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SUMMARY

Electropneumatic control drum actuators, capable of operating with either gaseous helium, nitrogen, or hydrogen as a working medium, are being used in the NERVA engine test program. Low-temperature testing of the actuator has been limited to using helium as a working medium. To gain further confidence in actuator performance in the 30 to 80 K temperature range, a test program using gaseous hydrogen was conducted. For the test program, actuator performance was measured in terms of its ability to function in a closed loop positioning system.

The results of the test program showed that the actuator tested, while in continuous operation, performed satisfactorily when subjected to step changes in temperature from ambient to the 30 to 80 K range. The step changes in temperature include lowering both the coolant gas temperature while holding the drive gas at ambient temperature, and lowering both the drive and coolant gas temperatures.

The test program also showed, for the actuator tested, that if the actuator is locked in one position and then subjected to a step change in temperature to the 30 to 80 K range, performance after unlocking is erratic.

Also, for the actuator that was tested, locking operation was erratic during the first test when the actuator was operated with both cryogenic coolant and drive gas. However, the lock mechanism was

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replaced and no further erratic performance was noted that was associated with the locking mechanism.

INTRODUCTION

The power level of a nuclear reactor is controlled by varying its reactivity. In the NERVA engine, variation in reactivity is accomplished by rotating control drums, changing the amount of reflecting surface exposed to neutron generation from the reactor core. A control drum actuator is used to rotate the control drums. The actuator for the NERVA engine is an electropneumatic device, capable of operating with either gaseous helium, nitrogen, or hydrogen as a working medium.

The control drum actuators to be used in the NERVA engine test program are expected to be subjected to a cryogenic gaseous hydrogen environment of 30 to 80 K. Exhaustive low-temperature testing in this range has been performed using gaseous helium as a working medium (refs. 1 and 2). However, extensive low-temperature testing using gaseous hydrogen had not been conducted. To obtain further confidence in actuator performance using gaseous hydrogen, a test program was initiated at the Lewis Research Center. For the test program, actuator performance was measured in terms of its ability to function in a closed loop positioning system.

This memorandum presents a description of the test program undertaken and the data acquired from the testing.

EXPERIMENT EQUIPMENT DESCRIPTION

Actuator

The control drum actuators used in the NERVA test program are electropneumatic devices which convert an electric input signal into rotational output motion. Figure 1 shows a cross-sectional and cutaway view of the actuator. The basic components in the actuator are a torque motor, servo-valve, piston assembly and rack and pinion. The torque motor is a 2-coil permanent magnet type with the coils connected in parallel. The torque motor converts the electric input signal into a mechanical force capable of driving the servo-valve. The servo-valve is a two-sided, single-stage, 4-way valve with dynamic pressure feedback. Drive gas is supplied to the servo-valve at a constant pressure of 215 psia (148 N/cm^2). The servo-valve is designed to operate using ambient or cryogenic helium or hydrogen drive gas. Drive gas is ported by the servo-valve to opposing pistons that are attached to each end of a rack. A pressure differential across the pistons results in motion of the pistons and rack. The rack engages the pinion gear of the output shaft to change the linear piston motion into rotational output motion. A bearing and spring arrangement is used to maintain continuous engagement between rack and pinion. The pinion gear is supported by two radial ball bearings to provide optimum support for the rack and pinion assembly. Helical springs are located inside the pinion gear to provide soft mechanical stopping at the extremities of the output shaft travel and to limit load rebounding in response to changes in output shaft position.

A feedback potentiometer is coupled to the output shaft to provide continuous monitoring of the output shaft's relative position. The potentiometer is a 3-cup, conductive plastic rotary type with 2 cups electrically connected in a redundant feedback circuit.

A double locking mechanism is provided to prevent inadvertent operation of the acturator. The locking mechanism consists of a key-operated manual lock and a remote controlled pneumatic lock.

Coolant gas is supplied to the actuator to control component heating caused by the radiation environment. The coolant is supplied to the acactuator through a filter that surrounds the actuator output shaft. The coolant gas pressure is maintained at 650 psia (449 N/cm^2). The actuator housing is sealed with lead-coated Apex seals to form a closed pressure vessel that can accommodate the coolant gas.

Actuator Control System

Precise control of the actuator output shaft position is obtained by coupling the actuator with an electronic amplifier in a closed loop system as shown in figure 2. The feedback potentiometer develops a signal proportional to the output position. This signal is compared with the desired command signal at the control panel. Any error that is generated is amplified and sent to the torque motor to change the actuator's output position such that the error will be reduced to zero.

Simulated Control Drum

For the test program, the actuator was coupled to a simulated reactor control drum load. This load contained the inertia, coulomb friction and spring system that simulates the NERVA reactor control drum. The load also simulated the actuator mounting interface which contained supply gas and electrical connections for the actuator.

Cryogenic Gas Facility

Figure 3 is a schematic diagram of the cryogenic gas system used for the actuator test program. The system provided separately controlled coolant and drive gas supplies. Temperature control of each supply was obtained by mixing ambient gas with cryogenic gas from the LN_2 and LH_2 heat exchangers. The mixing was accomplished by regulating temperature control valves TCV1, 2, 3, and 4. Pressure control was obtained by regulating pressure control valves PCV1, 2, and 3.

Pressure control valve PCV4 was provided to regulate the system exhaust pressure. For the test program, however, the exhaust was maintained at atmospheric conditions.

A cryogenic gas filter was provided for the drive gas supply. A drive and coolant gas supply bypass around the actuator and lead system was provided that allowed the supply lines to be prechilled without chilling the actuator. Thus, the bypass arrangement provided a means for approximating a step change in temperature to the actuator and lead system.

Cu/Con thermocouples TC-1, TC-2, and TC-3 were added to me measure the temperature of the coolant, drive, and exhaust gases, respectively. These thermocouples were located approximately 30 cm from the actuator. Cu/Con thermocouple TC-4 measured the actuator skin temperature and was located on the actuator housing. Cu/Con thermocouple TC-5 measured the drive supply bypass gas temperature and was located approximately 15 cm upstream of valve RSOV-3. Resistance thermometer RT-3 was located near thermocouple TC-1 to provide redundant coolant temperature measurement. Resistance thermometers RT-1 and RT-2 were used to measure the coolant and drive gas temperatures after the final mixing stage. Resistance thermometer RT-4 was used to measure the gas temperature at the outlet of the cryogenic filter.

TEST PROGRAM

Low-temperature testing of the actuator using hydrogen drive and coolant gas is summarized in Table I.

TABLE I

Thermal cycle number	Desired coolant temperature, K	Desired drive gas temperature, K	Position loop command during cooldown
1	30 to 80	30 to 80	3°/sec ramp
2	30 to 80	Ambient	3°/sec ramp
3	30 to 80	30 to 80	Actuator locked

For all three thermal cycles the actuator was operated in a closed loop positioning system. Thermal cycle 1 was run with a step change in temperature of both the drive and coolant gas. During the cooldown period, the actuator was subjected to a 3°/sec, 100° p-p position ramp. Thermal cycle 2 was run with a step change in coolant gas temperature while the drive gas temperature was held at ambient temperature. During the cooldown period, the actuator was subjected to a 3°/sec, 100° p-p position ramp. Thermal cycle 3 was a repeat of thermal cycle 1 except that during the cooldown period the actuator was locked in its 15° position.

Performance Data

To determine the effects due to the low-temperature environment, actuator performance was measured in terms of its ability to function in closed loop positioning system.

For each thermal cycle, base line data was recorded prior to the step change in gas temperature. After the actuator had been subjected to the temperature step change and had reached temperature equilibrium, a set of comparison data was recorded. The base line data and the comparison data consisted of the following specific tests:

(1) Velocity limit test. - This test consisted of applying a 100° peak-to-peak (p-p) step in position command to the actuator. The rate of change of actuator position to a step command is limited to a specified maximum value. This maximum value is verified by this test. For the cold flow test program, the velocity limit was held at 100°/sec.

(2) Dynamic resolution test. - This test checked the ability of the actuator to follow a position command of a specified ramp at a specified frequency. A 100° p-p, 3°/sec ramp was used as the position command.

(3) 18° p-p step response test. - This test consisted of applying an 18° p-p step in position command to the actuator. This test checked the small signal response of the actuator. In this case, the actuator performance is not restricted by the velocity limit. The actuator response is specified in terms of the rise time, overshoot and settling time of the output position.

(4) Scram-turnaround test. - This test measured the ability of the actuator to return to a full in or 0° position with the loss of electrical power. For the test, the actuator was commanded to scram during a transient position change in which the position was changing toward the full out or 180° position and was moving with a controlled velocity of 100°/second. The test measured the time required to stop motion due to the dynamic command and achieve initial velocity toward the actuator's full in position. This test also determined maximum angular velocity and acceleration of the actuator and to measure the rebound of the actuator after it reaches the scram position.

(5) 4° p-p frequency response test. - This test determined the response of the actuator to sinusoidal position commands of various frequencies. The response is specified in terms of the actual position amplitude and position phase shift referred to the position command signal.

Instrumentation

Dynamic response measurements of key position loop parameters were recorded on an eight-channel recording oscillograph. These parameters included:

(1) $\Delta\theta_d$ the change in the position loop demand signal, deg
(2) $\Delta\theta_o$ the change in the position loop output signal, deg
(3) TMI actuator torque motor current, mA
(4) θ_e position loop error signal, deg
(5) θ_o position loop output signal, deg
(6) P_1 actuator cylinder 1 chamber pressure, newton/cm^2
(7) P_2 actuator cylinder 2 chamber pressure, newton/cm^2
(8) Actuator lock switch position (ON or OFF)

In addition, the following temperature parameters were recorded on a 24-channel strip chart recorder:

(1) TC-1 coolant gas temperature, K
(2) TC-2 drive gas temperature, K
(3) TC-3 exhaust gas temperature, K
(4) TC-4 actuator housing temperature, K

The drive and coolant gas supply pressures were recorded on individual strip chart recorders.

RESULTS AND DISCUSSION

This section is divided into two parts. The first part, General Test Results, discusses the general test results during each of the three thermal cycles. Included in the discussion are the equilibrium conditions reached and a summary of the actuator performance during each thermal cycle.

The second part, Data, presents the data taken during the thermal cycles. The performance data presented is compared with the base line data taken prior to the thermal cycles.

General Test Results

Thermal cycle 1. - The equilibrium temperatures reached during thermal cycle 1 were:

$$T_{drive} = 67\ K$$

$$T_{coolant} = 56\ K$$

$$T_{skin} = 61\ K$$

The actuator performed well both during chilldown and during the comparison testing performed after temperature equilibrium had been reached. One exception was noted. Following the successful completion of the scram test, either the actuator did not lock in the 15^{o} position, or its control circuitry failed to give indication of locking. Noting this condition, the actuator lock circuitry was left energized and the actuator was slowly warmed to determine at what temperature the actuator would lock and give positive indication of locking. At the following temperature condition of the actuator, control of locking was regained:

$$T_{drive} = 86\ K$$

$$T_{coolant} = 128\ K$$

$$T_{skin} = 97\ K$$

The actuator was brought back to ambient temperature conditions with no further indication of erratic performance.

As a result of this performance, the locking mechanism in the actuator was replaced after thermal cycle 1.

Thermal cycle 2. - The equilibrium temperatures reached during thermal cycle 2 were:

$$T_{drive} = 278 \text{ K}$$

$$T_{coolant} = 39 \text{ K}$$

$$T_{skin} = 78 \text{ K}$$

The actuator performed well during the entire cycle. The actuator locked successfully when commanded and the lock gave no evidence of erratic performance at any time during the entire cycle.

Thermal cycle 3. - The equilibrium temperature reached during thermal cycle 3 was:

$$T_{drive} = 61 \text{ K}$$

$$T_{coolant} = 39 \text{ K}$$

$$T_{skin} = 69 \text{ K}$$

For thermal cycle 3, the actuator position loop was locked in the 15° position during the chilldown. When the actuator reached thermal equilibrium, the position loop was unlocked and a 3°/sec position ramp was initiated. The time response of the recorded position loop parameters is shown in figures 4(a) and (b). After following the ramp for 20 sec, the actuator apparently froze and failed to continue following the position ramp. As shown in figure 4(a), the actuator attempted to respond to a change in the manual command position, but it tended to drift away from any command position location. The actuator drifted toward the 180° position; however, it would scram when the output position exceeded the 120° position.

Figure 4(b) shows the time response of the position loop parameters recorded as the drive gas was warmed in an attempt to regain control of the actuator position loop. During this warmup, a 3°/sec 100° p-p ramp command was applied. Control of the actuator was regained at the following temperature conditions:

$$T_{drive} = 83\ K$$

$$T_{coolant} = 47\ K$$

$$T_{skin} = 50\ K$$

The position ramp command was continued and the drive gas temperature was again lowered. A set of comparison data was taken at the following equilibrium temperatures:

$$T_{drive} = 67\ K$$

$$T_{coolant} = 56\ K$$

$$T_{skin} = 64\ K$$

Data

Oscillograph traces. - Figures 5 to 8 present dynamic response measurements of the base line data and the comparison data generated from the three thermal cycles. These figures are oscillograph traces of the position loop parameters, previously discussed in the test program section, plotted against time.

Figures 5(a) to (d) show the time response to a 100° p-p step command for the base line data and the three thermal cycles. These traces show the actuator response to large signal input commands. The slope of the output position trace (θ_o) is a measure of the maximum velocity limit as set by the actuator control circuit and remained at 100°/sec during all of the temperature cycles.

