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ABSTRACT

One purpose of this study was to determine whether the fuel salt temperature inside the reactor could be controlled with a closed-loop servo controller. An "on-off" type controller was demonstrated using four different control signals. The stability of the system when using the controller was of primary interest.

These studies indicated that the system was stable for large and relatively fast power demand changes when using the controller with any one of the four control signals.

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- I. Introduction: It is desirable to provide a controller for controlling the fuel temperature inside the reactor. There are many control concepts that would do the job.

The decision was made to try a simple "on-off" controller. E. R. Mann of the Instrumentation and Controls Division proposed four control signals which have definite possibilities and suggested that they be demonstrated on the analog computer. This report covers the analog computer demonstrations.

- II. Description of the System Simulated: A schematic flow sheet of the MSRE system is shown in Figure 1. The temperature symbols are identified in Figure 2. The design information used in these studies is listed in Figure 3. The analog computer diagram is filed in the Engineering and Mechanical Division print files on Drawings 40331 and 40332.

The simulation of the thermal system and nuclear system as used in these studies has been discussed in previous preliminary reports.<sup>1</sup> There were two changes, however, that were significant. The temperature coefficient of reactivity of the graphite was changed from:

$$-2 \times 10^{-4} \frac{\delta K}{K-^{\circ}F} \quad \text{to} \quad -6 \times 10^{-5} \frac{\delta K}{K-^{\circ}F}$$

and the total secondary salt loop transit time was changed from 13 seconds to 24.2 seconds.

- III. Description of Controller: The controller simulated was a simple "on-off" servo controller. The rod drive motor was a constant speed motor, driving the rods at a constant velocity sufficient to change the reactivity at a rate of:

$$.0002 \frac{\delta K}{K\text{-sec.}}$$

For the sake of simplicity, the rod worth was considered to be linear throughout the range used in these studies. The "time constant" of the controller was assumed to be 50 milliseconds. This "time constant" is the time required for the rod speed to attain 63% of full speed subsequent to receiving a demand signal to move the rods. The "dead band" of the controller was  $\pm 2^{\circ}F$ .

- IV. Description of the Control Signals Used: The four different control signals used with the above described controller were as follows:

A. Control Signal No. 1,  $\epsilon_1$

The equation expressing  $\epsilon_1$  is as follows:

$$\frac{1}{G} \epsilon_1 = m \left\{ \phi - \left( T_{o_r} - T_{i_r} \right) - g(t) \right\} + n \left\{ \left( T_{o_r} + T_{i_r} \right) - 2T_{sp} \right\}$$

where,

$G$  = control signal gain factor or amplification factor.

$m$ ,  $n$ , and  $a$  are constants that may be varied at will.

$\phi$  = neutron flux

$T_o ]_r$  = Fuel salt temperature at the reactor outlet.

$T_i ]_r$  = Fuel salt temperature at the inlet to the reactor.

$$g(t) = \lambda_2 \int_0^t \left[ a \phi - \left( T_o ]_r - T_i ]_r \right) - g(t) \right] dt$$

This can be considered as a "reset mechanism." = *integrator*

$T_{sp}$  - The desired mean fuel temperature in the reactor.

The controlled variable in  $\epsilon_1$  is the mean fuel temperature in the

reactor,  $\frac{T_o ]_r + T_i ]_r}{2}$ . This variable appears only in the

second term of the control signal. If this term alone is used as the control signal, the system is unstable.

