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ON-LINE CALIBRATION OF HFIR CONTROL RODS USING THE ROD OSCILLATION TECHNIQUE

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ABSTRACT

The digital computer at the HFIR will need accurate control rod calibration data to perform reactivity balance calculations. The purpose of this study was to evaluate the rod oscillation method of measuring differential control rod worth. The oscillation method is especially attractive for on-line calibrations, because the measurement does not interrupt the normal operation of the reactor or alter the steady-state power level and, furthermore, it is relatively fast. The accuracy of rod worth obtained using the oscillation method was determined by comparing the results with rod bump-period measurements. The rod worths obtained using the two methods agreed to within 2%. Measurement of differential rod worth at one rod position required 20 sec using the oscillation method and approximately 2 min using the rod bump technique. Therefore, the rod oscillation method should provide accurate and fast on-line control rod calibration data for reactivity balance calculations at the HFIR.

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INTRODUCTION

An on-line digital computer will be used at the HFIR to calculate the reactivity balance in order to prevent unsafe automatic shim plate withdrawal due to abnormal core reactivity losses.¹ To perform the reactivity calculations the computer must have accurate up-to-date shim regulating* and shim safety rod calibration data. Since the HFIR control rods have an expected core life of 6-12 months,² during which rod worth as a function of position is expected to change significantly because of the high flux; a means of calibrating the rods while the reactor is at full power (100 Mw) is needed.

To provide control-rod calibration data, the rod oscillation method of control-rod calibration was evaluated. Other studies^{3,4} have shown this method to be faster than and as accurate as rod bump-period measurements. Also, the rod oscillation method is particularly suited for on-line calibrations while the reactor is at power, because the mean reactor power level does not change significantly during the measurement.

A series of tests was made at the HFIR to determine the feasibility of using this method to calibrate the shim regulating rod while on line. To evaluate the rod oscillation method, results are compared with rod bump-period measurements made during initial reactor critical tests⁵ and also with period calibrations made at the same rod position and time as the rod oscillation tests. Calibrations were also made during a normal HFIR fuel cycle while the reactor was operated at 100 Mw to determine if on-line calibrations could be made. During a reactor startup, tests were made at three power levels with the same regulating rod position to check the power-to-reactivity gain predicted by a theoretical model⁶ used to calculate the HFIR power-to-reactivity transfer function. Additional tests were performed to determine if the worth of the shim-safety rods could be inferred, using the calibrated regulating rod as a reference.

¹ B. R. Lawrence, H. P. Danforth, and J. B. Bullock, A Mathematical Model for the High Flux Isotope Reactor Reactivity Calculation, ORNL-TM-1472 (October 1966).

² F. T. Blinford and E. N. Cramer, The High-Flux Isotope Reactor, ORNL-3572 (May 1964).

³ F. J. Jankowski, D. Klein, and T. M. Miller, The Rod-Oscillator Method for Calibrating Control Rods, WAPD-T-323 (March 1956).

⁴ C. W. Griffin and J. G. Lundholm, Jr., Calibration of the SRE Shim Rods by the Oscillation Method, NAA-SR-3764 (November 1960).

⁵ R. D. Cheverton, private communication.

⁶ B. R. Lawrence, Determination of the Power vs Reactivity Frequency Response Function of a Power Reactor, with Application to the High Flux Isotope Reactor, ORNL-TM-1471 (July 1966).

* Hereinafter referred to as the regulating rod.

The author wishes to express his appreciation for the assistance given by W. F. Johnson in installing and calibrating the differential transformer, and to C. B. Stokes and the HFIR operating personnel for their assistance in performing the tests. He is also grateful to J. C. Robinson (University of Tennessee) and R. C. Kryter (ORNL) for their most helpful discussions relating to the theoretical aspects of the experiment.

