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SUBJECT: MSRE - Analog Computer Simulation of the System With a Servo Controller

TO: G. A. Cristy

FROM: O. W. Burke

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.

CONTENTS

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.[1] There were two changes, however, that were significant. The temperature coefficient of reactivity of the graphite was changed from:

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

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°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, ϵ_1

The equation expressing ϵ_1 is as follows:

$$\frac{1}{G}\epsilon_1 = m \quad a\left\{\phi - \left(T_o\Big]_r - T_i\Big]_r\right) - g(t)\right\} + n\left\{\left(T_o\Big]_r + T_i\Big]_r\right) - 2T_{sp}\right\}$$

where,

G = control signal gain factor or amplification factor.

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

ϕ = neutron flux

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

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

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

This can be considered as a "reset mechanism."

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

The controlled variable in ϵ_1 is the mean fuel temperature in the reactor, $\dfrac{\left.T_o\right]_r + \left.T_i\right]_r}{2}$. 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 ϵ_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:

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

$$g(t) = a\,\phi - \left(\left.T_o\right]_r - \left.T_i\right]_r \right)$$

This insures that the first term in ϵ_1 will be zero for steady state operation whether the term:

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

is zero or not. For this reason, the constant, "a", does not have to be reset for various power levels. If ϵ_1 exceeds the dead band positively, rods will be inserted and if ϵ_1 exceeds the dead band negatively, rods will be withdrawn. The analog computer diagram used to obtain ϵ_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 τ_i and was considered to be 5 seconds.

The time constant of the g(t) circuit was arbitrarily 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 ϵ_1 and only their differences from ϵ_1 will be pointed out in the following descriptions of these signals.

B. Control Signal No. 2, ϵ_2.

The equation expressing ϵ_2 is as follows:

$$\frac{1}{G}\epsilon_2 = m\left\{a\,\phi - f_a\left(T_o\Big]_a - T_i\Big]_a\right) - g(t)\right\} + n\left\{\left(T_o\Big]_r + T_i\Big]_r\right) - 2T_{sp}\right\}$$

where,

f_a = air flow rate across the radiator

$T_o\Big]_a$ = outlet air temperature from radiator

$T_i\Big]_a$ = 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 (τ_3 = 2.5 and λ_4 = 0.04).

Note that the controlled variable is the same as for ϵ_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 ϵ_2 is shown in Figure 5.

C. Control Signal No. 3, ϵ_3.

The equation expressing ϵ_3 is:

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

where,

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

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

The controlled variable is the same as that in ϵ_1 and ϵ_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 ϵ_1. The analog computer diagram used to obtain ϵ_3 is shown in Figure 6.

D. Control Signal No. 4, ϵ_4.

The equation describing ϵ_4 is:

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

This control signal is the same as ϵ_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 ϵ_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 ϵ_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 ϵ_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 ϵ_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 ϵ_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.

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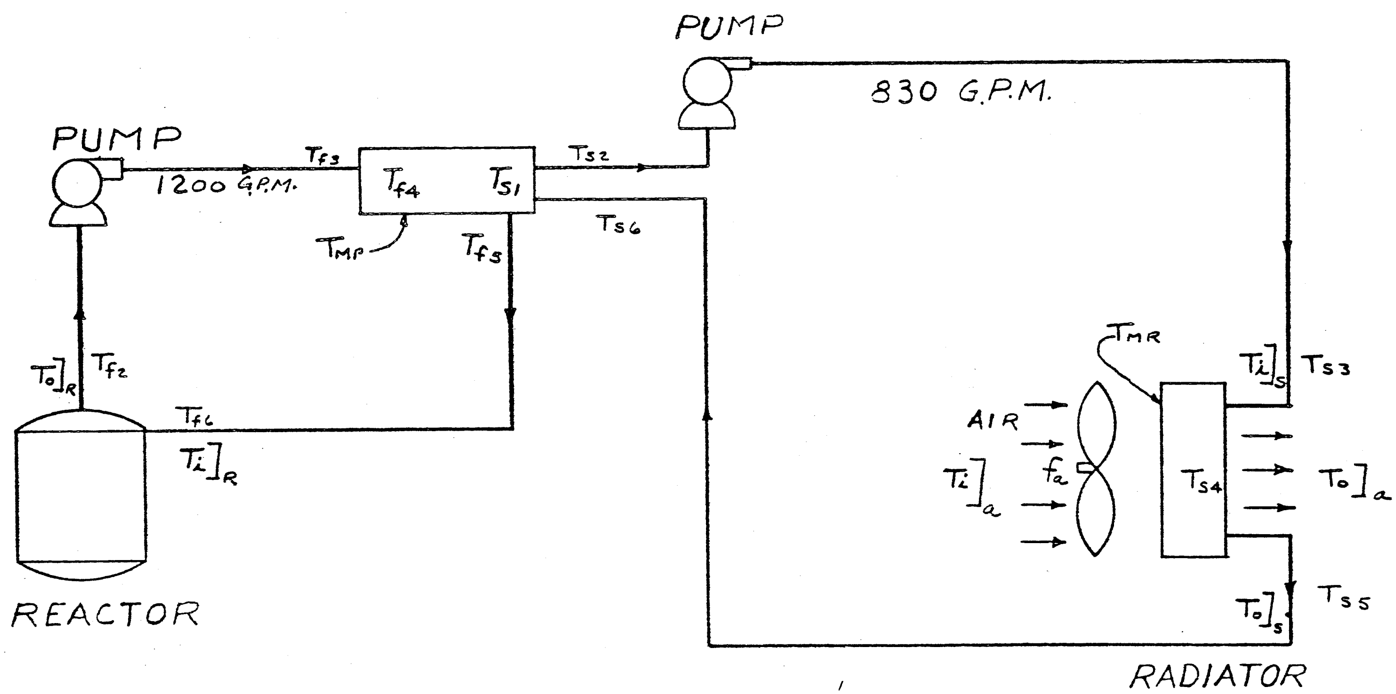

