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MASTER

LOFT PUMP SPEED CONTROLLER STABILITY AND
ACCURACY ANALYSIS

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DEPARTMENT OF ENERGY

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LOFT TECHNICAL REPORT
LOFT PROGRAM

FORM EG&G-229
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ABSTRACT

Two system modifications to the primary coolant pumps motor generators control systems have recently been completed. The range of pump speed operation has been extended and the scoop tube positioner motor replaced. This has necessitated a re-analysis of PSMG stability throughout its range of operation. System accuracy requirements of less than 4 Hz differential pump speed when operating at less than 35 Hz and 8.5 Hz differential pump speed when operating at greater than 35 Hz can be guaranteed by specifying the gain of the system. The installation of the new scoop tube positioner motor will increase the PSMG system's bandwidth and stability. Low speed pump trips should be carefully evaluated if the pump's operational range is to extend to 10 Hz.

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SUMMARY

The speed of the LOFT primary coolant pumps is regulated by the pump speed motor generator (PSMG) controller. Extending the low operational range of the pumps to 10 Hz has been proposed. This document is an analysis of the effects of that range extension on the stability and controllability of the pumps. Attention is directed to the probability of inadvertent low speed pump trips during low pump speed operation. The stability and controllability analysis is based on transfer functions derived in "LOFT Pump Speed Motor Generator Controller Frequency Response Analysis", LTR 144-12. Those transfer functions have been modified to account for the installation of a new, faster scoop tube positioner motor. The bode plots of the transfer functions have been recalculated for time constants typical of the new system components.

The results of the analysis indicate that a reset time of one minute and a proportional band of 260% will enable the system to meet the required accuracy of less than 4 Hz differential pump speed when operating at less than 35 Hz, and less than 8 Hz differential pump speed when operating at greater than 35 Hz. The observed accuracy of ± 0.48 Hz (2σ limits) for the pump low speed trip should be utilized when setting the trip set point.

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LOFT PUMP SPEED CONTROLLER STABILITY AND ACCURACY ANALYSIS

1.0 INTRODUCTION

The pump speed motor generator (PSMG) controllers regulate the speed of the primary coolant pumps. There is one for each pump. The PSMG controllers must maintain stable operation of the pumps between 15 Hz and 65 Hz pump speed. The PSMG controllers must also maintain a maximum of 4 Hz differential pump speed when operating less than 35 Hz, and a maximum of 8.5 Hz differential pump speed when operating at greater than 35 Hz. (See Appendix A.) The extension of pump speed operation to 10 Hz has been proposed, requiring the review of the pump low speed trip, and PSMG stability during low speed operation. Recently the system has been modified by the replacement of the scoop tube positioner motor, resulting in the need for a re-analysis of PSMG stability throughout its range of operation. The original analysis of this system was performed by H. R. Hansen and is documented in "LOFT PSMG Controller Frequency Response Analysis", LTR 144-12^[1].

2.0 DISCUSSION

2.1 System Transfer Functions

A derived set of system transfer functions^[1], is shown in Figure 1, a block diagram of the PSMG system.

Fig. 1 Block diagram of PSMG controller system.

K_1	gain of controller units 4 mm/volt
K_2	gain of scoop tube insert units 6.25%/hr
K_3	$\Delta T/\Delta X \theta = c$ units $\frac{\text{ft lbs}}{\%}$
K_T	tachometer gain 0.0429 units volt-s/rad
T_1	reset time on the controller units min
T_2	time for 90° insertion on scoop tube units min
T_3	$J/B_1 + B_2$ where J = moment of insert of generator and flywheel units min
B_1	T/θ units ft-lbs-s
B_2	$\Delta T/\Delta \theta x = c$ units ft-lbs-s

Block #2 contains the term T_2 , the time delay associated with the positioner motor. T_2 in the previous analysis was equal to 1 min in the worst case; now T_2 is equal to 15 s in the worst case. The only terms in the block diagram which are under the direct control of the system

engineer are T_1 and K_1 , the reset time and proportional band of the two mode controller (Block #1 in Figure 1).

