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A NUCLEAR REACTOR SIMULATOR FOR TEACHING PURPOSES

L. Orr, W. Kerr, and H. J. Gomberg

University of Michigan, Ann Arbor, Michigan

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Abstract

The nuclear power reactor furnishes an excellent illustration of many of the principles and problems involved in the field of Nuclear Engineering. The dynamics of a system which incorporates a reactor as a heat source can be treated very successfully by the use of an analog computer or simulator.

A portable electronic reactor simulator suitable for teaching purposes has been constructed. Its design and operation are discussed.

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Investigation of Reactor Power Plant Systems.

Perhaps the most interest provoking situation in which controlled nuclear reactions are used in an engineering application is in the nuclear power reactor. This application is a good one for teaching purposes, because it illustrates several types and complexities of nuclear measurement. The larger problem of correlating these measurements with measurements of temperature, flow, etc., and using this information to control the reactor is also worth considerable study.

The nuclear power reactor is part of an integrated system in which a nuclear reactor serves as a source of power, say in a steam-electric generating station. The problem has several interesting facets, that of reactor control, that of the control of the steam-electric part of the system, and the overall problem of determining the dynamic behavior of the integrated complex.

In Figure 1 is shown a block diagram of a possible simplified arrangement of such a system. The numbers indicate:

(1) Reactor.

(2) Control Rod Drive.

(3) Transducer, Error Signal to Control Rod Drive.

(4) Neutron Measuring Device.

(5) Comparator.

(6) Heat Transfer, Reactor Core to Coolant.

(7) Heat Exchanger, Reactor Coolant to Steam.

(8) Turbine.

(9) Electric Generator.

(10) Coolant Temperature and Flow Measuring Device.

(11) Steam Temperature and Flow Measuring Device.

(12) Power Demand Input.

Using the appropriate unclassified literature and reasonable engineering approximations a set of equations can be written to represent the flow of energy and information in the system.[1,2,3] Two items are of primary concern: nuclear kinetics in the reactor itself, and heat transfer in the reactor and the heat exchanger. In addition, since most reactors are designed in such a way that the reactivity is a function of temperature, the interrelationship of the two must be established.

Investigation shows that because of this relationship between reactivity and temperature the system has many of the characteristics of a feedback amplifier. It can thus be treated analytically by the well developed techniques that are available for the analysis of feedback amplifiers and automatic control systems. In most cases of interest the reactor kinetic equations are non-linear, hence the additional interesting problem of treating non-linear differential equations is introduced.

Several useful approaches to the problem are available. One of these involves linearization of the equations, and a

1 Superscripts refer to references at end of paper.

subsequent application of the linear theory of feedback systems, such as the Bode diagram type analysis, to investigate system stability.[4] This approach is interesting not only because it leads to useful results in this situation, but because it is so widely applicable to problems in the automatic control of large systems.

The effect of the non-linearity may also be treated, and appropriate unclassified publications are available.[5,6] Again the method of treating the problem may be much more generally applicable than to this specific situation.

Analog Computers

As an alternative or as a supplement to the analytical approach it may be desirable to use an analog computer or reactor simulator to study system performance. The use of the simulator allows the non-linearity of the system to be treated with facility. The simulator also allows easy and rapid variation of system parameters, and exhibits the changes in system performance which result therefrom.

An important advantage of an analog computer is that as one observes solutions developing on the recorder an intuitive "feel" for system performance is developed. This may be much more difficult to acquire from a purely analytical treatment.

The simulator which is used to treat the reactor-power-plant study can be either very elaborate or fairly simple. Although the simpler types have less precision, they have the advantages of compactness, portability and low cost. They serve admirably as demonstration units for teaching purposes.

Portable Unit.

A portable reactor simulator has been constructed at the University of Michigan which is of sufficient accuracy for teaching purposes. The equations simulated are, using the notation of Bell & Straus,[7]

$$dN/dt = (\delta k_{eff}/k l^{*})N - (\beta/l^{*})N + e^{\tau\Delta}\sum_{i}\lambda_i C_i + \frac{(T-T_o)K_1}{k}N + S. \qquad (1)$$

$$\frac{dC_i}{dt} = -\lambda_i C_i + (e^{-\tau\Delta}/l^{*})\beta_i N. \qquad (2)$$

$$Q = M\frac{dT}{dt} + W(T-T_C) \qquad (3)$$

Here in addition to the symbols defined by Bell & Straus:

T = temperature of the point reactor.