FIG. 1 BASIC FLOW DIAGRAM OF MSRE SYSTEM

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.
$\overline{T}_{hot}$	-	Mean circulating fuel temperature in the "hot leg" of the primary system.
$\overline{T}_{cold}$	-	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.

Figure 3

MSRE DESIGN POINT DATA AS OF 12-13-60

Reactor inlet temperature:	1175 $^{\circ}F$
Reactor outlet temperature:	1225 $^{\circ}F$
Mean graphite temperature: (with no fuel absorption)	1230 $^{\circ}F$
Residence time in reactor:	7.63 sec.
Film drop from graphite to fuel:	Linear with power
Heat capacity of graphite:	0.425 $\frac{BTU}{\# \, ^{\circ}F}$
Prompt γ and neutron heating in graphite:	6% of 10 MW

Residence time in piping from reactor outlet to H. E. inlet	3.09 sec.
Residence time in H. E.	2.24 sec.
Heat capacity of metal in H. E.	200 BTU/$^{\circ}F$
Avg. film drop between primary coolant and metal at D. P.	55.2 $^{\circ}F$
Avg. drop in metal at D. P.	56.7 $^{\circ}F$
Avg. film drop between metal and secondary coolant at D. P.	26.1 $^{\circ}F$
Film drop between primary coolant and metal as function of flow: See graph, displace curve if necessary so that at 6.2 fps velocity $\Delta T = 55.2 \, ^{\circ}F$.	
Mean secondary coolant temperature at D. P.	1062 $^{\circ}F$
Residence time in piping between H. E. outlet and reactor inlet (including coolant annulus)	9.04 sec.
Total circulation time	22.0 sec.

Temperature coefficient of reactivity of graphite:	$-6 \times 10^{-5} \, \delta K/K\text{-}^{\circ}F$
Temperature coefficient of reactivity of fuel:	$-3.3 \times 10^{-5} \, \delta K/K\text{-}^{\circ}F$
Melting point of primary coolant:	842 $^{\circ}F$
Melting point of secondary coolant:	860 $^{\circ}F$

Figure 3 (contd.)

Check points:

Thermal resistances: $\frac{\text{ft. hr. } ^{\circ}\text{F}}{\text{BTU}}$

in primary coolant film:	3.28×10^{-4}
in metal:	3.32×10^{-4}
in secondary coolant film:	1.56×10^{-4}

Simulator data for secondary loop

Air temperature rise in radiator		200 °F
Air suction temperature		100 °F
Air flow		166,000 cfm
		(7.11×10^5 #/hr)
Heat capacity of radiator		242 BTU/°F
Heat capacity of secondary salt		$0.57 \ \frac{\text{BTU}}{\# \ ^{\circ}\text{F}}$
Density of secondary salt		120 #/ft^3
Residence times of secondary salt:		
in primary heat exchanger		1.75 sec.
in piping to radiator		5.20 sec.
in radiator		7.14 sec.
in piping from radiator		10.11 sec.
	Total	24.20 sec.
Residence time of air in radiator		0.01 sec.
Temperature differences in radiator:		
in salt film		13.4 °F
in tube wall		78.4 °F
in air film		770.7 °F