The problem is to determine values for these coefficients to satisfy the accuracy and stability requirements of the system. The previous analysis recommended for normal and worst case, respectively, reset times of 1.5 min and 1 min, and proportional bands of 150% and 316%. The change of the scoop tube positioner motor will allow the increase of system accuracy and bandwidth.

The positioner motor's transfer function is contained within Block #2 and is the only nonlinear transfer function in the system description. Bode plots of the nonlinear transfer function for varying values of T_2 are given in Figure 2. The phase of this transfer function decreases at all frequencies as T_2 decreases causing the system increased stability at higher frequencies. The gain of the transfer function is approximately one throughout the range of interest (10 rad/min). Thus this nonlinear function may be approximated by a transfer function with gain of one and phase characteristics from Figure 2. A gain of unity must be conservative when analyzing system stability, as the real gain is always less than one.

2.2 System Stability and Accuracy

A sufficient criteria for insuring system stability is that the system gain be less than one when the phase shift is 180 degrees or greater. Figures 4 through 9 present bode plots of the system transfer function. The plots include both worst and average case T_2 values. Table I summarizes the required proportional bands such that system gain equals one when phase shift equals 180 degrees. If the system gain is less than the value in Table I the system will remain stable. The values in Table I are conservative, as the transfer function of Block #2 was assumed equal to one.

A further analysis of system stability is given in Figures 3 and 4, bode plots of system performance at 10 Hz with reset times of 1 min and

Fig. 2 Bode plot of scoop tube position transfer function.

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TABLE I

PROPORTIONAL BANDS THAT YIELD $K_{loop} = 1$ at 180°

Frequency	100 ft-lb		250 ft-lb		1000 ft-lb		2000 ft-lb		2500 ft-lb	
	$T_2=0.25$	$T_2=0.042$	$T_2=0.25$	$T_2=0.042$	$T_2=0.25$	$T_2=0.042$	$T_2=0.25$	$T_2=0.042$	$T_2=0.25$	$T_2=0.042$
10 Hz	n.c.	n.c.	70%	16%	251%	70%	254%	99%	n.c.	n.c.
15 Hz	n.c.	n.c.	56%	10%	158%	35%	n.c.	n.c.	160%	89%
30 Hz	n.c.	n.c.	71%	14%	141%	35%	n.c.	n.c.	158%	79%
45 Hz	n.c.	n.c.	71%	7%	63%	22%	n.c.	n.c.	100%	45%
60 Hz	n.c.	n.c.	25%	4.5%	71%	18%	n.c.	n.c.	75%	53%
75 Hz	20%	4%	n.c.	n.c.	50%	18%	n.c.	n.c.	18%	14%

n.c. = not calculated

Fig. 3 Bode plot of PSMG system, pump speed = 10 Hz, reset time = 15 second.

Fig. 4 Bode plot of PSMG system, pump speed = 10 Hz, reset time = 1 minute.

Fig. 5 Bode plot of PSMG system, pump speed = 15 Hz.

Fig. 6 Bode plot of PSMG system, pump speed = 30 Hz.

Fig. 7 Bode plot of PSMG system, pump speed = 45.Hz.

Fig. 8 Bode plot of PSMG system, pump speed = 60 Hz.

Fig. 9 Bode plot of PSMG system, pump speed = 75 Hz.

0.25 min, respectively. There is no essential difference between the two bode plots, hence, the system is insensitive to changes in reset time. The previous analysis of this system reached an equivalent conclusion regarding system sensitivity to reset time at higher frequencies.

