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ARGONAUT AUTOMATIC FLUX CONTROLLER
DESIGN REPORT

by

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NOMENCLATURE

G	Forward transfer function
$G_1(s)$	Zero-power reactor transfer function, $\frac{n_0 + \delta n}{\delta k_n}$ (s)
$G_1'(s)$	Zero-power reactor transfer function, $\frac{\delta n/n_0}{\delta k_n}$ (s)
$G_2(s)$	Controller transfer function
H	Feedback transfer function
K	Gain constant
K_2	Controller gain coefficient
ℓ^*	Mean effective neutron lifetime
n	Reactor power
n_0	Power demand
$P(s)$	Power transfer function
s	Laplace transform operator
T	Time constant
β_T	Total delayed neutron fraction
ϵ	Velocity servo error signal
δk	Reactivity
δk_D	Disturbance reactivity
δk_N	Net reactivity
δk_R	Control rod reactivity
δk_s	Shim rod reactivity
δn	Power error

$\delta n'$	Filtered power error
δt	Tachometer output voltage
$\delta \dot{k}_R$	Control rod reactivity rate
θ_R	Control rod angular position
$\dot{\theta}_R$	Control rod angular velocity
ω	Frequency, radians/second
ζ	Damping factor

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ABSTRACT

The purpose of designing an automatic flux controller for a training-research reactor and the usefulness of the equipment as a pedagogical tool is discussed. The design is presented in the form of a steady-state analysis based upon the small-signal linearization of the reactor kinetics transfer function. The measured controller performance and construction details of the equipment is given.

I. Introduction

The design of the automatic flux controller for the Argonaut reactor is based upon its use as a pedagogical tool. The equipment provides an instructional means whereby the student can become familiar with flux-control design. The practical problems related to the controller rod size, shape, and location within the reactor can be demonstrated. The circuit design can be analyzed and the transfer function measured. By application of linear feedback control system analysis, the student can investigate the stability and accuracy of control for various values of the controller parameters.

The equipment also furnishes an instructional method whereby the effect of a power-to-reactivity feedback which occurs in a nuclear power reactor can be demonstrated on a low-power training reactor.¹ By the use of a power-to-reactivity feedback path external to the reactor in the form of an automatic flux controller, the effect of a negative power coefficient on the reactor response can be studied. The reactivity input is sinusoidally oscillated to obtain the transfer function of the reactor both with and without the controller in operation. The method of Ref. 1 is then used to obtain the transfer function of the power-to-reactivity feedback through the application of a $1 + GH$ transformation plane. By a comparison of the transfer function thus obtained with the measured controller transfer function, the accuracy of the technique can be established.

¹J. A. DeShong, Jr. and W. C. Lipinski, Analysis of Experimental Power-Reactivity Feedback Transfer Functions for a Natural Circulation Boiling Water Reactor, ANL-5850 (July 1958).

The automatic flux controller system design is presented in the form of a steady-state analysis based upon the small-signal linearization of the reactor kinetics transfer function. The approximate values obtained for the controller parameters in the first stage of the design synthesis were based upon an empirical rule of thumb correlating the frequency and transient response. The final value of the parameters for the desired relative stability of the system were obtained by operating the actual control equipment in a closed loop with an electronic simulation of the Argonaut reactor kinetics.²

II. Design

A. General

The controller is designed to maintain automatically the Argonaut reactor flux (power output) constant at a preselected level of power demand. The accuracy of the control is established on the basis of a sinusoidal reactivity disturbance. The variations of peak power are held to less than $\pm 1\%$ of the power demand set-point for frequencies of disturbance up to 1 rad/sec. The power demand set-point is designed for operation of the Argonaut reactor at an output of 100 watts. A variable power demand level control is provided with a range of 100 ± 20 watts over which stable control is maintained.

Since the equipment is used for pedagogical purposes, it is analytically important to avoid speed saturation of the controller. To assure this condition, the maximum speed of the rod is permitted to exceed the generally acceptable maximum of $10^{-4} \delta k/\text{sec}$. The considerations for safe operation of the reactor dictate the selection of a very low reactivity worth for the controller rod (refer to Appendix B). Slow reactivity changes that take place in the reactor are compensated manually by the reactor operator through shimming action of the fine control rod. Reactivity changes with magnitudes that exceed the worth of the controller rod result in removal of power from the rod drive motor by action of a limit switch. For the above reasons, the normal interlocking of the automatic flux control circuit with the reactor shut-down circuit is not provided in this design.

The automatic flux control of a nuclear reactor can be obtained through application of an on-off (contactor) type of controllers,^{3,4} which is

²P. R. Bell and H. A. Straus, Electronic Pile Simulator, Rev. Sci. Instr., 21, 760-763 (1950).

³J. M. Harrer and J. A. DeShong, Jr., Discontinuous Servo for Control of Power Reactors, Nucleonics, 12 (No. 1), 44, (1954).