METHOD

To apply the rod oscillation technique to calibration of control rods, three criteria must be met. First, the rod to be calibrated must be oscillated at the particular frequency chosen. The HFIR servo system,⁷ because of its relatively fast response to power demand changes, fills this need. The regulating rod can be made to oscillate by inserting an oscillating power demand signal in addition to the normal demand. However, this technique is made slightly complicated for HFIR application because the HFIR has three servos for controlling the reactor. To offset this complication an oscillating demand signal was fed to one of the servos, and the other two were set at demand values that effectively reduced the system to one servo control.

The second criterion is that the peak-to-peak rod oscillation and the peak-to-peak reactor power fluctuation must be measured accurately. The power fluctuation is observed by recording the ac output of an ionization chamber. An accurate measurement of the rod oscillation, however, is a bit more complicated to obtain, because only a small degree of oscillation (approximately 0.030 in. p-p) is necessary owing to the large differential worth of the regulating rod at its peak worth (~ 1.60 dollars/in.). Larger oscillations would cause too much power fluctuation. To measure the rod movement accurately, a linear differential transformer was installed on the regulating-rod drive in the subpile room at the HFIR, and its signal was transmitted to the control room. The transformer was disengaged from the drive when a test was not being conducted.

The third criterion is that the reactor power-to-reactivity transfer function must be independent of rod position. Since at above 10 cps the power-to-reactivity gain of the HFIR is not independent of the neutron lifetime, and since the lifetime changes with rod position, the condition of constant gain as a function of rod position can only be assumed if the oscillation frequency is less than 10 cps. However, if the calibration frequency is less than 10 cps, the gain can be calculated theoretically or measured at one rod position using the rod bump-period method, and then can be assumed constant at other positions.

If these three conditions are satisfied, the differential worth of the regulating rod at a given rod position can be calculated using the relationship

⁷ L. C. Oakes, A Second Generation of Reactor Control Systems as Applied to the High Flux Isotope Reactor, ORNL-TM-1259 (September 1965).

$$\frac{\Delta k(\$)}{\text{in.}} = \frac{\Delta P/P_o}{G_R(f)\beta_e \Delta R}, \quad (1)$$

where

$\Delta k(\$)$ = reactivity in dollars,

ΔP = peak-to-peak power oscillation,

P_o = steady-state reactor power,

β_e = delayed neutron fraction (0.0071 for the HFIR),

ΔR = peak-to-peak oscillation of the regulating-rod (inches) about the desired rod position,

$G_R(f)$ = power-to-reactivity gain at frequency of oscillation, f .

The reactor gain $G_R(f)$ was obtained using a space-independent reactor kinetics model (point reactor) in conjunction with a general set of first order-equations that represented the thermal performance of the reactor.⁶ Figure 1 shows the power-to-reactivity gain vs reactor power at a frequency of 0.5 cps. Although the choice of this frequency was partly arbitrary, the servo demand response and the fact that the reactor gain at this frequency is independent of control rod position (neutron lifetime) were considered in making the decision. The following section describes the apparatus used to measure $\Delta P/P_o$ and ΔR . If these values are known, then the differential rod worth can be calculated using Eq. 1.

APPARATUS

Measurement of $\Delta P/P_o$

Figure 2 shows a block diagram of the experimental setup used to measure $\Delta P/P_o$ and ΔR . The output of the bandpass filter ΔV is related to the oscillating ion-chamber current ΔI , as follows

$$\Delta I = \frac{\Delta V}{R_i G_A G_F}, \quad (2)$$

Fig. 1. Theoretical Power-to-Reactivity Gain of the HFIR at 0.5 cps as a Function of Reactor Power.

Fig. 2. Diagram of Instrumentation Used for Calibration of Regulating Rod.

where

ΔV = peak-to-peak oscillation at the filter output as recorded on one channel of the two-channel chart recorder,

R_i = input resistor of the ac amplifier,

G_A = ac amplifier gain at 0.5 cps,

G_F = bandpass filter gain at 0.5 cps.

