σ_{a2} are much greater than ϕ_1 and Σ_{a1}, and v_2 is much less than v_1, so that

$$1 \simeq \frac{1}{v_2 \, \Sigma a_2 \, (1 + L_2^{\,2} \, B^2)}$$

i.e.

$$1 \simeq \frac{1}{v_2 \, \Sigma a_2 \, (1 + L_1^{\,2} \, B^2 + L_2^{\,2} \, B^2 - L_1^{\,2} \, B^2)}$$

$$\simeq \frac{k_{eff}}{v_2 \, \Sigma a_2 \, k_\infty \, (1 - \frac{L_1^{\,2}}{k_\infty} k_{eff} \, B^2)}$$

$$\simeq \frac{k_{eff}}{v_2 \, \Sigma a_2 \, k_\infty \, (1 - \frac{L_1^{\,2} \, B^2}{1 + M^2 \, B^2})}$$

Since $M^2 \, B^2$ and $L_1^{\,2} \, B^2$ are considerably less than unity, this equation may be approximated to by

$$A = \frac{1}{k_{eff}} = A_c \left[1 + L_1^{\,2} \, \Delta \, B_z^{\,2} \right]$$

where $\Delta \, B_z^{\,2}$ is the deviation from critical buckling.

In the present series of cores, $L_1^{\,2} \simeq 100 \text{ cm}^2$, i.e. 0.01 m^2 and $\frac{dp}{dB_z^{\,2}} \simeq -0.02 \text{ m}^2$ so that

$$A = A_c \left[1 + 0.01 \, \Delta \, B_z^{\,2} \right]$$

or

$$A = A_c \left[1 - \tfrac{1}{2} \, p \right]$$

In order to check this relation a number of AIMAZ calculations have been carried out to determine the generation time for different reactivities. The results are given in Table 3.2.

TABLE 3.2

Variation of generation time with reactivity

Core	$(k_{eff})_c$	Λ_c secs x 10^4	k'_{eff}	Λ' secs x 10^4	Δp	$\frac{\Delta\Lambda}{\Lambda_c} \times \frac{1}{\Delta p}$
SGM9	1.00723	2.68077	1.002525	2.68685	.00466	- 0.508
SGM10	1.00693	2.64420	1.002462	2.64983	.00443	- 0.480
SGM11	1.00731	2.72656	1.002808	2.73230	.00446	- 0.471
SGM11a	1.00654	2.78280	1.001526	2.78957	.00497	- 0.489
SGM12	1.01057	2.76261	1.006053	2.76816	.00445	- 0.452
SGM13	1.01056	2.83884	1.00554	2.84363	.00494	- 0.342

The AIMAZ results agree well with the predictions of the simple model given above, for which

$$\frac{\Delta\Lambda}{\Lambda_c} \times \frac{1}{p} = -0.5$$

The value of $\frac{dp}{dB_z^2}$ at critical is derived from the measurement of $\frac{d\alpha_o}{dB_z^2}$ using the relation

$$\frac{dp}{dB_z^2} = \frac{dp}{d\alpha_o} \cdot \frac{d\alpha_o}{dB_z^2}$$

The one group equation for α_o is

$$\alpha_o = \frac{\beta}{\Lambda}\left[1 - \frac{p}{\beta}\right]$$

and at critical,

$$\alpha_o = \frac{\beta}{\Lambda_c}$$

Assuming that β does not vary with buckling, the reactivity is given by

$$\rho = \beta\left[1 - \frac{\alpha_o}{\alpha_{oc}} \frac{\Lambda}{\Lambda_c}\right]$$

$$\therefore \frac{dp}{d\alpha_o} = -\frac{\beta}{\alpha_{oc}} \frac{\Lambda}{\Lambda_c} - \frac{\alpha_o}{\alpha_{oc}} \frac{\beta}{\Lambda_c} \frac{d\Lambda}{d\alpha_o}$$

But, from the above,

$$\Lambda = \Lambda_c (1 - \tfrac{1}{2} p)$$

$$= \Lambda_c \left[1 - \tfrac{1}{2} \beta \left(1 - \frac{\alpha_o}{\alpha_{oc}}\right)\right]$$

$$\therefore \frac{d\Lambda}{d\alpha_o} = \tfrac{1}{2} \Lambda_c \frac{\beta}{\alpha_{oc}}$$

$\therefore$ At critical,

$$\frac{dp}{d\alpha_o} = - \frac{\beta}{\alpha_{oc}} - \tfrac{1}{2} \frac{\beta^2}{\alpha_{oc}}$$

If it is assumed that Λ is constant, $\frac{dp}{d\alpha_o} = - \frac{\beta}{\alpha_{oc}}$, so that the error introduced is

$$\Delta \left(\frac{dp}{d\alpha_o}\right) = \tfrac{1}{2} \frac{\beta^2}{\alpha_{oc}}$$

i.e. $$\frac{\Delta \left(\frac{dp}{d\alpha_o}\right)}{\frac{dp}{d\alpha_o}} = - \tfrac{1}{2} \beta$$

$$\therefore \frac{\Delta \left(\frac{dp}{dB_z^2}\right)}{\frac{dp}{dB_z^2}} = - \tfrac{1}{2} \beta = -0.35\%$$

Thus the measured values of $H^3 \frac{dp}{dH}$ will be about 0.35% too low.

3.2.2. The effect of delayed neutrons on α_o

The time dependence of the neutron flux in the reactor is described by the inhour equation,

$$\rho = \omega_j \Lambda + \sum_i \frac{\omega_j \lambda_i}{\omega_j + \lambda_i}$$

Where $\frac{1}{\omega_j}$ is the reactor period, Λ is the prompt neutron generation time, and β_i and λ_i are the delayed neutron fraction and decay constant for the ith group of delayed neutrons.