⁴W. C. Lipinski, C. A. Pesce, and A. Hirsch, Automatic Control of Boiling Water Reactors, Paper No. CP 59-928 presented at AIEE General Meeting, Summer 1959, Seattle, Wash.

simple, compact and economical from both the initial cost and maintenance standpoints. For the training-research reactor such as the Argonaut, however, it is generally more desirable to have a continuous-type control to simplify the measurements and interpretation of results. Therefore, this type was selected as the basis for the present design.

The block diagram of the system in terms of the transfer function notation is shown in Figure 1. The reactor power output, n , is compared with the power demand signal, n_0 . With no disturbance acting on the system, the difference signal, δn (power error), has zero magnitude. Movement of a shim rod and/or the introduction of a disturbance reactivity changes the net reactivity input, δk_N , to the reactor from the initial zero value. The result is a change in the power output with a corresponding change in the power error. The response of the controller to the power error signal, $\delta n/n_0$, produces a reactivity change in opposition to the disturbance. The net reactivity input is thereby returned to the initial condition of zero magnitude, and power output becomes equal to power demand.

FIGURE 1
BLOCK DIAGRAM FOR AUTOMATIC FLUX CONTROL SYSTEM

B. Reactor Kinetics Transfer Function

The methods for obtaining the linearized transfer function of the nuclear reactor kinetics, either by calculation or by measurement, are well known.^{5,6,7} The general form of the transfer function is written in terms of the power error, $\delta n/n_0$, instead of the power output, n , as follows:

⁵M. A. Schultz, Control of Nuclear Reactors and Power Plants, McGraw-Hill Book Company, Inc., New York (1955).

⁶J. M. Harrer, R. E. Boyar, and D. Krucoff, Transfer Function of Argonne CP-2 Reactor, *Nucleonics*, 10 (August) 32-36 (1952).

⁷S. Glasstone, Principles of Nuclear Reactor Engineering, D. Van Nostrand Company, Inc., New York (1955).

$$G_1(s) = \frac{\delta n/n_0}{\delta k_N} = \frac{K_1 \prod_{i=1}^n (1 + sT_i)}{s \prod_{j=1}^n (1 + sT_j)} \quad (1)$$

The Argonaut reactor frequency response was calculated by the method of Ref. 6 using the Keepin and Wimett data on U^{235} for six delayed-neutron emitters ($n=6$) with $\beta_T = 0.0065$ and an average neutron lifetime of $\ell^* = 2 \times 10^{-4}$ sec.⁸ The calculated response normalized by the value of $1/\beta_T$ is shown in Figure 2 by the solid lines; the measured response is indicated by the circled points.

C. Controller Transfer Function

The automatic flux control system as shown in Figure 1 is a multiple input control loop. The net reactivity input, δk_N , is determined by the summation of the disturbance, controller, and shim rod reactivities. Thus, if the steady-state power output is to have zero error from the power demand set-point, consideration must be given to the step input type of disturbance reactivity. For zero steady-state (power) error, the controller must produce a rate of change of output (reactivity) that is proportional to the input (power error) signal.⁹ Based on the above considerations, the controller transfer function is expressed as

$$G_2(s) = \frac{\text{controller reactivity}}{\text{power error}} = \frac{K_2}{s} \quad (2)$$

The desired integration is obtained by using a two-phase servo motor to drive the controller rod through a 40-to-1 speed reducer. The low rotor inertia with high torque-to-inertia ratio makes this type of motor suitable for application in a high-performance servomechanism. The controller components are shown in block diagram form in Figure 3. The power to excite the motor control field is obtained from a single-stage push-pull type of magnetic amplifier. The control circuit of the magnetic amplifier in turn is excited by the power error signal after amplification from a high gain DC amplifier. Since the gear ratio is large, the motor load consists of the inertia and friction contained in the motor rotor and the first gear of the speed reducer. The load viscous friction therefore is of negligible magnitude. Thus, to prevent single-phase operation of the two-phase servo motor, kinetic damping is required. A DC tachometer geared with a 4-to-1 speed reduction from the servo motor shaft provides

⁸G. R. Keepin and T. F. Wimett, Reactor Kinetic Functions: A New Evaluation, Nucleonics, 16 (10), (1958).

⁹G. H. Fett, Feedback Control Systems, Prentice-Hall, Inc., New York (1954).

FIGURE 2
FREQUENCY RESPONSE OF ARGONAUT REACTOR

FIGURE 3
BLOCK DIAGRAM FOR ARGONAUT FLUX CONTROLLER

the required stabilization. The ion chamber current which represents the power signal, n , is put through a low-pass filter network to reduce the noise content. The tachometer output, δ_t , is subtracted from the filtered error signal, $\delta n'/n_0$, and the difference, ϵ , is fed to the input of the high gain DC amplifier. For a detailed description of the controller components refer to Appendix A.