The system accuracy requirements (Appendix A) of less than 4 Hz differential pump speed when operating at less than 35 Hz and 8.5 Hz differential pump speed when operating at greater than 35 Hz can be guaranteed by specifying the gain of the system^[2]. The PSMG system with a pole at zero, has zero steady state error to a step input, a finite steady state error to a ramp input and infinite error to a parabolic input. The integral of the transient error to a unit step input equals the steady state error to a unit ramp input. Hence, the steady state error to a unit ramp input must be less than the allowable system uncertainty.

$$E_{rss} = \frac{1}{K_{loop}} \quad (1)$$

where

E_{rss} = steady state error to a ramp input

K_{loop} = closed loop gain

E_{st} = transient error to stop input

$$\int_0^{\infty} E_{st} = E_{rss} \quad (2)$$

The minimum loop gain may be determined by setting E_{rss} equal to the desired accuracy. It is assumed that the uncertainty in one speed regulating system is independent of that in the other. Solving for the maximum allowable uncertainty in one system yields:

$$\sqrt{x^2 + x^2} = 4 \text{ Hz}$$

$$x = 2.83 \text{ Hz}$$

$$\sqrt{x^2 + x^2} = 8.5 \text{ Hz}$$

$$x = 6.01 \text{ Hz}$$

where

x = uncertainty in one system.

Solving Equation (1) for the minimum acceptable gain where

$$E_{\text{rss}} = \frac{1}{K_{\text{loop}}}$$

let

$$E_{\text{rss}} = 2.83 \text{ Hz}, 6.01 \text{ Hz}$$

then

$$K_{\text{loop}} = 14.58 \text{ DB}, 8.03 \text{ DB}$$

Thus, the minimum acceptable gain for a guaranteed error of less than 4 Hz differential pump speed to a unit ramp input is 14.58 DB. The system gain is usually less than 14.58 DB. Therefore, it is recommended that the maximum rate of change of pump speed be limited to 14 Hz/min when operating at less than 35 Hz and 29.7 Hz/min when operating at greater than 35 Hz. The preceeding limits of the rate of change of pump speed will allow the loop gain to be as low as zero DB. All normal system operating points are in excess of zero DB gain. Hence, system accuracy is assured at all times. This analysis does not include uncertainties associated with pump instrumentation. These uncertainties have been treated in a separate analysis, TREE-NUREG-1089, Volume 17^[3].

2.3 Low Speed Pump Trip

The extension of the pump's operational range requires a re-evaluation of the pump low speed trip accuracy and repeatability. The installed low speed trip relay is an ACROMAG Model #372-5-1. (The manufacturer's specifications are included as Appendix B.) Assuming independence between uncertainty sources, the root sum square method may be applied to obtain an overall expected accuracy:

$$\begin{aligned}
 \text{Trip point repeatability } \pm 0.1\% &= \pm 0.1\% \\
 \text{Temperature effect } \pm 0.02\%/^{\circ}\text{F} \times 20^{\circ}\text{F} &= \pm 0.4\% \\
 \text{Line voltage effect } \pm 0.1\% (\pm 10\% \text{ voltage}) &= \pm 0.1\% \\
 0.1^2 + 0.4^2 + 0.1^2 &= \pm 0.42\% \text{ of } 0\text{-}40 \text{ volts range} \\
 &= \pm 0.17 \text{ volts} \\
 &= \pm 0.32 \text{ Hz}
 \end{aligned}$$

Data from the last four LOFT blowdowns are presented in Table II.

TABLE II
PUMP LOW SPEED TRIP DATA

<u>Test</u>	<u>Pump #1 Trip^[a]</u>	<u>Pump #2 Trip^[a]</u>
L1-1	11.88 Hz	12.28 Hz
L1-2	12.24 Hz	12.35 Hz
L1-2	12.06 Hz	12.59 Hz
L1-3	11.9 Hz	12.24 Hz
L1-3A	12.34 Hz	12.3 Hz
L1-4	12.48 Hz	12.65 Hz ^[a]
Mean	12.15 Hz	12.40 Hz
Standard Deviation	0.24 Hz	0.17 Hz

