MASTER

Subcontract NP-1

WANL-TME-1976

October 31, 1969

Westinghouse Astronuclear Laboratory

XE PRIME POWER CONTROL

UNCLASSIFIED NERVA RESEARCH
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XE PRIME POWER CONTROL

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1.0 INTRODUCTION

This report describes the more salient features of the power control used on XE Prime. No attempt is made to compare the XE Prime controller with previous power controllers used on the ROVER Project. Emphasis is placed to show that the XE Prime power controller met all performance requirements without exception. The stability, bandwidth and static accuracy were sufficient to permit all of the engine performance maneuvers desired of XE Prime. These included 1) power holds, 2) power increase and decrease on short and long periods and 3) power control during bootstrap.

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2.0 DESCRIPTION

Reactor control may be placed in the power control mode at any time by operator choice, provided the nuclear flux loop has closed and there is not a power mode inhibit. The existence of a power mode inhibit (if active) prevents reactor control from being placed in the power control mode, until such time that the inhibit is either by-passed or the conditions causing the inhibit are no longer present.

In the power control mode, the power loop is closed, thereby using the logarithmic nuclear power as the controlled variable. A simplified block diagram of the power control loop is shown in Figure 1.

The reactor control drum position demand, Θ_D , is the output of the power controller in this mode. This signal positions the control drums so that the log power error ($1.25 \log N_E$) is reduced. The log power error is:

$$1.25 \log N_E = 1.25 (\log N_D - \log N_M)$$

where

N_D = power demand

N_M = power measured

$\log$ = base 10 logarithm

The control loop operates in a logarithmic manner. Since the nuclear kinetics gain is proportional to power level, making the feedback and demand signals proportional to the logarithm of power maintains an approximately constant loop gain regardless of power level.

The controller transfer function, $G_p(s)$, for the power control loop is:

$$\frac{\Theta_D}{1.25 \log N_E} = \frac{67 [1 + s/8.2 + (s/8.2)^2]}{s (1 + s/50)^2} \frac{\text{degrees}}{\text{volts}}$$

Also included in the Controller is a ± 45 degree per second velocity clamp.

Figure 1. Block Diagram Power Control Loop

The power control loop feedback signal may be the average signal from either the test stand control system (TSCS) nuclear detectors, or the engine control system (ECS) engine mounted nuclear detectors. The instrumentation associated with both the ECS and TSCS nuclear detectors is identical and contains logarithmic amplifiers and average/reject circuits. The logarithmic amplifiers condition and amplify the detector signals for the average/reject circuits. The average/reject circuits are redundant for both the ECS and TSCS systems. These average/reject circuits each average three logarithmic amplifier output signals and have the capability of automatically rejecting any one of the three signals from the average, if the signal deviates from the average by more than $\pm 20\%$ of the voltage equivalent of a decade of nuclear power. Only one channel may be rejected automatically. After automatic rejection of one channel, the automatic reject capability is disabled on the other two channels. As many as two of the input signals may be manually rejected, but no more than two may be simultaneously rejected by either manual or a combination of automatic and manual rejection. To further insure a dependable average measured logarithmic power signal, the averager outputs are auctioneered, presenting the highest of the two averages to the control system. In addition to taking the highest of the two averages, each averager output is compared with the nonrejected input signals. If the averager output signal is greater than the highest input that averager is rejected. After one averager is rejected, the other averager cannot be rejected. The combination of averager rejection and auctioneering to the highest averager output signal protects the system against both high and low malfunction of an averager. The range of the nuclear instrumentation is approximately 5 watts to 5500 megawatts.

The feedback signal desired for control purposes, ECS or TSCS average nuclear power, is chosen from the Lead Reactor Engineer's Console. The switch on the Lead Reactor Engineer's (LRE) Console, which determines the feedback, has been provided with an interlock to prevent feedback switching while operating in the power control mode. This interlock was provided to eliminate the possibility of a transient condition occurring because of feedback signal switching.