The additional benefit of the rate feedback stabilization is an increase in the bandwidth of the controller frequency response.⁹ The associated reduction in transfer function gain is compensated for by increasing the DC amplifier gain. Larger values of tachometer feedback produce greater bandwidth with the corresponding reduction in the magnitude and in the phase shift for the frequency region of interest.

The transfer function of the Argonaut controller using tachometer feedback stabilization can be shown analytically to have the following form:

$$G_2(s) = \frac{\delta k_R}{\delta n/n_0} = \frac{K_2}{s(1 + 2\zeta T_4 s + T_4^2 s^2)(1 + sT_6)} \quad , \quad (3)$$

where $\omega_4 = 1/T_4$ is the undamped natural frequency and ζ is the damping ratio for the motor-tachometer loop; T_6 is the input filter time constant; and K_2 is the controller gain coefficient.

The measured frequency response for selected values of the controller parameters is given in Figure 4, where curves are normalized by the value of β_T . The asymptotic approximation to the magnitude curve is shown by the dotted lines. The location of the double break-point frequency of the motor-tachometer loop, ω_4 , and the single break-point frequency for the input filter, ω_6 , are indicated. The relative position of the tachometer

FIGURE 4
FREQUENCY RESPONSE OF ARGONAUT FLUX CONTROLLER

feedback potentiometer is indicated by the numbers 2 and 10. Ten represents the position for maximum feedback. It can be seen that increased values of the tachometer feedback produce the following changes in the controller transfer function:

- (1) reduction in the magnitude of the coefficient term, K_2 ;
- (2) lowering of the damping ratio, ζ , with a corresponding reduction of the relative stability of the controller; and
- (3) increase in the motor-tachometer loop undamped natural frequency, ω_4 , resulting in less controller phase shift in the region of frequency interest.

The design calculations for the input circuit and the gain of the controller are contained in Appendix C.

D. Stability Analysis

The stability analysis of the controller design is based upon the reactor response to a sinusoidal perturbation of reactivity while operating at a fixed level of power demand. The power transfer function of the system is defined as the amplitude and phase relation of the power error, $\delta n/n_0$, with respect to the reactivity input disturbance function, δk_D . In terms of the Laplace Transform,

$$P(s) = \frac{\delta n/n_0}{\delta k_D} = \frac{G'_1}{1 + G'_1 G_2} \quad (4)$$

The rearranged block diagram for the system analysis is shown in Figure 5.

FIGURE 5
BLOCK DIAGRAM FOR SYSTEM ANALYSIS

The open-loop system transfer function is the following:

$$G_1'(s)G_2(s) = \frac{\delta k_R}{\delta k_N} = \frac{K_1 K_2 \prod_{i=1}^6 (1 + sT_i)}{s^2 (1 + 2\zeta T_4 s + T_4^2 s^2) (1 + sT_6) \prod_{j=1}^6 (1 + sT_j)} \quad (5)$$

Assuming that the controller loop remains stable, the denominator does not contain any positive real roots and there are no poles of the transfer function inside the right half of the complex frequency plane. Therefore, in terms of the Nyquist Stability Criterion, the controller will be stable if the locus of the open loop gain, $G_1'G_2$, plotted in the complex frequency plane, does not encircle the point $(-1,0)$.⁹ In terms of the attenuation-phase (Bode) diagrams, stable operation will exist if the open-loop magnitude, $|G_1'(s)G_2(s)|$, reaches the value of unity before the phase shift reaches the value of 180 degrees.

A plot of the open-loop frequency response for an arbitrary selection of the controller parameters is shown in Figure 6. The margin for increasing the gain or phase shift and maintaining absolute stability is indicated. For the conditions given, if the controller gain is increased greater than 14.5 db, without changing the indicated phase shift of the controller, the system will break into uncontrolled oscillation.

FIGURE 6
FREQUENCY RESPONSE OF SYSTEM OPEN LOOP

It is not only desirable to know if the system is absolutely stable, but it is also important to know the degree of relative stability. In terms of a step input disturbance function, it is necessary to know if the system will have a highly under-damped, a critically damped or a heavily-damped response. For a single-loop control system with unity feedback, considerable data has been published in the literature on feedback control systems correlating the frequency response phase margin and transient response damping ratio.^{9,10,11} Since the feedback in the Argonaut automatic flux control system is the controller transfer function, the information concerning unity feedback systems does not apply. As a guide in controller design, experience to date has shown that satisfactory controller operation is obtained when the phase margin is about 60 degrees.³ In this report, correlative data on transient and frequency response for one type of reactor and controller design is obtained from the measured power responses.