T_o = reference temperature of reactor.

T_C = average coolant temperature.

K_1 = temperature coefficient of reactivity.

Q = reactor heat output, directly proportional to .

M = thermal capacity of reactor.

W = heat transfer coefficient from reactor to coolant.

Basic Circuit.

The basic circuit used to simulate the reactor proper is essentially that of Bell & Strauss. This circuit is an analog of the one group, thermal point reactor equation. Five neutron delay groups are included.[8]

In addition, the effect of temperature rise in the reactor caused by increased activity is also simulated. The position of the control rods, or δk_{eff}, the coolant flow rate, the "source" magnitude and the temperature coefficient of reactivity, K_1, are under the control of the operator from the front panel.

A block diagram of the circuit is shown in Figure 2. A push-pull high gain dc amplifier, A, is connected as an integrator with feedback capacitor C_1. The output voltages +N and -N are proportional to the time integral of the input current $\sum i$, while the input voltage remains substantially constant. The panel voltmeter V_n indicates the neutron flux N at any instant. A current source i_o simulates the production of prompt neutrons, the rate being determined by the setting of the δk_{eff} control and the level of N.

Current sources $i_1 \ldots i_5$ represent the delayed neutrons, and the time constants of the delay networks, $\Delta_1 \ldots \Delta_5$, are set equal to the mean lives of their precursors. The time constants are fixed at the values: 0.62, 2.20, 6.52, 31.6 and 80.2 seconds. The delay fraction of each source is adjustable individually. The total delay fraction or per cent of delayed neutrons represents about 0.75 per cent of the total neutron production under steady-state conditions. There is a primary fixed source i_s which is independent of level N, but which is manually adjustable. A current K_1NT is also added to the integrator input representing the effect of temperature on reactivity.

The loss due to neutron absorption and diffusion through the reactor walls is given by i_d. This current is proportional to the level N. The sum Σi of all currents including the negative current i_d denotes the excess neutron production and determines the rate of change of reactivity. When $\Sigma i = 0$ for example, the reactor neutron population is constant.

A current proportional to the +N voltage is fed to a capacitor C. This represents the heat input to the reactor, and C represents its thermal capacity. A control simulating the coolant flow rate, determines the current flow rate out of capacitor C, and represents the rate of removal of heat from the reactor by the coolant. It is assumed that heat loss by radiation and conduction is small compared to that removed by the coolant. The voltage V_t on this capacitor represents the mean reactor temperature and is indicated by the panel voltmeter V_t.

As mentioned above, the effect of temperature variation on the reactor is obtained by feeding an additional source of neutrons K_1NT to the integrator input. K_1 is the temperature coefficient of reactivity, and is negative in practical controlled reactors. Thus the current contribution is actually negative. Since this contribution is proportional to the product of flux level N and temperature T, an electronic multiplier M is used to obtain the required product. The output of the current generator K_1 in the diagram is the required current, and is added to the integrator input. The magnitude of temperature coefficient of reactivity K_1 is under

the control of the operator.

Circuit Details.

The circuits used to accomplish the desired result are grouped into two sections. The first section contains the prompt and delayed neutron sources, the source balance control, the δk_{eff} control, the electronic integrator and the N meter. The circuitry associated with this section is quite similar to the original Bell & Straus[7] circuit, except that the δk_{eff} control is equipped with a vernier adjustment.

The second section contains the temperature circuit, coolant flow rate control, T meter, the N voltage converter, electronic multiplier and the K_1 control.

Temperature Circuit and Coolant Flow Rate Control.

Figure 3 is a simplified version of the temperature circuit showing the coolant flow rate control and T meter. The current i_1 represents the heat generated in the reactor, and this flows into capacitor C_{100} representing the thermal capacity of the reactor. This current is proportional to the voltage difference between the +N voltage, and the capacitor voltage which is always small compared to +N. The current i_2 flowing out of C_{100} through R_{102} and R_{104} represents the heat removed by the coolant, and this is proportional to the capacitor voltage. The capacitor voltage represents the mean reactor temperature and is indicated by the meter T. Spatial variation of temperature throughout the volume of the reactor is not represented in this simulator, since a point reactor is simulated.