The first term in  $\epsilon_1$  can be considered as a high frequency band pass stabilizing mechanism. It merely compares the rate of production of nuclear power to the rate of addition of heat to the fuel salt as it passes through the reactor. Note that for steady state operation:

$$\frac{d [g(t)]}{dt} = 0 = \lambda_2 \left[ a \phi - \left( T_o ]_r - T_i ]_r \right) - g(t) \right]$$
$$g(t) = a \phi - \left( T_o ]_r - T_i ]_r \right)$$

This insures that the first term in  $\epsilon_1$  will be zero for steady state operation whether the term:

$$\left[ a \phi - \left( T_o ]_r - T_i ]_r \right) \right]$$

is zero or not. For this reason, the constant, "a", does not have to be reset for various power levels. If  $\epsilon_1$  exceeds the dead band

positively, rods will be inserted and if  $\epsilon_1$  exceeds the dead band negatively, rods will be withdrawn. The analog computer diagram used to obtain  $\epsilon_1$  is shown in Figure 4.

The temperature sensing elements are thermocouples attached to the walls of the pipes containing the fluids whose temperatures are to be measured. There is a time lag between the time at which a change in temperature of the fluid occurs and the time at which this change is reflected in the thermocouple output signal. This time lag varies with different thermocouple designs, pipe wall thicknesses, etc. The time constant for this lag in the salt temperature thermocouples was designated as  $\tau_i$  and was considered to be 5 seconds.

The time constant of the  $g(t)$  circuit was <sup>and finally</sup> chosen as 10 times that of the thermocouple. This long time constant was necessary in order to get "reset action" and still not interfere with the stabilizing effect during transients.

The other three control signals are quite similar to  $\epsilon_1$  and only their differences from  $\epsilon_1$  will be pointed out in the following descriptions of these signals.

B. Control Signal No. 2,  $\epsilon_2$  .

The equation expressing  $\epsilon_2$  is as follows:

$$\frac{1}{G} \epsilon_2 = m \left\{ a \phi - f_a \left( T_{o_a} - T_{i_a} \right) - g(t) \right\} + n \left\{ \left( T_{o_r} + T_{i_r} \right) - 2T_{sp} \right\}$$

where,

$f_a$  = air flow rate across the radiator

$T_{o_a}$  = outlet air temperature from radiator

$T_{i_a}$  = inlet air temperature to radiator

The time constant used for the air temperature sensing elements was 2.5 seconds and that used in the  $g(t)$  circuit was 25 seconds ( $\tau_3 = 2.5$  and  $\lambda_4 = 0.04$ ).

Note that the controlled variable is the same as for  $\epsilon_1$ . The stabilizing portion of the control signal is now formed by comparing the rate of production of power in the reactor to the rate of removal of power from the secondary salt by the air flowing across the radiator. Note that a multiplier is required in this circuit.

The analog computer diagram used to formulate  $\epsilon_2$  is shown in Figure 5.

C. Control Signal No. 3,  $\epsilon_3$  .

The equation expressing  $\epsilon_3$  is:

$$\frac{1}{G} \epsilon_3 = m \left\{ a \phi - \left( T_i \right]_s - T_o \right]_s \right\} - g(t) \left\} + n \left\{ \left( T_c \right]_r + T_i \right]_r \right\} - 2T_{sp}$$

where,

$T_i \right]_s$  = secondary salt temperature at the radiator inlet

$T_o \right]_s$  = secondary salt temperature at the radiator outlet

The controlled variable is the same as that in  $\epsilon_1$  and  $\epsilon_2$  . The stabilizing circuit is formed by comparing the rate of power production in the reactor to the rate of power loss of the secondary salt as it flows through the radiator. No multiplier is required since the flow rate in the secondary salt system is constant.

The "time constant" potentiometer settings are the same as those used in  $\epsilon_1$  . The analog computer diagram used to obtain  $\epsilon_3$  is shown in Figure 6.

D. Control Signal No. 4,  $\epsilon_4$  .

The equation describing  $\epsilon_4$  is:

$$\frac{1}{G} \epsilon_4 = m \left\{ a \phi - \left( T_i \right]_s - T_o \right]_s \right\} - g(t) \left\} + n \left( T_o \right]_r - T_{sp} \right)$$

This control signal is the same as  $\epsilon_3$  except that a different controlled variable is used. The outlet fuel temperature from the reactor is the controlled variable. The analog computer diagram used to derive  $\epsilon_4$  is shown in Figure 7.