Figures 6(a) to (d) show the time response to 100° p-p, 3°/sec position ramp command for the base line data and the thermal cycles. Cryogenic temperatures seemed to have little effect on the position traces; however, the thermal cycle 3 (fig. 6(d)) torque motor current (TMI), pressure (P), and position error (θ_e) traces show the addition of high frequency oscillations.

Figures 7(a) to (d) show the time response to an 18° p-p position step command for the base line data and the thermal cycles. These traces show the actuator response to a small signal input command. To determine the temperature effect on the small signal response, the dead time and rise time values of the output position response were taken from these traces and shown in Table II.

TABLE II

	Warm BLD, msec	Thermal cycle 1, msec	Thermal cycle 2, msec	Thermal cycle 3, msec
Dead time	20	20	25	25
Rise time	125	140	150	200

Figures 8(a) to (d) show the time response to a scram test for the base line data and the thermal cycles. Little change was noted in the dynamic responses with the exception of thermal cycle 3. In this case, the performance is somewhat slower than in the other tests. Figure 8(b) shows that the actuator did not lock during the thermal cycle 1 scram test, as noted earlier.

Frequency response curves. - Figures 9(a) to (d) are Bode plots of amplitude ratio and phase shift of data reduced from the base line and thermal cycle frequency response tests. The input amplitude of the sine wave used in all tests was 4° p-p and the tests were performed about the 90° position of the actuator. The curves indicate that the cryogenic temperatures had little effect other than to somewhat reduce the actuator's band width.

SUMMARY OF RESULTS

A test program established to examine actuator performance using low temperature gaseous hydrogen as a working medium yielded the following results:

1. The actuator, while in continuous operation, performed satisfactorily when subjected to step changes in temperature from ambient to the 30 to 80 K range. The step changes in temperature include both lowering the coolant gas temperature while holding the drive gas at ambient temperature, and lowering both the drive and coolant gas temperatures.

2. For the condition of locking the actuator at ambient temperatures and then cooling to the 30 to 80 K range, performance after unlocking was erratic.

3. During the first temperature cycle, lock operation was erratic when the actuator was operated with both cryogenic coolant and drive gas. The lock mechanism was replaced, however, and no further erratic performance due to the locking mechanism was noted during the remainder of the test program.

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1. Josephson, J.: Servo-Analysis and Dynamic Testing of the Prototype NERVA XE Pneumatic Actuator-Amplifier Subsystem. Rep. WANL-TME-1537, Westinghouse Elec. Corp., Nov. 1966.
2. Buckley, S.; and Armstron, D.: A Stability Analysis of the NERVA XE Control Drum Actuator Servo-Valve. Rep. WANL-TME-1625, Westinghouse Elec. Corp., Sept. 1967.

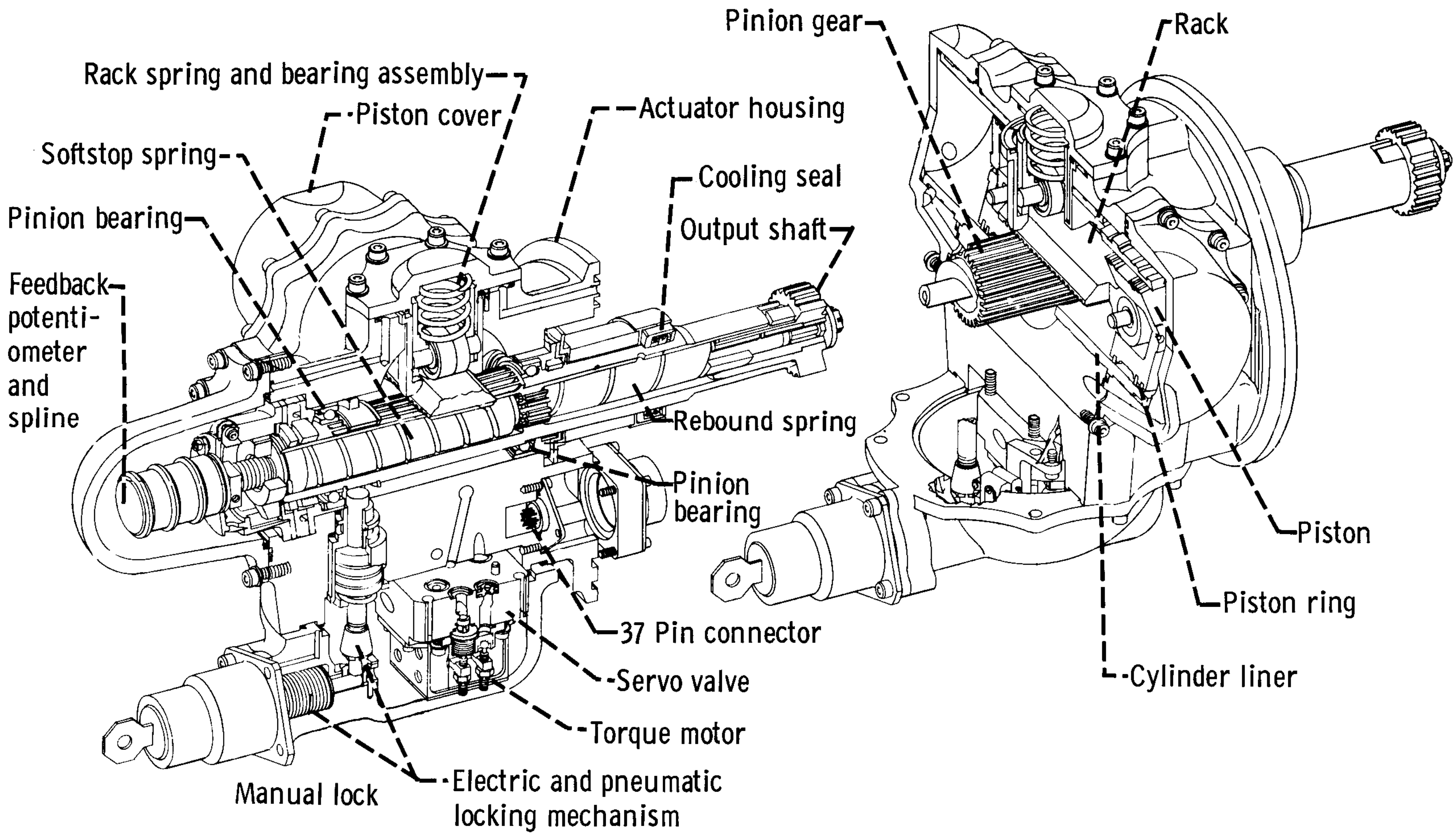


Figure 1. - Nerva actuator.

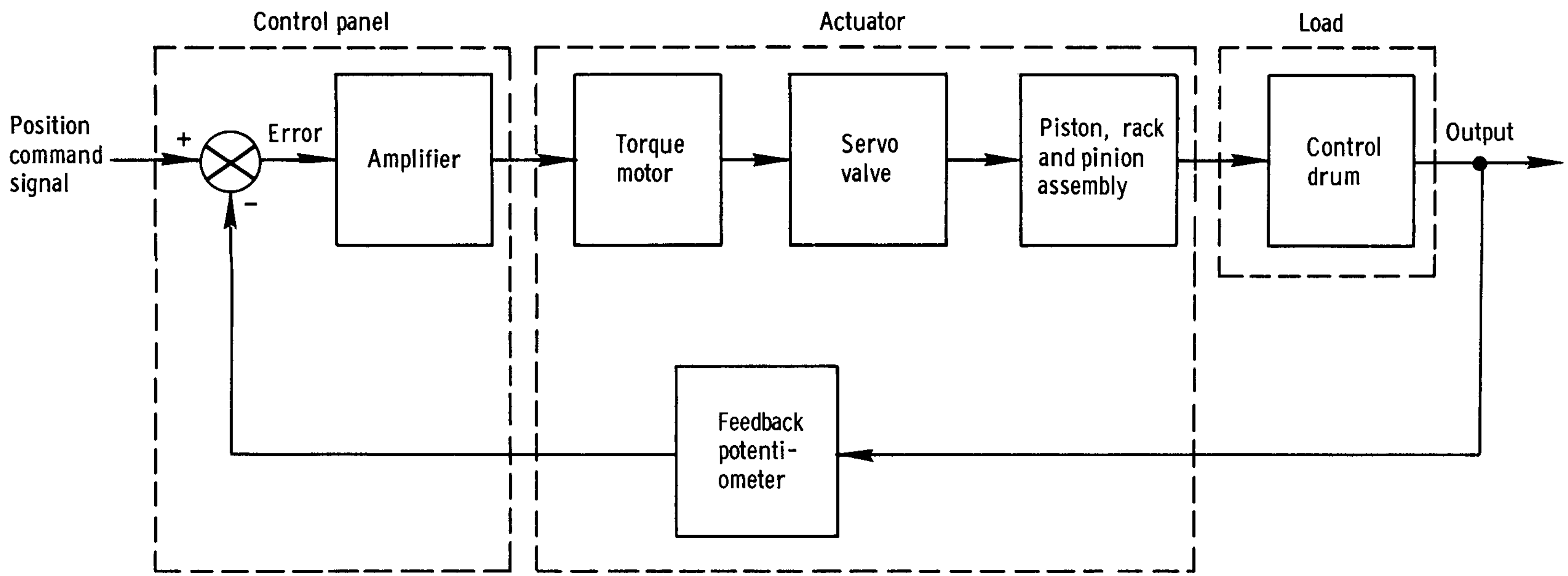
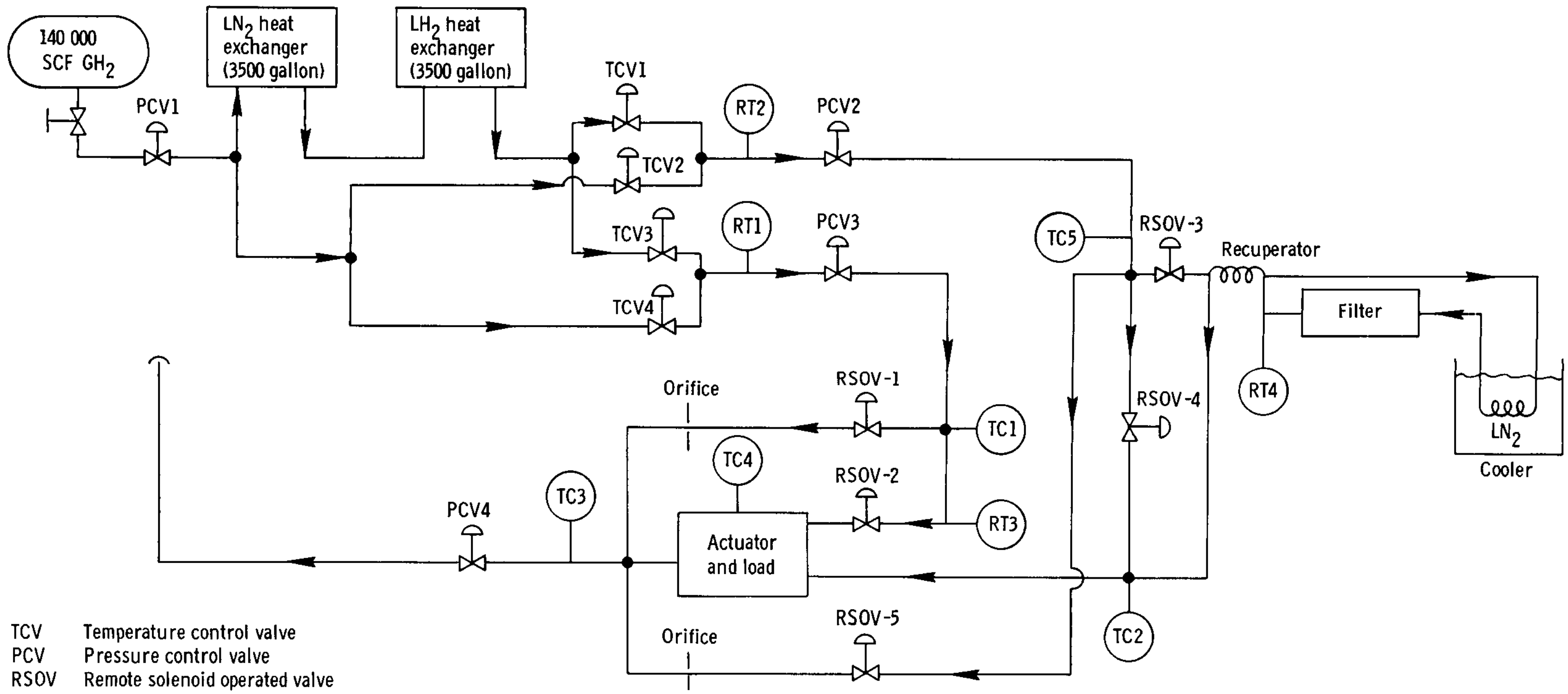


Figure 2. - Actuator control system.



TCV Temperature control valve
PCV Pressure control valve
RSOV Remote solenoid operated valve
TC Thermocouple
RT Resistance thermometer

Figure 3. - Cryogenic gas system for actuator tests.

