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PNEUMATIC NUTATOR ACTUATOR MOTOR

By

G. R. Howland

Prepared For

NATIONAL AERONAUTICS & SPACE ADMINSTRATION

CONTRACT NAS3-5214

THE Bendix CORPORATION

BENDIX PRODUCTS AEROSPACE DIVISION
SOUTH BEND, INDIANA 46620

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THIRD QUARTERLY REPORT

PNEUMATIC NUTATOR ACTUATOR MOTOR

by

G. R. Howland

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 31, 1965

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PNEUMATIC NUTATOR ACTUATOR MOTOR

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ABSTRACT

This is the third quarter report of a twelve-month program to design, fabricate and test a prototype pneumatic nutator actuator motor for drum control of a nuclear reactor.

During the third quarter, both the mechanical components and the fluid logic circuit were assembled and tested. Performance of the motor, operated by a mechanical commutation system, is described. The results of the logic circuit optimization program is also given.

PNEUMATIC NUTATOR ACTUATOR MOTOR

By

G. R. Howland

SUMMARY

This report describes the third quarter accomplishments of a twelve-month program to develop a pneumatic actuator motor of a new concept. The actuator motor operates from a pneumatic power supply and produces a high torque, low speed mechanical output proportional to a pneumatic input pressure differential signal. The commutation logic of the motor is accomplished by closed loop fluid interaction (vortex type) devices.

The mechanical components of the motor were assembled and tested. Commutation was accomplished by a mechanical valving assembly which was externally driven. The maximum obtainable torque was measured for various input speeds. A discussion is given of possible methods of improving the motor performance.

Initial testing and adjustment of the complete commutation logic circuit is described. Measurements of the logic circuit output indicates that the circuit will be capable of operating and controlling the motor.

The anticipated goals for the fourth and final quarter are listed.

SECTION 1

INTRODUCTION

The Pneumatic Nutator Actuator Motor is being developed by Bendix Products Aerospace Division under Contract NAS3-5214 for NASA-Lewis Research Center. The purpose of the contract is to build and evaluate a pneumatic actuator motor for control of a nuclear reactor. The required performance is given in the specifications of Contract NAS3-5214. The motor is of a different concept from the conventional gear, vane or piston type actuators. The logic circuits required to operate the motor have no moving parts and are composed of fluid interaction (vortex type) devices.

During the third quarter, the mechanical components of the actuator hardware were assembled and tested. The motor was operated by means of a mechanical commutation valving driven externally.

The pure fluid commutation plates were assembled and tested. Optimization of the bleed orifice sizes was obtained.

Section 2 outlines the present status of the mechanical components. Section 3 describes the status of the commutation circuitry. The fourth quarter goals are given in Section 4.

SECTION 2

MECHANICAL COMPONENTS

2.1 INITIAL ASSEMBLY

The actuator motor mechanical components were initially assembled to verify the assembly procedure. The only problem encountered during assembly (except for a minor bearing relief requirement) was the scram spring. This spring is a torsional clock type. It was found that excess friction was developed by the coils rubbing together. After discussion with the vendor, a more stringent specification was written and new springs are being manufactured. Delivery is expected about the middle of April.

For initial evaluation of the motor performance, the unit was assembled without the scram spring, torsion shaft, drum brake and dynamic seal.

2.2 BREAK-IN RUNNING

After initial assembly and adjustment, the motor was run continuously at an input commutation speed of 1000 rpm (5.6 rpm output speed) for fifteen minutes in each direction. No output load was applied. On disassembly some flaking of the molybdenum disulphide lubricant on the gear teeth was noted. After approximately ten hours of running, mostly under high load condition, no further flaking of the lubricant was evident and the gear teeth appear in excellent condition.

2.3 PERFORMANCE MEASUREMENTS

After run-in, the pressures supplied to the bellows were monitored by gages on the mechanical commutator. It was found that the commutator was "breaking before making", causing the number of pressurized bellows to vary between three and four, depending on the angular position of the commutator. The distribution slot in the commutator was modified to provide a more even pressure distribution. Figure 2-1 shows the pressure variations in bellows #1 and #5. It can be seen that the reduction in one bellows pressure is accompanied by a corresponding increase in the other bellows pressure. In order to obtain this symmetry, the supply and vent ports of the commutator are "short circuited" during portions of the commutation cycle. This short circuit causes an increase in the supply flow and a consequent reduction in the bellows pressure. This reduction can be seen in Figure 2-1 each time a bellows is pressurized. Unsuccessful attempts were made to add capacitance to the inlet and bellows supply lines to minimize this pressure variation.

Maximum output torque for a given commutator speed was determined by loading the output shaft until the gear teeth disengaged. A plot of maximum output torque against input commutator speed is shown in Figure 2-2. Output shaft speed can be obtained by dividing the input speed by 180.

This method of shaft loading will indicate the torque obtained when the pressurized bellows pressure is at a minimum. By monitoring the transient bellows pressure and measuring the minimum obtained, the output torque can be corrected to determine the actuator performance assuming a uniform bellows pressure. This corrected torque versus speed curve is shown in Figure 2-3. The corrected curve indicates the maximum torque which could be obtained with the self-commutation circuit.

The torque required to back drive the motor was found by holding the mechanical commutator stationary and applying sufficient torque to the output shaft to cause tooth disengagement. This torque is shown in Figure 2-4 for various combinations of pressurized bellows.