For n delayed neutron groups there are (n + 1) roots ω_j, one of which is $-\alpha_o$, where α_o is the prompt neutron decay constant.

Hence,

$$\rho = \sum_i \frac{\alpha_o \beta_i}{\alpha_o - \lambda_i} - \alpha_o \Lambda \qquad (1)$$

If $\alpha_o >> \lambda_i$ this reduces to

$$\rho = \beta - \alpha \Lambda$$

which is the standard pulsed source equation used in Section 3.1. In the present series of cores the λ_i are not negligible in comparison with α_o, and an estimate of the error introduced by using the simple pulsed source equation must be made.

The first term in (1) may be rearranged to give

$$\sum_i \frac{\alpha_o \beta_i}{\alpha_o - \beta_i} = \sum_i \left[\beta_i + \frac{\lambda_i \beta_i}{\alpha_o - \lambda_i}\right]$$

$$\simeq \beta + \frac{1}{\alpha_o} \sum_i \lambda_i \beta_i$$

Hence

$$\rho = \beta + \frac{1}{\alpha_o} \sum_i \lambda_i \beta_i - \alpha_o \Lambda$$

At critical, $\rho = o$, and

$$\alpha_{oc} \Lambda_c = \beta_c + \frac{1}{\alpha_{oc}} \sum_i \lambda_i \beta_i$$

Assuming that $\Lambda = \Lambda_c$ and $\beta = \beta_c$, then

$$\rho = \beta + \frac{1}{\alpha_o} \sum_i \lambda_i \beta_i - \frac{\alpha_o}{\alpha_{oc}} \left[\beta + \frac{1}{\alpha_{oc}} \sum_i \lambda_i \beta_i\right]$$

$$= \beta \left(1 - \frac{\alpha_o}{\alpha_{oc}}\right) + \frac{\sum_i \lambda_i \beta_i}{\alpha_o} \left[1 - \frac{\alpha_o^2}{\alpha_{oc}^2}\right]$$

$$= \beta \left(1 - \frac{\alpha_o}{\alpha_{oc}}\right) \left[1 + \frac{\sum_i \lambda_i \beta_i}{\beta} \left(\frac{1}{\alpha_o} + \frac{1}{\alpha_{oc}}\right)\right]$$

and

$$\frac{d\rho}{d\alpha_o} = - \frac{1}{\alpha_o^2} \sum_i \lambda_i \beta_i - \frac{1}{\alpha_{oc}} \left[\beta + \frac{1}{\alpha_{oc}} \sum_i \lambda_i \beta_i\right]$$

$$= - \frac{\beta}{\alpha_{oc}} - \sum_i \lambda_i \beta_i \left[\frac{1}{\alpha_o^2} + \frac{1}{\alpha_{oc}^2}\right]$$

$$= - \frac{\beta}{\alpha_{oc}} \left[1 + \frac{\sum_i \lambda_i \beta_i}{\beta} \frac{1}{\alpha_{oc}} \left(1 + \frac{\alpha_{oc}^2}{\alpha_o^2}\right)\right]$$

∴ at critical

$$\frac{dp}{d\alpha_o} = - \frac{\beta}{\alpha_{oc}} \left[1 + \frac{2}{\alpha_{oc}} \frac{\sum_i \lambda_i \beta_i}{\beta}\right]$$

Since some 80% of the fissions in the reactor take place in U_{235} at thermal energy, it is sufficiently accurate to calculate the term

$$\frac{\sum_i \lambda_i \beta_i}{\beta}$$

from the delayed neutron constants for U_{235} thermal fission alone, giving

$$\frac{\sum_i \lambda_i \beta_i}{\beta} \simeq 0.38 \text{ sec}^{-1}.$$

Since,

$$\frac{dp}{dB_z^2} \propto \frac{dp}{d\alpha_o}$$

and with $\alpha_{oc} = 25 \text{ sec}^{-1}$, it may be seen that use of the simple pulsed source equation will underestimate $\frac{dp}{dB_z^2}$ by approximately 3%.

4. Comparison of Measured values of $\frac{dp}{dH}$ with AIMAZ Calculations

The theoretical values of $H^3 \frac{dp}{dH}$ have been determined by computing k_{eff} for two or more values of axial buckling in the vicinity of the measured critical buckling, using the code AIMAZ. In Table 4.1 these values are compared with the results from both period and pulsed source measurements.

The results of the period measurements are plotted against the AIMAZ values in Fig. 1. It is seen that the discrepancy between theory and experiment does not vary with the value of $H^3 \frac{dp}{dH}$.

It is noted from Table 4.1 that $H^3 \frac{dp}{dH}$ is approximately independent of boron concentration of the moderator, but increases with decreasing coolant density (i.e. with increasing D_2O content).