Since $\Delta P/P_o = \Delta I/I_o$, the fractional power oscillation is given by

$$\frac{\Delta P}{P_o} = \frac{\Delta I}{I_o} = \frac{\Delta V}{R_i G_A G_F I_{DC}}, \quad (3)$$

where I_{DC} is the measured dc component of the ion chamber signal.

Measurement of ΔR

The regulating-rod oscillation ΔR (output of the differential transformer) was recorded on the other channel of the two-channel recorder. The differential transformer was calibrated before each measurement by deflecting the transformer a known amount and observing the deflection on the two-channel recorder. Figure 3 shows the way in which the transformer is coupled to the regulating-rod drive. The carrier amplifier signal was transmitted to the control room where the recorder was located along with the electromagnet power supply used to couple the differential transformer to the rod drive. A typical recording made during a test is shown in Fig. 4. Values of ΔV and ΔR were obtained by averaging 10 cycles of the recorder trace (~ 20 sec for the test).

TESTS AND RESULTS

Comparison with Rod Bump-Period Measurement

Rod bump-period measurements and rod oscillation tests were made at the beginning of an HFIR fuel cycle to check the differential rod worth at the critical position using a new set of rods. (Use of new rods allowed the results to be compared with previous period measurements.) The period measurement was made at 40 kw and the

HFIR CONTROL ROD MOTION DETECTOR

Fig. 3. Differential Transformer Mounting on Regulating Rod Drive.

Fig. 4. Recorder Trace Taken During Regulating-Rod Calibration Test.

oscillation test at 17 Mw (this was necessary because the minimum demand on the HFIR servo is 10 Mw). A theoretical reactor gain of 139 was used to calculate the differential rod worth from the oscillation data. The period measurement gave a regulating rod worth of 1.58 dollars/in. at a position of 17.45 in.⁸ The oscillation test yielded a worth of 1.55 dollars/in. at 17.41 in. Since these results obtained with the two methods agree to within 2% and also with previous measurements⁵, we conclude that the theoretical model gives a good prediction of the power-to-reactivity gain at a power of 17 Mw.

On-Line Regulating Rod Calibration at 100 Mw

During the same HFIR fuel cycle (cycle 9) the regulating rod was calibrated periodically during the life of the core while the reactor was running at 100 Mw. Data were obtained at rod positions from 18.26 in. to 24.74 in. as fuel burnup required that the regulating and shim rods be withdrawn. The differential shim regulating-rod worth vs withdrawal position obtained from these measurements is plotted in Fig. 5. For comparison, a complete calibration curve (obtained at zero power using the rod bump-period technique⁵) is also plotted in Fig. 5. The curves agree as to shape, but the oscillation method predicts a consistently higher worth per inch. There are two possible explanations for this result. First, as mentioned previously, operating experience on the first two sets of HFIR rods had shown that the rod worth increases considerably during the first core cycle (~22 days) at 100 Mw. This could account for the differences in Fig. 5, since the rod bump-period calibration was made using new rods that had not been run at 100 Mw. Additional period measurements at the beginning of succeeding fuel cycles could show this, but time did not permit these measurements to be made.

A second explanation for the higher worth predicted by the oscillation-technique is that the reactor gain G_R used to reduce the data was too small. Even though the theoretical model checked well at 17 Mw, the power coefficients of reactivity used in the model may not be correct for higher power levels. Further tests proved that this was true, as discussed in the next section.

Rod Calibration as a Function of Power

Additional tests were made during the next HFIR startup (cycle 10) to check the gain change predicted by the model for a power increase from 17 to 100 Mw. The tests were run at 17.4, 56.7, and 100 Mw with the same regulating rod position (before xenon buildup).

⁸ Private communication from T. M. Sims, ORNL.

Fig. 5. Comparison of Regulating-Rod Worth Obtained Using Oscillation Method with the Worth Measured Using the Rod Bump-Period Method.