Previous experience with nutator gear concepts has shown that the mechanical efficiency (n) is independent of the direction of drive. The efficiency can be calculated from the output torque (T_o) and the back driving torque (T_r) as follows:

$$n = \sqrt{\frac{T_o}{T_r}}$$

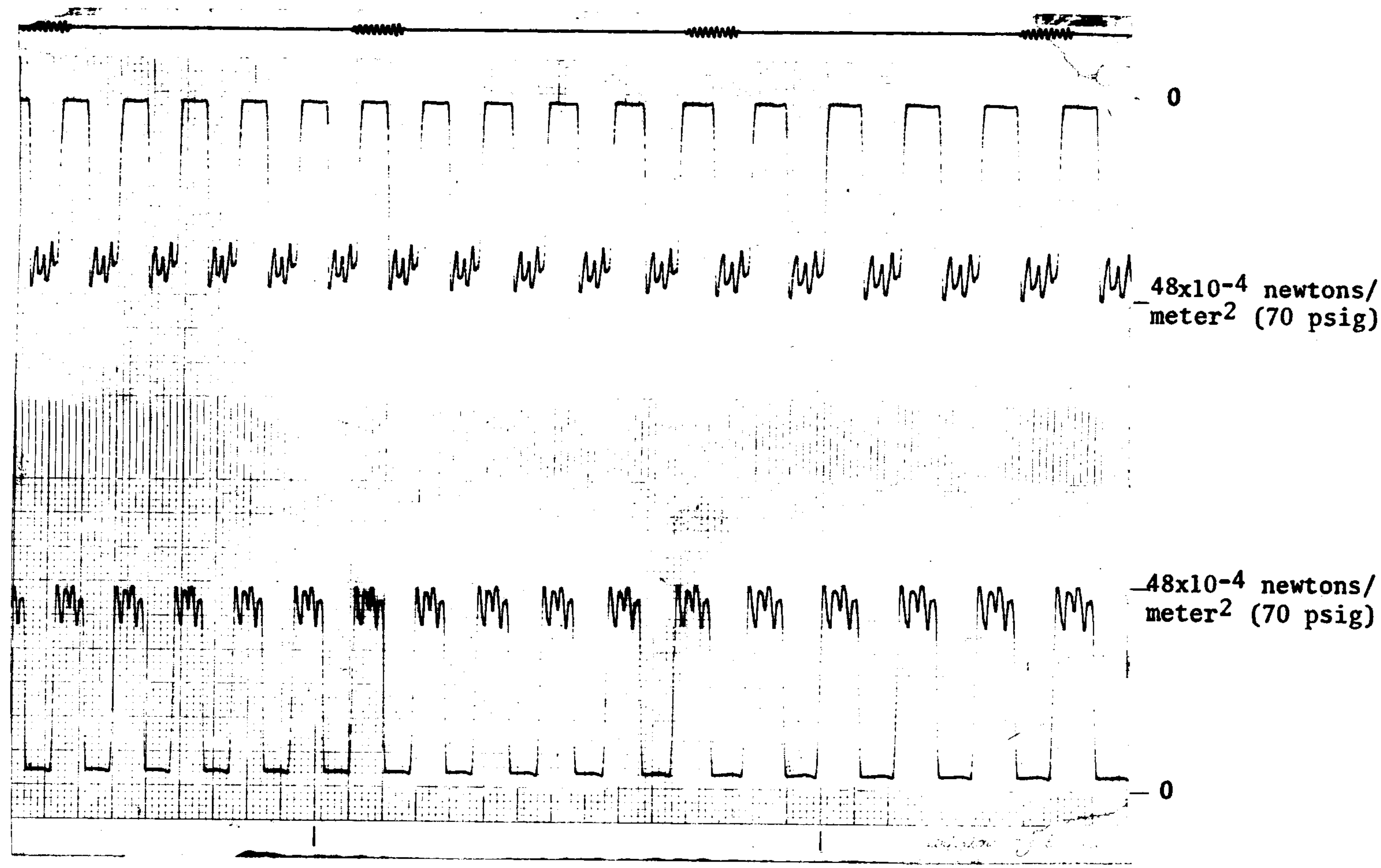


FIGURE 2-1 PRESSURE PROFILE - BELLOWS #1 AND #5 MECHANICAL COMMUTATOR

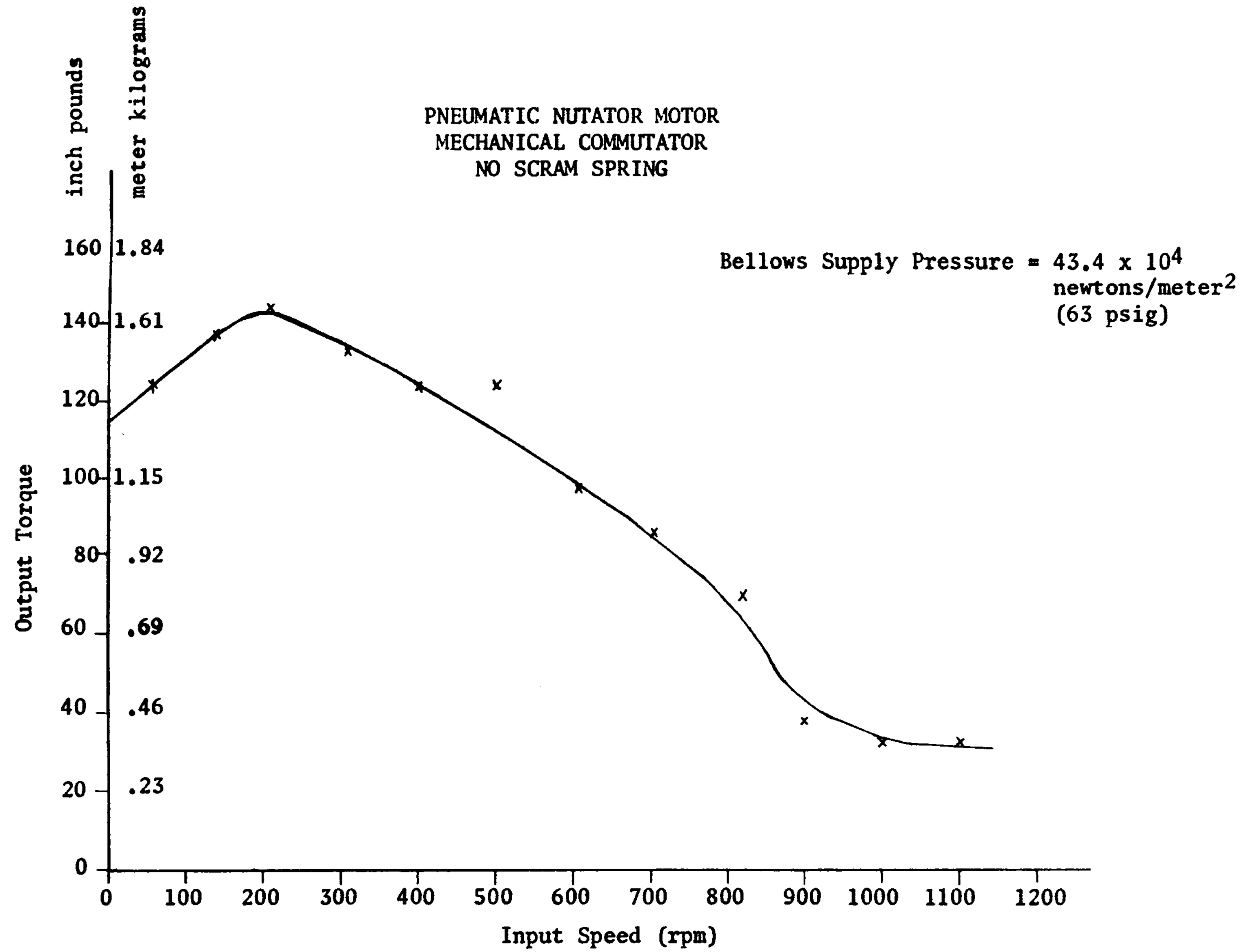