TABLE 4.1

Comparison of measured height coefficient with AIMAZ

Core	No. of channels in core	B^{10} content p.p.m.	Coolant % D_2O	$H^3 \frac{dp}{dH}$ cm^2 x 10^{-3}		
				AIMAZ	Period	Pulsed Source
SGM1	68	0.00	0.0	4.47	3.98 ± .07	3.87 ± .09
SGM2	68	0.00	25.0	4.68	4.19 ± .08	3.72 ± .09
SGM3	68	0.00	50.0	4.95	4.56 ± .08	4.51 ± .06
SGM3/R	52	0.00	50.0	4.97	4.70 ± .08	-
SGM5	68	1.93	50.0	4.93	4.44 ± .08	4.47 ± .04
SGM6	68	4.89	50.0	4.92	4.66 ± .08	4.42 ± .07
SGM7	68	6.92	50.0	4.92	4.47 ± .07	4.29 ± .27
SGM9	68	6.92	25.0	4.60	4.38 ± .07	-
SGM10	68	6.92	0.0	4.38	4.13 ± .07	-
SGM11	68	4.92	0.0	4.40	4.00 ± .07	3.95 ± .06
SGM11a	68	4.92	49.7	4.92	4.62 ± .08	-
SGM12	52	4.92	0.0	4.40	4.05 ± .07	-
SGM13	52	4.92	49.3	4.88	4.63 ± .08	-

This may be explained by simple one group theory, which may be expected to be fairly accurate in this system because of the high degree of moderation.

$$k_{eff} = \frac{k_\infty}{1 + M^2 B^2}$$

$$\rho = 1 - \frac{1}{k_{eff}} = 1 - \frac{1}{k_\infty} - \frac{M^2 B_r^2}{k_\infty} - \frac{M^2 B_z^2}{k_\infty}$$

$$\therefore \quad \frac{dp}{dB_z^2} = - \frac{M^2}{k_\infty} \propto H^3 \frac{dp}{dH}$$

where $M^2 = \frac{D}{\Sigma a}$ and $k_\infty = \frac{\nu \Sigma_f}{\Sigma a}$

A change in boron concentration of the moderator will to a first approximation affect only Σa, so that $H^3 \frac{dp}{dH}$ will remain constant. A decrease in coolant density will to a first approximation cause only an increase in $D(= \frac{1}{3\Sigma s})$, so that $H^3 \frac{dp}{dH}$ will increase.

The differences between AIMAZ and the period measurements, and between the period measurements and the pulsed source measurements are given in Table 4.2.

TABLE 4.2

Difference between AIMAZ, period and pulsed source measurements

Core	$\frac{\text{AIMAZ - period}}{\text{period}}$	$\frac{\text{Period - pulsed source}}{\text{period}}$ %
SGM1	12.3 ± 2.0	2.8 ± 2.9
SGM2	11.7 ± 2.1	-
SGM3	8.6 ± 1.9	1.1 ± 2.2
SGM3/R	5.7 ± 1.8	-
SGM5	11.0 ± 2.0	- 0.7 ± 2.0
SGM6	5.6 ± 1.8	5.2 ± 2.3
SGM7	10.1 ± 1.7	4.0 ± 6.2
SGM9	5.0 ± 1.7	-
SGM10	6.1 ± 1.8	-
SGM11	10.0 ± 1.9	1.3 ± 2.3
SGM11a	6.5 ± 1.9	-
SGM12	8.6 ± 1.9	-
SGM13	5.4 ± 1.8	-
Mean	8.2 ± 0.7 (rms) 0.5 (stat.)	2.3 ± 0.9 (rms) 1.3 (stat.)

The close agreement between the rms and statistical errors on the mean differences quoted in Table 4.2 shows that the scatter of the results is consistent with the expected experimental errors.

It is seen that the pulsed source measurements give results which are on average 2.3 ± 0.9% lower than the period measurements. This is in good agreement with the considerations of Section 3.2, which suggest that the pulsed source results are too low by approximately 3.3%.

It is also seen that the AIMAZ values are on average 8.2 ± 0.7% higher than the results of the period measurements. It is possible that this is due to an error in the value of delayed neutron fraction, β, used to determine the experimental values of $\frac{dp}{dH}$. In this connection it is informative to compare the values of β/l, where l is the prompt neutron lifetime at critical computed by AIMAZ, with the values of α_{oc} determined from the pulsed source measurements. According to the one group theory of pulsed source measurements, these quantities should be equal. The values are given in Table 4.3.

TABLE 4.3

Comparison of α_{oc} with AIMAZ of β/l

Core	$\beta \times 10^2$	$l \times 10^4$ secs.	β/l	α_{oc}	$\frac{\alpha_{oc} - \beta/l}{\beta/l}$ %
SGM1	.7063	.2906	24.30	26.5 ± .4	9.1 ± 1.7
SGM3	.7144	.2958	24.15	24.2 ± .2	0.2 ± .8
SGM5	.7124	.2889	24.66	24.6 ± .2	- 0.2 ± .8
SGM6	.7077	.2786	25.40	25.6 ± .3	0.8 ± 1.2
SGM7	.7079	.2721	26.02	30.7 ± 1.3	18.0 ± 5.0
SGM11	.7116	.2727	26.09	27.9 ± .3	6.9 ± 1.2
Mean					5.8 ± 2.9 (rms) 1.0 (stat.)

It is seen that on average the values of α_{oc} are 5.8 ± 2.9% higher than β/l. Because delayed neutrons have been ignored, it is to be expected that α_{oc} will be approximately 1.5% greater than β/l (see Section 3.2.2). The resulting discrepancy is thus 4.3% ± 2.9%. This is just over one standard deviation from the value of 8.2 ± 0.7% by which the period measurements of $\frac{dp}{dH}$ are lower than AIMAZ. It is therefore concluded that the results of the pulsed source measurements are not inconsistent with a possible error in β of -8.2%.

5. Reactivity Changes between Cores

5.1 Basis of the measurement

The difference in reactivity between two cores, A and B, is given by

$$(p_B - p_A)_A = \frac{1}{2} \left(H^3 \frac{dp}{dH}\right)_A \left(\frac{1}{H^2_B} - \frac{1}{H^2_A}\right)$$

according to the reactivity scale of core A, and

$$(p_B - p_A)_B = \frac{1}{2} \left(H^3 \frac{dp}{dH}\right)_B \left(\frac{1}{H^2_B} - \frac{1}{H^2_A}\right)$$

according to the reactivity scale of core B,

where H_A and H_B are the extrapolated critical heights of the two cores.