When the net capacitor current $i_1 - i_2$ is zero, the mean reactor temperature remains constant. Changing the setting of the coolant flow rate control, R_{104} varies the current i_2, representing a change in the coolant flow rate, and upsets the temperature stability, until a new stable point is established.

To give a suitable output to the electronic multiplier, an adjusted T voltage is required. This is furnished by the tap on R_{106}. For the temperature corresponding to the stable shutdown value, this control is adjusted to give an adjusted T voltage of -8.0 volts.

N Voltage Converter

The N voltage converter is a 330 kc Hartley oscillator. This is shown in Figure 4 at the left side. The N voltage is decoupled, and used as the B+ supply voltage to the oscillator. The circuit constants and bias values are so arranged that the amplitude of the oscillator output is approximately proportional to the N voltage over a fairly wide range of values, as indicated by the curve in Figure 5. This converted N voltage is used to feed the N input of the electronic multiplier.

Electronic Multiplier

The product NT is required for simulating the effect of temperature upon reactivity. The circuit performs this by generating a source of "negative" neutrons proportional to K_1NT as described above. Since K_1 is generally negative in actual reactors, the current K_1NT is bled off from the integrator input, as indicated in the block diagram, Figure 2.

The circuit performing the multiplication is accurate to several per cent over the range of useful operation, which is satisfactory for demonstration purposes, but perhaps not adequate for accurate analog computation. It is based on the principle that certain variable gain tubes have a transconductance vs grid voltage curve closely approximating a straight line. The 6SK7, operated at a fixed screen voltage of 100 volts gives an almost straight line relationship between transconductance and control grid voltage in the region of control grid voltages from -8 to -2 volts. The circuit in Figure 4 shows the method of obtaining zero gain at e_c = -8 volts by adding the neutralizing resistor R_{117}.

The converted N voltage is fed to the grid of the 6SK7 through C_{109}, while the adjusted T voltage, which is the grid bias, is fed in through R_{113}. The plate load is a resonant tank tuned to oscillator frequency, and the output is taken from the 6SK7 plate. This output is zero for e_c = -8v., and for other values it is proportional to the product NT.

The multiplier output is rectified, and fed to a dc amplifier and inverter stage having as its output a current proportional to K_1NT. The multiplier response is indicated in Figure 6 for three values of N voltage. The output current is negative for a negative setting of K_1 which is the normal mode of operation, and this current is drawn from the integrator input as described above.

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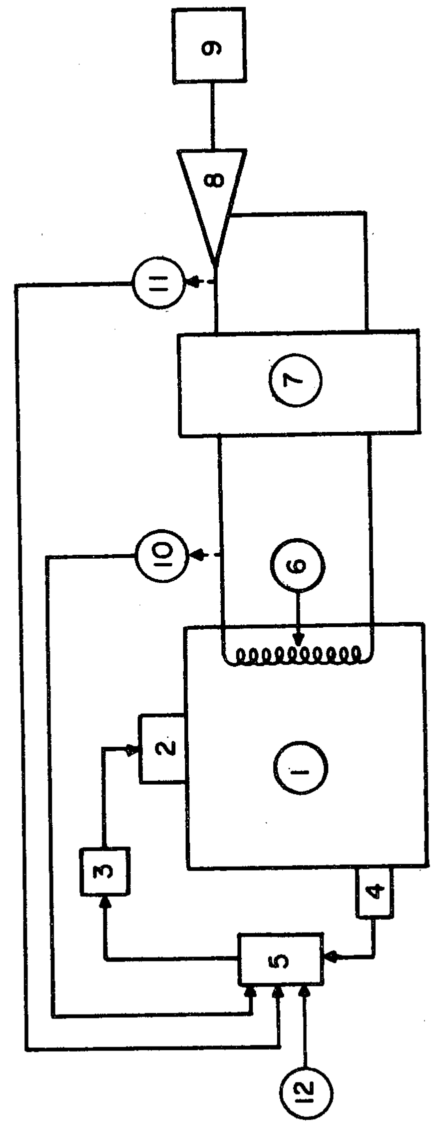