FIGURE 2-2 OUTPUT TORQUE VERSUS INPUT SPEED

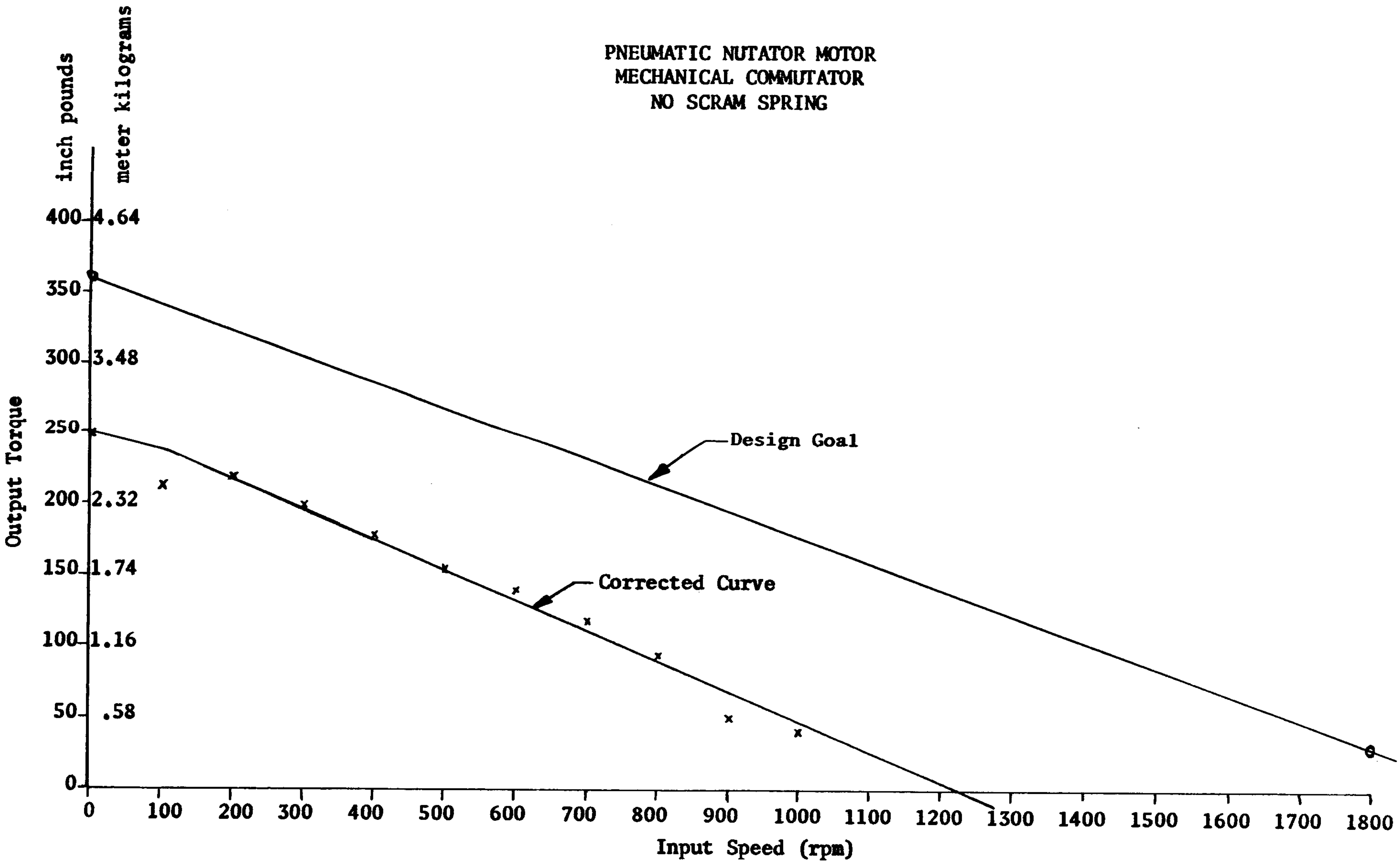


FIGURE 2-3 CORRECTED OUTPUT TORQUE VERSUS INPUT SPEED

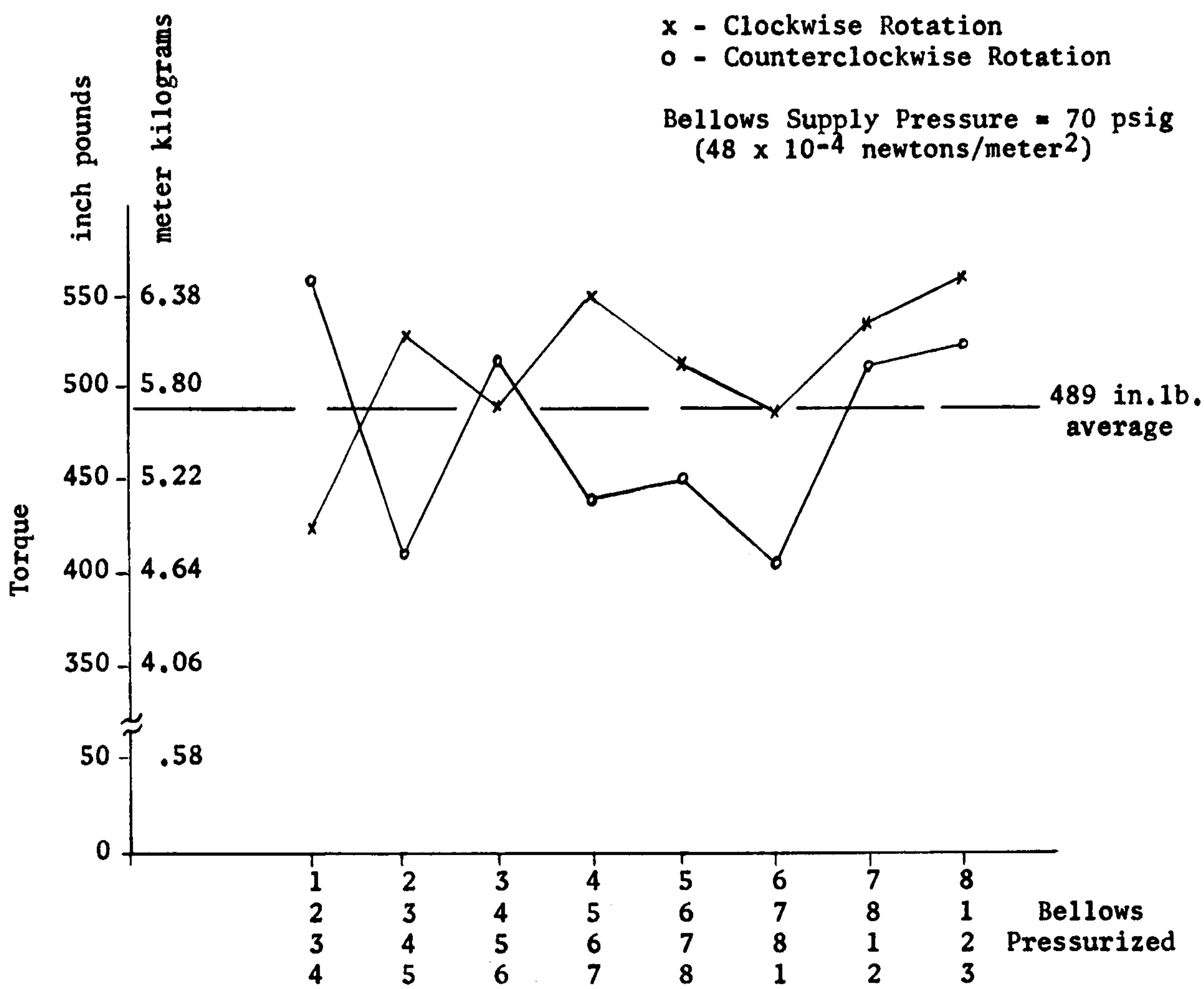


FIGURE 2-4 REVERSED STALL TORQUE

or, from Figures 2-3 and 2-4,

$$n = \sqrt{\frac{2.89}{5.65}} = 71.5\%$$

This efficiency agrees closely with the original design estimate (68%).

Further testing of the motor was started to determine the torque versus supply pressure characteristics, but was terminated when a rapid deterioration in output torque was noted. Disassembly of the unit showed that all four flexure pivots were either broken or badly distorted. It is felt that a failure of the pivots resulted from the shock loading employed by the method of test and is not indicative of the performance under normal operation. The pivot holes were rebored to take larger flexure pivots. This will increase the torque capacity by 50%.