For each core the extrapolated critical height has been measured by axial fission chamber scans. The reactivity changes are deduced using the values of $H^3 \frac{dp}{dH}$ determined from the period measurements, and are given in Table 5.1.

TABLE 5.1

Reactivity changes between cores

Core	$H^3 \frac{dp}{dH} \times 10^{-3}$ cm^2	$\frac{1}{H_c^2} \times 10^5$ cm^{-2}	$(\Delta p)_A$ %	$(\Delta p)_B$ %
SGM1	3.98 ± .07	4.809 ± .033		
			- 0.235 ± .092	- 0.247 ± .096
SGM2	4.19 ± .08	4.691 ± .032		
			- 0.620 ± .090	- 0.675 ± .098
SGM3	4.56 ± .08	4.395 ± .029		
SGM3	4.56 ± .08	4.395 ± .029		
			+ 0.474 ± .097	+ 0.489 ± .100
SGM3/2	4.70 ± .08	4.603 ± .031		
SGM3	4.56 ± .08	4.395 ± .029		
			- 1.785 ± .089	- 1.738 ± .086
SGM5	4.44 ± .08	3.612 ± .022		
			- 2.822 ± .074	- 2.961 ± .078
SGM6	4.66 ± .08	2.341 ± .011		
			- 1.741 ± .043	- 1.670 ± .039
SGM7	4.47 ± .07	1.594 ± .006		
SGM7	4.47 ± .07	1.594 ± .006		
			+ 0.226 ± .021	+ 0.221 ± .021
SGM9	4.38 ± .07	1.695 ± .007		
			+ 0.217 ± .023	+ 0.204 ± .021
SGM10	4.13 ± .07	1.794 ± .008		
SGM10	4.13 ± .07	1.794 ± .008		
			+ 1.681 ± .043	+ 1.628 ± .042
SGM11	4.00 ± .07	2.608 ± .013		
SGM11	4.00 ± .07	2.608 ± .013		
			- 0.620 ± .036	- 0.716 ± .042
SGM11a	4.62 ± .08	2.298 ± .011		
SGM11	4.00 ± .07	2.608 ± .013		
			+ 1.176 ± .049	+ 1.191 ± .050
SGM12	4.05 ± .07	3.196 ± .018		
SGM11a	4.62 ± .08	2.298 ± .011		
			+ 1.160 ± .048	+ 1.162 ± .048
SGM13	4.63 ± .08	2.800 ± .015		
SGM12	4.05 ± .07	3.196 ± .018		
			- 0.802 ± .050	- 0.917 ± .057
SGM13	4.63 ± .08	2.800 ± .015		

5.2 The dependence of $\frac{dp}{dB_z^2}$ on buckling

The above expression assumes that $H^3 \frac{dp}{dH}$ is independent of buckling over the range between H_A and H_B. This is not true according to multi-group theory, and an approximation to the variation may be deduced from the two group equation for k_{eff},

$$k_{eff} = \frac{k_\infty}{(1 + L_1^2 B^2)\ (1 + L_2^2 B^2)}$$

$$\therefore \quad p = 1 - \frac{(1 + L_1^2 B^2)\ (1 + L_2^2 B^2)}{k_\infty}$$

$$= 1 - \frac{1}{k_\infty} - \frac{(L_1^2 + L_2^2)}{k_\infty}(B_r^2 + B_z^2) - \frac{L_1^2 L_2^2}{k_\infty}(B_r^2 + B_z^2)^2$$

$$\therefore \quad \frac{dp}{dB_z^2} = -\frac{(L_1^2 + L_2^2)}{k_\infty} - \frac{2L_1^2 L_2^2}{k_\infty}(B_r^2 + B_z^2)$$

$$= \left(\frac{dp}{dB_z^2}\right)_C - \frac{2L_1^2 L_2^2}{k_\infty} \Delta B_z^2$$

where $\left(\frac{dp}{dB_z^2}\right)_C$ is the value at critical, and ΔB_z^2 is the variation from the critical buckling. The variation of k_∞ with buckling due to fast fission is negligible.

$$\therefore \quad \Delta\left(\frac{dp}{dB_z^2}\right) = -\frac{2L_1^2 L_2^2}{k_\infty} \Delta B_z^2$$

For the present series of cores, $L_1^2 \simeq 120\ cm^2$ and $L_2^2 \simeq 80\ cm^2$, so that

$$\Delta\left(\frac{dp}{dB_z^2}\right) \simeq -0.0002\ \Delta B_z^2$$

where B_z^2 is in m^{-2}.

In order to check this expression, values of $\frac{dp}{dB_z^2}$ for several cores have been calculated by AIMAZ using different values of axial buckling. The results are given in Table 5.2.

TABLE 5.2

Variation of $\frac{dp}{dB_z^2}$ with B_z^2

Core	B_z^2 m^{-2}	$\frac{dp}{dB_z^2}$ m^2	$\Delta \frac{dp}{dB_z^2} / \Delta B_z^2$ m^4
SGM2	4.485 4.690	- 0.02366 - 0.02375	- 0.00044
SGM3	3.950 4.440	- 0.02501 - 0.02510	- 0.00018
SGM5	2.935 3.950	- 0.02486 - 0.02513	- 0.00026
SGM6	1.942 2.935	- 0.02480 - 0.02506	- 0.00025

It is seen that in the worst case, a change in buckling of $1m^{-2}$ produces a change in $\frac{dp}{dB_z^2}$ (i.e. in $H^3 \frac{dp}{dH}$) of approximately 2%. Since $\frac{dp}{dB_z^2} \simeq 0.02$, a change in reactivity of 2N will produce a change in $\frac{dp}{dB_z^2}$ of approximately 2%. The assumption that $\frac{dp}{dB_z^2}$ is constant will therefore produce an error of approximately 1% in the measurement of a reactivity change of 2N.

