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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Investigation of Reactor Power Plant Systems.

Perhaps the most interesting 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.
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.\textsuperscript{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 subsequent application of the linear theory of feedback systems, such as the Bode diagram type analysis, to investigate system stability.\textsuperscript{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.\textsuperscript{5,6} Again the method of treating the problem may be much more generally applicable than to this specific situation.

\textbf{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

\textsuperscript{1} Superscripts refer to references at end of paper.
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,

\[
\frac{dN}{dt} = \left( \frac{\delta k_{eff}}{k_{1}^{\infty}} \right) N - \left( \frac{\beta}{1^{\infty}} \right) N + \epsilon \frac{T}{k_{1}} \sum \lambda_{i} c_{i} + \frac{(T-T_{0})k_{1}}{k} N + S. \tag{1}
\]

\[
\frac{dG_{i}}{dt} = - \lambda_{i} c_{i} + \left( e^{-T / \lambda_{i}} / \lambda_{i} \right) \beta_{i} N. \tag{2}
\]

\[
Q = W \frac{dT}{dt} + W(T-T_{0}) \tag{3}
\]

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

- \( T \) = temperature of the point reactor.
- \( T_{0} \) = reference temperature of reactor.
- \( T_{c} \) = average coolant temperature.
- \( K_{1} \) = temperature coefficient of reactivity.
- \( Q \) = reactor heat output, directly proportional to the time integral of the input current \( \delta k_{eff} \), while the input voltage remains substantially constant.
- \( S \) = 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.

In addition, the effect of temperature rise in the reactor caused by increased activity is also simulated. The position of the control rods, or \( \delta k_{eff} \), 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 \( \delta k_{eff} \), while the input voltage remains substantially constant.

The panel voltmeter \( V_{n} \) indicates the neutron flux \( N \) at any instant. A current source \( i_{0} \) simulates the production of prompt neutrons, the rate being determined by the setting of the \( \delta k_{eff} \) 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 \( i_{6} \) which is independent of level \( N \), but which is manually adjustable. A current \( K_{1} NT \) is also added to the integrator input representing the effect of temperature on reactivity.

Basic Circuit.

The basic circuit used to simulate the reactor proper is essentially that of Bell & Straus. This circuit is an analog of the one group, thermal point reactor equation. Five neutron delay groups are included.
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 $\Xi i$ of all currents including the negative current $i_d$ denotes the excess neutron production and determines the rate of change of reactivity. When $\Xi i = 0$ 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 $K_1NVT$ 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 $\delta k_{eff}$ control, the electronic integrator and the $N$ meter. The circuitry associated with this section is quite similar to the original Bell & Straus circuit, except that the $\delta k_{eff}$ 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, \( R_{10j} \), varies the current \( i_3 \), 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 \( e_c = -8 \) volts 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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References

FIG. 2

TEMPERATURE CIRCUIT AND COOLANT FLOW RATE CONTROL

FIG. 3

BLOCK DIAGRAM OF REACTOR SIMULATOR
Fig. 4

N VOLTAGE CONVERTER AND ELECTRONIC MULTIPLIER

Fig. 5

N VOLTAGE CONVERTER RESPONSE
ADJUSTED T VOLTAGE OR 6SK7 GRID BIAS

RECTIFIED MULTIPLIER OUTPUT CURRENT $\mu$ AMPS

FIG. 6
MULTIPLIER RESPONSE