V. Procedure and Results: The system without a controller was shown to be unstable subsequent to any appreciable perturbation. The system was also shown to be unstable when using the controller with only the second term in the above control signals.

The stability of the system with the above controllers was checked subsequent to large changes in the power demand or load. The changes in the load for the four runs, each using one of the four above described control signals to the controller, were not precisely equal in magnitude and rate of change. The change in load was accomplished by manually turning a potentiometer. Also, no attempt was made to get optimum settings for M and N in each case. Therefore, the results cannot be compared quantitatively. In later runs linear ramp load changes will be used, and optimum

values of M and N used, so that controllers can be compared. Recordings of the controlled variable and the neutron flux were made subsequent to a load change, while using each of the four control signals to the controller. The conditions for these runs were as follows:

- A. Using  $\epsilon_1$  as the control signal, M, as shown on the computer diagram, was set at .877 (quite arbitrarily) and N was set at 0.5. The load, or the heat removal rate by the air across the radiator, was set at approximately  $\frac{1}{2}$  megawatt and the system permitted to stabilize. The load was increased from  $\frac{1}{2}$  mw to 10 mw in 15 seconds, approximately at a constant rate. The curves obtained are shown in Figure 8. On all the curves only a relatively short time is shown. It can be seen that the curves are converging, which indicates stability.
- B. Using  $\epsilon_2$  as the control signal, M, as shown on the computer diagram, was set at 0.877 and N set at 0.5. The load was changed from approximately 1.6 mw to 10 mw in 17 seconds. The resulting curves are shown in Figure 9.
- C. Using  $\epsilon_3$  as the control signal, M, as shown on the computer diagram, was set at 0.25 and N was set at 0.5. The load was changed from approximately 1.6 mw to 10 mw in 13 seconds. The resulting curves are shown in Figure 10.
- D. Using  $\epsilon_4$  as the control signal, M, as shown on the computer diagram, was set at 0.50 and N was set at 1.00. The load was changed from approximately 1.6 mw to 10 mw in 11 seconds. The resulting curves are shown in Figure 11.

The conclusion reached was that the system would be stable using the controller with any of the four control signals.

It should be pointed out that the constants M and N on the actual installation could be changed over a considerable range. No attempt was made to get the optimum settings on the computer, due to time limitations.