It may be seen from Table 5.1 that all of the reactivity changes measured were less than 2N, with the exception of SGM5 - SGM6, which was 3N. The error introduced by variation of $\frac{dp}{dB_z^2}$ is therefore ignored.

6. Comparison of Measured Reactivity Changes with ATMAZ

If a change is made from Core A to Core B, by variation of some parameter X, say, then it is possible to predict either the change in buckling required to keep the reactor critical, $(\Delta B_z^2)_p$, or the change in reactivity at either of the critical bucklings, $(\Delta p)_{B_z^2\ A}$ and $(\Delta p)_{B_z^2\ B}$.

These quantities are related by the mathematical identity

$$\left(\frac{\partial p}{\partial B_z^2}\right)_x \left(\frac{\partial B_z^2}{\partial x}\right)_p \left(\frac{\partial x}{\partial p}\right)_{B_z^2} = -1$$

so that for a given change Δx,

$$(\Delta p)_{B_z^2} = - \left(\frac{\partial p}{\partial B_z^2}\right)_x (\Delta B_z^2)_p \qquad (6.1)$$

Two values of $(\Delta p)_{B_z^2}$ are obtained according to the reactivity scales of either Core A or Core B, depending on the value of $(\frac{\partial p}{\partial B_z^2})$ used in Equation 6.1.

In principle, ΔB_z^2 is the difference in critical buckling predicted by AIMAZ for the two cores. However, in all the present cores AIMAZ overestimates the critical buckling (i.e. it overestimates the reactivity). Thus, if the AIMAZ values of critical buckling are used, values of reactivity changes will be obtained according to the reactivity scale of a reactor whose height is less than that of the true core.

The buckling difference according to the Core A scale is therefore defined as the difference between the measured buckling of Core A (for which AIMAZ predicts a reactivity p_A), and the buckling for which AIMAZ predicts the same reactivity, p_A, for Core B.

i.e.

$$(\Delta B_z^2)_A = B_z^2{}_B(p_A) - B_z^2{}_A(\text{exp.})$$

$$= B_z^2{}_B(\text{exp}) - B_z^2{}_A(\text{exp}) + \frac{p_A - p_B}{(\frac{\partial p}{\partial B_z^2})_{\text{Core B}}}$$

where p_A and p_B are the AIMAZ predictions of reactivity for the two cores, using their respective measured bucklings.

In all cases the values of $\frac{\partial p}{\partial B_z^2}$ for the two cores being compared are sufficiently similar for a single value of ΔB_z^2 to be used, given by

$$\Delta B_z^2\,(\text{AIMAZ}) = \Delta B_z^2\,(\text{exp.}) + \frac{p_A - p_B}{\left(\frac{\partial p}{\partial B_z^2}\right)_{\text{mean}}} \qquad (6.2)$$

The above expressions assume that $\frac{\partial p}{\partial B_z^2}$ is independent of buckling. As shown in Section 5.2, errors introduced by this assumption are less than 1%, and cancel with the corresponding errors in the experimental values.

The values of ΔB_z^2 calculated from Equation 6.2 are given in Table 6.1, together with the reactivity differences derived from these using Equation 6.1. The reactivity differences are compared with experiments in Table 6.2, and the buckling differences in Table 6.3.

Both Tables 6.2 and 6.3 show large discrepancies for changes to all three of the reflected cores (SGM3/R, SGM12 and SGM13). It may be seen from Table 6.2 that AIMAZ overestimates the reactivity worth of the change to these cores by some 0.5N.

TABLE 6.1

AIMAZ values of reactivity differences

Core	$-\frac{d\rho}{dB_z^2} m^2$	B_z^2 (exp) m^{-2}	ρ (AIMAZ)	ΔB_z^2 m^{-2} (AIMAZ)	$(\Delta\rho)_A N$	$(\Delta\rho)_B N$
SGM1	.0227	4.75	.00619			
				- 0.115	- 0.261	- 0.273
SGM2	.0237	4.63	.00630			
				- 0.295	- 0.699	- 0.740
SGM3	.0251	4.34	.00618			
SGM3	.0251	4.34	.00618			
				+ 0.406	+ 1.018	+ 1.026
SGM3/R	.0252	4.54	.01137			
SGM3	.0251	4.34	.00618			
				- 0.826	- 2.073	- 2.065
SGM5	.0250	3.56	.00503			
				- 1.241	- 3.101	- 3.095
SGM6	.0249	2.31	.00525			
				- 0.796	- 1.985	- 1.985
SGM7	.0249	1.573	.00377			
SGM7	.0249	1.573	.00377			
				+ 0.242	+ 0.603	+ 0.564
SGM9	.0233	1.673	.00718			
				+ 0.084	+ 0.196	+ 0.186
SGM10	.0222	1.77	.00688			
SGM10	.0222	1.77	.00688			
				+ 0.822	+ 1.825	+ 1.833
SGM11	.0223	2.575	.00726			
SGM11	.0223	2.575	.00726			
				- 0.337	- 0.752	- 0.839
SGM11a	.0249	2.27	.00650			
SGM11	.0223	2.575	.00726			
				+ 0.723	+ 1.612	+ 1.612
SGM12	.0223	3.155	.01046			
SGM11a	.0249	2.27	.00650			
				+ 0.653	+ 1.626	+ 1.613
SGM13	.0247	2.764	.01045			
SGM12	.0223	3.155	.01046			
				- 0.391	- 0.872	- 0.966
SGM13	.0247	2.764	.01045			

