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Westinghouse Astronuclear Laboratory

ON-OFF TEMPERATURE CONTROLLER

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ON-OFF TEMPERATURE CONTROLLER

I. INTRODUCTION

An On-Off type temperature controller has been developed for experimental testing during the NRX/EST test series. This controller eliminates the neutron flux signal as a control variable and includes circuitry, which in conjunction with the present variable-rate drum actuator, simulates an On-Off actuation system. Eventually, the On-Off temperature controller will be combined with a simple, constant velocity drum actuator for reactor control.

This report contains the completed design and test specifications for the On-Off temperature controller which will be tested on the NRX/EST. This controller can be used with an On-Off actuation system by merely removing those components which simulate the actuator On-Off characteristics.

II. BACKGROUND

The present NERVA engine control system consists of three basic control loops. These are the power, temperature, and pressure loops. Analysis has shown that it is advantageous to eliminate the power loop. Therefore, the On-Off controller was developed to control temperature directly without an inner power loop.

The basic reason for selecting an On-Off controller is the potential simplicity, reliability, and lower cost of a constant-rate drum actuator. Also, the maximum required drum actuator velocity, $\pm 1^\circ/\text{sec.}$, makes the system very attractive from the safety point of view. This actuator will move the reactor control drums in or out at a constant velocity or keep the drums stationary depending on the control signal.

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Also, the On-Off controller might be somewhat simpler and cheaper than a corresponding linear controller, especially for high power application.

Earlier Analysis Work Done

During the earlier phases of the design work, analytical and graphical analyses were made in order to understand the fundamental behavior of the On-Off controller. The first work was done with a power On-Off controller and is described in WANL-TME-1168, "Analysis and Simulation Feasibility Study for NRX-A On-Off Controller," by E. Honka and J. Josephson on May 11, 1965. A very much simplified model of the NRX reactor control system was adopted for the analysis. It was possible to obtain a second degree non-linear differential equation representation for the system which was studied in the phase plane. Although the mathematical model for this analysis was quite crude and inaccurate, a fair amount of understanding of the basic system behavior was gained and phenomena noticed in the later analog computer study could be explained.

The present temperature On-Off controller (without the power controller) operated in the same system as the earlier power On-Off controller. Thus, some similarities between these controllers and control systems should be expected. However, the reactor nuclear power can be considered as a primary variable in the system. The power control loop is fast and relatively easy to handle. On the other hand, the temperature at any location of the reactor system is just an indication that something has already happened. The control signal derived from the temperature is delayed because of various sized thermal capacities in the system. Therefore, it is necessary to build into the system a large amount of anticipation in the form of a predictor switching control network for the On-Off temperature controller.

III. SYSTEM DESCRIPTION AND OPERATION

Figure 1 shows the schematic diagram of the actual On-Off controller and its predictor switching-control network. Figure 2 shows the idealized analog computer study of the On-Off controller performance. The voltage transfer function of the switching control network is:

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$\frac{e_o}{e_i} = 20 \frac{(1+3S)}{(1+0.015S)(1+0.1S)}$. The predictor term here is $(1 + 3S)$, and the two lag terms $(1 + 0.15S)$ and $(1 + 0.1S)$ are used for filtering high frequency noise that would otherwise cause continual switching of the On-Off controller. The values of these network parameters are not critical, but it should be noted that the filtering poles should filter out only high frequencies. Otherwise, the system slows down so that it cannot follow fast transients and may lead to steady or expanding oscillations at some low frequency.

The fact that the lead time constant in the controller predictor network is only 3 seconds and in the earlier power controller was eight seconds, is to be attributed mainly to the fact that some additional filtering in the form of a second pole has decreased somewhat the need for anticipation in the controller switching.