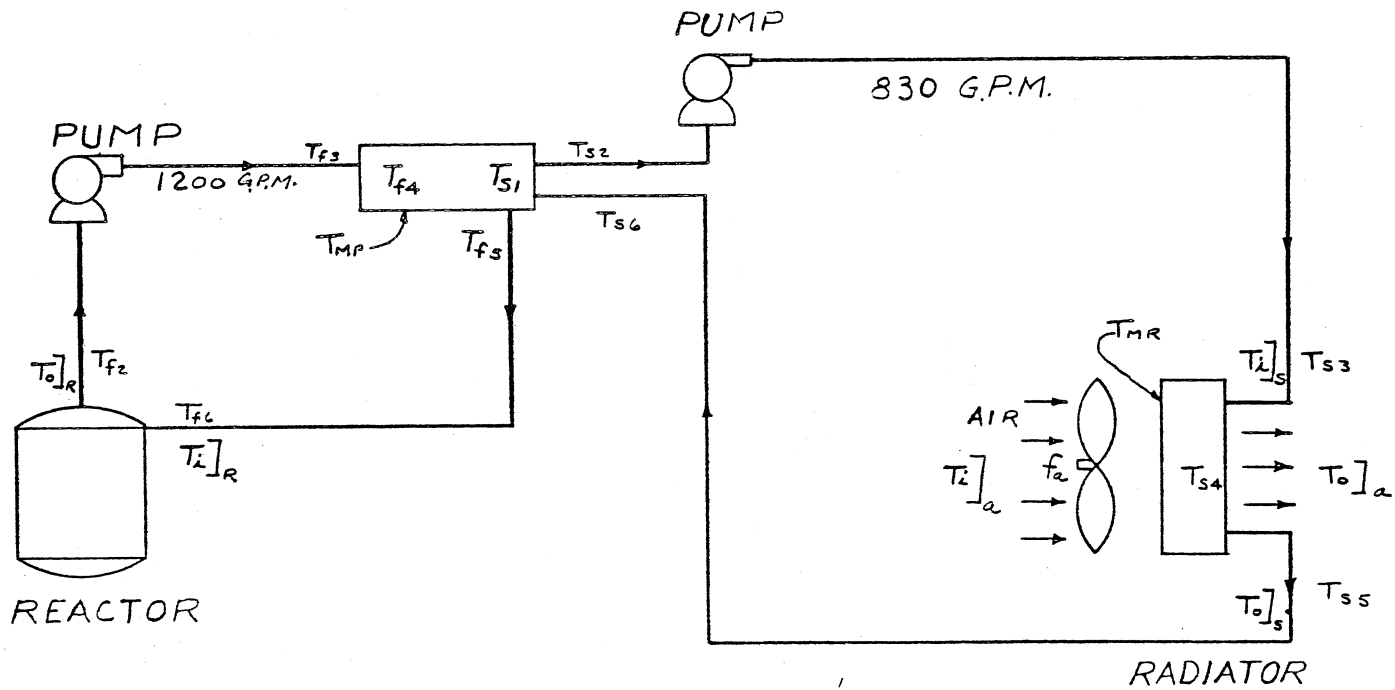


FIG. 1 BASIC FLOW DIAGRAM OF MSRE SYSTEM



Figure 2

IDENTIFICATION OF TEMPERATURE SYMBOLS

$T_{f1}$	-	Circulating fuel mean temperature in the reactor core.
$T_{f2}$	-	Circulating fuel temperature at the outlet of the reactor core.
$T_{f3}$	-	Circulating fuel temperature at the inlet to the primary heat exchanger.
$T_{f4}$	-	Circulating fuel mean temperature in the primary heat exchanger.
$T_{f5}$	-	Circulating fuel temperature at the outlet of the primary heat exchanger.
$T_{f6}$	-	Circulating fuel temperature at the inlet to the reactor core.
$T_g$	-	Mean temperature of the graphite in the reactor core.
$T_{mp}$	-	Mean temperature of the metal in the primary heat exchanger wall.
$T_{s1}$	-	Mean temperature of the secondary salt in the primary heat exchanger.
$T_{s2}$	-	Secondary salt temperature at the outlet of the primary heat exchanger.
$T_{s3}$	-	Secondary salt temperature at the inlet to the radiator.
$T_{s4}$	-	Mean temperature of the secondary salt in the radiator.
$T_{s5}$	-	Secondary salt temperature at the radiator outlet.
$T_{s6}$	-	Secondary salt temperature at the inlet to the primary heat exchanger.
$T_{mr}$	-	Mean temperature of the metal in the radiator.
$\bar{T}_{hot}$	-	Mean circulating fuel temperature in the "hot leg" of the primary system.
$\bar{T}_{cold}$	-	Mean circulating fuel temperature in the "cold leg" of the primary system.
$T_{ma}$	-	Mean air temperature in the radiator.

Figure 2 (contd.)

- $T_i]_r$  - Fuel temperature at reactor core inlet.
- $T_o]_r$  - Fuel temperature at reactor core outlet.
- $T_i]_s$  - Secondary salt temperature at the radiator inlet.
- $T_o]_s$  - Secondary salt temperature at the radiator outlet.
- $T_i]_a$  - Cooling air temperature at radiator inlet.
- $T_o]_a$  - Cooling air temperature at radiator outlet.