FIG. I BLOCK DIAGRAM, REACTOR POWER PLANT

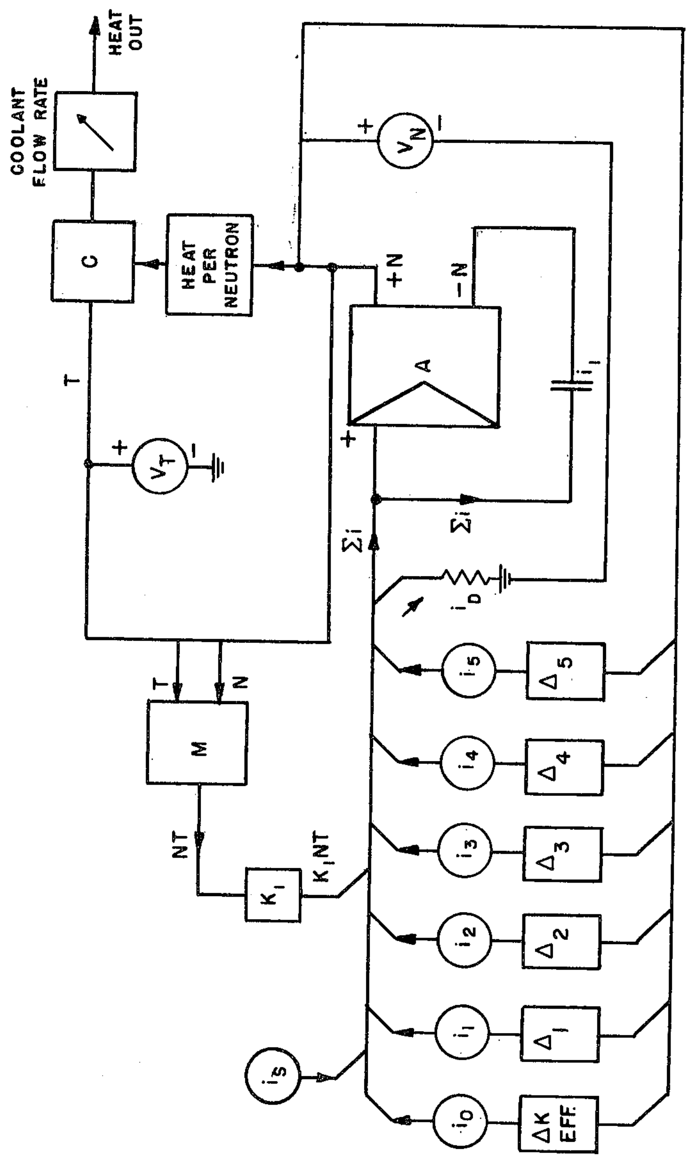

FIG. 2

BLOCK DIAGRAM OF REACTOR SIMULATOR

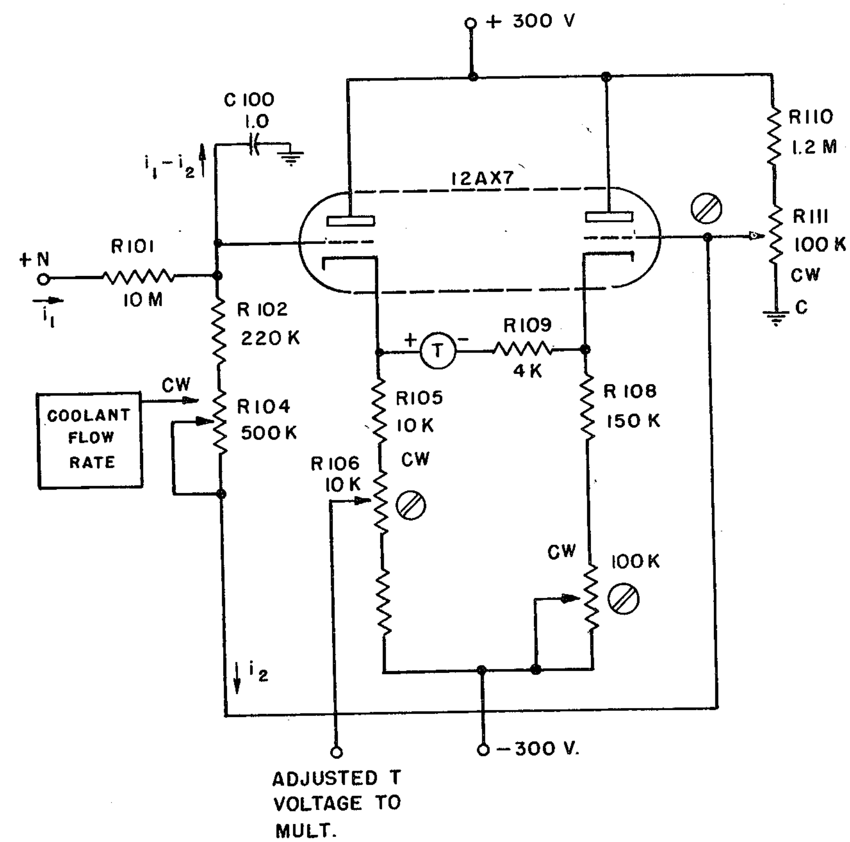