The system deadband is a measure of the magnitude of the temperature error for which no control drum movement is demanded. The most accurate control of the system would be obtained if the deadband is zero. In order to prevent unnecessary switching of the controller caused by small amplitude noise in the system, it is a reasonable compromise between controller switching period and system performance to make the deadband of the controller approximately equal to the temperature oscillations (i.e., temperature error variations in steady state caused by the On-Off controller action without deadband). Then the system oscillation and accuracy will stay about equal both in the transient and in the slowly drifting, nearly steady state, conditions. When the system drifts away from its zero error condition, the correction action starts as soon as the temperature error reaches the size of the deadband and brings the system back inside the deadband. There is practically no overshoot outside the deadband region because the system has been at near steady state condition, drifting slowly.

In the case where the system is in a transient state, the slope of the transient causes the differentiating predictor network to switch the On-Off controller into corrective action sooner for steeper transients. This tends to eliminate the effect of the deadband and thus the oscillations and the error of the system may be kept about constant in both the steady state and transient conditions as long as the control effort, exercised by the output of the controller, is sufficiently large.

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The output from the controller is a sequence of step inputs to the system. The amplitude of the steady state oscillations of the temperature error, and other system variables, are directly dependent on the magnitude of the steps in this sequence. On the other hand, the system can handle larger and faster transients without excessively large peak errors if the constant magnitude of the On-Off controller output is made larger. If the transient is so large or fast that the On-Off controller puts out its maximum control effort by staying at one of its states for a prolonged time, any additional noise that switches the On-Off controller decreases its control effort, and allows the errors to become larger. A deadband in the On-Off controller reduces the switching of the controller when the control signal is noisy and, in some cases, also reduces the error in the transient response.

As seen from the above discussion, the choice of On-Off temperature controller parameters is a compromise between various design criteria. The maximum control effort should be large in order to follow fast transients and should be small to provide small ripple amplitude in steady state. The controller deadband should not be too large, or excessive system drift will occur, and yet it should not be too small or excessive actuator wear will result from unnecessary switching. The remainder of this report discusses the selection of the controller parameters based on a compromise between steady state and transient performance. The final selections are based primarily on the results of analog computer runs.

IV. SYSTEM DESIGN AND ANALYSIS

Preliminary analyses of the system performance were made using phase plane analysis. These studies lead to initial estimates of desired controller parameters (i.e., the time constants, gain, deadband, and demand velocity) which were then adjusted on the analog computer to give satisfactory system performance.

The engine system model used on the analog computer for these studies was the NRX/EST CAM II C model. Predictions for the tests of this controller to be run during Phase II, Run 4 of the NRX/EST test series were also based on the CAM II C analog model.

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In order to choose the best values for the controlling parameters, a series of analog computer runs were made. This parametric study led to the final selection of the On-Off controller parameters. Table 1 is a partial list of the analog runs which were made. The runs listed in this table are included in the figures of this report in order to indicate the effect on system performance of the various controller parameters. The first seven runs listed were made with the parameters of the final compensation network.

ANALOG COMPUTER RUNS

Run 1 is a reference run with the linear no-flux loop temperature controller. This run is provided for comparison purposes. In all later runs the linear no-flux loop temperature controller is replaced by the On-Off controller with its associated switching network.

It should be noted that analog computer runs 10, 11, 13, 14, and 17...21 are made using an ideal switching circuit simulation of the On-Off controller and the runs 2...9, 12, 15, 16, and 22...27 are made using the On-Off controller breadboard with its associated networks.

In all runs except 4 and 5, the system chamber pressure demand P_{gD} has been slaved to the measured temperature T_g . This is done in order to correspond to the NRX/EST On-Off controller system where $P_D = f(T_m)$. In runs 4 and 5, the system is in an unslaved condition.