TABLE 6.2

Comparison of Reactivity Changes with AIMAZ

Core	No. of channels	B^{10} content ppm	Coolant % D_2O	ΔpN^{A}_{B} AIMAZ	ΔpN^{A}_{B} EXP	AIMAZ-EXP% / EXP
SGM1	68	0.00	0.0			
				- 0.261	- 0.235 ± .092	+ 11.1 ± 43.8
				- 0.273	- 0.247 ± .096	+ 10.5 ± 43.0
SGM2	68	0.00	25.0			
				- 0.699	- 0.620 ± .090	+ 12.7 ± 16.4
				- 0.740	- 0.675 ± .098	+ 9.6 ± 15.9
SGM3	68	0.00	50.0			
SGM3	68	0.00	50.0			
				+ 1.018	+ 0.474 ± .097	-
				+ 1.026	+ 0.489 ± .100	-
SGM3/R	52	0.00	50.0			
SGM3	68	0.00	50.0			
				- 2.073	- 1.785 ± .089	+ 16.1 ± 5.8
				- 2.065	- 1.738 ± .086	+ 18.8 ± 5.9
SGM5	68	1.93	50.0			
				- 3.101	- 2.822 ± .074	+ 9.9 ± 2.9
				- 3.095	- 2.961 ± .078	+ 4.5 ± 2.8
SGM6	68	4.89	50.0			
				- 1.985	- 1.741 ± .043	+ 14.0 ± 2.8
				- 1.985	- 1.670 ± .039	+ 18.9 ± 2.8
SGM7	68	6.92	50.0			
SGM10	68	6.92	0.0			
				+ 1.825	+ 1.681 ± .043	+ 8.6 ± 2.8
				+ 1.833	+ 1.628 ± .042	+ 12.6 ± 2.9
SGM11	68	4.92	0.0			
SGM11	68	4.92	0.0			
				- 0.752	- 0.620 ± .036	+ 21.3 ± 7.0
				- 0.839	- 0.716 ± .042	+ 17.2 ± 6.9
SGM11a	68	4.92	49.7			
SGM11	68	4.92	0.0			
				+ 1.612	+ 1.176 ± .049	-
				+ 1.612	+ 1.191 ± .050	-
SGM12	52	4.92	0.0			
SGM11a	68	4.92	49.7			
				+ 1.626	+ 1.160 ± .048	-
				+ 1.613	+ 1.162 ± .048	-
SGM13	52	4.92	49.3			
SGM12	52	4.92	0.0			
				- 0.872	- 0.802 ± .050	+ 8.7 ± 6.8
					- 0.917 ± .057	+ 5.3 ± 6.5
SGM13	52	4.92	49.3	- 0.966		

TABLE 6.3

Comparison of Buckling Changes with AIMAZ

Core	No. of channels	B^{10} content ppm	Coolant % D_2O	B_z^2 m^{-2}		AIMAZ-EXP% / EXP
				AIMAZ	EXP	
SGM1	68	0.00	0.0			
				- 0.115	- 0.12 ± .05	- 4.2 ± 40.0
SGM2	68	0.00	25.0			
				- 0.295	- 0.29 ± .04	+ 1.7 ± 14.0
SGM3	68	0.00	50.0			
SGM3	68	0.00	50.0			
				+ 0.406	+ 0.20 ± .04	-
SGM3/R	52	0.00	50.0			
SGM3	68	0.00	50.0			
				- 0.826	- 0.78 ± .04	+ 5.9 ± 5.4
SGM5	68	1.93	50.0			
				- 1.241	- 1.25 ± .02	- 0.7 ± 1.6
SGM6	68	4.89	50.0			
				- 0.796	- 0.737 ± .013	+ 8.0 ± 1.9
SGM7	68	6.92	50.0			
SGM10	68	6.92	0.0			
				+ 0.822	+ 0.805 ± .015	+ 2.1 ± 1.9
SGM11	68	4.92	0.0			
SGM11	68	4.92	0.0			
				- 0.337	- 0.305 ± .017	+ 10.5 ± 6.2
SGM11a	68	4.92	49.7			
SGM11	68	4.92	0.0			
				+ 0.723	+ 0.580 ± .022	-
SGM12	52	4.92	0.0			
SGM11a	68	4.92	49.7			
				+ 0.653	+ 0.494 ± .019	-
SGM13	52	4.92	49.3			
SGM12	52	4.92	0.0			
				- 0.391	- 0.391 ± .023	0.0 ± 5.9
SGM13	52	4.92	49.3			

In the remainder of the cores studied the discrepancy in reactivity worth is some 8% greater than that in buckling change. This corresponds to the discrepancy in $\frac{dp}{dB_z^2}$ noted in Section 4. It is seen that AIMAZ predicts the change in buckling with coolant composition to well within the experimental errors, but that it overestimates the change in buckling with boron content by 4.4% ± 2.0%.

7. Reactivity Worths of Perturbations

The changes in critical height caused by the introduction of certain perturbations into the cores have been measured, and the reactivity worths have been determined from the measured values of $\frac{dp}{dH}$. The results are given in Tables 7.1, 7.2, 7.3 and 7.4, and are compared with AIMAZ values where these have been calculated.