[a] Trip point set at 12.5 Hz

The observed accuracy of ± 0.48 Hz and the predicted accuracy of ± 0.32 Hz agree. Significant improvements in the accuracy of the pump low speed trip are probably not possible, thus, a pump low speed trip accuracy of ± 0.48 Hz is recommended for analysis purposes. The extension of pump operational range offers no foreseeable difficulties in the operation of pump low speed trip.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The installation of the new scoop tube positioner motor, will increase the PSMG system's bandwidth and stability. A proportional band of 260% and reset time of one minute is recommended to assure system stability under all operating conditions. The proportional band may be lowered to the values specified in Table I if the requisite system conditions are met. Zero steady state uncertainty for step inputs is guaranteed due to the system configuration. However, to minimize uncertainties occurring during transients, limits of 14.4 Hz/min. when operating at less than 35 Hz and 29.7 Hz/min when operating at greater than 35 Hz are suggested. The pump low speed trip observed accuracy is ± 0.48 Hz (2σ limits). Careful evaluation of the possibility of low speed pump trips is recommended if the pump's operational range is to be extended to 10 Hz.

4.0 REFERENCES

1. H. R. Hansen, LOFT PSMG Controller Frequency Response, LTR 144-12 (December 1977).
2. K. Ogata, Modern Control Engineering, Englewood Cliffs, N. J.: Prentice Hall, 1970.
3. G. L. Biladeau, L. D. Goodrich, Jr., P. A. Quinn, LOFT Experimental Measurements Uncertainty Analyses, Volume XVII "LOFT Uncertainty Analysis of Process Information Recorded on Data Acquisition and Visual Display System", TREE-NUREG-1089, (to be published).

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APPENDIX A

SPECIFICATION OF PRIMARY COOLANT PUMP OPERATING CONDITIONS

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Aerojet Nuclear Company

Interoffice Correspondence

December 26, 1974

L. A. Cook
TAN 630

SPECIFICATION OF PRIMARY COOLANT PUMP OPERATING CONDITIONS - Hmb-168-74

- References:
- (1) ANC letter Hmb-88-73, H. M. Burton to L. A. Cook, 7-16-73, TAR 00012
 - (2) ANC letter LAC-45-73, L. A. Cook to H. M. Burton, 9-27-73, TAR 00012 and TAR 00025
 - (3) ANC letter COD-8-73, C. O. Doucette to H. M. Burton, 12-19-73, IP-01.01-CF, Items Requiring Design Engineering Action

Reference (1) presented a partial set of resolutions to technical questions relative to IP-01.01-CF, Primary System Initial Fill Procedures. Item Nos. 11 and 18 pertained to the requirements for simultaneous starting or operation of the two primary coolant pumps (PCP's). Reference (2) reiterated the need for determining firm PCP starting and operating characteristics. The PCP parameters presented herein are the results of extensive analytical effort by R. A. Livingston and are intended to resolve the remaining TAR items pertaining to PCP operation. In addition, this same information will resolve items 3a through c and 8 of Reference (3).

The unresolved TAR items, Numbers 11 and 18, are repeated below to aid in review of the information presented herein:

- 11. Per letter Hmb-58-73, primary coolant pumps must be started simultaneously through use of mechanical or electrical interlocks on the starting devices. An ECRA specifying these interlocks needs to be issued. Since the interlocks are needed on the generator field breakers, the reactor safety implications of these interlocks must also be evaluated. Is it also necessary to stop the pumps simultaneously? (Refer to precautions and Limitations 4.1)
- 18. Per Hmb-58-73, primary coolant pump speeds must be ramped simultaneously. An ECRA is needed to incorporate any plant modifications which are necessary to provide this capability. (Refer to Section 6.5.8)

PCP starting and operating requirements are as follows: All frequencies quoted refer to the individual generator frequency indications and the parenthetical speed is for the pump rotor.