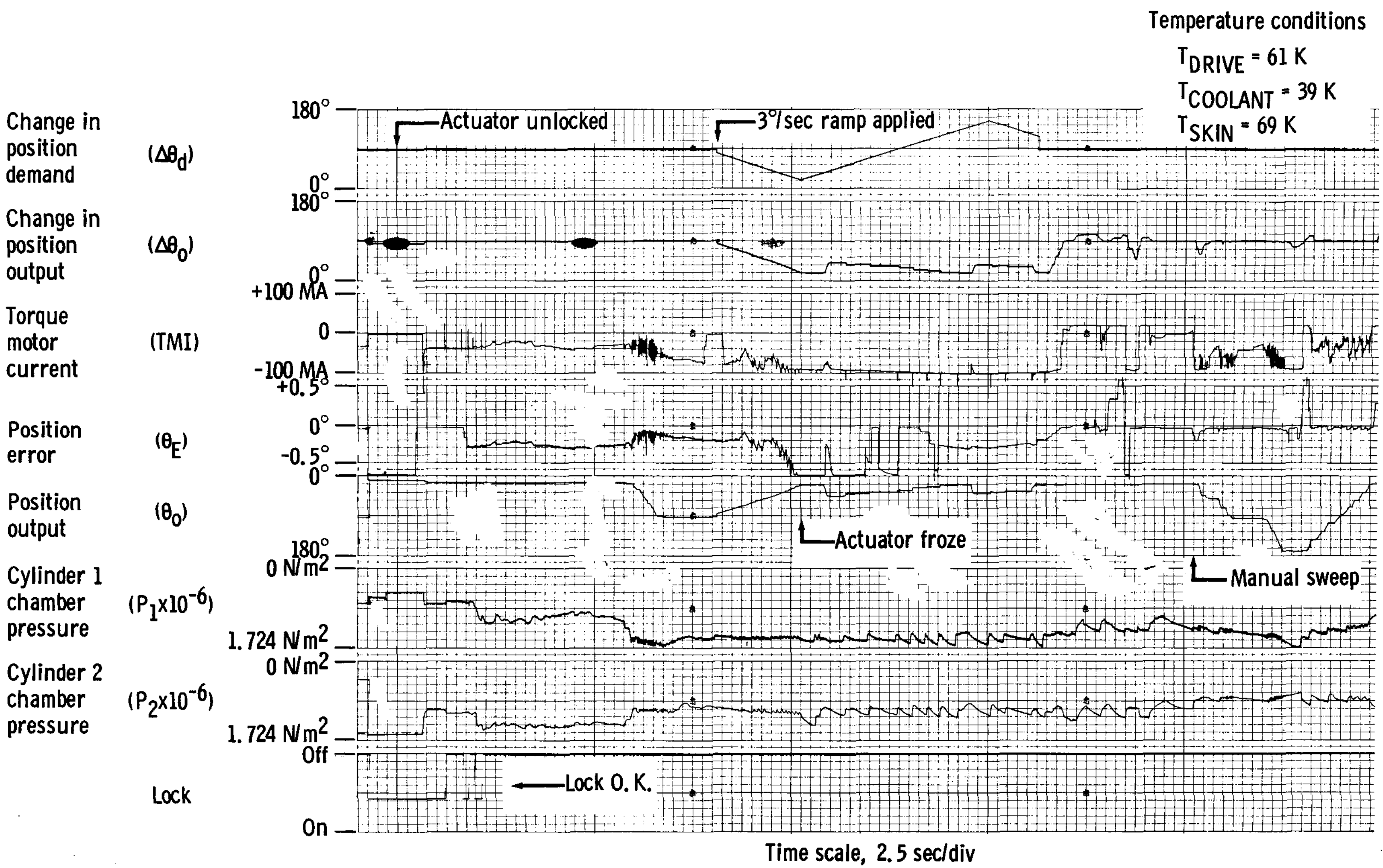


Figure 4(a). - Thermal cycle 3, actuator unlocked and 100° P-P, 3°/sec ramp applied.

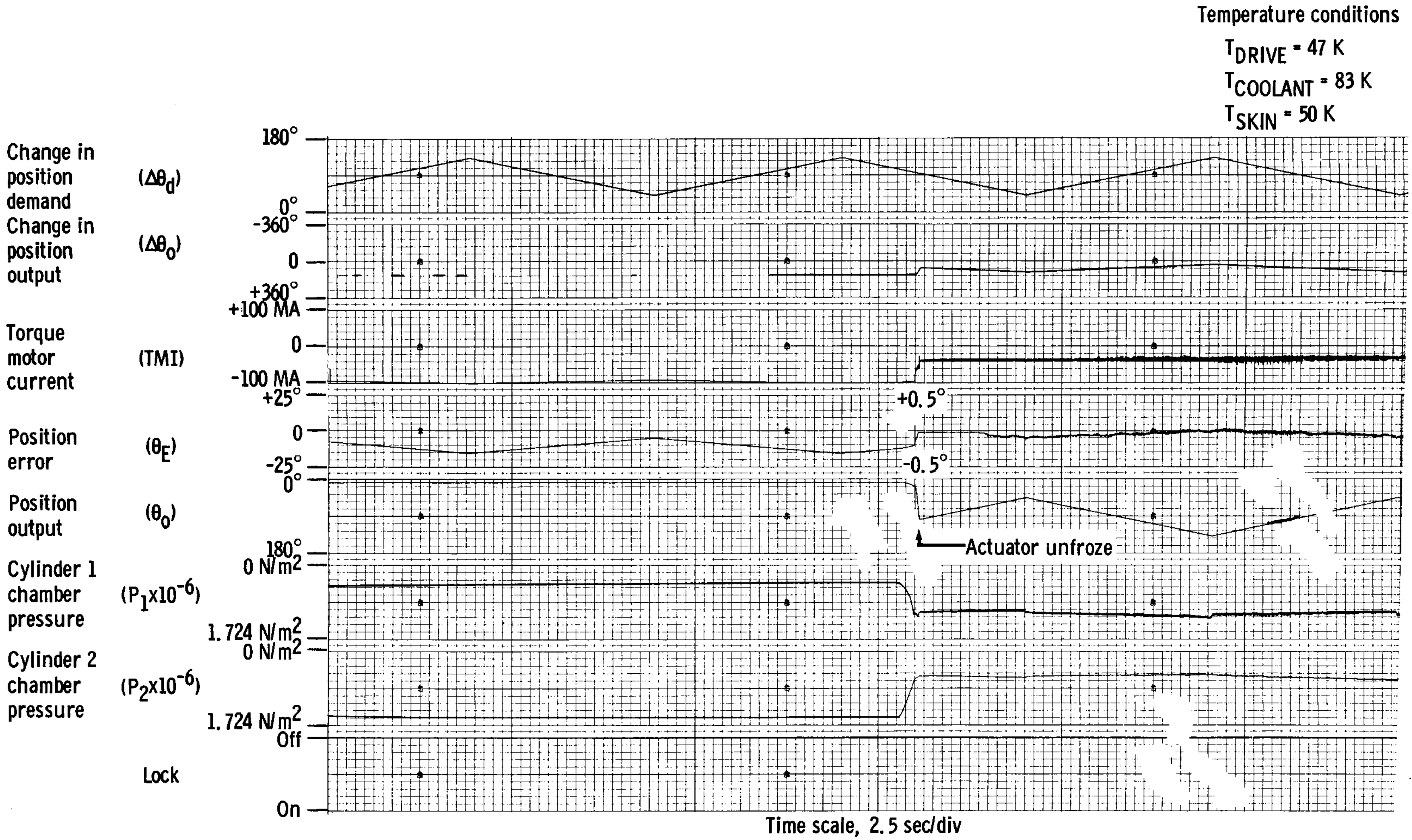
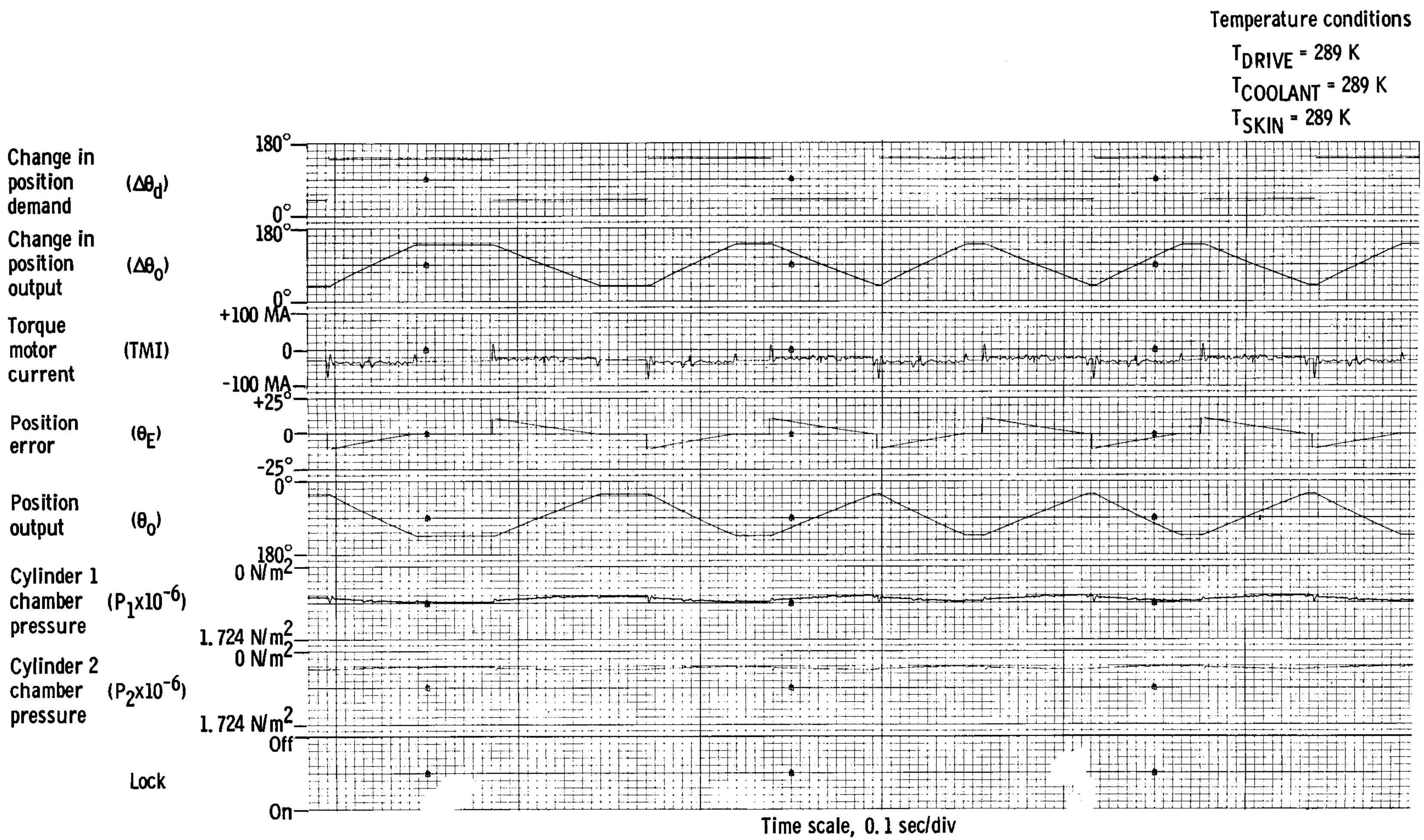
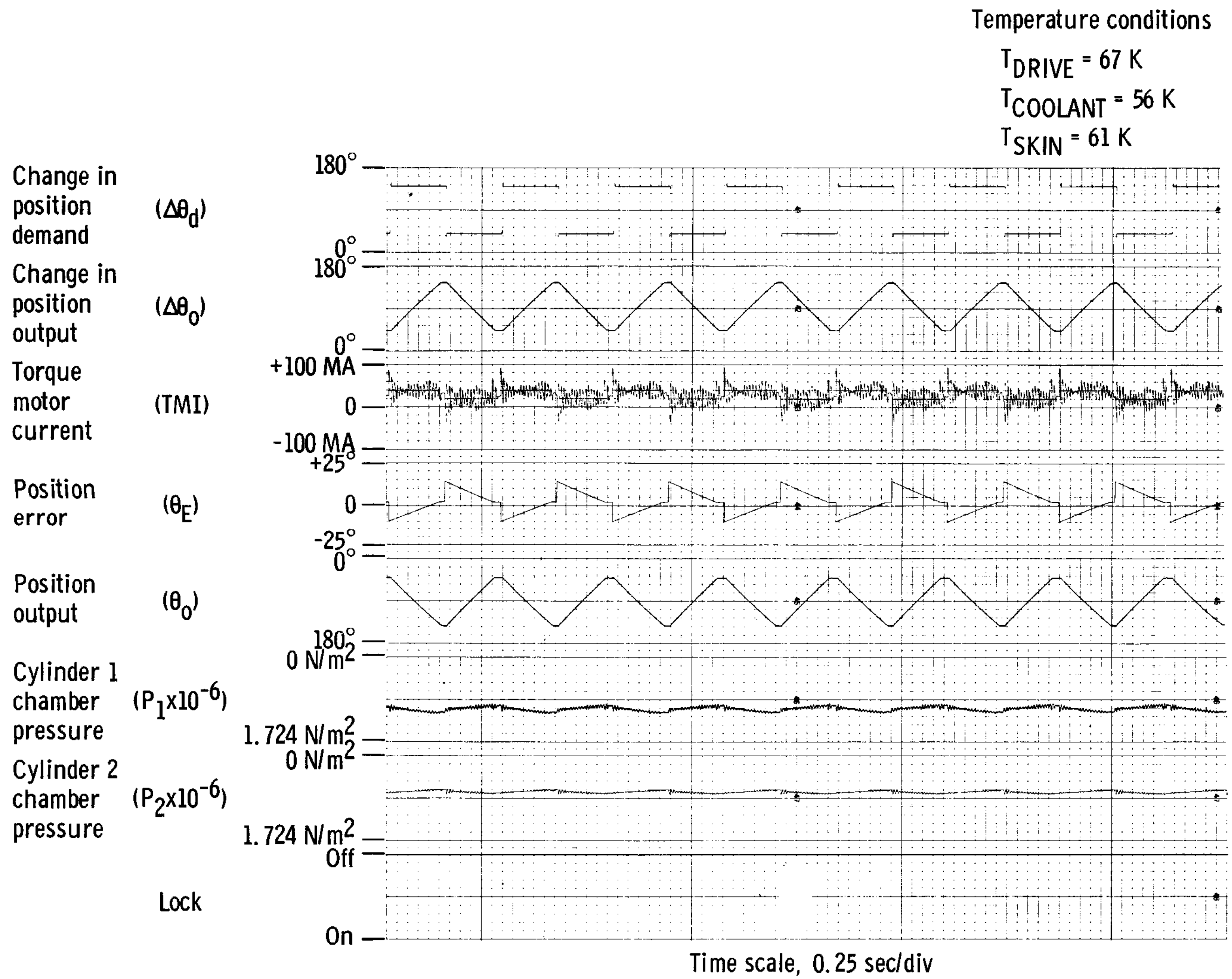


Figure 4(b). - Thermal cycle 3. Continuation of 100° P-P, 3°/sec ramp.