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3.0 PERFORMANCE MEASUREMENTS

The Log Power Controller performance was evaluated during EP-1/SL-2 and EP-1A. The results of this evaluation indicated that the power controller would meet all performance criteria of the XE-Prime test series.

3.1 Steady State

The static accuracy of the power controller was evaluated for time periods of power holds during EP-1/SL-2 and EP-1A. In each of the four time periods evaluated, the static accuracy was found to be between 1 and 2 percent of log power as a percent of operating point. This level of static accuracy was considered suitable for XE testing. The static accuracy was checked periodically throughout the XE-Prime test series and found to be constant within measurement accuracy of 1 to 2 percent.

The design analysis of the power controller was performed on an analog computer with an actual drum actuator used in the simulation. The drum actuator was operated in the actuator test laboratory and was connected to the analog. The analysis on the analog computer, using a single drum actuator, indicated that a power loop limit cycle would exist. The limit cycle was induced by the stiction of the drum actuator. It was believed that on the test article, with 12 drum actuators acting in parallel, the power loop limit cycle would be less than the amplitude observed on the analog computer. The reason for expecting the reduction in the limit cycle amplitude was the belief that the 12 actuators would not "jump" together, as was the assumed condition on the analog, but would act independently at different demand amplitudes and thereby decrease the amplitude of the effective drum jumps. However, in order to be assured that the power control loop performance would be satisfactory on the test article, the power controller was designed so that satisfactory performance was obtained on the analog computer using a single drum actuator.

Test data obtained during EP-1/SL-2 and EP-1A verified that a power loop limit cycle did exist. This limit cycle was carefully examined using the test data and found to agree (within measurement accuracy) with the predictions that were based on a single drum actuator. A comparison of prediction and test data is presented in the first row of Table I for steady state (infinite period) conditions. The close agreement between test data and the predictions is the result of very similar drum actuator characteristics; when these characteristics were similar no significant reduction in the effective amplitude of the drum jumps occurred.

Spot checks throughout the XE Prime test series indicated that this limit cycle remained approximately constant. Because the limit cycle is a result of the stiction in the drum actuators, the constant nature of this limit cycle is a good indication that the dynamics of the actuators are also constant.

TABLE I
SUMMARY XE-PRIME POWER CONTROL
LIMIT CYCLE

Period (Sec)	Amplitude ⁽¹⁾ (P-P% Power)		Frequency (Hz)	
	Prediction	Test ⁽²⁾	Prediction	Test ⁽²⁾
∞	2	4	0.4	0.33
5		6.5		0.7
4	7		0.7	
2	15	15.5	1.0	0.9

(1) Peak to peak change in watts as a percent of operating point

(2) Average value

3.2 Dynamic Response

Design analysis indicated that the power loop limit cycle would increase in amplitude and frequency when increasing power on a constant period for power ramps of greater than two decades. During the first two decades of power increase, the drums are moving to the position required to maintain the constant period, and the stiction induced limit cycle is not apparent. This limit cycle performance of the power controller is shown in Figure 2 where the power demand was increased on a 2 second period for approximately 3 decades during EP-1A. It is of interest to note that the limit cycle amplitude of the control drum position demand is approximately 0.5 degrees peak to peak. Data from EP-1/SL-2 and EP-1A were used to evaluate the cycle on constant period demand ramps and found to be in good agreement with predictions. Comparison data for constant period demands are shown in Table 1.

TEST STD POWER
PERIOD-VOLTS
NC817..N 3

Figure 2. XE EP1A Power Control Limit Cycle

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The stability margin and bandwidth of the power controller were tested by inserting small signal transients in the log power controller during EP-1A at an operating condition of 100 KW. From this transient data frequency response information was obtained. A Bode plot of the corrected data (See Appendix I)* is included as Figure 3.

It can be seen that the system is essentially as predicted with a bandwidth of approximately 0.8 Hz. The Nichols Chart, Figure 4, of these data shows the phase margin to be 70° and the gain margin to be greater than 20 db.

* It should be noted that the data used in Spear report EP-1A memo 10 was not corrected for the effect discussed in Appendix I.