FIG. 3

TEMPERATURE CIRCUIT AND COOLANT FLOW RATE CONTROL

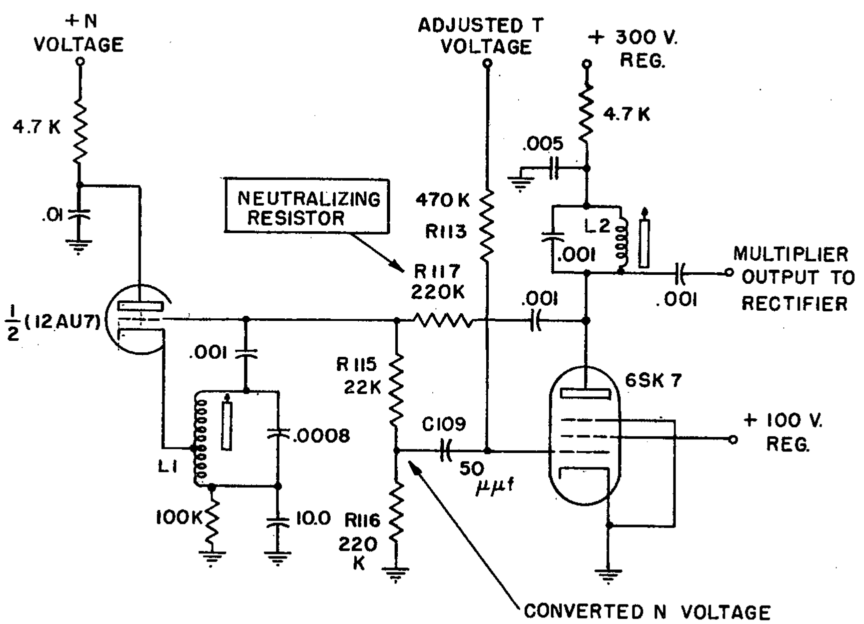

FIG. 4
N VOLTAGE CONVERTER AND
ELECTRONIC MULTIPLIER