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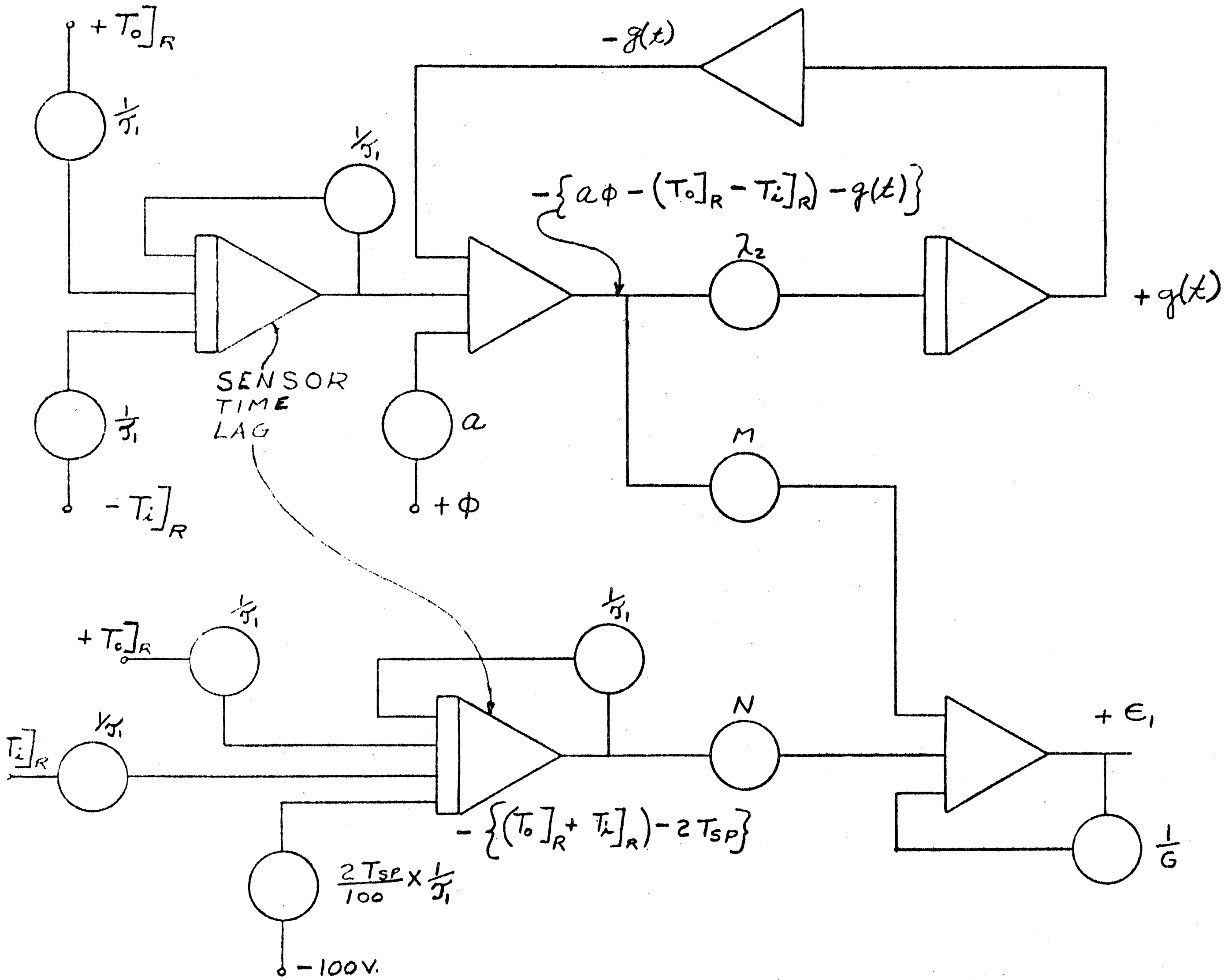
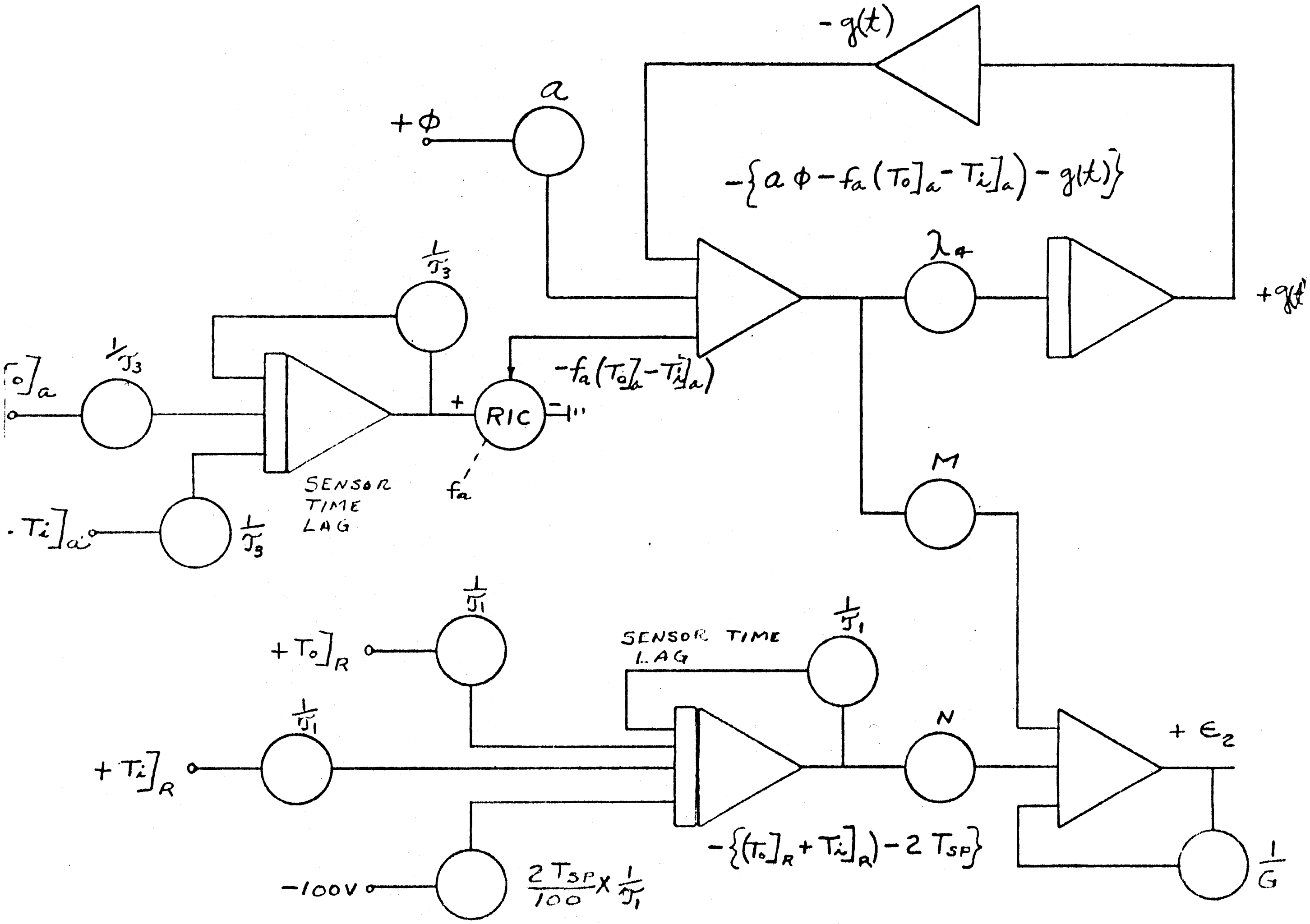