The maximum corrected output torque obtained was 2.89 meter-kilograms (250 in. lbs.) (see Figure 2-3). With a measured efficiency of 71.5%, the internal torque developed is 4.05 meter-kilograms (350 in. lbs.). The design internal torque is 7.05 meter-kilograms (610 in. lbs.). It appears that the motor is producing only 57% of the design value. This torque reduction can be caused by one or more of the following factors.

(a) Bellows pressure is measured upstream of a 1.015×10^{-3} meter (.040 inch) diameter orifice. Any appreciable bellows leakage would reduce the actual bellows pressure below the measured value.

(b) Bellows effective area is less than the design requirements.

(c) The nutation angle is incorrectly set.

(d) Inaccuracies in gear profiling has resulted in a reduced angle of force centroid.

To investigate these possible causes, the following action was taken:

(a) A bellows test fixture was fabricated to allow pressurization of an individual bellows assembly. A check of all the bellows showed that only two of the sixteen on hand (eight spare) had appreciable leakage. The eight bellows taken from the motor had negligible leakage.

(b) Two bellows were selected at random and the force for a given applied pressure was measured. The force measurement gave an effective bellows area of 2.67×10^{-4} meters^2 (.414 in.^{2}) and 2.65×10^{-4} meters^2 (.411 in.^{2}). These areas are within the allowable limit of 2.80×10^{-4} meters^2 ±5% (.435 in.^{2} ±5%).

(c) &
(d) The nutation angle and the gear profile cannot be measured directly and any indirect measurement is open to question. After repair of the flexure pivots, it is expected that the motor will be operated with the pure fluid commutation circuit. Shims will be added at the outer casing junction and under the pivot points to vary the nutation angle. The optimum nutation will then be determined by the angle which results in maximum output torque.

The repaired actuator motor is presently being assembled. The commutation pressure pick-offs will be adjusted for operation with the pure fluid circuitry.

SECTION 3

COMMUTATION CIRCUIT

3.1 LOGIC CIRCUIT TESTS

The commutation circuit plates shown in Figure 3-7 of the Second Quarterly Report (reference NASA CR-54282) were assembled with the appropriate test plates and functionally checked. A large amount of leakage occurred both radially between the plates and axially along the bolt holes. The leakage also changed after disassembly, making it difficult to size the fixed orifices for the selector and power valve supply pressures.

The bellows pressures could, however, be sequenced in the proper order and the operation of the logic circuit was verified. "Krylon" and grease were used for sealing purposes, but it was found that Krylon prevented easy separation of the plates and grease contaminated the flow channels. The method found most successful, and presently being used, is to lap and silver plate all plates before assembly. A photograph of the plate assembly is shown in Figure 3-1.

The bleeds were re-manifolded so that the supply pressures are in series rather than in parallel, from a common plenum. Test on the model commutation circuit had indicated that a series orifice arrangement provided the most optimum bellows pressures.

Many attempts were made to optimize the bleed sizes used to obtain these pressures. The effects of various changes are summarized below:

CAUSE	EFFECT
(1) Decrease in selector valve bleed size.	Improves minimum but reduces maximum bellows pressure.