The stability criterion for the automatic flux control system was established on the basis that Eq. (5) does not contain any positive real roots. Since the controller is a negative feedback device, the possibility for an unstable condition exists. To prevent the roots of the $(1 + 2 \zeta T_4 s + T_4^2 s^2)$ term of the controller from appearing in the right half of the complex frequency plane, the design of the tachometer feedback circuit provides an upper limit for the magnitude of the feedback voltage, δt (refer to Appendix C).

E. Control Accuracy

In addition to providing the requirements for stable operation of the controller, it is necessary to insure that the control will be performed within the desired limits of accuracy. The power-to-reactivity transfer function was defined by Eq. (4). Referring to Figure 6, in the frequency region below the cross-over frequency, ω_3 , the open-loop gain, $G_1^1 G_2$, is greater than unity (0 db). The value of the power transfer function can therefore be approximated as

$$P(s) \approx 1/G_2 \quad . \quad (6)$$

For very low frequencies, where $G_1^1 G_2 \gg 1$, the approximation is accurate and the power is equal to the inverse of the feedback transfer function, G_2 . In this frequency region, G_2 for the controller is equal to K_2/s . Therefore, in the low-frequency region,

$$P(s) = s/K_2 \quad , \quad (7)$$

¹⁰H. Chestnut and R. W. Mayer, Servomechanisms and Regulating System Design, J. Wiley and Sons, Inc., New York (1951) Vol. I.

¹¹J. G. Truxal, Automatic Feedback Control System Synthesis, McGraw-Hill Book Company, Inc., New York (1955).

indicating that the magnitude of sinusoidal power variations is directly dependent upon the frequency of disturbance and indirectly dependent upon the magnitude of the controller gain coefficient.

Thus, to provide greater accuracy of control, the "tightness" of the system is increased by increasing the gain of the controller. The upper limit for the controller gain is bounded by the consideration for the relative stability requirement of the design.

III. Performance Measurements

The performance of automatic flux control on a nuclear reactor requires that certain preliminary safety precautions be observed. For a discussion of these considerations, refer to Appendix B.

A. Power Frequency Response

To obtain the frequency response, the reactor power is oscillated sinusoidally about the fixed level of approximately 100 watts by means of a specially constructed cadmium rod placed in the central opening of the internal thermal column.^{12,13} The peak value of the sinusoidal reactivity disturbance is 0.03% δk . The power oscillations are obtained by reading the current output of an ionization chamber suitably located in the reactor to read the average power variation.

The measured data for several values of the controller parameters are plotted in Figure 7. The adjustable tachometer-feedback potentiometer was set for four different positions. The power frequency response for each position is indicated in the figure. The solid line curve represents the power frequency response of the reactor without the controller in operation.

The accuracy of control established by the design specification was that $\delta n/n_0$ be less than 1% peak with sinusoidal reactivity input peak value of 0.03% δk at $\omega = 1$ rad/sec. In percentage figures,

$$\frac{\delta n}{n_0} = 0.03 \left| \frac{\delta n/n_0}{\delta k} \right|_{\omega=1} < 1\% \quad (8)$$

¹²G. S. Pawlicki, ANL International Institute of Nuclear Science and Engineering Experiment, Measurement of the Transfer Function of the Argonaut, (April 14, 1958).

¹³R. H. Armstrong et al., Argonaut Engineering Construction and Cost, ANL-5704 (March 1957).

The measured accuracy of control, phase and gain margins, and the magnitudes of the peak power response and the frequency where the peak occurs for selected settings of the tachometer feedback potentiometer are tabulated in Columns 1 through 5 of Table I.

FIGURE 7
POWER FREQUENCY RESPONSE

Table I

TABULATED PERFORMANCE DATA

Tachometer Feedback Potentiometer Setting	1	2	3	4	5	6	7	8
	POWER FREQUENCY RESPONSE					POWER TRANSIENT RESPONSE		
	Accuracy of Control ^b $\frac{\delta n}{n_0} (\%)^a$	Phase Margin, Degrees	Gain Margin, db	Peak Power Response		Power Oscillation		
				Magnitude, ^c db	Frequency, rad/sec	Peak Magnitude, $\frac{n_0 - n}{n_0} (\%)^a$	Settling Time, ^d sec	Type of Damping
2.0	0.53	58	11.4	2.90	9.0	3.96	0.79	Under
4.0	0.62	60	12.5	2.68	9.2	3.96	0.35	Slightly Under
5.0	0.67	63	13.8	2.36	9.8	3.96	0.39	Critical
10.0	0.87	75	16.5	1.00	11.8	3.96	0.95	Over

^aThe peak amplitude of sinusoidal and step-input reactivity disturbances used to obtain the above data was 0.03% δk .

^bBased upon the design specification frequency of $\omega = 1$ rad/sec (see Eq. (8))

^cMeasured from the normalized magnitude of zero decibel.

^dTime required to return power to $\pm 0.5\%$ of initial power level of 100 watts.