$$\lambda_2 \cong 0.1\left(\frac{1}{\tau_1}\right)$$

$$\frac{1}{G}\epsilon_1 = M\left\{a\phi - \left(T_o]_R - T_i]_R\right) - g(t)\right\} + N\left\{\left(T_o]_R + T_i]_R\right) - 2\,T_{SP}\right\}$$

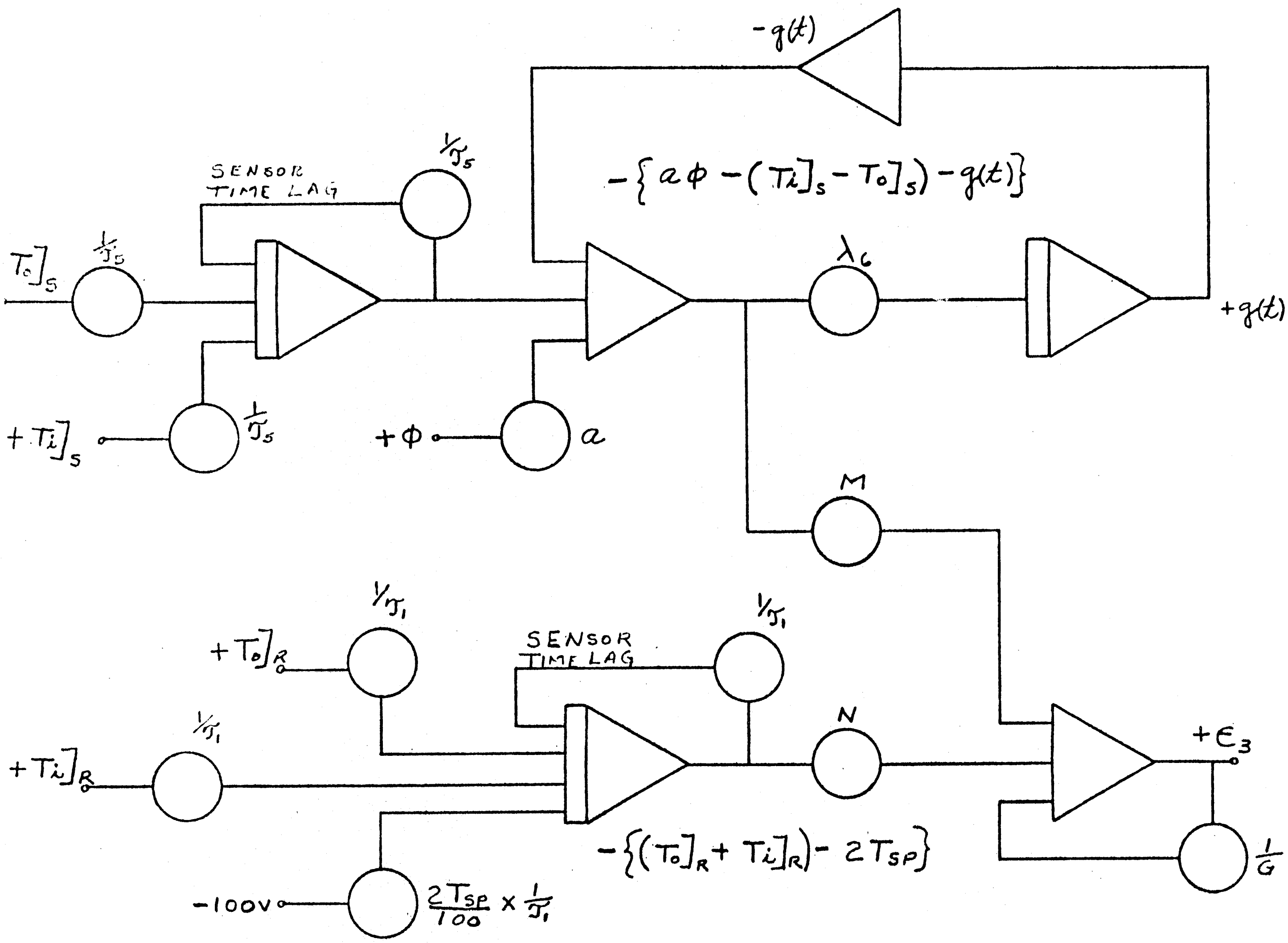
FIG. 4. GENERATOR CIRCUIT FOR ϵ_1



$$\lambda_4 \cong 0.1(1/T_3)$$

$$\frac{1}{G}\,\epsilon_2 = M\{a\phi - f_a(T_o]_a - T_i]_a) - g(t)\} + \{(T_o]_R + T_i]_R) - 2T_{SP}\}N$$

FIG. 5 GENERATOR CIRCUIT FOR ϵ_2.



$$\lambda_6 \cong 0.1\left(\frac{1}{\tau_s}\right)$$

$$\frac{1}{G}\,\epsilon_3 = M\left\{a\phi - \left(T_i]_s - T_o]_s\right) - g(t)\right\} + N\left\{\left(T_o]_R + T_i]_R\right) - 2T_{SP}\right\}$$

FIG. 6 GENERATOR CIRCUIT FOR ϵ_3.