TABLE 7.1

Reactivity Worth of Perturbations in SGM1

Description of change	ΔpN EXP	ΔpN AIMAZ	$\frac{\text{AIMAZ-EXP}}{\text{EXP}}$ %
Pencil loops in 0.09 and G.13	- 0.46 ± .02	- 0.47	+ 2.2 ± 4.4
Empty displacement tube in G.13	- 0.09 ± .01	-	-
K. tube in J10	- 0.76 ± .03	-	-
BF_3 counter (12EB 40) in core centre	- 0.07 ± .01	-	-

TABLE 7.2

Reactivity Worths of Perturbations in SGM6

Description of change	ΔpN EXP	ΔpN AIMAZ	$\frac{\text{AIMAZ-EXP}}{\text{EXP}}$ %
8 displacement tubes emptied	- 0.32 ± .01	- 0.28	- 12.5 ± 3.1
21 displacement tubes emptied	- 1.14 ± .03	- 1.15	+ 0.9 ± 2.6
Reactivity oscillator inserted in closed position in K11	- 0.67 ± .02	-	-
Reactivity oscillator inserted in open position in K11	- 0.81 ± .02	-	-
Poison tube in 0.09	- 0.71 ± .02	- 0.74	+ 4.1 ± 2.8
Poison tube in K11	- 1.25 ± .03	- 1.26	+ 0.8 ± 2.4

TABLE 7.3

Reactivity Worths of Perturbations in SGM7

Description of change	$\Delta\rho N$ EXP	$\Delta\rho N$ AIMAZ	$\frac{\text{AIMAZ-EXP}}{\text{EXP}}$ %
1.2% PuO_2/UO_2 cluster in J.10	+ 0.55 ± .02	-	-
1.35% UO_2 cluster (No. 32) in L.10	- 0.07 ± .01	-	-
1.35% UO_2 cluster (No. 35) in L.10	- 0.07 ± .01	-	-
1.35% UO_2 cluster (No. 10) in L.10	- 0.07 ± .01	-	-
3% UO_2 cluster (No. 34) in L.10	+ 0.85 ± .02	-	-
2.28% Pencil loop in K.11	- 0.31 ± .02	- 0.36	+ 16.1 ± 6.5
1.24% Pencil loop in K.11	- 0.34 ± .02	- 0.41	+ 20.6 ± 5.9
Segmented 3% UO_2 cluster in L.10 (50% D_2O)	+ 0.86 ± .03	-	-
Segmented 3% UO_2 cluster in L.10 (0% D_2O)	+ 1.15 ± .03	-	-
Cluster No. 32 (t = 0.1") in L.10 (50% D_2O)	- 0.08 ± .01	-	-
Cluster No. 19 (t = 0.2") in L.10 (50% D_2O)	- 0.08 ± 0.1	-	-
Cluster No. 35 (t = 0.3") in L.10 (50% D_2O)	- 0.08 ± .01	-	-
Strain Gauge on 2.28% cluster in J.10	- 0.05 ± .01	-	-
1.24% Trefoil in K.11	- 0.32 ± .02	- 0.32	0.0 ± 6.3
2.28% Trefoil in K.11	- 0.26 ± .02	- 0.22	- 15.4 ± 7.7

TABLE 7.4

Perturbations in SGM13

Condition	ΔpN EXP	ΔpN AIMAZ	$\frac{\text{AIMAZ-EXP}}{\text{EXP}}$ %
3% cluster, IE366, in D14	+ 0.08 ± .01	+ 0.08	0.0 ± 12.5
3% SGP cluster in D14	+ 0.13 ± .01	+ 0.13	0.0 ± 7.7
3% SGP cluster in L10	+ 0.83 ± .03	+ 0.83	0.0 ± 3.6
3% cluster, IE367, in D14	+ 0.09 ± .01	+ 0.10	11.1 ± 11.1
7% Superheat clusters in D12 & D14	+ 0.35 ± .02	+ 0.08	-
3% Superheat clusters in D12 & D14	- 0.05 ± .01	- 0.24	-
AGR cluster in D12 Empty superheat channel in D14	- 0.40 ± .02	-	-
7% Superheat cluster in D12 3% SGP clusters in D14 & F12 3% "Natural" cluster in F14 Empty superheat channel in F16 2.28% cluster in H16	+ 1.65 ± .04		
3% "Natural" cluster in J10	+ 0.90 ± .03	-	-
3% "Natural" cluster with H_2O coolant in J10	+ 1.04 ± .03	-	-
75% D_2O coolant in J10 & F14	- 0.05 ± .01	- 0.06	+ 20 ± 20
75% D_2O in L10 & F14	- 0.06 ± .01	- 0.06	0 ± 17
100% D_2O in L10 & F14	- 0.10 ± .01	- 0.10	0 ± 10
100% D_2O in J10 & F14	- 0.09 ± .01	- 0.09	0 ± 11

Clean core condition: 52 channels, 4.92 p.p.m. B^{10}, 49.3% D_2O.

In general AIMAZ predicts the reactivity worths of the perturbations extremely well, with the exception of the superheat clusters in SGM13, whose reactivity worth was underestimated by some 0.25N. Excluding these two cases, the average discrepancy between AIMAZ and experiment is + 2.8 ± 2.3%. Because of the discrepancy of 8.2% in $\frac{\partial p}{\partial B_z^2}$, it may be inferred that AIMAZ underestimates the change in critical buckling due to the perturbations by an average of 5.4 ± 2.3%.

8. Conclusions

The moderator height coefficient of reactivity has been measured by both divergent period and pulsed source techniques. The results from the two methods are in good agreement with each other, but are 8.2% + 0.7% lower than those predicted by AIMAZ. The two most likely causes of this discrepancy are an error of + 8% in the leakage calculated by METHUSELAH, or an error of - 8% in the effective delayed neutron fraction used in the analysis of the experimental results.