B. Power Transient Response

To establish a measure of the relative stability of the automatic flux control system, a step input of negative reactivity was approximated by permitting a rapid drop of the fine control rod. The fine control rod calibration curve was used to establish a rod drop interval equal to a negative 0.03% δk . The recorded transient response for the selected parameter values is plotted in Figure 8. The peak power excursion measured in terms of percentage of the steady-state value is tabulated in Column 6 of Table I; the time required for the power to return to $\pm 0.5\%$ of the initial value (settling time) is given in Column 7. In Column 8, the degree of damping is recorded.

C. Correlation of Frequency and Transient Response

From the data in Table I, it can be seen that for the system to have a slightly under-damped power transient response, the frequency response phase margin should be 60 degrees. A 63-degree phase margin would result in a critically damped power transient response. A phase margin greater than 63 degrees would exist in a system which is over damped and a phase margin less than 63 degrees in a system which is under damped.

A qualitative measure of the relative stability of the automatic flux control system can be obtained by an inspection of the power frequency response. With reference to Figure 7, it can be observed that a smooth

FIGURE 8
POWER TRANSIENT RESPONSE

roll-off from the $P(s) = 1/G_2(s)$ curve to the $P(s) = G_1'(s)$ curve results in the case of the over-damped response. For the under-damped system, the power frequency response curve rises rather sharply from the $P(s) = 1/G_2(s)$ curve and has a relatively narrow peak in returning to the $P(s) = G_1'(s)$ curve. As the degree of system damping decreases, the peak power variation increases and the frequency at which the peak occurs is decreased.

IV. Conclusions

The automatic flux controller applied to a training-research reactor, such as the Argonaut, provides a valuable pedagogical tool for demonstrating the effect of a negative coefficient of reactivity feedback on the power response of a nuclear reactor. The indirect technique of obtaining the power-to-reactivity feedback transfer function through a $1 + GH$ transformation plane can be studied and the degree of accuracy of the method established.

In addition, the equipment provides a practical means of demonstrating the important aspects of nuclear flux control design. The considerations for stable operation and accuracy of control are readily observed. A correlation between power frequency response and power transient response demonstrates that an automatic flux control system will have the generally desired relative stability when the phase margin is 60 degrees.

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*On loan from Allis-Chalmers Company

APPENDIX A

EQUIPMENT DESCRIPTION

The equipment assembly for the Argonaut automatic flux control is pictured in Figure 10, showing the controller actuator and the control panel rack. The schematic wiring diagram for the equipment is shown in Figure 9. A detailed description of the components is given below.

A. Controller Rod Actuator

The controller rod actuator is located in the #10 horizontal stringer opening of the external thermal column.¹³ The end of the rod actuator containing the neutron-absorbing material is placed in close proximity with the shroud of the coarse control rod. The remainder of the opening is filled with sectors of graphite reflector notched at the corners to receive the control cabling.

Figure 11 shows the construction details of the controller rod actuator. The rod is circular in shape and consists of two 180-degree sectors of cadmium - one fixed and the other movable. Both sectors are $3\frac{3}{4}$ in. in diameter and $\frac{1}{32}$ in. thick. The rotating sector is mounted on a $3\frac{3}{4}$ -in. diameter by $\frac{1}{8}$ -in. thick aluminum disk mounted on a $\frac{1}{4}$ -in. diameter shaft. The fixed sector is attached to a $3\frac{7}{8}$ -in. square, $\frac{3}{8}$ -in. thick clear plastic frame machined to receive the aluminum disk and attached to the end of a $3\frac{7}{8}$ x $3\frac{7}{8}$ x 12-in. graphite reflector by 4 mounting screws.

The rod shaft is driven by a 115-volt, 60-cycle, two-phase induction type servomotor with a rated 5-watt output. A gear box is used to produce a net speed reduction of 40 to 1 between motor shaft and rod shaft. The maximum rated no-load speed of 3580 rpm for the two-phase motor reflected through the 40-to-1 gear reduction produces saturation at a rod shaft speed of 89.6 rpm.

The rotor of a 60-cycle selsyn transmitter is connected to the rod shaft by a 1-to-1 gear ratio and is used for remote indication of rotor shaft position. Also connected to the rotor shaft is a circular right angle cam mounted on a $1\frac{3}{4}$ -in. gear. The cam is used to operate the Rod Travel Limit switch. The gear can be used to operate a potentiometer (mounted temporarily in the position occupied by the selsyn) when the controller rod is used with a reactor kinetics simulator.

A DC tachometer is connected to the shaft of the servomotor by means of a 4-to-1 speed-reduction gearing. The output of the tachometer is used to provide the required kinetic damping of the amplifier-motor loop.