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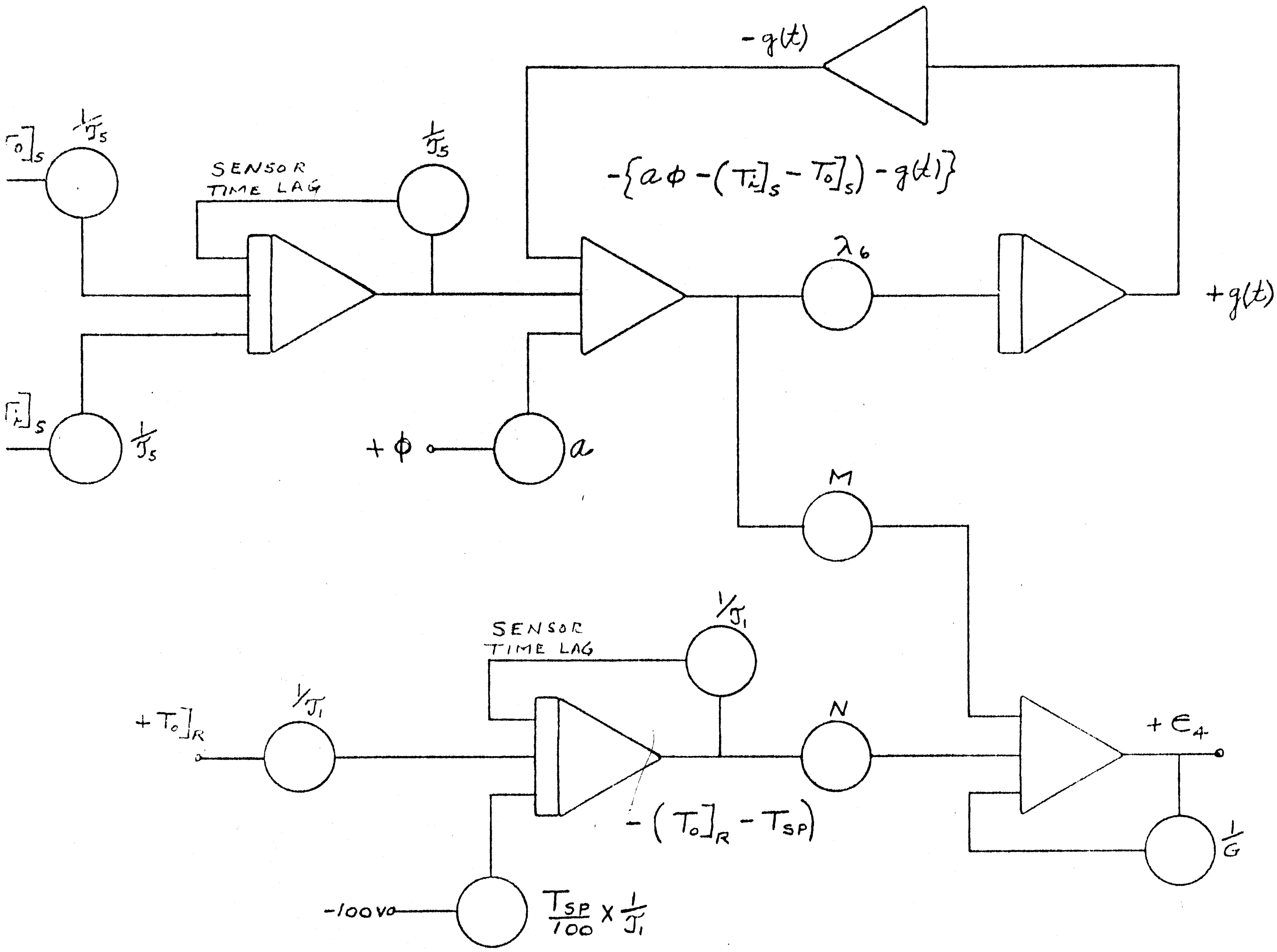

$$\lambda_6 \cong 0.1\left(\frac{1}{\tau_s}\right)$$

$$\frac{1}{G}\,\epsilon_4 = M\left\{a\phi - \left(T_i]_s - T_o]_s\right) - g(t)\right\} + N\left(T_o]_R - T_{SP}\right)$$

FIG. 7 GENERATOR CIRCUIT FOR ϵ_4.