The results indicate that the theoretical model was not properly constructed to satisfactorily predict reactor gain as a function of power. Since the model is correct at 17.4 Mw (comparison with period measurement confirms this), and if the true rod worth does not change with power, then the reactor gain at 56.7 and 100 Mw can be inferred from these tests by computing the gain that would yield the same rod worth at all three power levels. The gains computed in this way (Table 1) are higher than the theoretical values by approximately 7% at 56.7 Mw and 9% at 100 Mw.

Figure 6 shows an on-line (oscillation method) rod calibration curve calculated from data taken during fuel cycle 9 at 100 Mw (Fig. 5), using a value of 102 instead of 93.2 for the reactor gain G_R , and a rod bump-period calibration curve calculated from data taken with new rods at zero power.⁵ The difference between the curves is most likely attributable to buildup of a tantalum isotope in the rod during initial operation at 100 Mw. This reasoning is supported by the observation that the largest difference in worth between the new rods and irradiated rods is in the part of the rod which was in the region of highest flux for the longest time before the calibration was made.

Table 1. Rod Worth vs Reactor Power

	Reactor Power, Mw		
	<u>17.4</u>	<u>56.7</u>	<u>100.0</u>
Theoretical G_R	138	117	93
Rod worth computed using theoretical G_R , dollars/in.	1.55	1.65	1.69
Experimentally determined G_R using 1.55 dollars/in. as a reference	138	125	102
Ratio of experimental G_R to theoretical G_R	1.00	1.07	1.09

On-Line Shim-Safety-Rod Calibration at 100 Mw

Once the regulating rod was calibrated using the oscillation method, the four shim safety rods were individually calibrated using a trade-off scheme, with the calibrated regulating rod as a reference. After each shim rod was withdrawn 0.1 in.,

Fig. 6. Regulating-Rod Worth Determined by Use of Oscillation Method and Experimentally Determined Reactor Gain.

the amount the regulating rod had to be inserted to maintain the reactor critical was recorded. The shim-rod calibration data taken during fuel cycle 9 are plotted in Fig. 7 along with data obtained by rod bump-period measurements at zero power.⁵ Figure 7 shows the total worth of the four shim rods (sum of the individual worths). The considerable spread in the data is probably due to an inability to read the rod position accurately (the readings were taken from the dial on the reactor operating console). A more consistent set of calibration data could be obtained by withdrawing the shim-safety rods farther during each test or by pulling them as a group so that small errors in reading the rod movement would not greatly influence the calibration.

Fig. 7. Shim Safety Plate Calibration Determined by Use of the Regulating Rod Comparison Method.

CONCLUSIONS AND RECOMMENDATIONS

The oscillation method of control-rod calibration can be used to obtain on-line values of rod worth for use by the HFIR shim computer. This method of rod calibration requires only approximately 20 sec to obtain a value of differential rod worth and is especially attractive since it does not interrupt the normal operation of the reactor or alter the steady-state value of reactor power. However, before the method is programmed for the on-line digital computer, further investigations should be carried out:

1. Make additional comparisons with period calibrations to determine if the oscillation method gives the correct value of reactivity.
2. Determine the optimum frequency of oscillation (considering servo demand response, reactor gain, etc.) that will give the most reliable results.
3. Study other means of measuring the shim regulating rod movement during a test. (Due to the small amplitude of rod movement, this is probably the greatest source of error in the calibration.)
4. Plan the best way of performing the calibration using the on-line computer. This would include completely automating the calibration so that the rod worth could be obtained at the demand of the digital computer.

Also, the rod oscillation test should be considered as a possible means of diagnosing reactor anomalies, either in control-rod-worth changes or in reactor parameter changes that influence the power-to-reactivity gain. Theoretical investigations to determine the sensitivity of the gain to various parameter changes would be required to assess the value of the oscillation method for on-line reactor diagnosis.

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