- 1. Maintain the pressure-temperature envelope transmitted in letter HLC-770-73, 7-9-73.
- 2. The two pumps should be operated as a unit for normal conditions. The normal startup and shutdown of each pump does not need to occur precisely simultaneously, and mechanical or electrical interlocks on the generator

field circuit are not required. The maximum desirable delay for initiating action for the second pump should be approximately 5 seconds. When starting or stopping the PCP's, the speed of each should be adjusted to or preset to start at 36 ± 2 Hz (2130 ± 118 rpm). Pump shutdown shall be initiated by opening the generator field circuits (no flywheel coastdown).

3. Jogging of only one pump for venting procedures is permissible for periods up to 5 seconds at speeds of 36 ± 2 Hz (2130 ± 118 rpm). This type of operation, however, is very inefficient for sweeping air around the system to the high point vents because of the excessive amount of bypass flow through the idle pump. For this reason, it is recommended that all jogging be conducted with both PCP's.
4. Changes in the steady state operating speed of the pumps must be incremental so that the differential speed does not exceed 8.5 Hz (500 rpm) when adjusting speeds from 34 Hz (2012 rpm), or greater. For adjusting speeds below 34 Hz, the differential speed shall not exceed 4 Hz.
5. If one of the two operating pumps is inadvertently de-energized (either with the generator field circuits open or in the flywheel coastdown mode as electrically coupled to the generator), the operating pump shall be stopped by de-energizing the motor-generator set and allowing the flywheel coastdown transient. This situation shall be an Emergency Condition and action for stopping the operating pump shall be taken as soon as possible.
6. Minimum powered speed shall be 15 Hz (887 rpm) for the lower speed of the two pumps. During a coastdown with the motor-generator sets, the generator field circuit shall be opened when the indicated speed is in the range of 15 to 20 Hz (887 to 1183 rpm). As an aid to operator action during a loss of flow (loss of site power) situation, the I&C design group will provide a low frequency alarm to signal the approach of the coastdown frequency to the above minimum value. This alarm shall be actuated from a frequency source other than the present visual indicators to assure redundancy and thus avert a premature shutdown of the PCP's because of an erroneous frequency signal. Design activity for electrical brakes or constant speed PCP operation during post-LOCE reflood periods will not be initiated until firm programmatic criteria are established.

The following information summarizes the technical justification or conclusions reached in analyzing the varying pump operating modes and in specifying the operating conditions itemized above. The limitation that requires operating both PCP's together is based upon generally accepted "good" or "verified" practice for operation of parallel pumps. This general rule results in either pump antireverse rotation devices or a system piping arrangement with either shutoff or check valves on the pump discharge line. In either case free-rotor "windmilling" of the idle pump is prevented and thus the requirement for a starting torque value to overcome reverse direction flow and pump inertia does not exist. The LOFT pumps were originally designed for parallel operation in the SPERT III loop where the discharge lines each contained check valves, and, therefore, the design did not include antireverse rotation devices. The initial LOFT primary coolant system modeling parameters did not allow the use of check valves. Information developed for an equivalent circuit analysis of

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the pump motor capabilities and presented as Figure 1 when compared with pump operating characteristics, presented in Figures 2, 3, and 4, shows that sufficient torque is available to start the free-wheeling pump when the operating pump speed is no greater than approximately 60 Hz (3550 rpm).

The proper performance of the internal thrust bearing is another factor which restricts single pump operation. As the non-operating pump windmills, the resulting bypass flow through this pump in the reverse direction lowers the effective system resistance. Because of this lower flow resistance, the operating pump capacity increases to a flow of 132% of the design value when operating at only 50.7 Hz (3000 rpm). This value was obtained from Figure 3 and coupled with the data of Figure 5, this critical pump speed is determined to be a maximum from the thrust bearing loading which equals the maximum calculated design capacity. Secondly, the windmilling operation of the nonpowered pump must be a sufficiently high enough speed to produce a hydraulic bearing force capable of supporting the combined hydraulic thrust load and rotor weight, and thus preventing rubbing of the Graphitar thrust pads. Operation of one pump at 34 Hz (2012 rpm) produces a reverse direction free rotation (windmilling) of the nonpowered pump at approximately 1400 rpm. The thrust bearing load capacity at this speed is sufficient to prevent rubbing of the Graphitar thrust pads. Rubbing will occur during periods of pump low speed operation (as during startup and shutdown). Rubbing which exceeds periods of 5 seconds will remove the essential slight crown of 0.0002" on the Graphitar thrust pads.