Run 2. During this run, the On-Off controller had its nominal parameter values, deadband = $\pm 30^\circ R$, output = ± 1 degree per second (control drum rate demand), and the predictor network as in Figure 1. This run shows the system behavior when the slaved (i.e., pressure demand obtained as a function of measured temperature) system temperature demand, T_{gD} , is ramped from $1700^\circ R$ to $2500^\circ R$ and back down at $25^\circ R/\text{second}$. At the beginning and end of the ramps, we notice about $\pm 70^\circ R$ peaks in the temperature error. At about $2500^\circ R$, T_{gD} is stepped to $2600^\circ R$ and back to $2500^\circ R$. From the graph it can be seen that temperature error oscillations at $2500^\circ R$ are about $\pm 15^\circ R$ and at the lower temperature level about $\pm 25^\circ R$. The hundred degree steps in the temperature demand cause about an equal error in temperature which persist about 3 seconds and then within 3 seconds is reduced to its zero-average value. This indicates that the On-Off temperature controller is a relatively fast device for controlling temperature. The normal temperature controller with

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the flux loop requires approximately 45 seconds to reach steady state for a step response at this power level.

Run 3 is exactly the same as Run 2, but with 10°R rms noise with a frequency range of 1 to 50 cps added to the temperature error before the predictor network. It should be noted that the magnitude of this noise varies somewhat from case to case.

It is quite obvious that this noise penetrates the On-Off controller quite easily. This happens because of the differentiating nature of the predictor network. Also, we can notice a dither-like effect of this noise, which tends to linearize the On-Off controller output. This results in smoother control of temperature. About the same type of effect can be obtained if the On-Off controller has no deadband. However, the controller temperature loop is so slow that the switching of the On-Off controller without deadband does not happen often enough to achieve a really smooth control. The On-Off controller switching period could be decreased and the smoothness of the control increased by an increase in the predictor time constant or by decreasing the lag time constants.

In this case, it seems that the addition of some noise in the system has slightly improved the total control performance (this improvement is obtained at the cost of additional switching of the On-Off controller). Also, the peak errors during the transients have not increased because the On-Off controller's $\pm 1^{\circ}/\text{second}$ output is quite adequate to handle the encountered transients.

Run 4 indicates what happens to the system in the unslaved condition when T_{8D} is kept at 2500°R and P_{8D} is ramped down to 80 psi, where the tie rod exit gas temperature (T_{Tre}) = 1000°R . Under these conditions, the system gets into an unstable limit cycle with a period of about 25 seconds. This limit cycle becomes stable when the pressure P_{8D} is increased to about 125 psi. The natural controller limit cycle, with $\pm 15^{\circ}\text{R}$ temperature error oscillations and a period of six seconds, appears when P_{8D} is 230 psi. Again, this tendency toward instability at low pressure levels is not a behavior that can be found only in the On-Off controller circuit, but expresses itself also in the linear controller system. It might be possible to reduce the magnitude of this limit cycle at low pressures by increasing the predictor time constant or by decreasing the filtering lag time constants. However,

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these changes might deteriorate the system behavior under other circumstances(i.e., the output of the controller might become noisier).

It is to be noted that the output of the On-Off controller is quite oscillatory when the control signal input to the controller is within the deadband and the output should be equal to zero. These low magnitude oscillations at the output of the On-Off controller are caused by the penetration of the input noise through the operational amplifier. This is because the diode clamps used to obtain the deadband are not ideal and do not change their characteristics from zero conductance to infinite conductance at one point.

Run 5 is the same as Run 4, but with about 10°R rms noise added to the measured temperature as in Run 3. Again, noise penetrates the system easily. Otherwise the performance is not changed very much.

Runs 6 and 7 have the same On-Off controller as above. Now the chamber temperature demand of the slaved system is ramped at the rate of $25^{\circ}\text{R}/\text{second}$ from the reactor power level of 14% to full 100% and back down to 14%. For Run 4, the system is without noise and in Run 5 about 10°R rms noise with the frequency content of about 1 cps to 50 cps has been added into the temperature error before the predictor network. In both these runs, which extend over a wider operation range than Runs 2 and 3, the system behavior is quite similar to that in Runs 2 and 3. Again, the addition of the noise to the system improves the system linearity and thus decreases the temperature error variations during steady state and constant temperature ramps.