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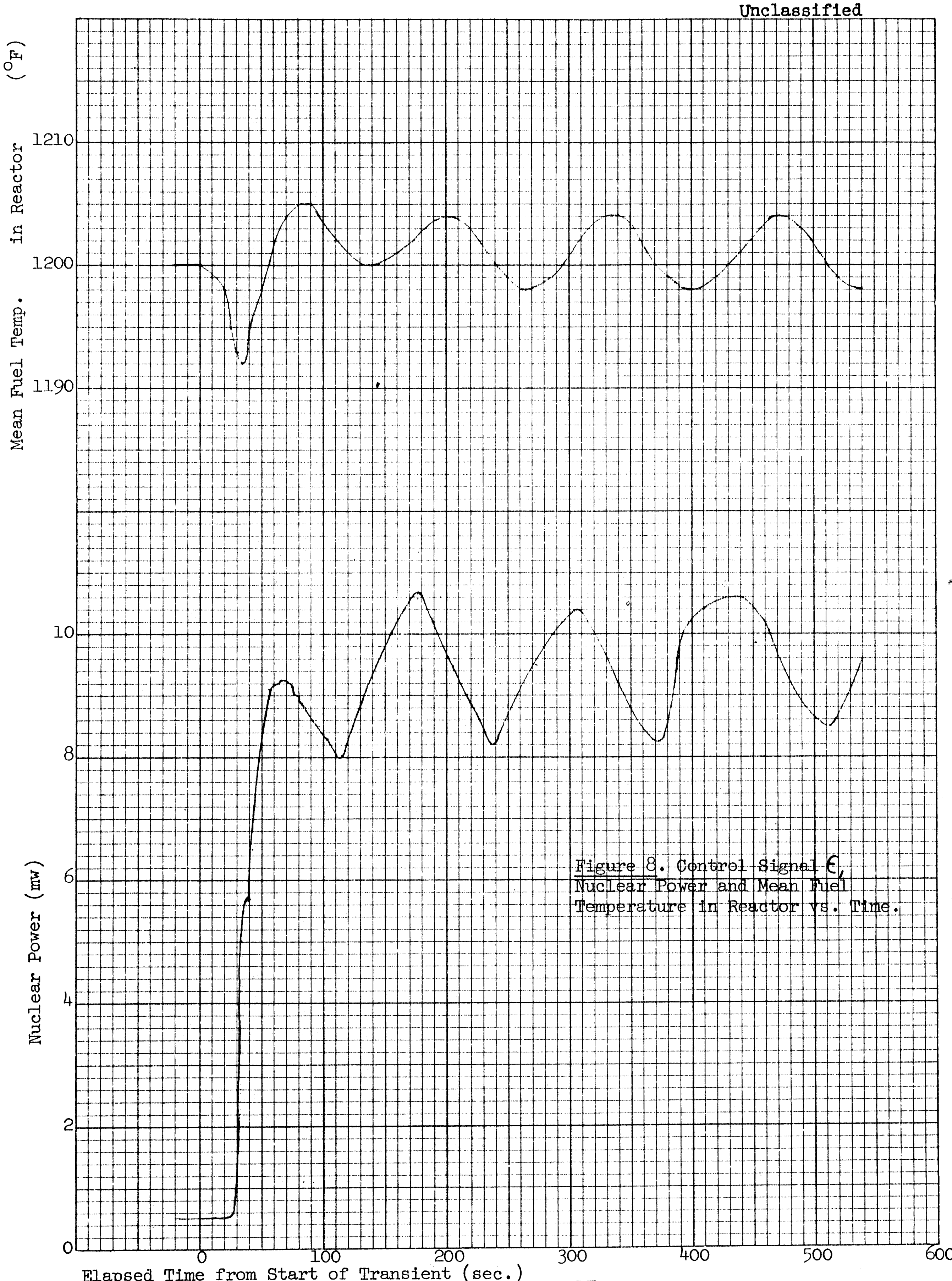

Figure 8. Control Signal ε, Nuclear Power and Mean Fuel Temperature in Reactor vs. Time.