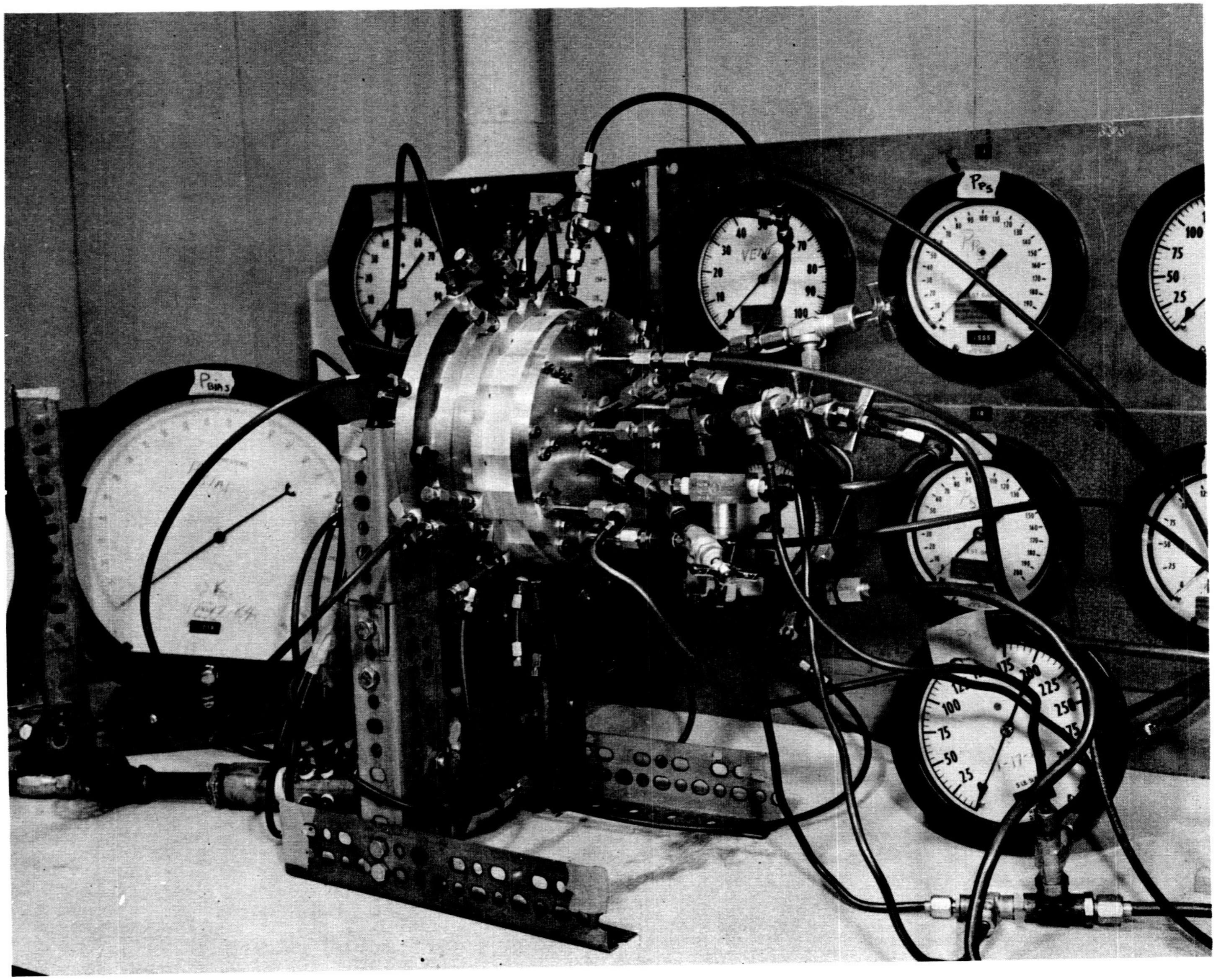


FIGURE 3-1 COMMUTATION PLATE TEST SETUP

CAUSE	EFFECT
(2) Increase in size of power valve bleeds.	Improves maximum but increases minimum bellows pressure.
(3) Increase in size of pick-off bleeds.	Improves bellows pressure differential.

Reversing the bleed sizes has the opposite effect. It was extremely difficult to find an optimum combination of the bleeds. Consequently, two new test plates were fabricated making it possible to simulate all bleeds externally by hand valves. These valves made it much easier to set up the optimum point, and in the final analysis, the pressure-flow characteristics can be measured to determine equivalent bleed sizes. The test plates were lapped and assembled with the commutation plates. By spot checking several points in the commutation circuit, adjusting the hand valves, and rechecking the points, an optimum setting of the valves was obtained and data were recorded for each step of the commutation circuit. The performance of this circuit is shown in Figures 3-2(a) and 3-2(b).

Figure 3-2(a) indicates the average pressure differential obtained between the four pressurized outputs and the four non-pressurized outputs for each sequence of pick-off pressure. Figure 3-2(b) shows the average pressure levels of the pressurized and non-pressurized outputs.

It can be seen that the pressure differential was a maximum when the four pressure pick-offs were covered, and a minimum when the pick-offs were open. This was particularly noticeable when the right directional signal was applied (P_{DR} Hi). This variation was due to the variation in total flow applied to each of the selector valves. The flow variation caused a change in the selector supply pressure, which in turn affected the ability of the selector output to control the power valve.