Runs 1 to 7 were made to demonstrate the general performance of the On-Off temperature controller. Runs 8 to 27 are enclosed here to give some idea about the effects of parameter variations and were used in determining the final compensation values for the On-Off controller.

Runs 8 to 14 describe the effects of magnitude changes in the On-Off controller output circuit. The actual On-Off controller network along with a temperature ramp of $\dot{T}_{\text{SD}}=25^{\circ}\text{R}/\text{second}$ is used in Runs 8, 9, and 12, and the idealized model of the On-Off controller along with a temperature ramp of $\dot{T}_{\text{SD}}=50^{\circ}\text{R}/\text{second}$ is used in Runs 10, 11, 13, and 14.

In Runs 8 and 9, $\dot{\theta}_D = 1^{\circ}/\text{second}$, deadband (DB)=0 and the predictor network gain (g)=20. Run 8 has no noise and Run 9 has about 10°R rms noise added to the measured temperature.

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In Runs 10 and 11, the idealized analog computer model of the On-Off controller was used and the output and the deadband were the same as in Runs 8 and 9. In Run 10, there was no noise but about 10°R rms noise was added to T_g in Run 11. In Run 10, the temperature demand was ramped at about $50^{\circ}\text{R}/\text{second}$, and the transient peak temperature error is about 180°R . This is more than twice the corresponding error for the $25^{\circ}\text{R}/\text{second}$ ramp rate in Runs 8 and 9.

In Runs 12, 13, and 14, the On-Off controller output ($\dot{\theta}_D$) = $\pm 0.5^{\circ}/\text{second}$ and $\text{DB} = 0$. The actual On-Off controller network and a temperature ramp rate ($\dot{T}_{gD}$) = $25^{\circ}\text{R}/\text{second}$ is used in Run 12 and the idealized model of the On-Off controller with the ramp rate of $50^{\circ}\text{R}/\text{second}$ is used in Runs 13 and 14. Runs 12 and 13 are without noise, and in Run 14, approximately 10°R rms noise has been added to the measured temperature.

Because the output of the On-Off controller is a sequence of opposing polarity steps to the system, it is easy to visualize that within reasonable limits the steady state ripple magnitude in the temperature error is about proportional to the output magnitude of the On-Off controller. A glance to the recordings of Runs 8 and 12 will prove this statement. On the other hand, it is also easy to see from Run 13 that during the steeper transients (i.e., $50^{\circ}\text{R}/\text{second}$ temperature ramps) the On-Off controller, with $\dot{\theta}_D = \pm 0.5^{\circ}/\text{second}$, must stay at one position a long time. It has not quite enough power to effectively control the peak error during the transient. A considerably shorter time is spent on the clamp when the On-Off controller with $\dot{\theta}_D = 1^{\circ}/\text{second}$ is used. This indicates a better, faster control of the $50^{\circ}\text{R}/\text{second}$ transient as can be seen when comparing Runs 10 and 13. The Runs 12, 13, and 14 clearly show the marginal amount of control power when $\dot{\theta}_D = \pm 0.5^{\circ}/\text{second}$ for 50°R temperature ramp without noise and for 25°R ramp with noise. It seems that for a $25^{\circ}\text{R}/\text{second}$ ramp, $\dot{\theta}_D = \pm 0.5$ is adequate. It is evident that $\dot{\theta}_D = 0.5^{\circ}/\text{second}$ is not enough to control the existing transients in noisy conditions. From Run 11, we can see that the value $\dot{\theta}_D = \pm 1^{\circ}/\text{second}$ is much better. This is, as mentioned earlier, because the switching of the On-Off controller caused by the noise reduces the maximum control effort available from the controller. From this point of view, it seems quite clear that the value $\dot{\theta}_D = \pm 1^{\circ}/\text{second}$ is a better choice even if it causes about twice the steady state ripple than does $\dot{\theta}_D = \pm 0.5^{\circ}/\text{second}$.