With both PCP's operating, a coastdown of both pump motors from the generator flywheels is allowable during a LOCE/LOCA to a minimum speed range of 15 to 20 Hz (887 to 1183 rpm). Under the condition of both PCP's operating at the start of either a loss of flow situation or a blowdown, the hydrodynamic load carrying capability of the thrust bearing is sufficient for the hydraulic rotor thrust and the rotor weight combination. Below this speed range, the generator field circuit must be de-energized which allows the rapid coastdown of the PCP motors.

It is anticipated that the above PCP information, plus supplemental information requested in Reference (3) and reviewed during the meetings the week of January 14, 1974, will resolve the previous areas of concern and allow finalization of the IP test procedures. Any further questions may be directed to myself or J. P. Kester, extension 6268.

H. M. Burton, Manager
LOFT Technical Support Branch

JPK:dw

Attachments: As stated

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APPENDIX B

SPECIFICATIONS FOR ALARM RELAYS

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specifications for alarm relays:

372-S-1 Single Point Alarm Relay—SINGLE

372-D-1 Dual Point Alarm Relay—DUAL

INPUT RANGE (Selectable)	INPUT RESISTANCE
1-5 Ma. DC	200 ohms
4-20 Ma. DC	50 ohms
10-50 Ma. DC	20 ohms
0-1 Volt DC	10,000 ohms min.

NOTE: All four input ranges listed at left built into all models as standard to fit normal alarm relay applications.

OUTPUT: SPDT relay, contacts rated at 2 Amperes, 117 V AC, resistive. DUAL has two relays. Optional Hermetically Sealed Relay, available at extra cost.

ADJUSTMENTS: Trip point continuously adjustable from 0% to 110% of span, nominally, using 20-turn metal film potentiometer, screwdriver set. DUAL uses two 20-turn potentiometers, fully independent.

DEADBAND is continuously adjustable from 1% to 10% of span, nominally, using a single potentiometer, screwdriver set. DUAL uses two DB. ADJ. potentiometers, fully independent.

ACCURACY:

For Constant Conditions: Trip Point repeats within $\pm 0.1\%$.

Temperature Effect: Less than $\pm 0.02\%$ per $^{\circ}\text{F}$ of span from 32°F to 122°F (0-50

Line Voltage Effect: Less than $\pm 0.1\%$ of span for a $\pm 10\%$ change.

DUAL, less than $\pm 0.2\%$ for $\pm 10\%$ change.

RESPONSE: Nominally 150 milliseconds when driven 5% of span beyond set point.

TEMPERATURE: 0-50 $^{\circ}\text{C}$ (32° - 122°F) Operating, -40°C to 85°C storage.

POWER REQUIREMENTS: 117 Volts $\pm 10\%$, 50 to 500 Hz; SINGLE 3 Watts, DUAL 5 Watts nominal.

REFERENCE: Dual-regulated temperature compensated Zener supply, built-in.

CALIBRATION: Units are shipped from the factory with all range resistors built-in for all four input ranges. User field-selects desired input range in less than one minute by cutting jumper wires on circuit board. Trip point is then calibrated by first setting the DB. ADJ. potentiometer(s) to minimum, then applying input signal(s) at desired trip level(s) and adjusting TRIP SET potentiometer(s). DB. may be increased for greater noise rejection, as desired.

SHIPPING WEIGHT: 5 pounds (3 pounds net).

WARRANTY: Standard Acromag One Year Repair Warranty.

LIST PRICES: See Bulletin 2-005.9, "Alarm Relays - Selection and Ordering Guide."

Prices include standard domestic packing and one set of instructions.

TERMS: Net 15 days, F.O.B. Factory.

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