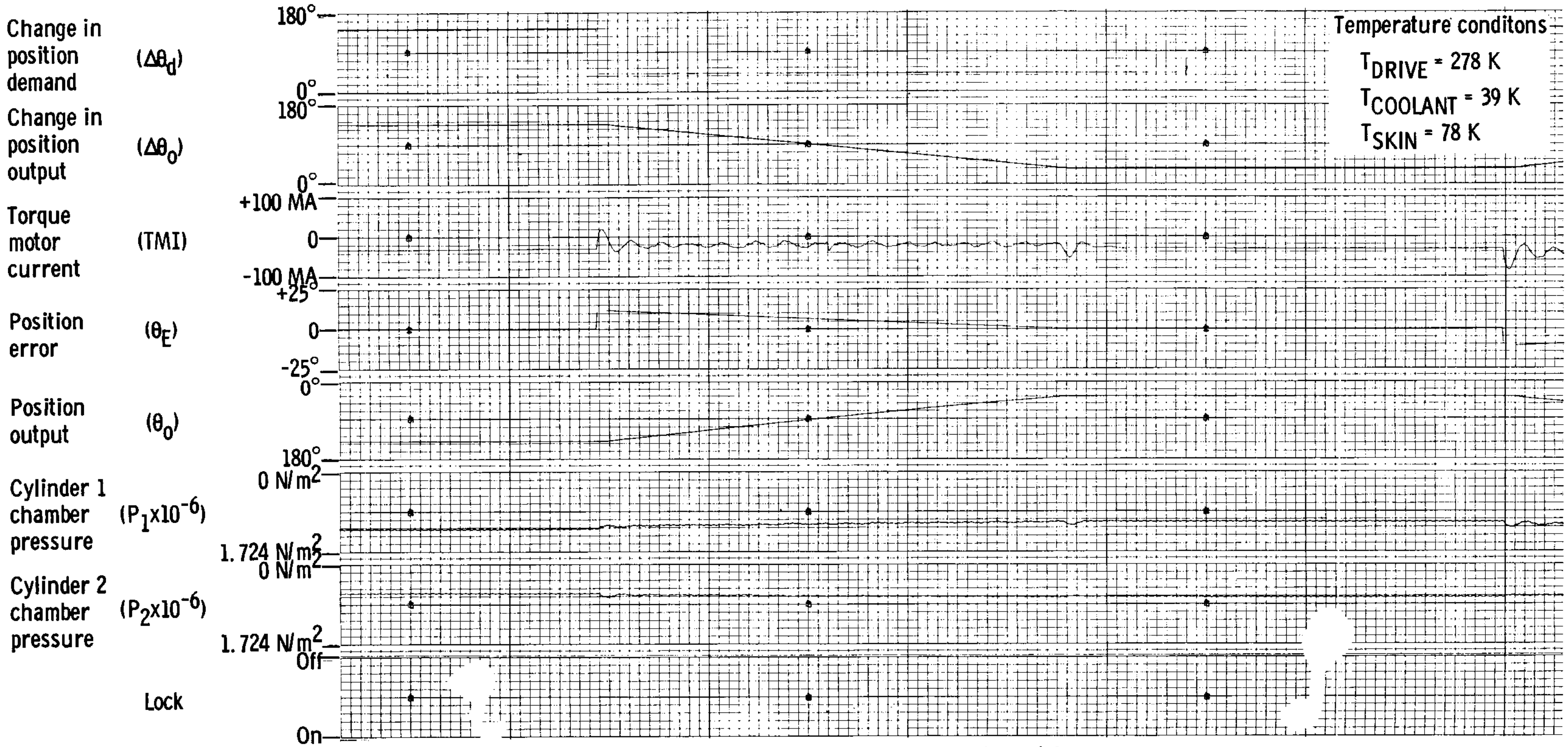
(a) Base line data.

Figure 5. - Time response to a 100° P-P step in position command.



(b) Thermal cycle 1.

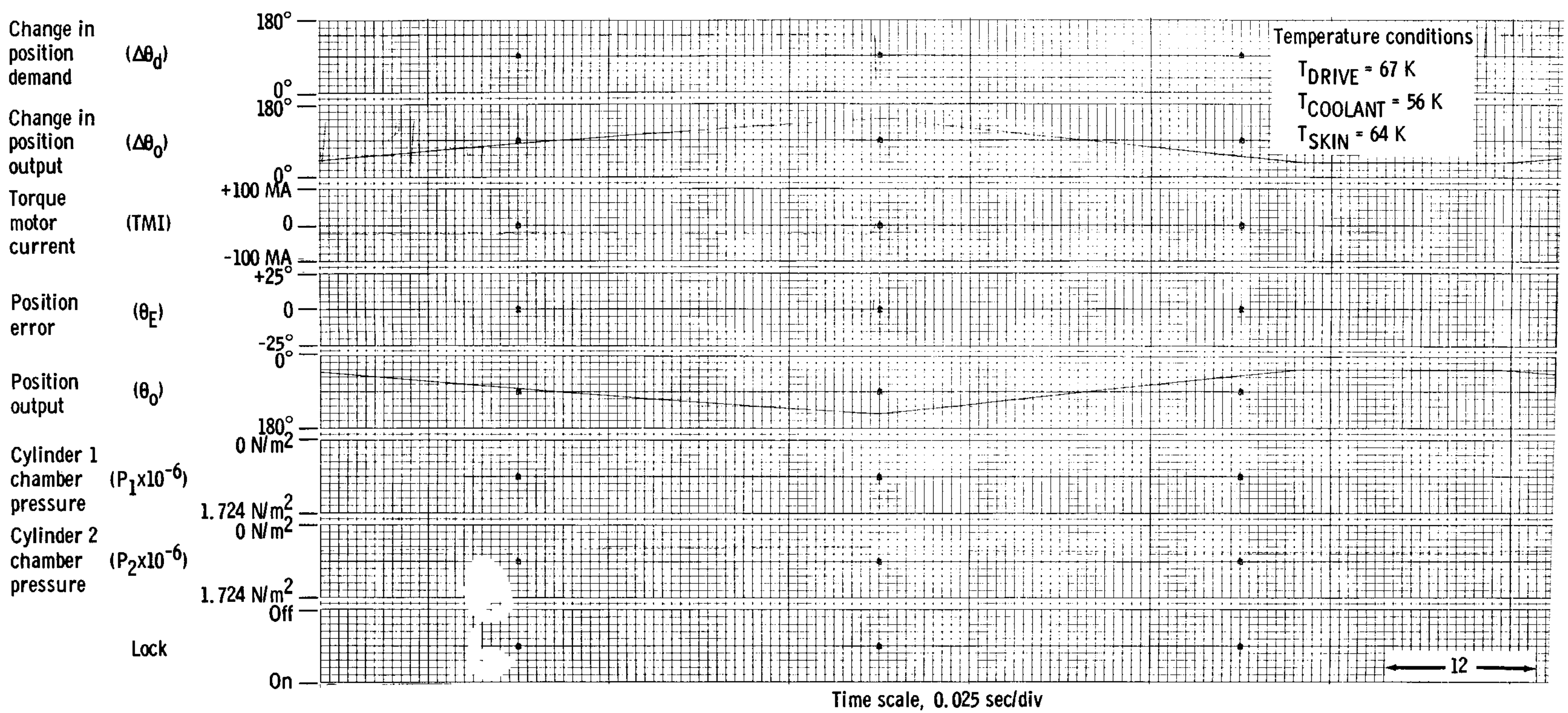
Figure 5. - Continued.



Time scale, 0.025 sec/div

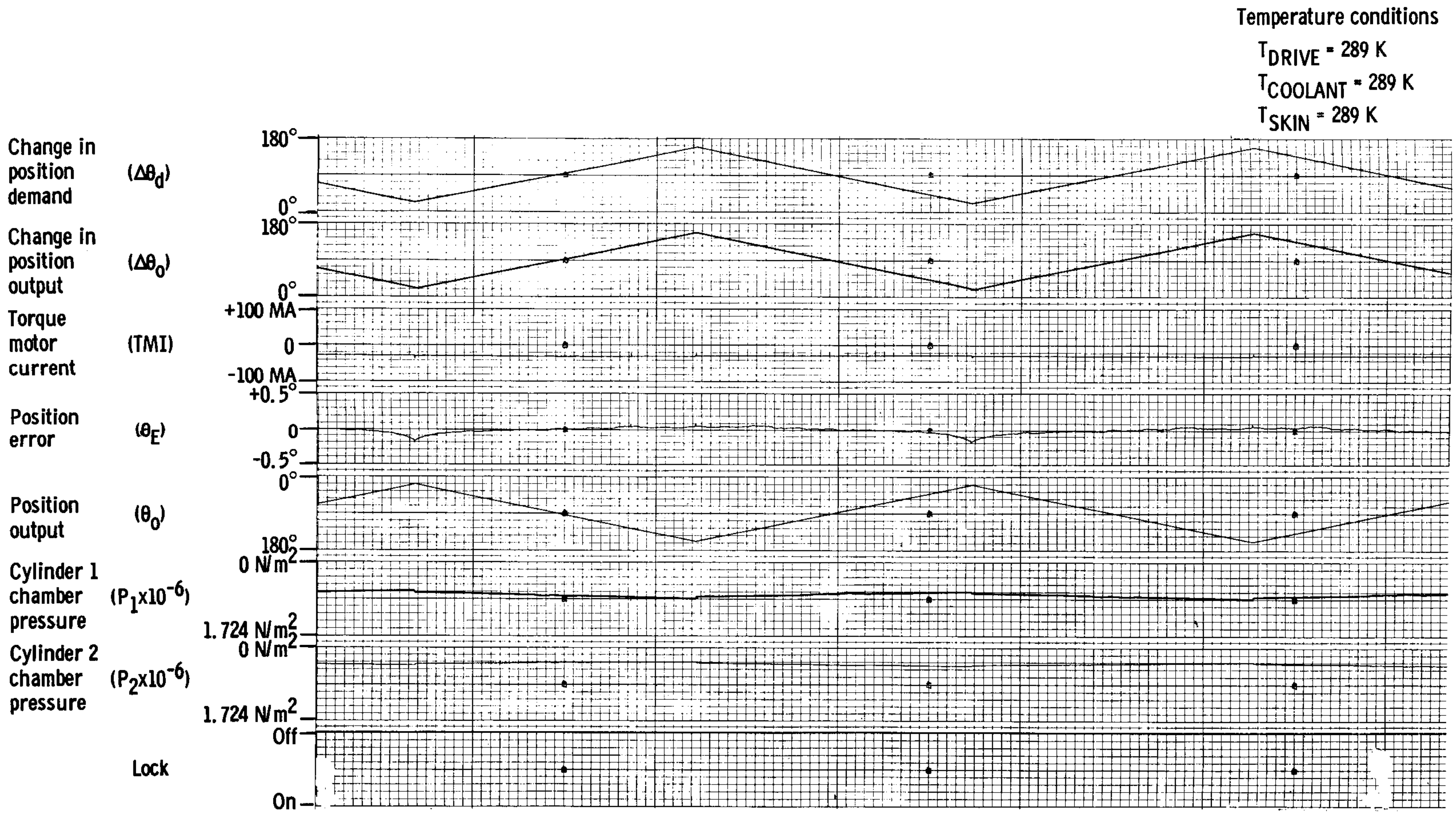
(c) Thermal cycle 2.

Figure 5. - Continued.



(d) Thermal cycle 3.

Figure 5. - Concluded.



Time scale, 2.5 sec/div

(a) Base line data.

Figure 6. - Time response to a 100° P-P, 3°/sec ramp in position command.