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Runs 15 ($\dot{\theta}_D = \pm 1^\circ/\text{second}$, $DB=0$, no noise, $g=10$) and 16 ($\dot{\theta}_D = \pm 1^\circ/\text{second}$, $DB=0$, no noise, $g=30$) provide a comparison of the gain effects in the predictor network. In an ideal On-Off controller, where the slope of the controller output changes from infinity to zero instantaneously, the gain of the predictor network has no effect on the system performance.

However, in the diode circuit used for the On-Off controller minor differences are noted for different values of gain. This is caused, primarily, by the fact that the diodes do not provide hard limiting. For larger controller gains, the diodes are driven further into saturation, thus causing a slightly greater control effort. As seen from Runs 15 and 16 there is very little difference in system performance for the two values of gain. A gain of 20 was selected for the final NRX/EST system.

Runs 17 through 21 describe the effect of drastic changes of the controller time constants in the idealized On-Off controller when $\dot{\theta}_D = \pm 0.5^\circ/\text{second}$ and $DB=0$. In this case, (for the idealized controller) gain of the predictor network is immaterial. As seen from these runs no stability problems arise for these changes. This indicates that the implementation of this controller is not critical from a stability point of view.

In Run 17, without noise, and Run 18, with noise, the small lag time constant of 0.015 seconds is eliminated and we notice how the On-Off controller output becomes noisier within its switching region.

Runs 19, without noise, and 20, with noise, describe the system behavior when the lead time constant is decreased from 3 to 1 second. From Run 19, we can see that the anticipation of this 1 second predictor time constant is not quite enough. It allows the temperature error to oscillate more than if the time constant were 3 seconds.

Run 21, with no noise, describes what happens when the predictor time constant is increased to 10 seconds. This change from 3 seconds to 10 seconds does not seem to have much effect on the system performance. Therefore, it was decided to keep the 3 second predictor time constant because it requires smaller component values than the 10 second time constant. However, if the reactor system is to be run at low pressures, which cause low values of flow and thus a slower total system, it is advisable to increase the predictor time constant.

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The analog computer Runs from 22 to 27 were again runs with the actual, breadboard, On-Off controller. These runs were made to show how relatively insensitive the system performance is to changes in the controller. Runs 22 and 23 show that a small (about 10%) change in the predictor time constant does not significantly change the On-Off controller performance. The Runs 24 to 27, together with Runs 2 and 3, give an indication of the effect of deadband in the actual On-Off controller circuit. As explained earlier, it might be desirable to keep the deadband less than, or equal to, the maximum temperature error oscillations in quasi-steady state conditions when the deadband is zero. This is done in order to not increase the system errors unnecessarily.

Run 24, without noise, and Run 25, with noise, describe the system when the On-Off controller deadband is equal to $\pm 20^\circ\text{R}$. Run 26, without noise, and Run 27, with noise, describe the system where $\text{DB} = \pm 40^\circ\text{R}$. There were no significant differences discovered and a reasonable compromise was chosen with the deadband $\pm 30^\circ\text{R}$.

V. CONCLUSION

In the foregoing analog computer analysis, we have explored the proposed On-Off controller performance under varying circumstances, including those under which the On-Off controller is to be tested in the NRX/EST tests.

The proposed On-Off controller works satisfactory within the test conditions and also at most other tested conditions. Only if the On-Off controller is to be used at very low pressure and flow conditions where the plant is slow, is it recommended that the predictor time constant be increased from its presently proposed value of 3 seconds to larger values.

It was also found that the system is relatively insensitive to small changes in controller parameters which allows a reasonable tolerance in components chosen for the detail design and implementation.