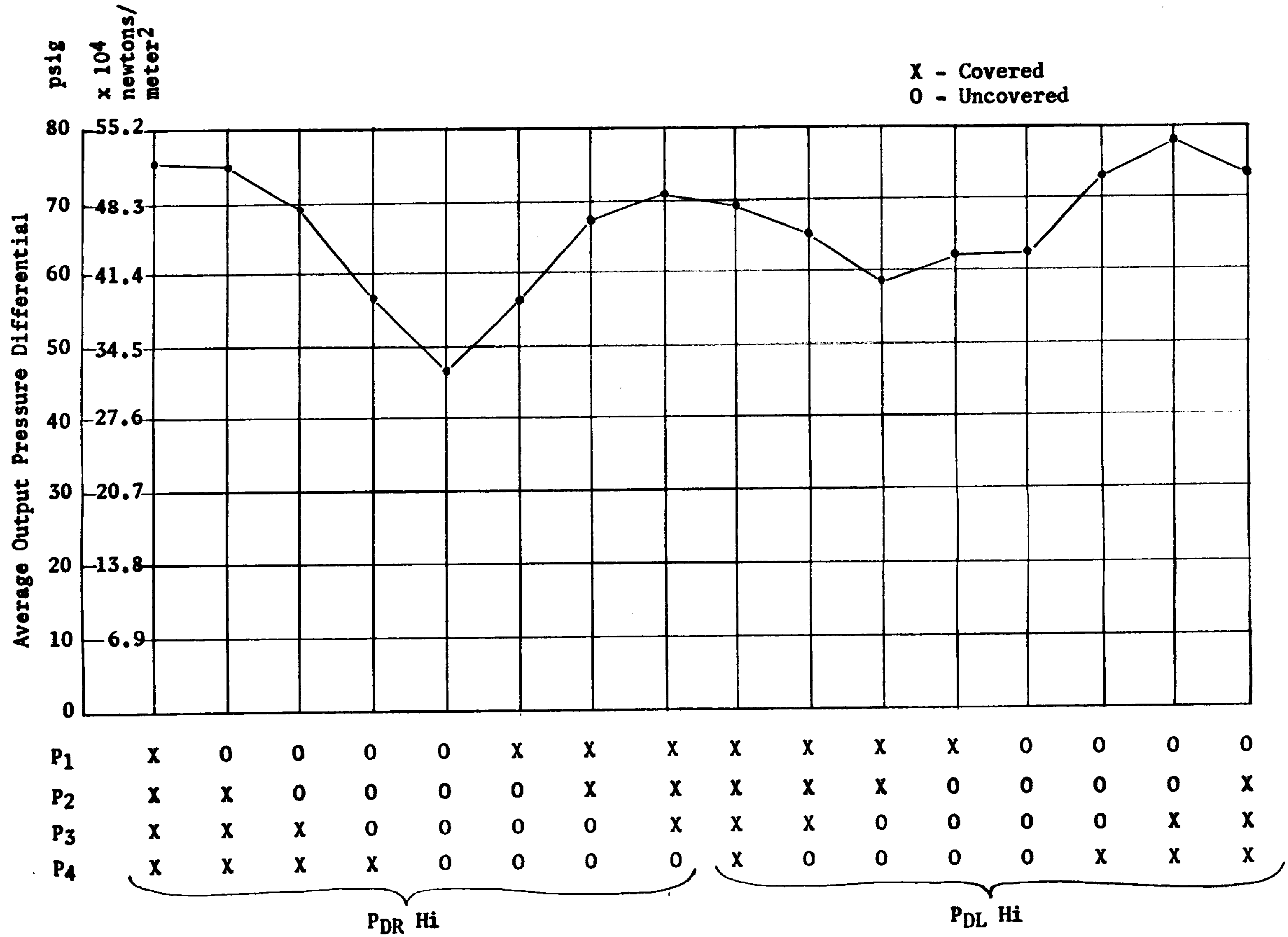
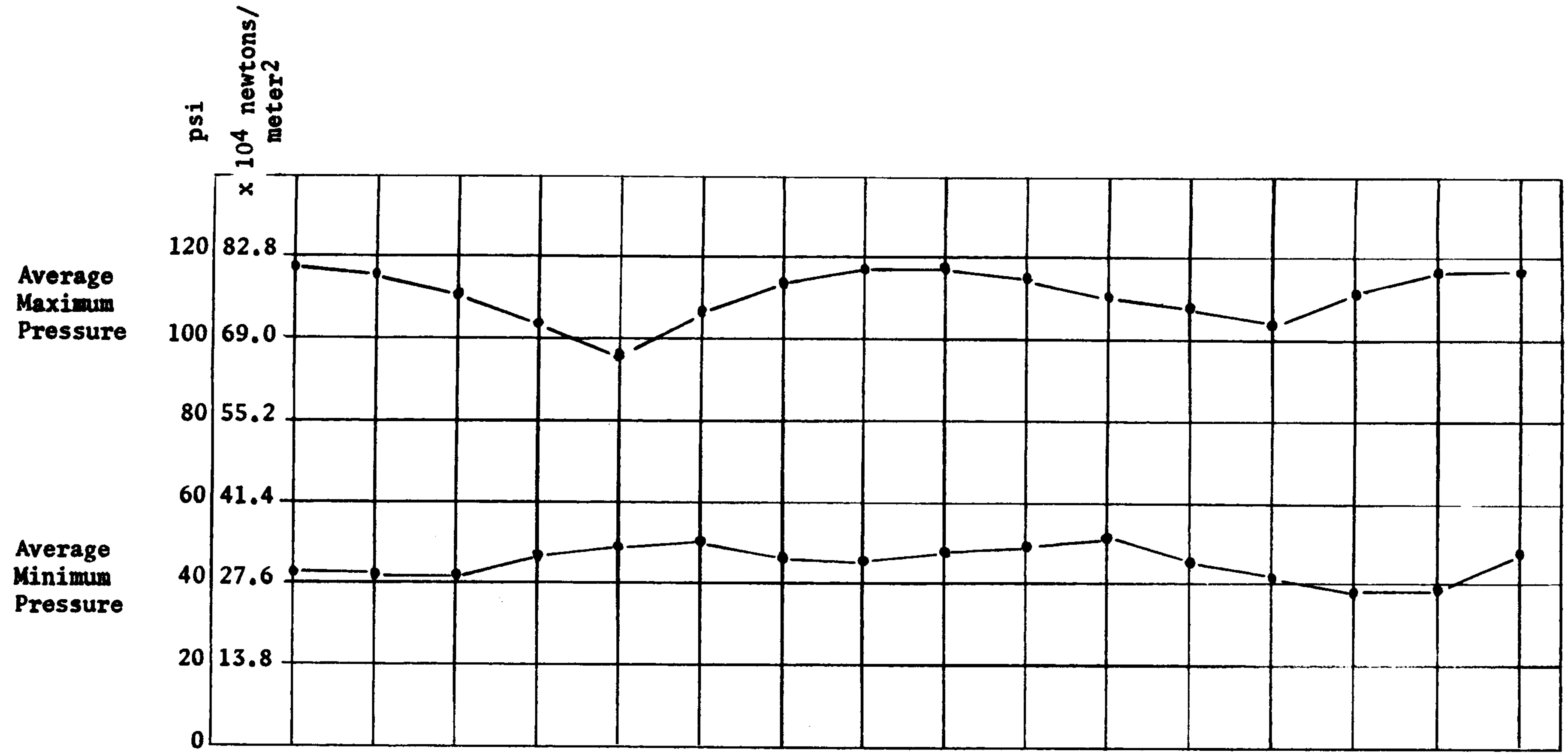


FIGURE 3-2(a) LOGIC CIRCUIT OUTPUT PRESSURE DIFFERENTIAL



P_1	X	0	0	0	0	X	X	X	X	X	X	X	0	0	0	0
P_2	X	X	0	0	0	0	X	X	X	X	X	0	0	0	0	X
P_3	X	X	X	0	0	0	0	X	X	X	0	0	0	0	X	X
P_4	X	X	X	X	0	0	0	0	X	0	0	0	0	X	X	X

P_{DR} Hi (first eight columns) P_{DL} Hi (last eight columns)

X - Covered
0 - Uncovered

FIGURE 3-2(b) LOGIC CIRCUIT OUTPUT PRESSURE LEVEL

Considerable improvement in the pressure differential variation can be obtained by employing a vortex pressure regulator across the selector supply. It is not proposed to attempt this modification until performance of the complete actuator motor has been determined. The commutation circuit, adjusted to give the performance shown in Figure 3-2, will be used to operate the actuator motor.