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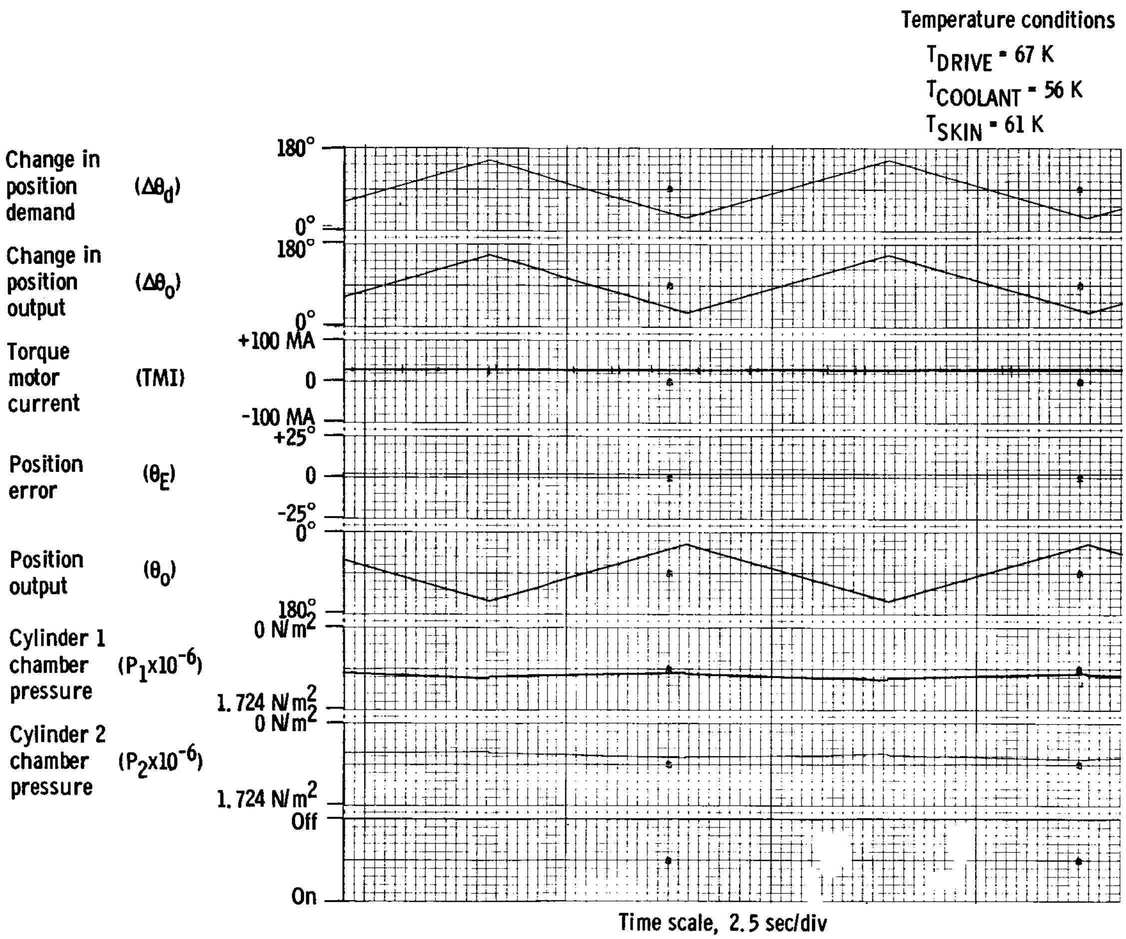
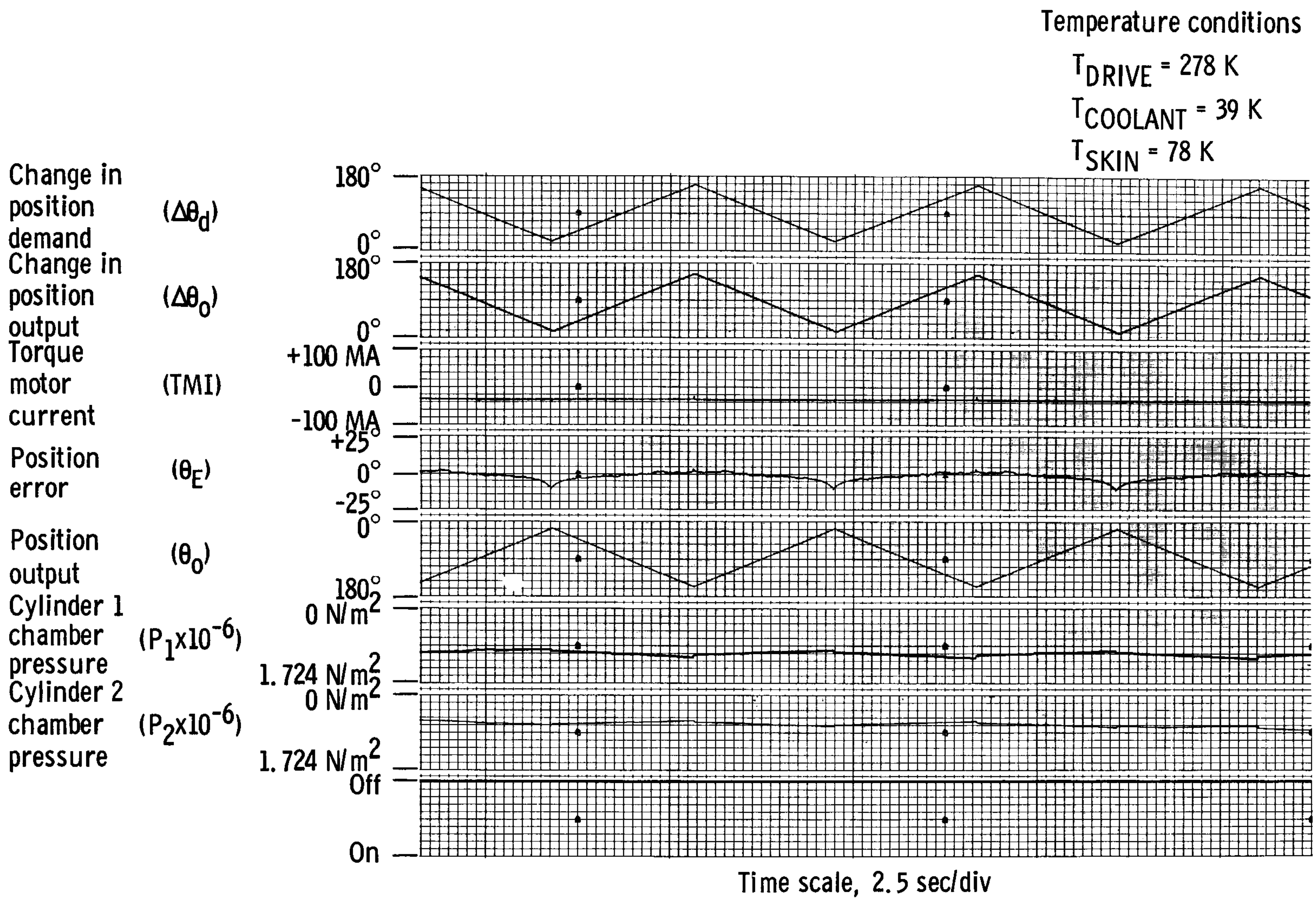


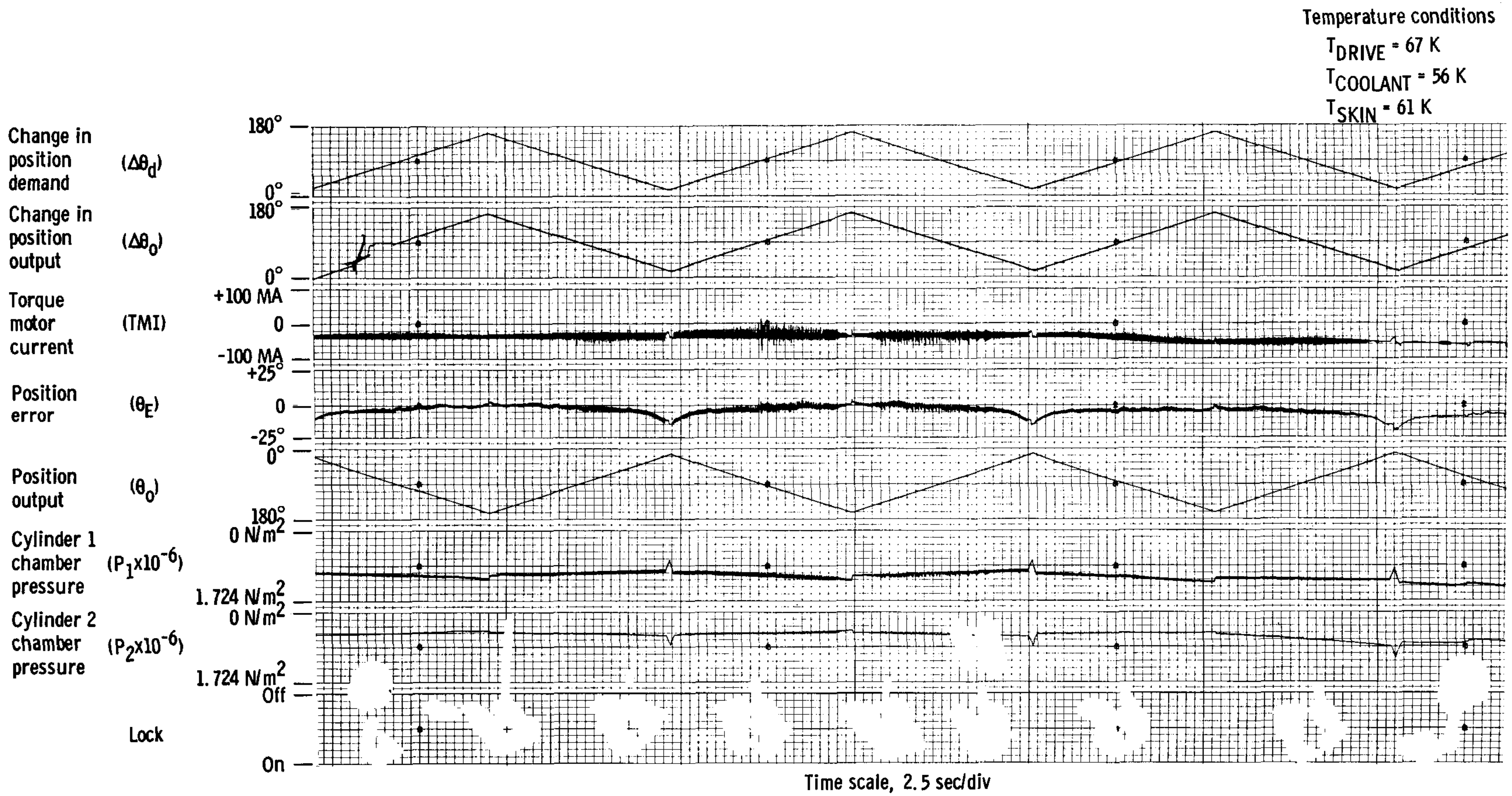
(b) Thermal cycle 1.

Figure 6. - Continued.



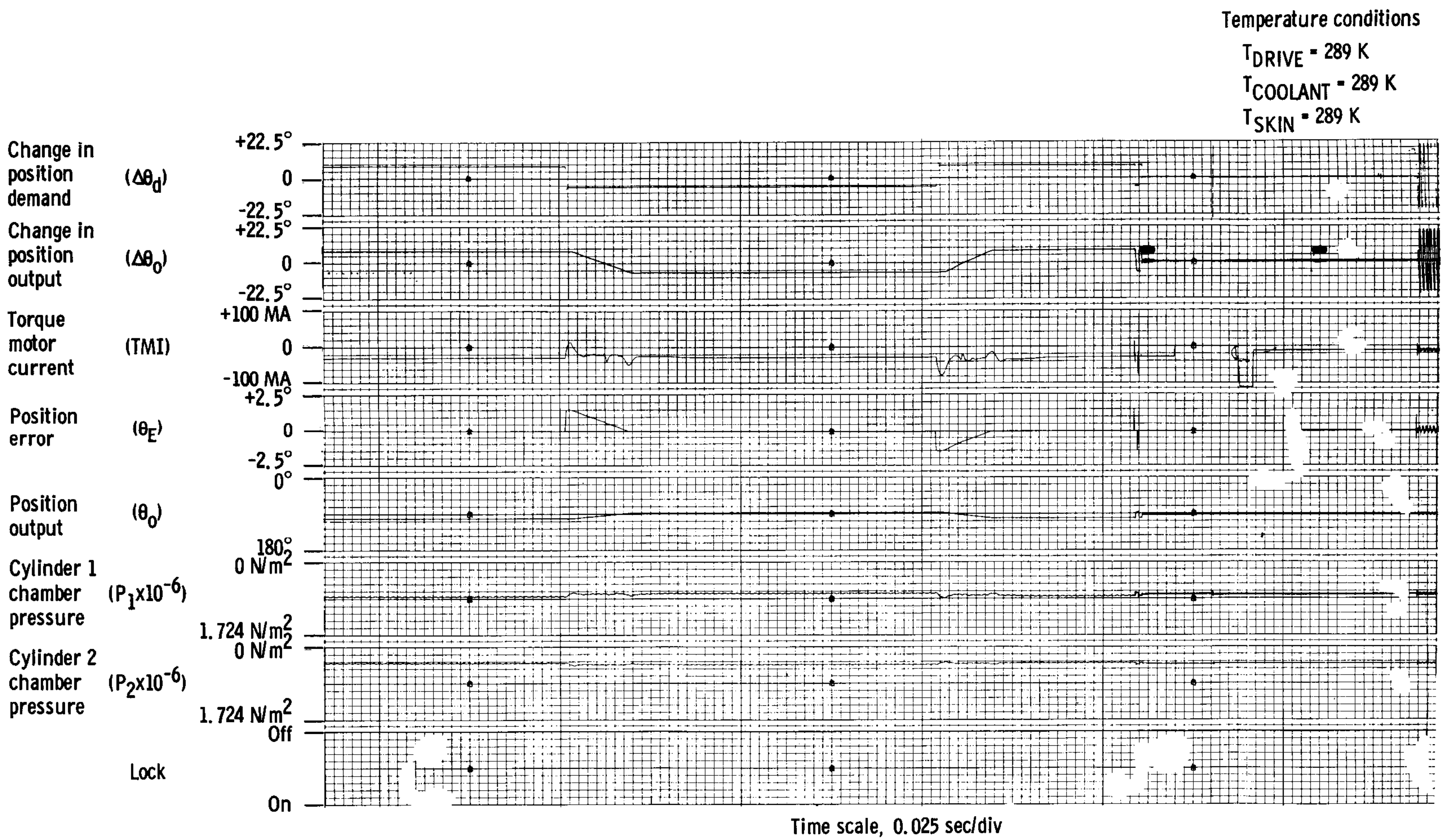
(c) Thermal cycle 2.