TABLE OF RUNS

No.	Controller Network (Idealized or Actual)	$\dot{T}_{8D}$ ($^{\circ}\text{R}/\text{sec.}$)	T_{8D} Min. ($^{\circ}\text{R}$)	T_{8D} Max. ($^{\circ}\text{R}$)	Θ_D ($^{\circ}/\text{sec.}$)	DB ($^{\circ}\text{R}$)	Predictor Network gain g	10°R RMS Noise	Note
1	Linear controller								Reference Run
2	Act.	25	1700	2500	1	30	20	no	Step
3	Act.	25	1700	2500	1	30	20	yes	Step
4	Act.	0	2500	2500	1	30	20	no	Unslaved
5	Act.	0	2500	2500	1	30	20	yes	Unslaved
6	Act.	25	1700	4100	1	30	20	no	
7	Act.	25	1700	4100	1	30	20	yes	
8	Act.	25	1700	2500	1	0	20	no	
9	Act.	25	1700	2500	1	0	20	yes	
10	Id.	50	1800	2550	1	0		no	
11	Id.	50	1800	2550	1	0		yes	
12	Act.	25	1700	2500	0.5	0	20	no	
13	Id.	50	1850	2600	0.5	0		no	
14	Id.	50	1500	2550	0.5	0		yes	
15	Act.	25	1700	2500	1	0	10	no	
16	Act.	25	1700	2500	1	0	30	no	
17	Id.	50	1850	2600	0.5	0		no	$R_1 = 0$
18	Id.	50	1800	2600	0.5	0		yes	$R_1 = 0$
19	Id.	50	1850	2600	0.5	0		no	$C_2 = 1 \mu\text{f}$
20	Id.	50	1800	2600	0.5	0		yes	$C_2 = 1 \mu\text{f}$
21	Id.	50	1850	2600	0.5	0			$C_2 = 10 \mu\text{f}$
22	Act.	25	1750	2600	1	30	20	no	$C_2 = 3.3 \mu\text{f}$
23	Act.	25	1700	2500	1	30	20	no	$C_2 = 2.7 \mu\text{f}$
24	Act.	25	1700	2500	1	20	20	no	
25	Act.	25	1700	2500	1	20	20	yes	
26	Act.	25	1700	2500	1	40	20	no	
27	Act.	25	1700	2500	1	40	20	yes

T_D - Temperature Demand Signal.
 T_M - Temperature Measured Signal.
 $\dot{\theta}_D$ - Control Drum Velocity Signal.
 θ_D - Control Drum Position Signal.

Figure 1

On-Off Temperature Controller for NRM/TST
 (Actual Circuit)

Switching Control
Predictor Network

On-Off and Constant Velocity Actuator
Simulation Circuitry

Figure 2

Idealized Analog Computer Simulation of the On-Off

Temperature Controller for NRX/EST

Run 13 ●
Idealized model of On-Off controller network
slaved system, $1880^\circ\text{R} \leq T_{8D} \leq 2600^\circ\text{R}$, $T_{8D} = 50^\circ\text{R}/\text{Sec}$
 $|\dot{\Theta}_D| = 0.5^\circ/\text{Sec.}$, $DB = 0$, no noise.

Run 18 ■
Idealized model of On-Off controller, slaved system,
 $1800^\circ R \leq T_{8D} \leq 2600^\circ R$, $T_{8D} = 50^\circ R/Sec$.
 $\dot{\Theta}_D = 0.5^\circ/Sec$, $DB = 0$, $R_1 = 0$, about $10^\circ R$ RMS
noise added to T_8

Run 20 a
 Idealized model of On-Off controller, slaved system,
 $1800^{\circ}\text{R} \leq T_{8D} \leq 2600^{\circ}\text{R}$, $T_{8D} = 50^{\circ}\text{R}/\text{Sec}$,
 $|\dot{\Theta}_D| = 0.5^{\circ}/\text{Sec}$, $\text{DB} = 0$, $C_2 = 1\text{ }\mu\text{f}$ ($R_1 = 5\text{ k}\Omega$ as
 usual), approx mately 10°R RMS noise added to T_8

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