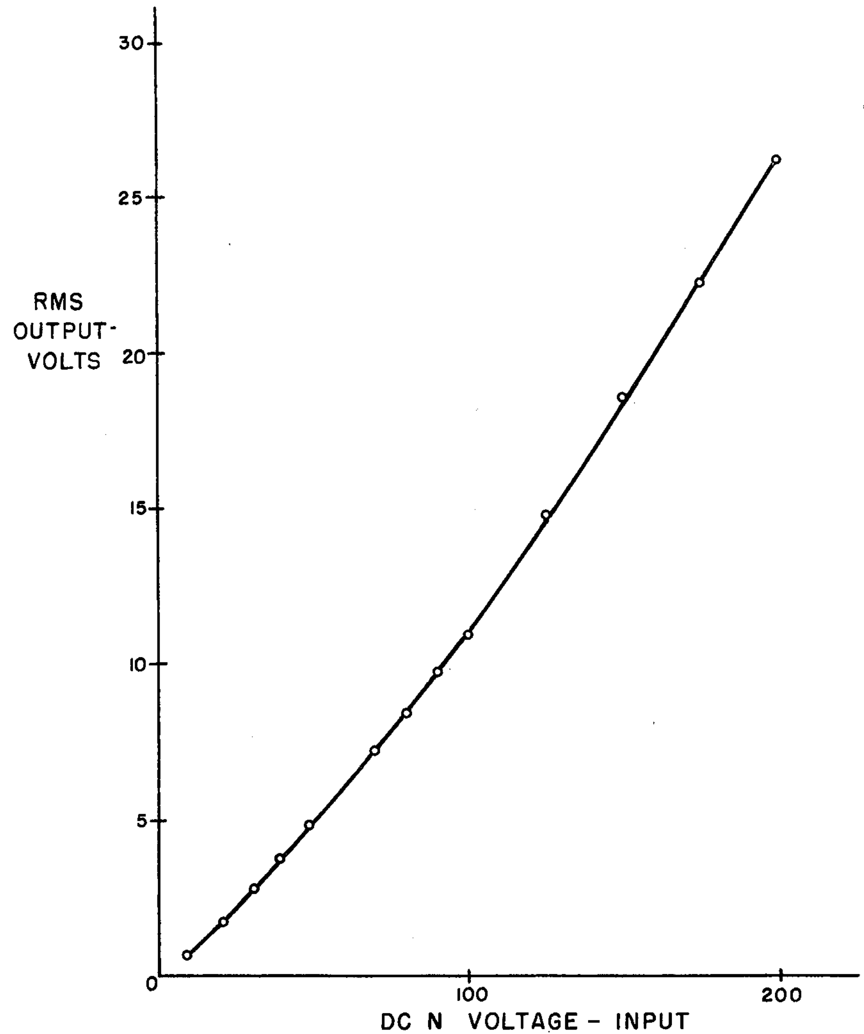

FIG. 5
N VOLTAGE CONVERTER RESPONSE

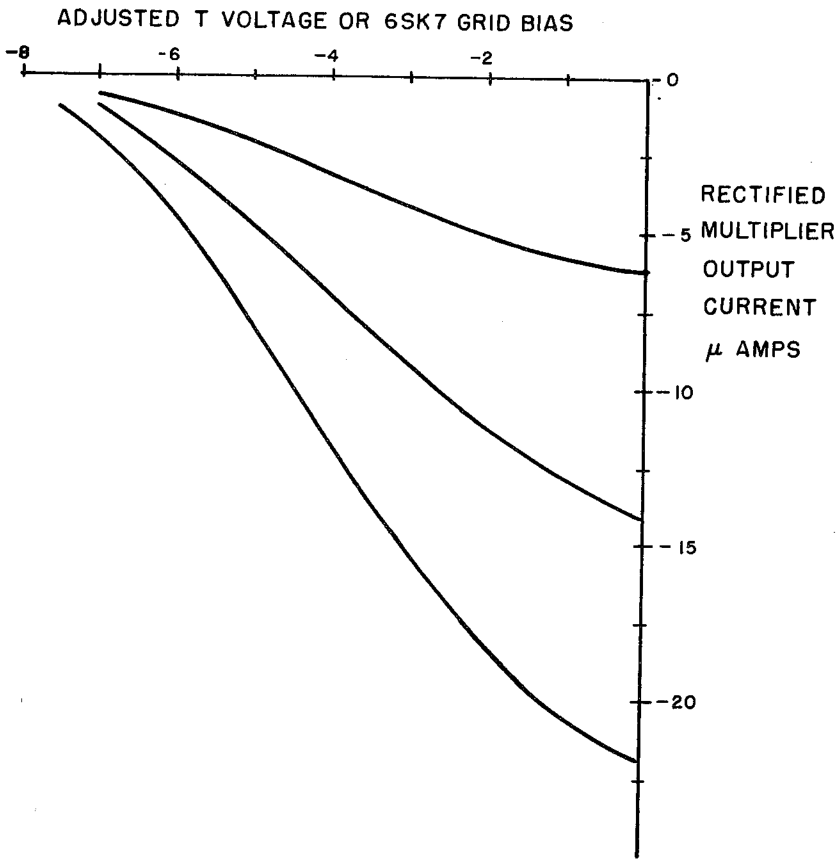

FIG. 6
MULTIPLIER RESPONSE