Figure 6. - Continued.



(d) Thermal cycle 3.

Figure 6. - Concluded.



(a) Base line data.

Figure 7. - Time response to an 18° P-P step in position command.

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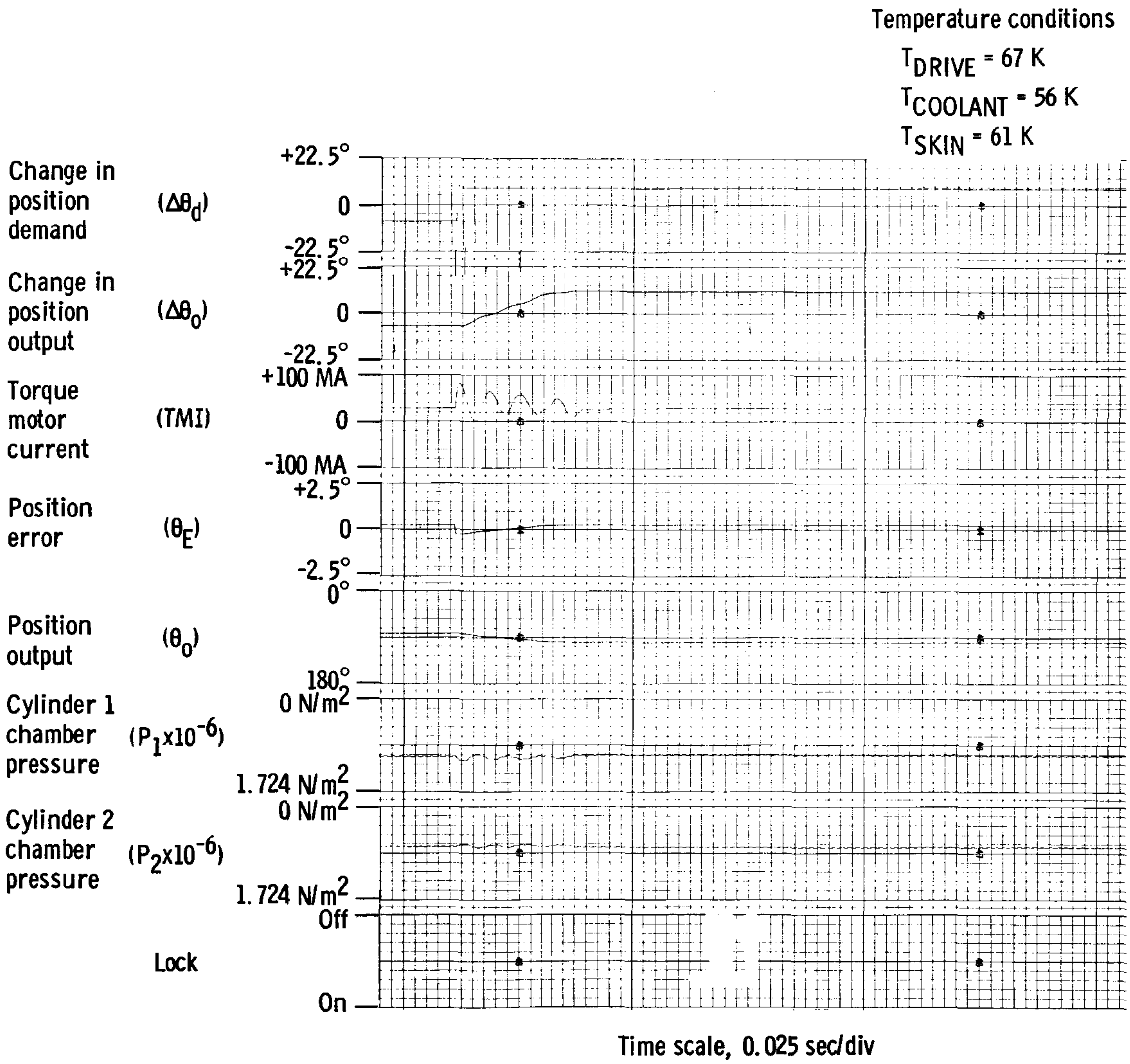
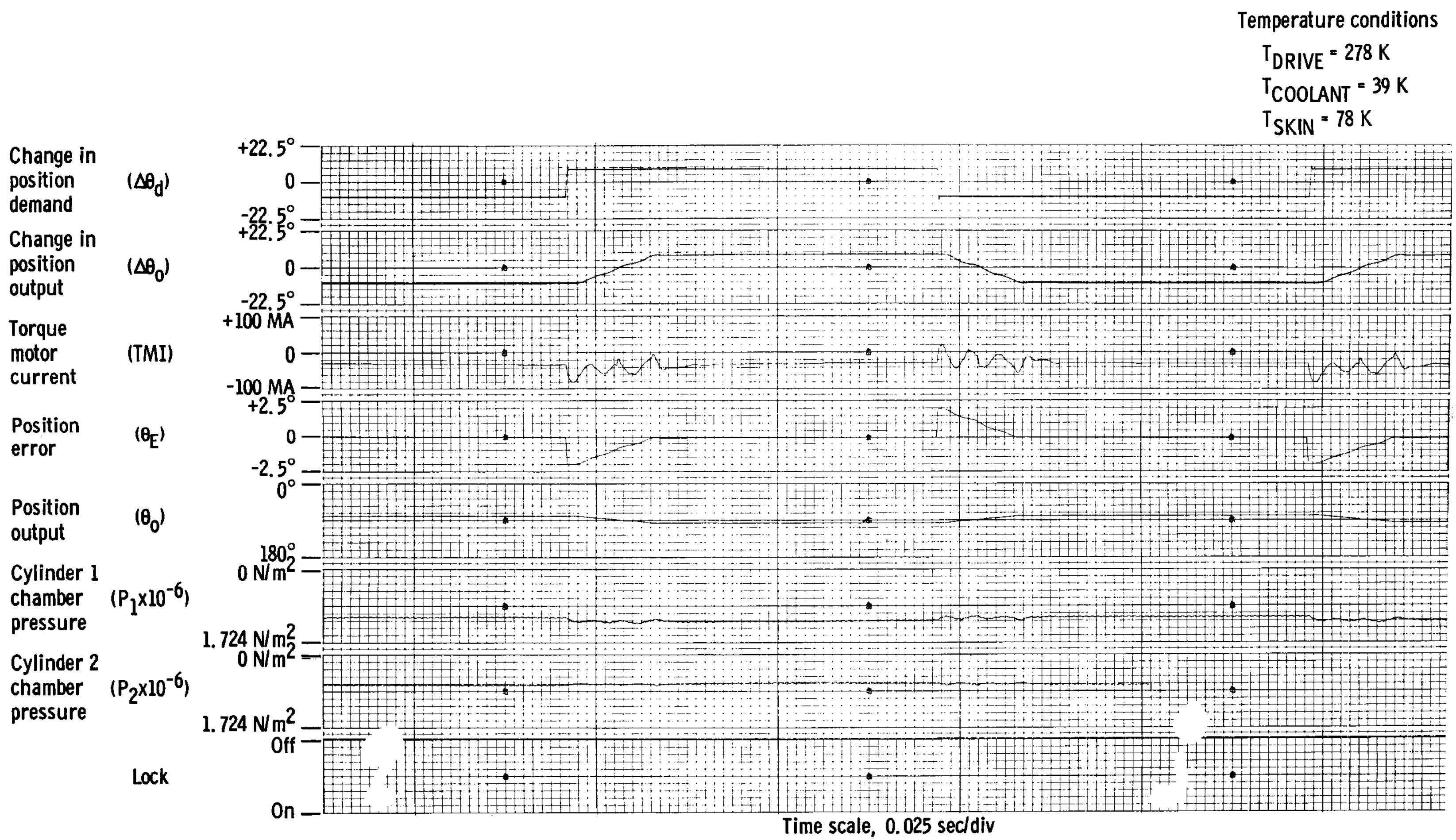


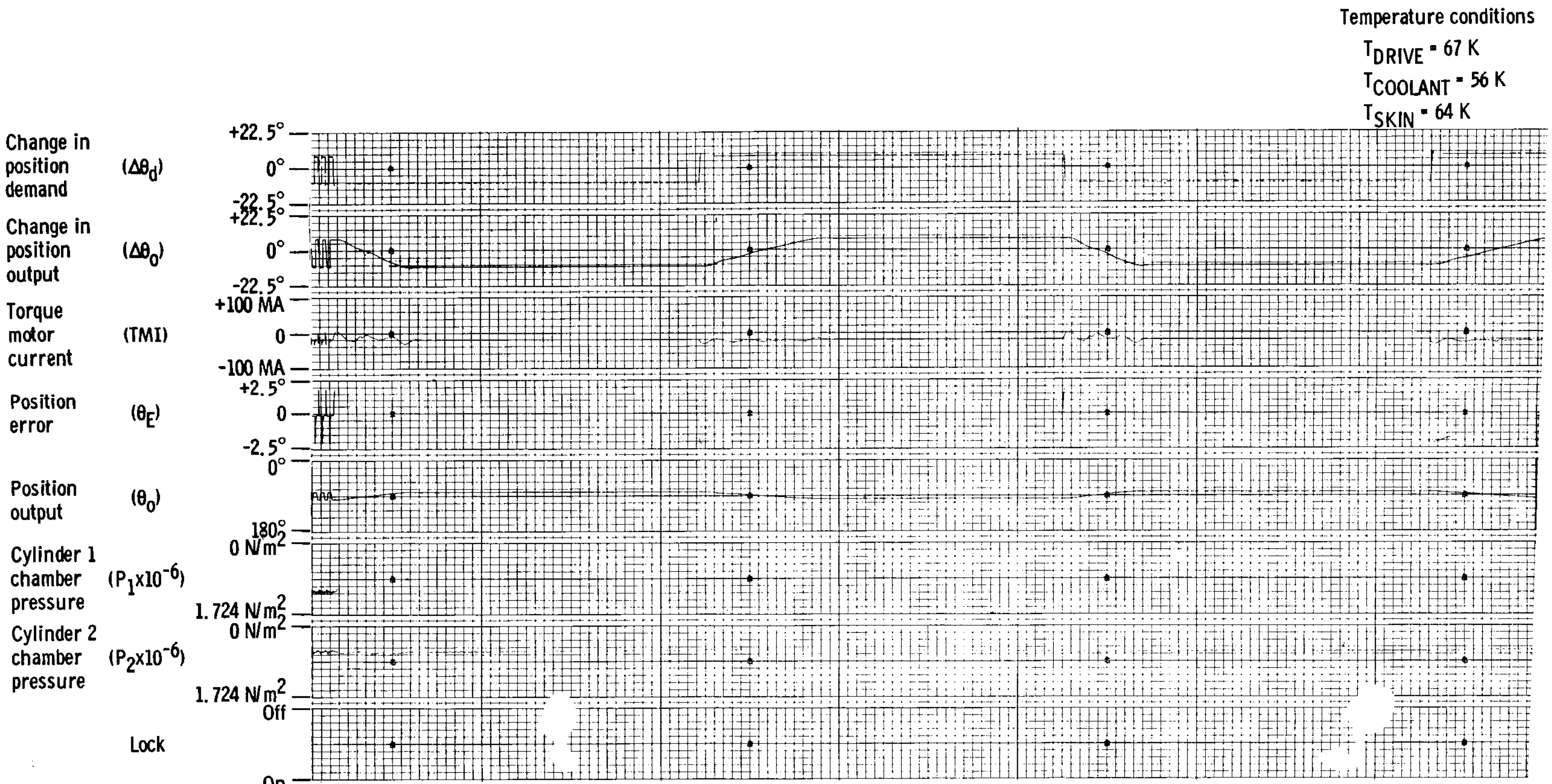
(b) Thermal cycle.

Figure 7. - Continued.



(c) Thermal cycle 2.