Figure 3. XE-Prime Log Power Response (Meas. to Demand) Data from EP-1A

Figure 4. XE-Prime Log Power Response (Meas. to Demand)
Data from EP-1A Indicated Frequencies in HZ

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4.0 SUB-CRITICAL OPERATION

The third start-up during EP-IIA included 4.5 seconds of operation in power control with the drums at a sub-critical position. This resulted from making a nuclear autostart with power demand less than a decade above the existing decay power. The nuclear autostart drum program was terminated with the drums at 93° (cold critical 100.1°) by the power loop closing. The demanded 5 second period was maintained even though the drum angle did not equal the cold critical angle until 4.5 seconds later.

A study of these data indicated that the control mechanism was sub-critical neutron multiplication, and that this phenomenon might be utilized for a rapid restart with closed loop power control. This possibility was examined utilizing an analog three group log kinetics model. The analog studies showed that the sub-critical neutron multiplication will provide sufficient control for any sequence of operation provided that power demand is less than or equal to the measured decay power at the time control is selected and the demanded power increase is made on a two second or greater period. The analog predictions indicated that starting with the demand several decades below the measured power and then increasing the power demand on a two second period to a level two decades above the initial power would result in a minimum period of 0.833 seconds for approximately 0.5 seconds and a maximum drum velocity of $36^\circ/\text{sec}$.

The operational sequence that would yield the quickest nuclear restart would be:

- 1) Set power demand slightly below measured decay power
- 2) Select power control
- 3) Increase power demand to desired level on a two second period.

The analog studies cited above indicate that this sequence would result in a smooth, fast and safe restart. However, this method is a significant departure from previous power control operations and it was decided to approach this operation with caution.

The transients (power and drum position) can be reduced by either increasing the period or starting the power demand ramp with the drums near the critical angle. The operational sequence below was devised to permit starting with the drums at some angle between zero and the critical angle.

- 1) Manually set the control drums to the desired initial angle.
- 2) Null the power controller error by adjusting the power demand to equal the measured power.
- 3) Select power control.
- 4) Increase power demand on a desired period to a desired power level.

Four such runs were made during the post EP-5C xenon test as summarized in Table 2.

TABLE 2
SUMMARY SUB-CRITICAL OPERATION

<u>Demanded Period (In Seconds)</u>	<u>Initial Drum Angle (In Degrees)</u>	<u>Minimum Period (In Seconds)</u>	<u>Max. Drum Vel. (In Deg/Sec.)</u>
5	47	2.9	9.3
2	57	1.16	16
5	32	3.0	13
2	38	1.13	24

The two runs made with the two second period are good demonstrations of the power controller's capabilities while operating sub-critical. These two runs are included as Figures 5 and 6. Figure 5 is a plot taken directly from the data tapes*; whereas Figure 6 is a composite made from data tapes and data taken from the EP-5C SPEAR report.

For comparison, a plot of the prediction run that corresponds to the test run of Figure 6 is included as Figure 7. Prediction comparison was chosen for this run as it was the most severe run performed (i. e., shortest period demand coupled with a start with drum angle furthest from the cold critical angle). The shortest period in the prediction was 1.07 sec, whereas the shortest period experienced for this run during the actual test was 1.13 sec.

* Duplicate tapes delivered to WANL

PWR DEMO GEN
- LOGWATT
CC629..E 4

AVG TEST STD LOG
PWR-LOGWATT
NC815..N 5

Figure 5. XE-Prime EP-5C
Sub Crit Power Control

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Figure 6. XE-EP-5C Sub Crit Power Control

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Figure 7. Prediction of Sub-Critical Control
 $T_D = 2$ Sec, Start at $\theta_M = 40^\circ$

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The only significant differences between the prediction run and the actual test run are in the amount of power rise and in the critical drum angle set in the analog model (analog 80° ; actual 98°). It should be noted, however, that the positions relative to the critical angle are in good agreement.