FIGURE 10
ARGONAUT FLUX CONTROLLER ASSEMBLY

FIGURE II
CONTROLLER ROD ACTUATOR

A ten-turn 500-ohm potentiometer is used in a voltage divider circuit to control the magnitude of the tachometer feedback voltage within the limits required for stable operation of the controller (see Section II-D and Appendix C). A resistor and rectifier are mounted adjacent to the tachometer. In automatic control, the resistor and rectifier are used in conjunction with the Rod Travel Limit switch, S-3, to provide dynamic braking action when the switch is operated. Operation of the switch occurs when the cam rotates ± 110 degrees from the mean operating position (indicated at 270 degrees) and the follower rolls off the cam. In manual control, the rectifier and resistor are used with the Manual Rod Control switch, S-2, to obtain the braking action. Control cable leads are connected to three terminal strips mounted at the rear of the controller rod actuator.

The ability of this type of rod construction to produce the required reactivity change was established by preliminary static tests conducted on a mock-up which simulated the rod design. The triangle points in Figure 12 show the results of one set of measurements taken by the rod drop-period measurement method with the reactor at approximately a 10-watt power level. The measured reactivity change was $\pm 0.043\%$ δk about

the mean rod position of 270° . The circled points in Figure 12 are the measured controller rod reactivity variation taken with the controller rod actuator in operation on the reactor. These points were obtained by exchanging reactivity between the controller rod and the fine control rod. The dynamic reactivity worth is based upon the fine control rod calibration curve. The controller rod transfer function is thus $\delta k_R / \theta_R = 2.73 \times 10^{-4} \delta k / \text{rad}$. The static reactivity worth of the controller rod was established by first reading the fine control rod position with a clean reactor critical at a 1-watt power level. Then, after dropping the fine rod, the controller rod was inserted and the reactor returned to criticality at the original power level. The difference in the fine control rod positions read on the fine rod calibration curve established the static worth of the controller rod in its mean position to be equal to $0.32\% \delta k$.

FIGURE 12
CALIBRATION CURVE FOR CONTROLLER ROD

B. Ionization Chamber

The neutron flux is detected with a parallel-plate-type B^{10} -coated ionization chamber. The measured impedance of the chamber with 500 volts across the plates is 3×10^9 ohms. The location chosen for the chamber is the spare control rod pocket of the reactor.¹³ Initial consideration was given to the #8 and #12 horizontal stringer openings in the external thermal column. However, the results of preliminary static reactivity tests using a mock-up of the controller rod indicated that considerable rod shadowing of the ion chamber would occur at these locations.

With the ion chamber located in the spare control rod pocket and the reactor critical at a power level of 100 watts, the measured chamber

output is 5.7×10^{-6} amp. The chamber is operated with +500 volts across the plates obtained from a regulated power supply rated at less than 50-millivolt change from no load to full load. The ripple voltage of the output is less than 500 microvolts.

C. Control Panel Rack

The control panel rack contains a 60-cycle receiver selsyn mounted on the upper panel and used to provide remote indication of the controller rod position. A magnetic amplifier with its associated control circuit and switches is mounted on the panel below the Rod Position Indicator Panel. Figure 13 gives the details of construction for the Rod Control Panel, pointing out the location of the magnetic amplifier and the control switches.

The input signal to the magnetic amplifier is attenuated by the Input Level control in order that the pre-amplifier will reach saturation slightly before the magnetic amplifier. For the particular magnetic amplifier used in this controller, saturation is reached when the input voltage is 28 v DC from grid to grid on the control circuit triodes.

The Balance control is used to adjust for equal quiescent current flow through both halves of the magnetic amplifier input circuit. The magnitude of this current is adjusted to the manufacturer's recommended 5 mamp by means of the Bias control.

Front panel controls include a Main Control switch, SW-1, for transfer from Off to either the Manual or Automatic operation. In the Manual position, a jogging switch, Manual Rod Control, SW-3, is available for movement in either the $+\delta k$ or $-\delta k$ direction. A Limit Reset switch, SW-4, is provided to recover rod control after the cam-actuated Limit Trip switch, SW-3, has been operated.

The power-error signal measured at the output of the high-gain pre-amplifier is indicated on the meter mounted on the Power Control Panel shown in Figure 14. Controls are available for adjustment of meter balance and sensitivity. The sensitivity of the 50-0-50 microampere meter is adjusted to read 1 to 1 with the pre-amplifier output voltage.

Front panel control of power in the range of 80 to 120 watts is available by means of the Power Demand Level control. The Power Demand Set control is also part of this circuit. It is adjusted to provide - 1.5 volts across the input terminals of the high gain pre-amplifier when the DC voltage at the terminal marked #11 is -20 v DC and the ion chamber current has zero value. The -20 v DC is obtained by adjustment of the bias control on the DC power supply. A 0.01-mfd capacitor is used with 2-megohm resistors

FIGURE 13
ROD CONTROL PANEL

FIGURE 14
POWER CONTROL PANEL

to provide the desired low-pass filter network. A ten-turn, 500-ohm precision potentiometer is used to control the degree of damping provided in the amplifier motor loop. The potentiometer is adjustable to provide closed-loop reactor power response ranging from over damped to under damped conditions. The details of this input circuit is described in Appendix C.