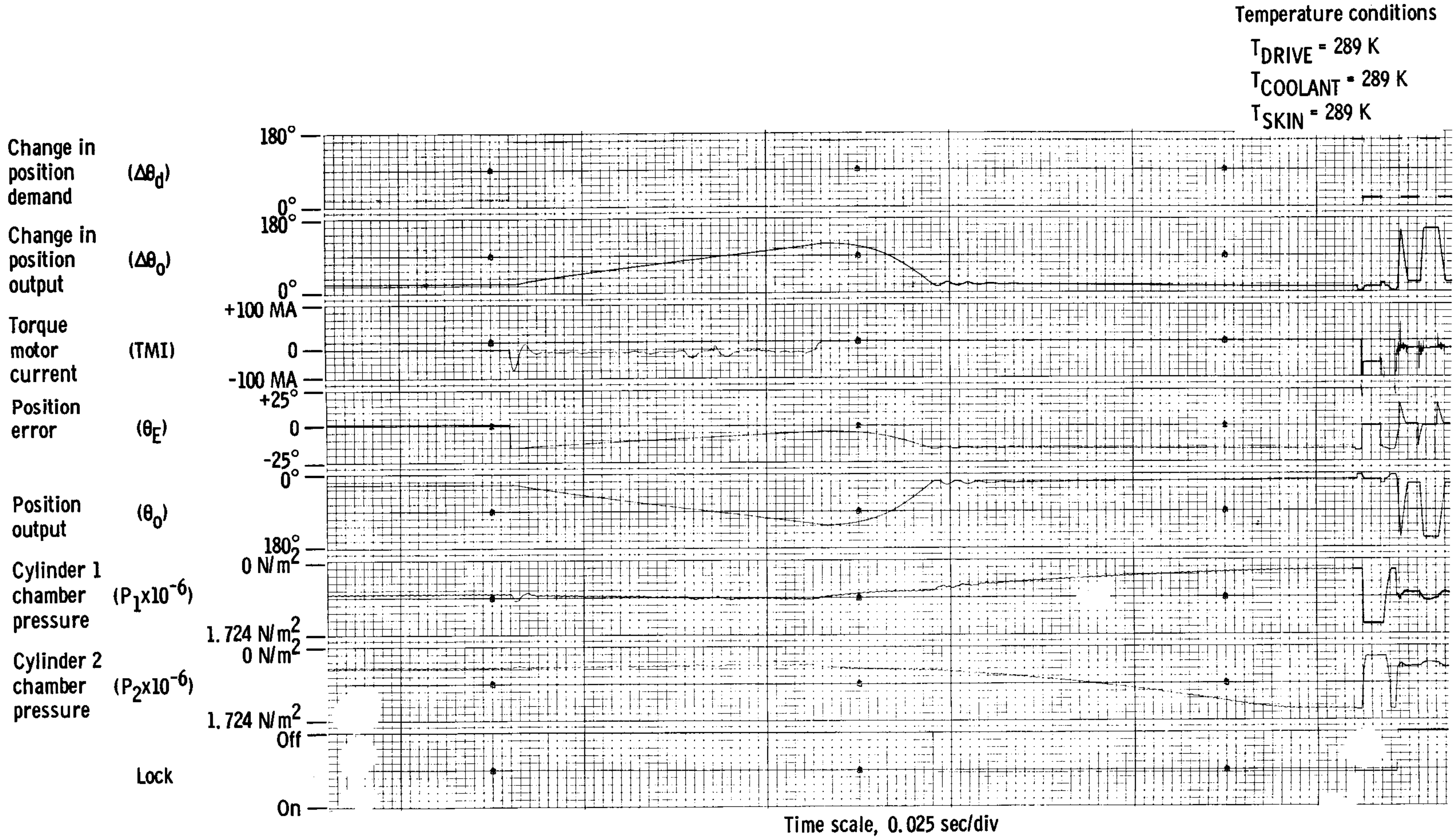
Figure 7. - Continued.



Time scale, 0.025 sec/div

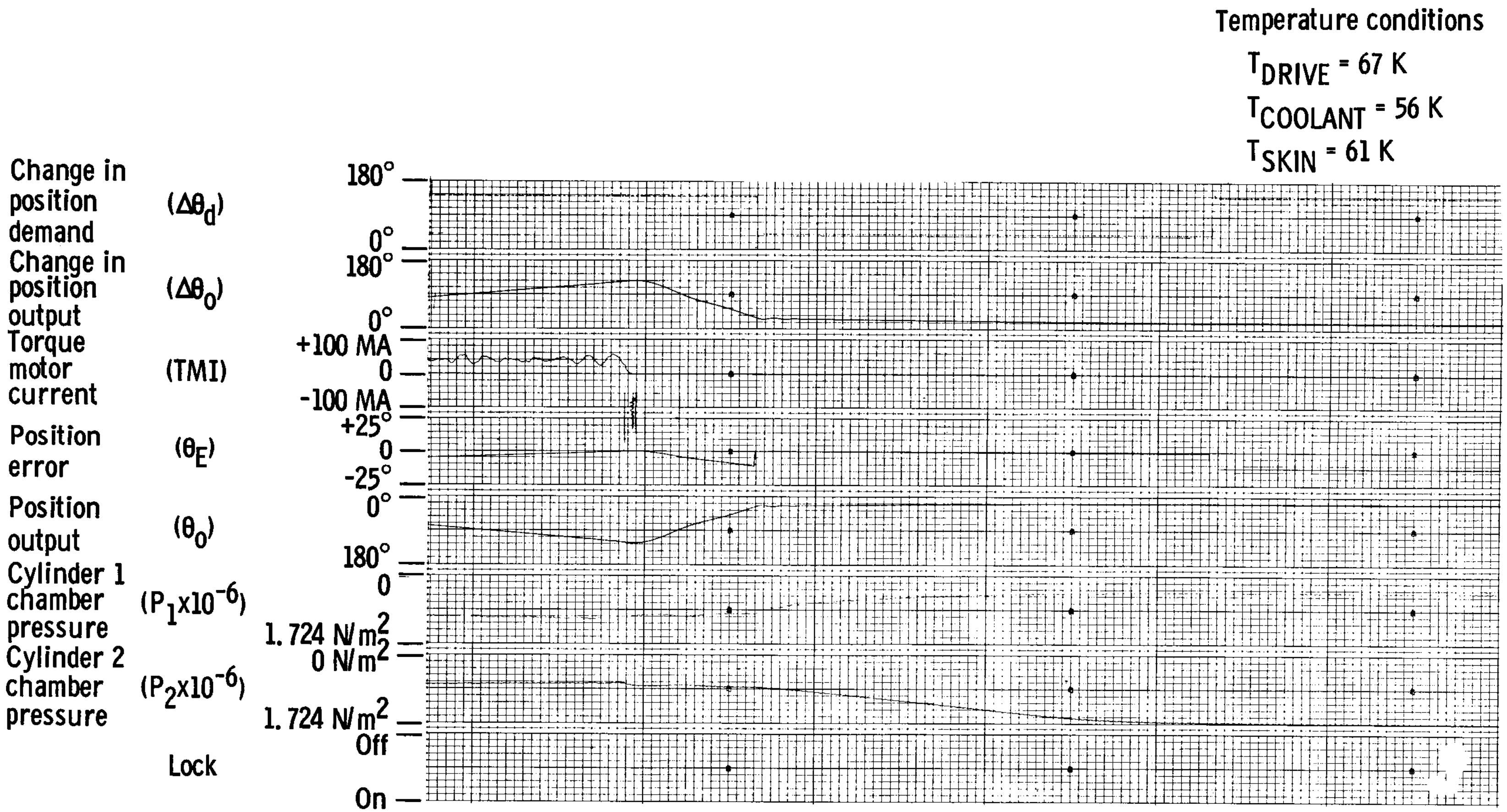
(d) Thermal cycle 3.

Figure 7. - Concluded.



(a) Base line data.

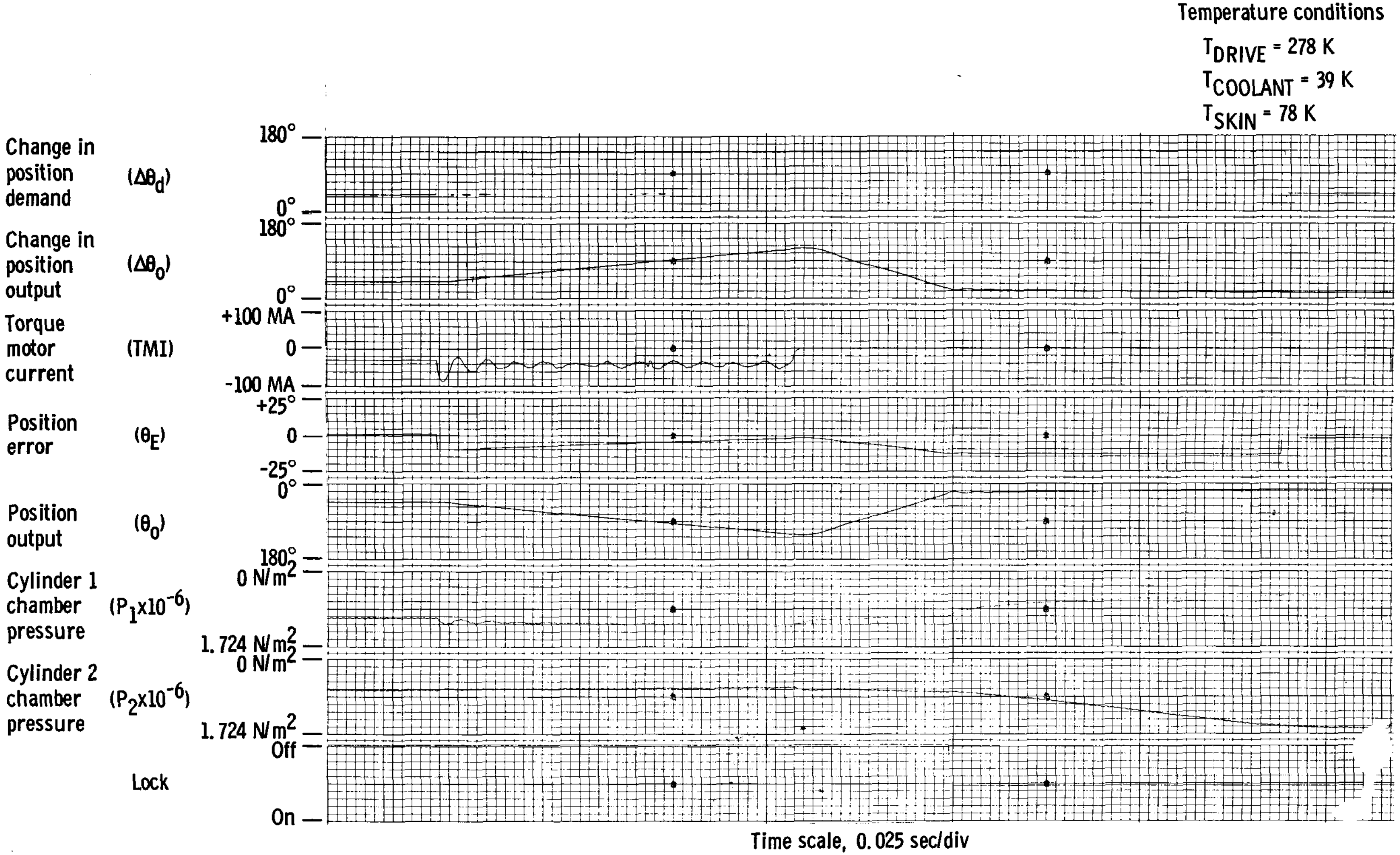
Figure 8. - Time response to a scram turnaround test.



Time scale, 0.025 sec/div

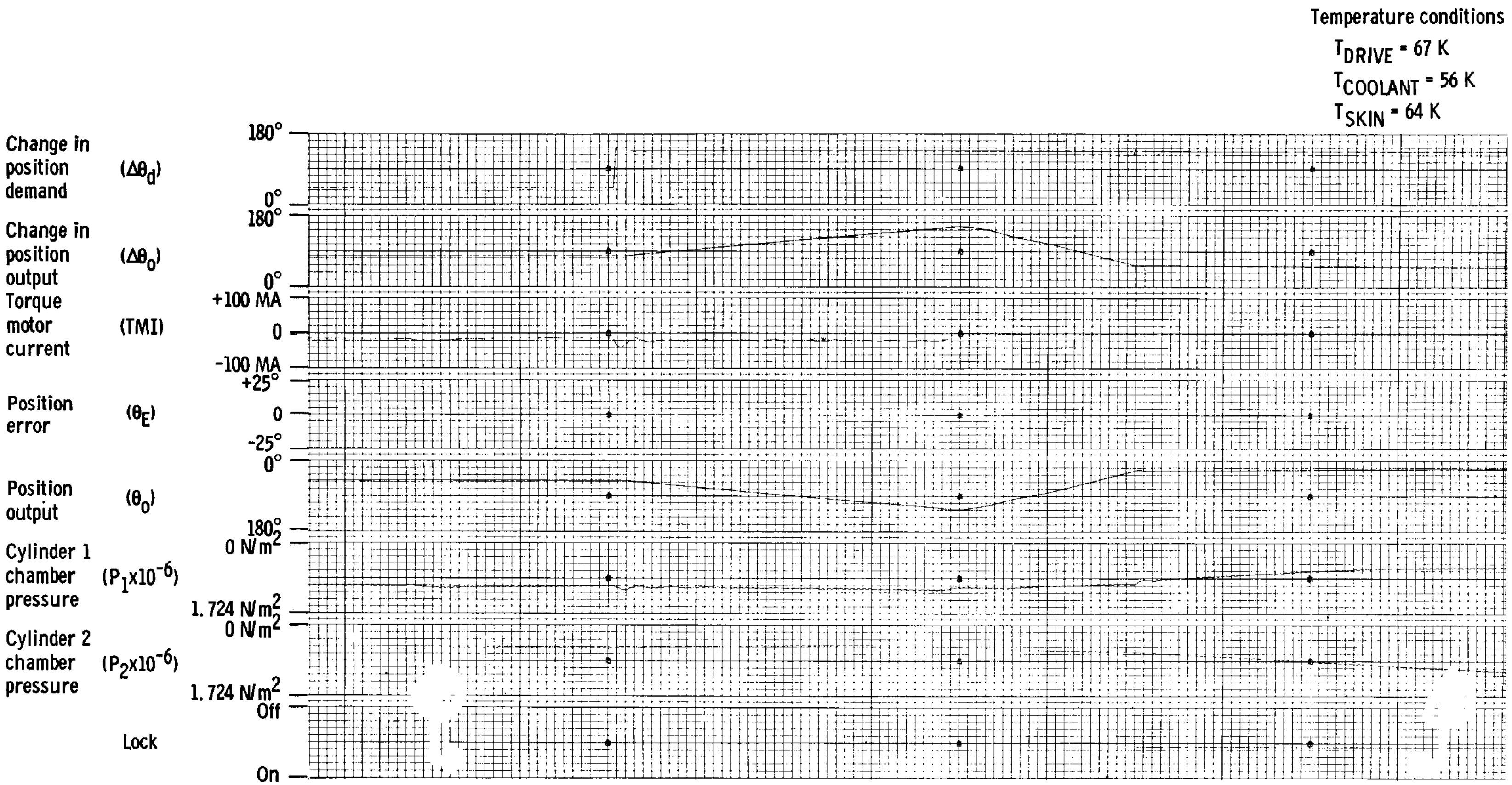
(b) Thermal cycle 1.