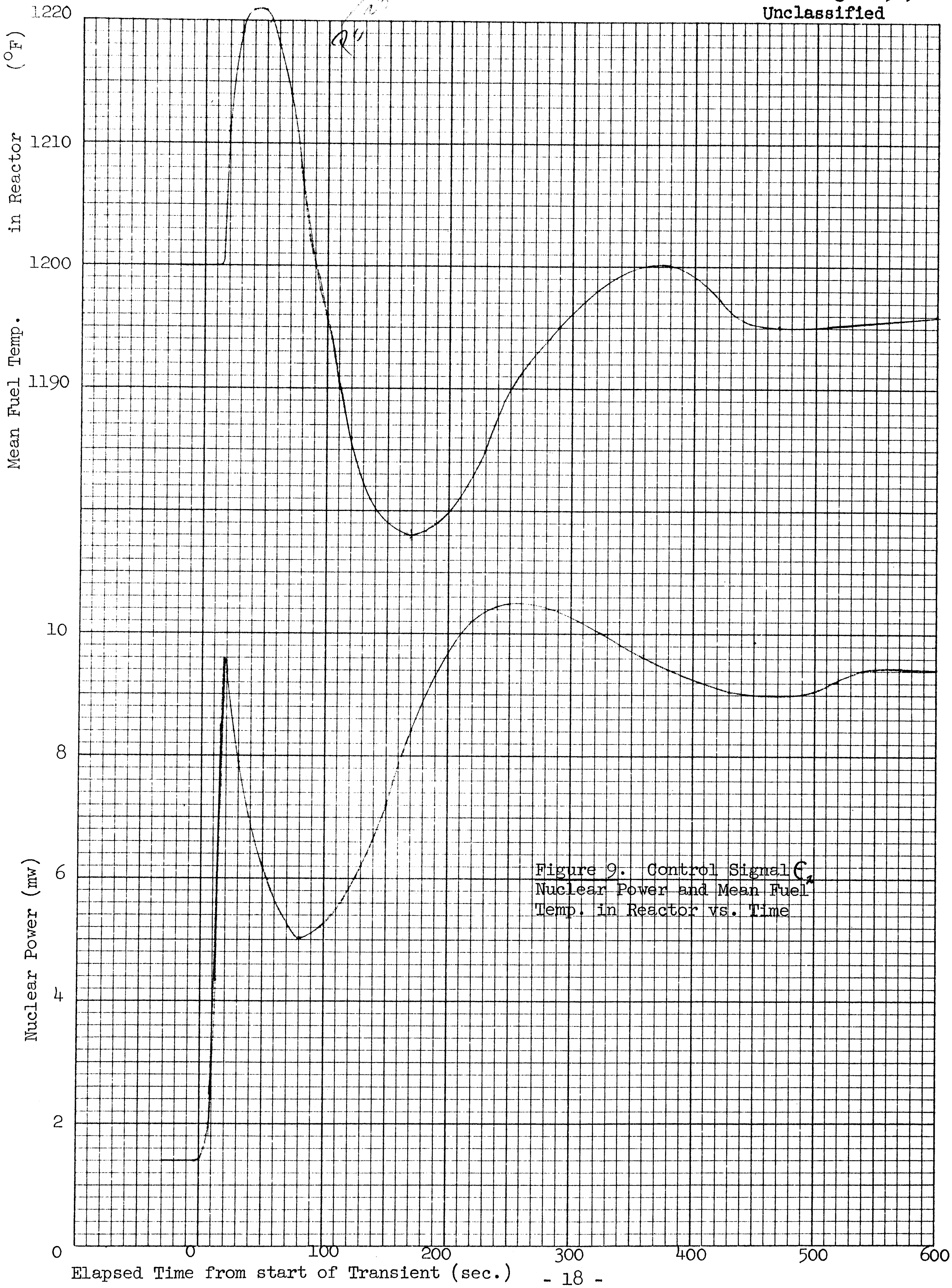

Figure 9. Control Signal ϵ_x Nuclear Power and Mean Fuel Temp. in Reactor vs. Time

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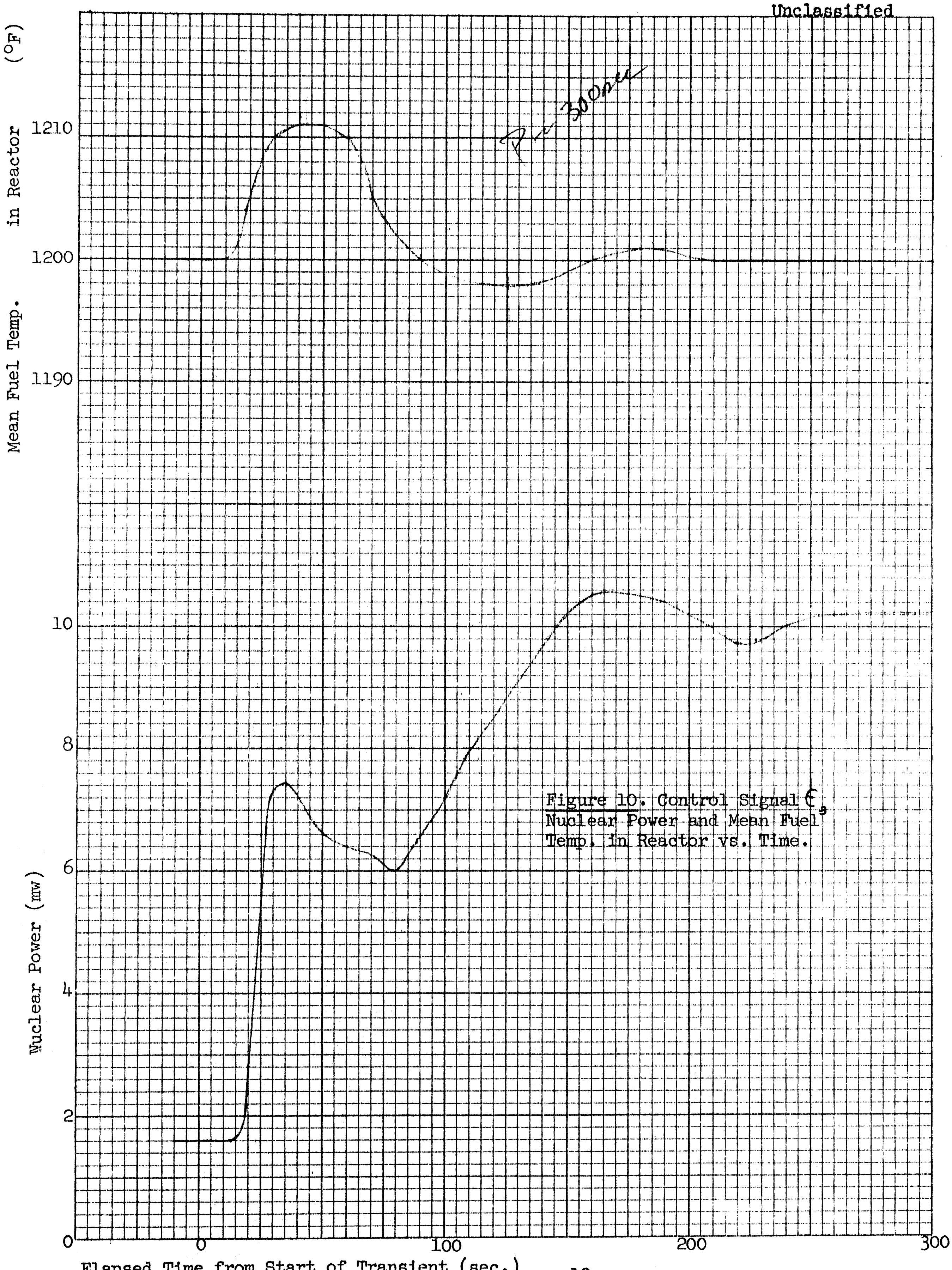