If the calculated leakage is high by 8%, then using the one group equation

$$k_{eff} = \frac{k_\infty}{1 + M^2 B^2}$$

$$\Delta k_{eff} = - \frac{M^2 B^3}{k_\infty} \frac{\Delta M^2}{M^2}$$

$$\simeq - \frac{0.2}{1.2} \times 0.08$$

$$\simeq - 0.013$$

so that the AIMAZ prediction of k_{eff} would be low by 1.3%. The AIMAZ prediction is in fact, on average, 0.6% greater than unity, so that correcting for such an error in the leakage would give a predicted k_{eff} 1.9% greater than unity.

The effective delayed neutron fraction has been calculated for each core using fraction of fissions occurring in each isotope calculated by AIMAZ. Any error in this calculation is unlikely to exceed 2%, so that an error of 8% must be traced back to the original delayed neutron data (4).

The measured changes in critical buckling and the reactivity changes deduced from them using the measured values of height coefficient have been compared with AIMAZ predictions. It is seen that AIMAZ predicts the buckling change with coolant composition to well within the experimental errors, but that it overestimates the change with boron content by some 4%. The discrepancies in reactivity worth are some 8% higher than in buckling, corresponding to the discrepancy in height coefficient.

ACKNOWLEDGEMENTS

The author is indebted to his colleagues in the DIMPLE team who performed the experiments, to Mr. K. C. Kendall who performed the AIMAZ calculations, and to Mr. A. J. Briggs and Mr. D. A. Newmarch who gave much helpful advice during the preparation of this memo.

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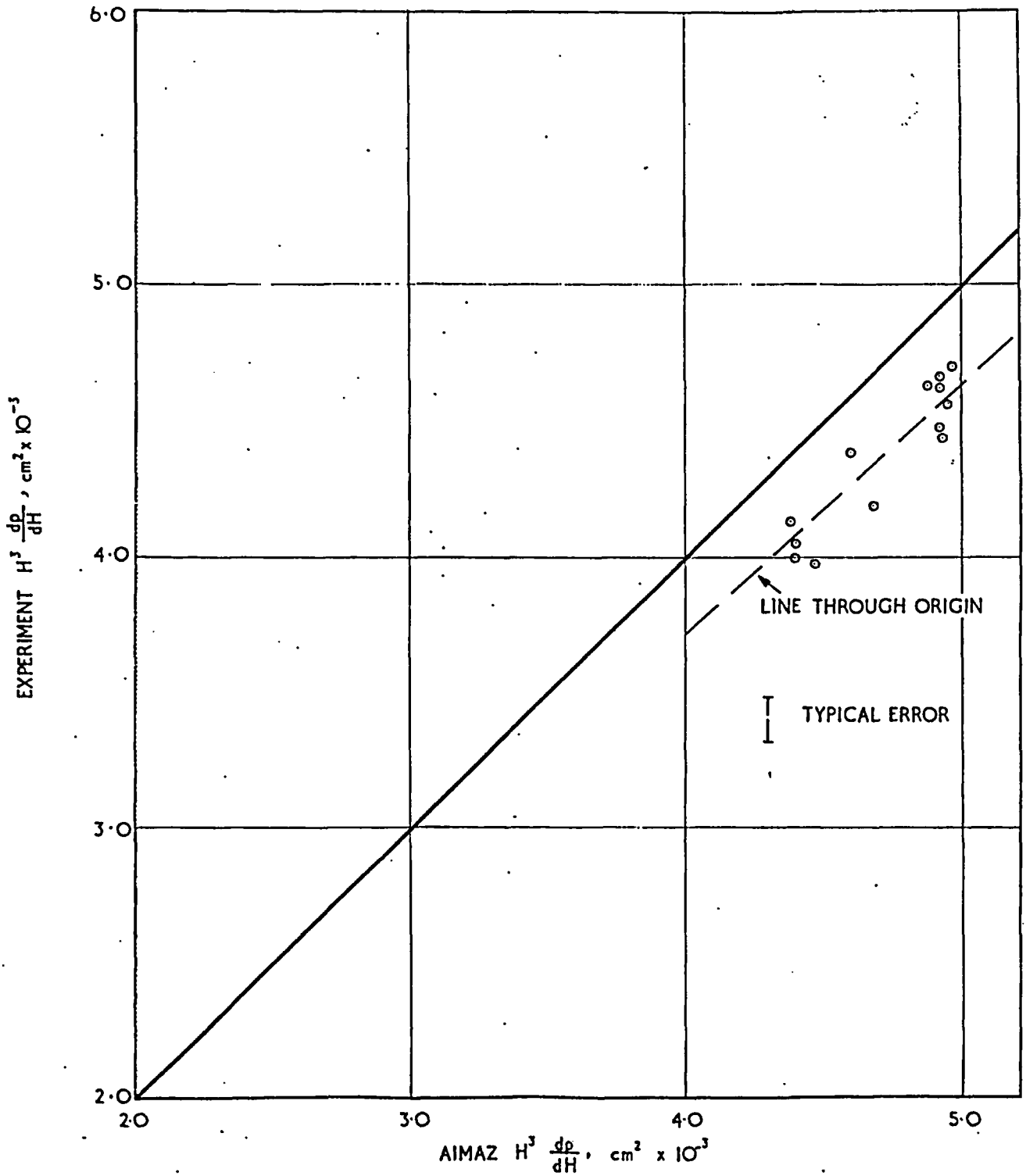

FIGURE 1. COMPARISON OF AIMAZ VALUES OF $H^3 \frac{d\rho}{dH}$ WITH PERIOD MEASUREMENTS.