Figure 8. - Continued.



(c) Thermal cycle 2.

Figure 8. - Continued.



Time scale, 0.025 sec/div

(d) Thermal cycle 3.

Figure 8. - Concluded.

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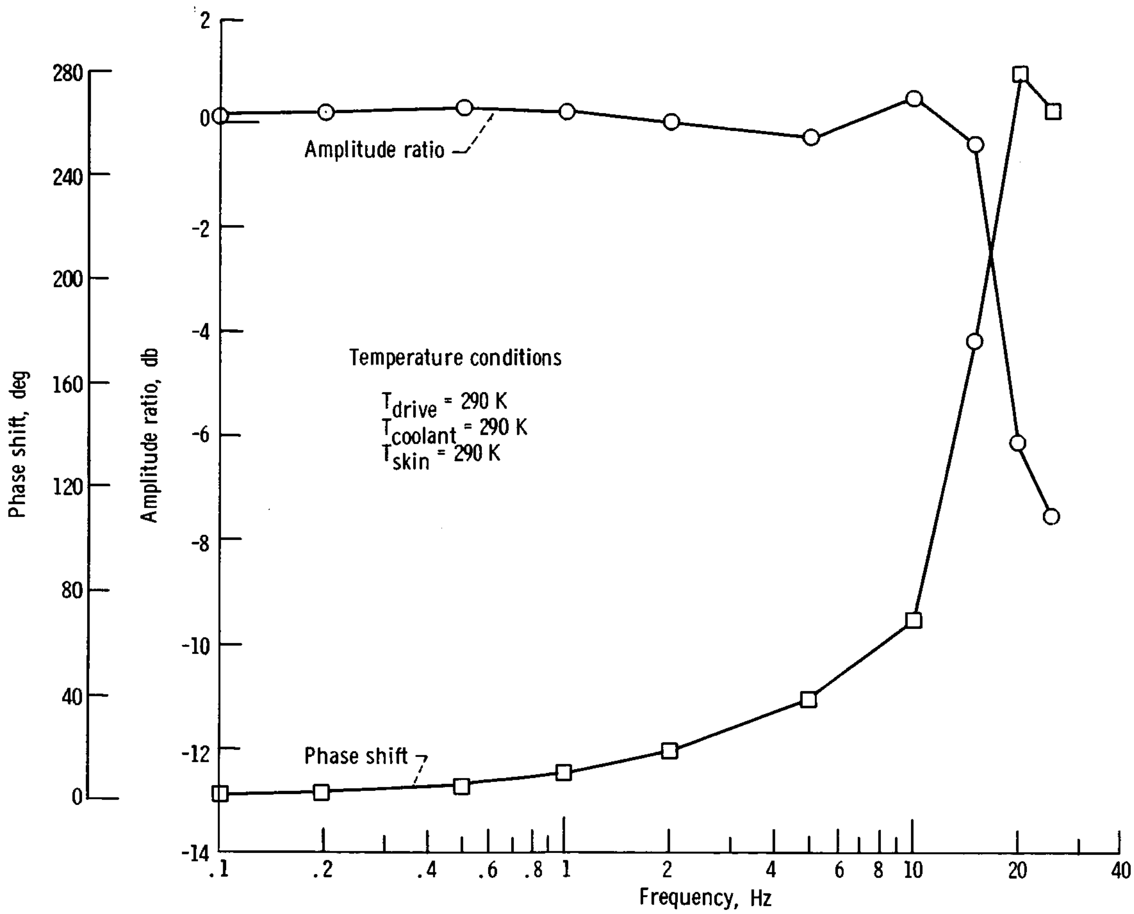
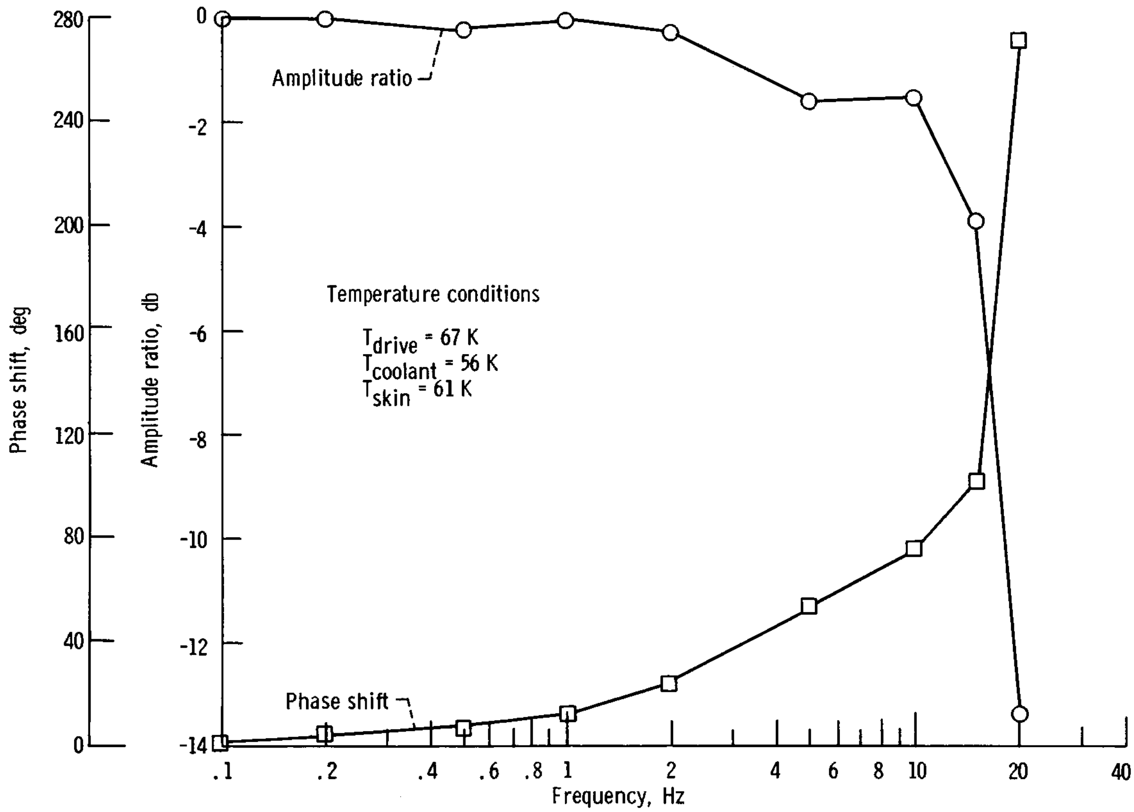


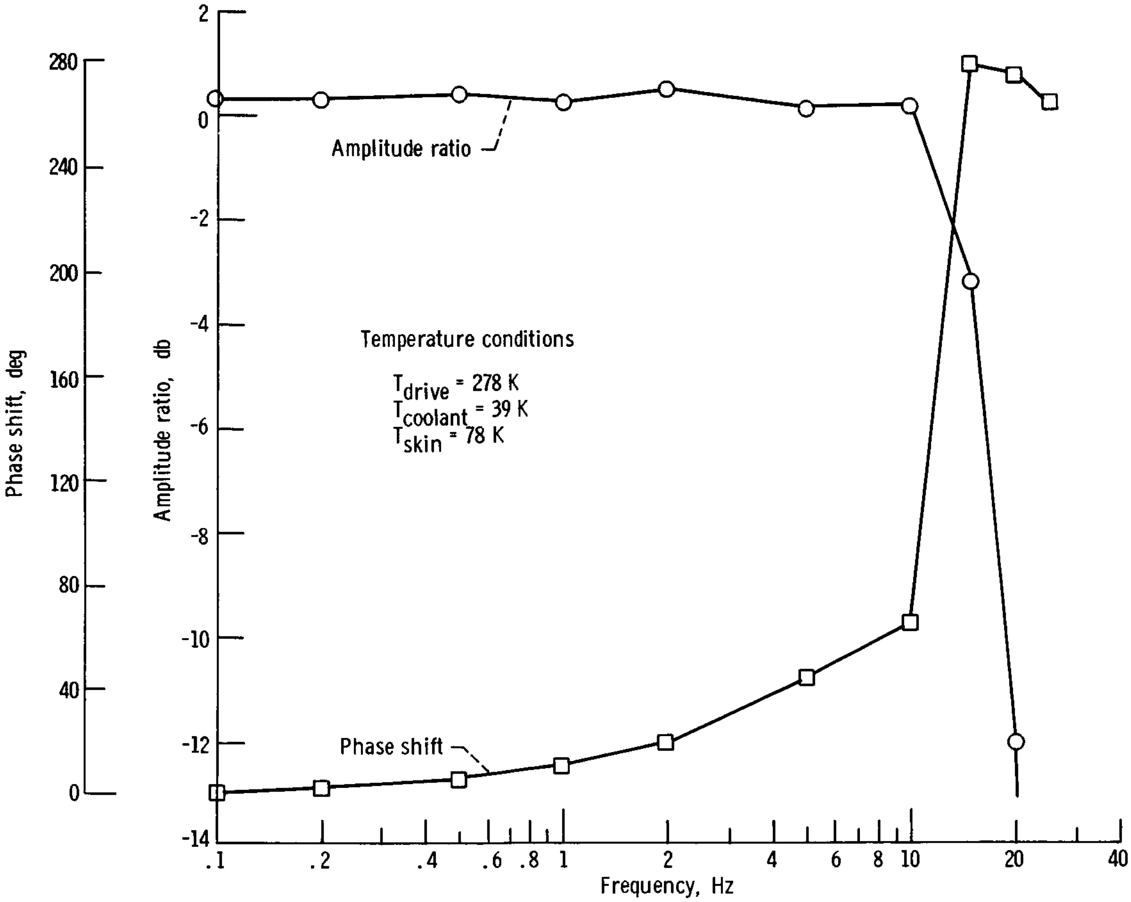
(a) Base line data - actuator frequency response.

Figure 9



(b) Thermal cycle number 1 - actuator frequency response.

Figure 9. - Continued.



(c) Thermal cycle number 2 - actuator frequency response.

Figure 9. - Continued.

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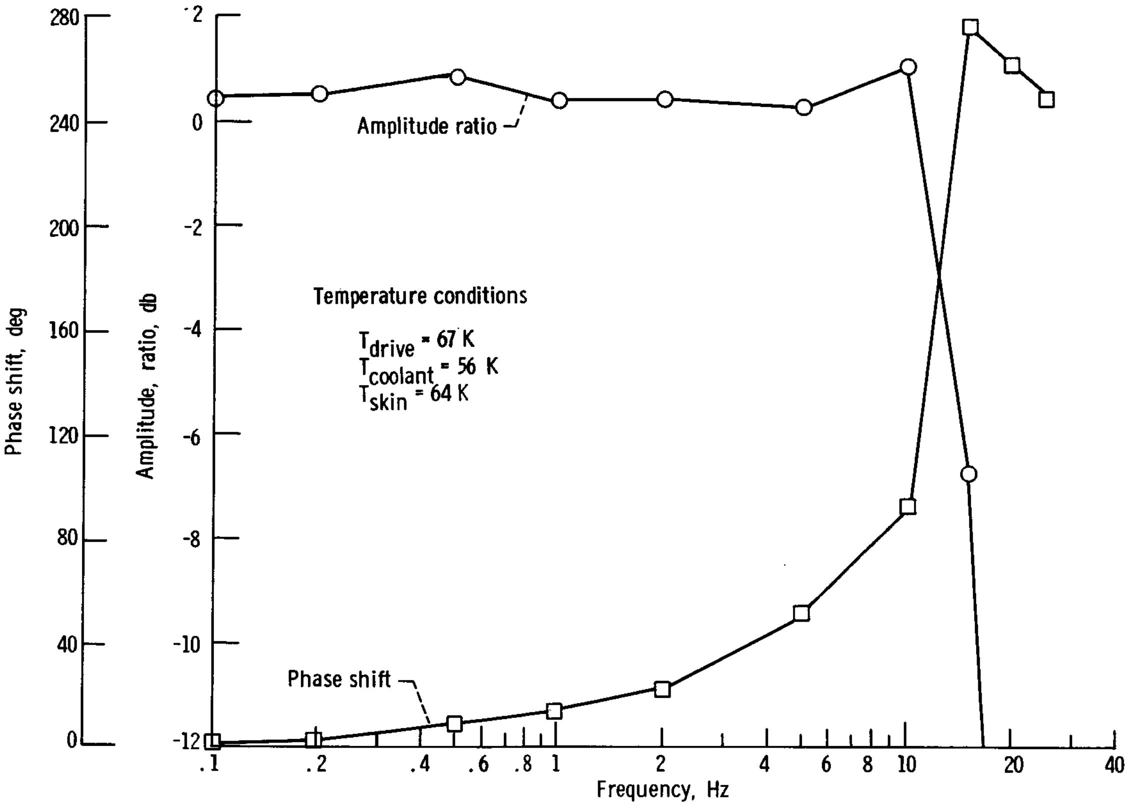

(d) Thermal cycle number 3 - actuator frequency response.

Figure 9. - Concluded.