Figure 10. Control Signal ϵ_3 Nuclear Power and Mean Fuel Temp. in Reactor vs. Time.

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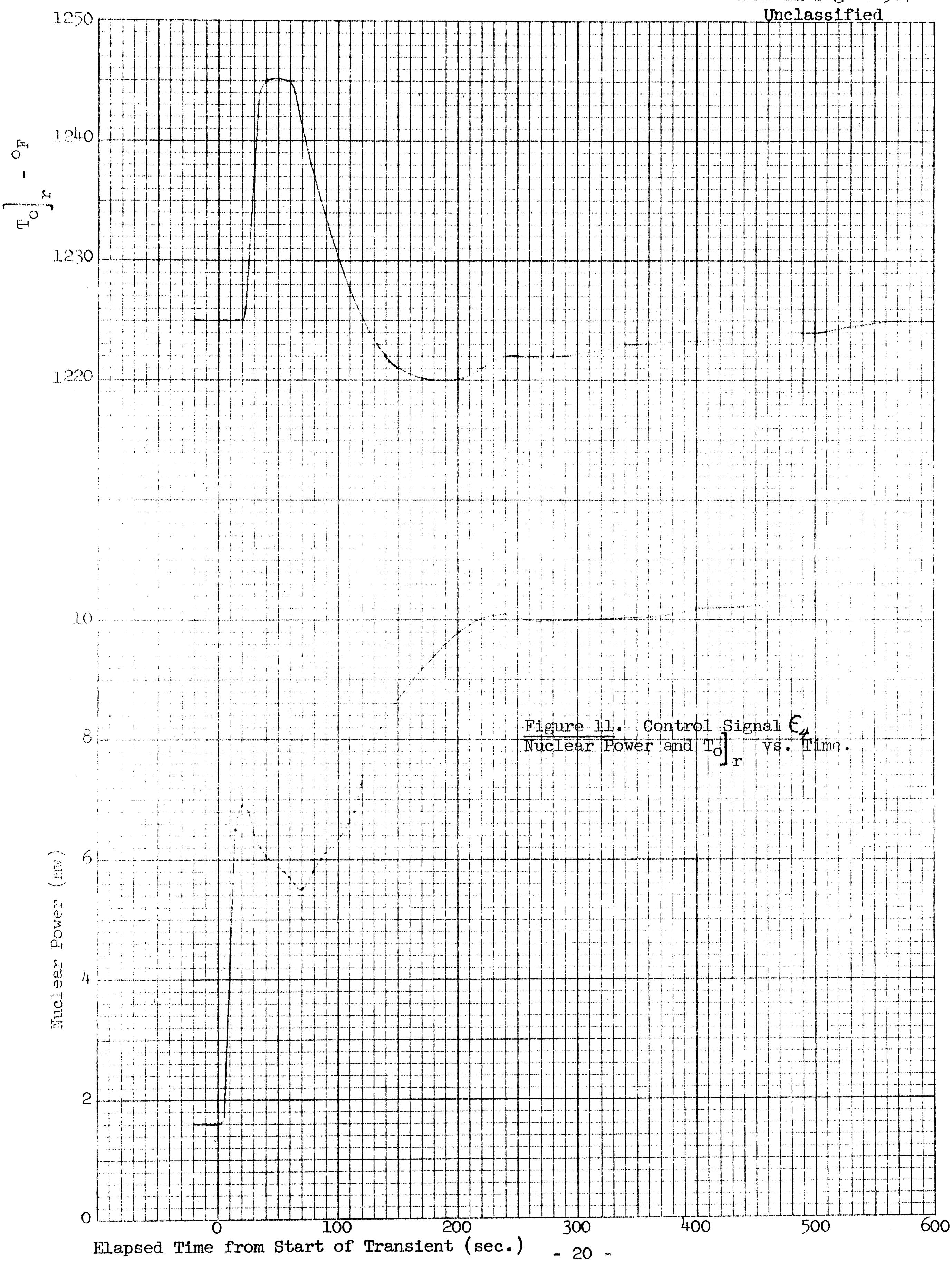

Figure 11. Control Signal ϵ_4
Nuclear Power and $T_o]_r$ vs. Time.

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