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5.0 MODE LOGIC

The XE Prime mode logic was constructed such that if either temperature or program was selected while in power control, the drum control would transfer to temperature as soon as chamber temperature reached temperature loop closure (TLC) set point. However, if program was selected, the power demand generator would not transfer to follow-up until the system transferred to program (TLC and pressure null both satisfied).

The result of this method of implementation makes it possible to be in temperature control without the power demand generator being in follow-up. In the example shown in Figure 8 had the system been transferred from temperature control to power control the resulting drum transient could have resulted in a scram or other unsatisfactory condition.

To minimize the possibility of unwanted transients, it is required that a demand source either be "in control" or in "follow-up" (i.e., tracking measured quantity). It is recommended that the possibility of switching errors of this nature be carefully guarded against in all future designs.

6.0 CONCLUSIONS

The XE Prime power controller met all performance requirements without exception. Early in the test series, the performance characteristics were determined and it was concluded that the phase margin (70°), gain margin (~ 20 db), bandwidth (0.8 Hz) and the static accuracy (1 to 2 percent) were sufficient to permit all of the engine performance maneuvers desired of XE Prime.

The controller compensation was selected to maintain stability if known drum sticktion induced a limit cycle in the power control system. The limit cycle did occur and the controller held the power peaks in watts to 2 percent of the operating point for steady state conditions and 7.5 percent of the operating point while operating on a sustained two second period.

Late in the test series, a test was planned and conducted to evaluate the controllers capabilities while operating with the drums sub-critical and relying on decay power and sub-critical neutron multiplication for control. This test was successful and indicates that the power controller could be utilized in a fast restart procedure.

PWR DMND GEN
- LOGWATT
CC629..E 1
AVG TEST STD LOG
PWR-LOGWATT
NC815..N 2

Figure 8. XE-Prime EP-7 Power Demand
Generator Error

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6.0 CONCLUSIONS

The XE Prime power controller met all performance requirements without exception. Early in the test series, the performance characteristics were determined and it was concluded that the phase margin (70°), gain margin (~ 20 db), bandwidth (0.8 Hz) and the static accuracy (1 to 2 percent) were sufficient to permit all of the engine performance maneuvers desired of XE Prime.

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APPENDIX I

The XE Prime power controller is equipped with an auxiliary input. This input is used to insert perturbations into the system for performance testing. The scaling of this input is such that a full scale test signal (15 V) would cause a power change in watts of only 43.5 percent of point. During normal operation, the auxiliary input is grounded in order not to affect power control operation.

A block diagram of the power control system would appear as Figure A1.

FIGURE A1

where:

- A is the test perturbation signal input
- B is the normal demand input
- $K_1 G(s) 1$ represents the power controller forward loop compensation
- $K_2 G(s) 2$ represents the system from drum demand to measured log power

Y_1 is the transfer admittance of the test input

Y_2 is the transfer admittance of the feedback and normal input

The data taken during EP-1A represents the frequency response from A to C. To determine the stability margin and bandwidth of the operating system, it is required that the response from B to C be known. The correction factor can be determined by considering the equivalent block diagram of Figure A2.

FIGURE A2

It can be seen from Figure A2 that to convert A to C response data (R_{A-C} to B to C response (R_{B-C}), Equation 1 should be used.

$$R_{(A-C)} \left(\frac{Y_2}{Y_1} \right) = R_{(B-C)} \quad (1)$$

The data as processed accounted for only the d. c. gain difference and did not include the frequency variant part of this conversion. It is necessary, therefore, to convert only the a. c. part which modifies Equation 1 to:

$$R_{(A-C)} \left(\frac{Y_2 (ac)}{Y_1 (ac)} \right) = R_{(B-C)} \quad (2)$$

For the XE-Prime power controller

$$\frac{Y_2 (ac)}{Y_1 (ac)} = \frac{1 + \frac{S}{8.2} + \left(\frac{S}{8.2} \right)^2}{\left(1 + \frac{S}{6.66} \right) \left(1 + \frac{S}{50} \right)} \quad (3)$$

A Bode plot of this correction factor is included as Figure A3

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Figure A-3. Correction Curve for Power Controller Frequency Response