The high-gain pre-amplifier used in the controller is a chopper-stabilized DC amplifier with a 1-megohm input impedance and an output that delivers ± 20 mamp maximum current to the load resistors. The input attenuator is set on the 2-mv/line position, thus providing a total voltage gain of 455 for the high-gain pre-amplifier.

The power supply used for both the ion chamber voltage and the negative DC voltage of the power demand circuit is mounted on the lower part of the control panel rack. The main line switch with 20-amp fuse protection and power-on pilot lamps are contained on the lower panel mounted directly above a cooling air intake filter and blower assembly.

APPENDIX B

SAFETY CONSIDERATIONS

In addition to the considerations for the stable operation of the automatic flux controller, there are two safety problems that are apparent: (1) management of the static reactivity; and (2) control over the variable reactivity.

The measured static reactivity worth of the controller rod in its mean position is 0.32%; the oscillator rod in its mean position is worth 0.28% and the two ion chambers 0.06%. If the fuel loading is limited to 0.7% above the clean reactor, only 0.04% available excess reactivity remains to put the reactor on a positive period. The 0.7% excess reactivity is less than the limit set at 0.75% in the Hazard Report.¹⁴ Padlocking the oscillator and the stringer in which the controller rod is located and locating the chambers beneath the reactor top shield provides the assurance that the Argonaut Supervisor has administrative control of the excess fuel loading.

To take the reactor up to power on a reasonable period, the controller rod and the reactivity oscillator are displaced to positions of positive reactivity relative to their mean reactivity positions. It is necessary to guarantee that this positive reactivity change is within safe bounds. The nature of the design of the controller and the reactivity oscillator do not permit an increase in the amount of cadmium because of physical space limitations. The rotating control elements employed preclude any possibility of getting positive reactivity changes greater than the design values of $\pm 0.03\%$ for the reactivity oscillator and $\pm 0.043\%$ for the controller rod.

A malfunction of the control system leading to in-phase oscillations of the controller and the reactivity oscillator combined could not result in a total reactivity oscillation of amplitude more than 0.073%. This is a perfectly safe amplitude for a reactor oscillation test and would not produce any transient period indications sufficient to give a false period scram on the Argonaut period meter circuit. A failure of the automatic control rod drive and the reactivity oscillator drive which would cause both elements to stop so as to introduce the maximum reactivity of 0.073% into the system would not cause a serious period.

¹⁴D. H. Lennox and C. N. Kelber, Summary Report on the Hazards of the Argonaut Reactor, ANL-5647 (1956).

APPENDIX C

DESIGN CALCULATIONS1. Input Circuit

The controller input circuit consists of all of the networks between the output of the ionization chamber and the input to the high-gain DC amplifier. Included in this circuit is an RC filter used to reduce the noise content of the ionization chamber current, a current source used to "cancel out" the DC component of the chamber current, and a current source for tachometer feedback stabilization.

With the ionization chamber located in the space control rod opening and the Argonaut reactor operating at the indicated power level of 100 watts, the measured output of the chamber with 500 volts across the electrodes is 5.7×10^{-6} amp. To provide the required stable control over the range from 80 to 120 watts, a Power Demand Level potentiometer is used in a circuit designed on the universal or Ayrton shunt principle. The potentiometer circuit compensates for the nonlinearity of reactor gain as the operating power level is varied by providing essentially a $1/n_0$ control over the adjustable power range. The circuit is designed so that the wiper arm of the 0.5-megohm Power Demand Level potentiometer is at the center position when the reactor is operating at 100 watts.

The 40,000-ohm Power Demand Set potentiometer connected across a negative 20-volt DC power supply is wired as the "bucking" current source through application of a 3-megohm resistor in series with the wiper arm of the potentiometer (refer to Figure 9). The parallel combination of the 3-megohm and 1-megohm input resistors results in a 0.75-megohm net impedance. A value of 12 volts was arbitrarily set as the power demand reference. With the Power Demand Level control in the mid position the shunting arm resistance can be computed as follows:

$$I_{3\text{meg}} = \frac{12}{3 \times 10^6} = 4 \times 10^{-6} \quad ; \quad I_{\text{input}} = 5.7 \times 10^{-6} \text{ amp}$$

$$E_{1\text{meg}} = 0 \quad .$$

Then the voltage across the upper half of the Power Demand Level potentiometer is:

$$E = (0.25 \times 10^6)(4 \times 10^{-6}) = 1 \quad .$$

This same voltage also appears from the arm of the Power Demand Level potentiometer to ground, and the resistance from the bottom of the potentiometer to ground is:

$$R = \frac{E}{I_{in} - I_{3\text{meg}}} - 0.25\text{meg} = \frac{1}{(5.7-4) \times 10^{-6}} - 0.25\text{meg}$$

$$= 0.588 - 0.25 = 0.338 \cong 0.33\text{meg} \quad .$$

To provide tachometer feedback stabilization current, the voltage output of the DC generator is "tapped" by means of a voltage divider circuit consisting of a fixed 510-ohm resistor in series with a 500-ohm, ten-turn potentiometer (Tachometer Control) and a fixed 20,000-ohm resistor. The wiper arm of the tachometer potentiometer is connected to the shunting arm of the Ayrton shunt circuit. The selection of the resistance values used in the voltage divider circuit was made on the basis of the test results obtained using the reactor kinetics simulator. The resistors selected restrict the magnitude of the tachometer feedback voltage between the upper and lower boundary values which would result in self-sustained oscillations. The gain of the controller can be adjusted between the upper and lower limits by positioning the tachometer potentiometer through its full range of value. The closed-loop reactor power transient response is thereby adjustable from the condition of over damped to under damped response.

The input circuit filter consists of a 0.01-microfarad condenser and a pair of 2-megohm resistors placed between the collector electrode of the ionization chamber and the wiper arm of the Power Demand Level Control. The break point frequency of the RC filter is measured at $\omega_6 = 100 \text{ rad/sec}$ (see Figure 4).

2. Controller Gain

The magnitude of the controller gain is established by the magnitude of the open-loop reactor gain at the desired cross-over frequency (ω_3 in Figure 6). For the condition where $\omega_3 = 4 \text{ rad/sec}$, there is obtained $G_1'(s) = +43.7 \text{ db (absolute)}$. Since $G_1'(s)G_2(s) = 1$ (zero db) at the cross-over frequency, then,

$$G_2(s) = 1/G_1'(s) = -43.7 \text{ db (absolute)} \quad . \quad (1)$$

In the frequency region under consideration, the controller gain attenuates at the rate of 20 db/decade. Thus at $\omega = 1 \text{ rad/sec}$, the controller is

$$G_2(s) = \frac{\delta k_R}{\delta n/n_0} = K_2 = (-43.7 + 12.6)\text{db} = -31.1\text{db} = \frac{1}{35.5} \quad , \quad (2)$$

which in terms of reactivity rate is

$$\delta k_R = \left(\frac{1}{35.5} \times \frac{\delta n}{n_0} \right) \delta k/\text{sec} \quad . \quad (3)$$

To establish the preliminary adjustment of the controller parameters in order to obtain the desired reactivity rate, the controller is operated at a constant speed by removal of the electrical circuit that restricts the rod travel and applying a fixed error signal to the input.

The power-error signal can be assumed to have the approximate value determined by the magnitude of the open-loop reactor power frequency response at the cross-over frequency, or

$$\delta n/n_0 = \frac{1}{\beta_T} \times \delta k = \frac{1}{0.0065} \times \frac{0.0003}{1} = 0.0459 \quad . \quad (4)$$

For $n_0 = 5.5 \times 10^{-6}$ amp, there is obtained $\delta n = 0.253 \times 10^{-6}$ amp. Substitution of $\delta n/n_0$ into equation (3) yields

$$\delta \dot{k}_R = 0.0459/35.5 = 0.00132 \text{ } \delta k/\text{sec} \quad . \quad (5)$$

From the measured rod data (see Appendix A),

$$\delta k_R = (2.83 \times 10^{-4}) \theta_R \quad . \quad (6)$$

In terms of reactivity rate, $\omega = 1 \text{ rad/sec}$,

$$\delta \dot{k}_R = (2.83 \times 10^{-4}) \dot{\theta}_R$$

or

$$\begin{aligned} \dot{\theta}_R &= \frac{10^4}{2.83} \times \delta \dot{k}_R = \frac{10^4}{2.83} \times \frac{13.2}{10^4} \\ &= 4.65 \text{ rad/sec} \quad . \end{aligned} \quad (7)$$

To obtain a measure of the required reactivity rate, the tachometer output is recorded. The magnitude of the tachometer voltage for the desired output with the input signal of $\delta n = 0.253 \times 10^{-6}$ amp is

$$\begin{aligned} \delta_t &= 10 K_T \dot{\theta}_R = \frac{10}{1} \times \frac{1}{15} \times \frac{4.65}{1} \\ &= 3.1 \text{ volts} \quad , \end{aligned} \quad (8)$$

where K_T is the tachometer constant in terms of volts per radian per second and the factor 10 is the gear ratio between the rod shaft and tachometer shaft.

The final value for the controller parameters is obtained by operating the controller equipment in closed-loop with the reactor kinetics simulator.