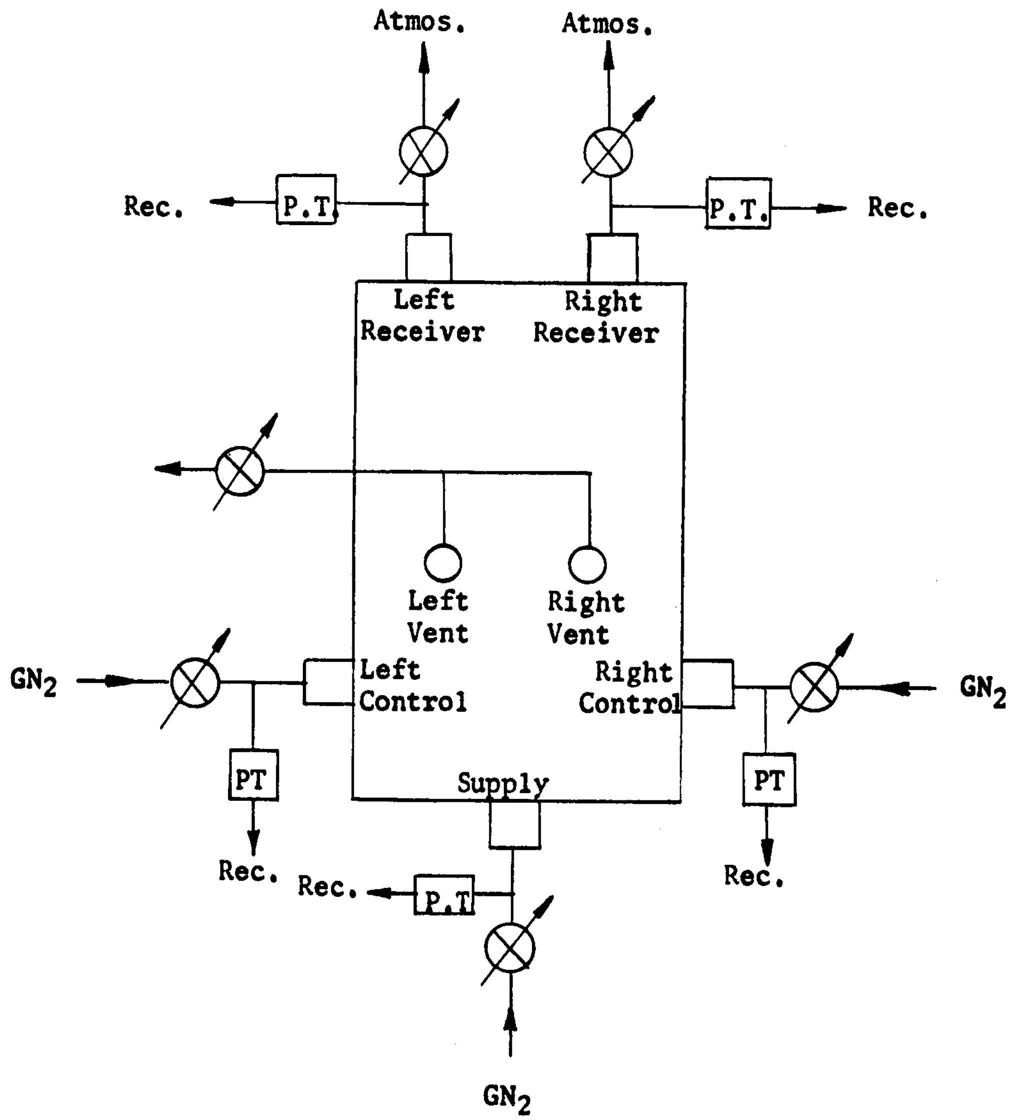
3.2 PRESSURE ERROR VALVE

No further work beyond that reported in the Second Quarterly Report was performed on the pressure error valve. The sizing of this valve will be done when the total system performance has been evaluated.

3.3 BISTABLE DIRECTIONAL AMPLIFIER

A bistable flip-flop was obtained from the Bendix Research Laboratories Division for evaluation. The purpose of the tests was to determine the performance of a typical flip-flop under conditions of high supply and high vent pressures. Tests were conducted with 10.3×10^4 newtons/meter^2 (15 psig) and 131×10^4 newtons/meter^2 (190 psig) supply pressures. In both cases, there is approximately a 10.3×10^4 newtons/meter^2 (15 psi) drop from supply pressure to receiver pressure. The control ports were pressurized slowly by manually operated valves.

Figure 3-3 is a flow diagram of the test setup. Strain gage-type pressure transducers were used. Figure 3-4 illustrates the receiver and control pressures of the amplifier at six different operating points. Supply pressure remained constant throughout testing. Points 3 and 6 involve control flow continuing into the amplifier after the main stream has changed positions. The control flow occurring at this point was determined by maintaining the control port hand valve at exactly the same position as it was when the bistable valve was at the threshold of switching.



Rec. - Recorder
P.T. - Pressure Transducer
Atmos. - Atmosphere

FIGURE 3-3 TEST SETUP FOR MODEL DIRECTIONAL AMPLIFIER

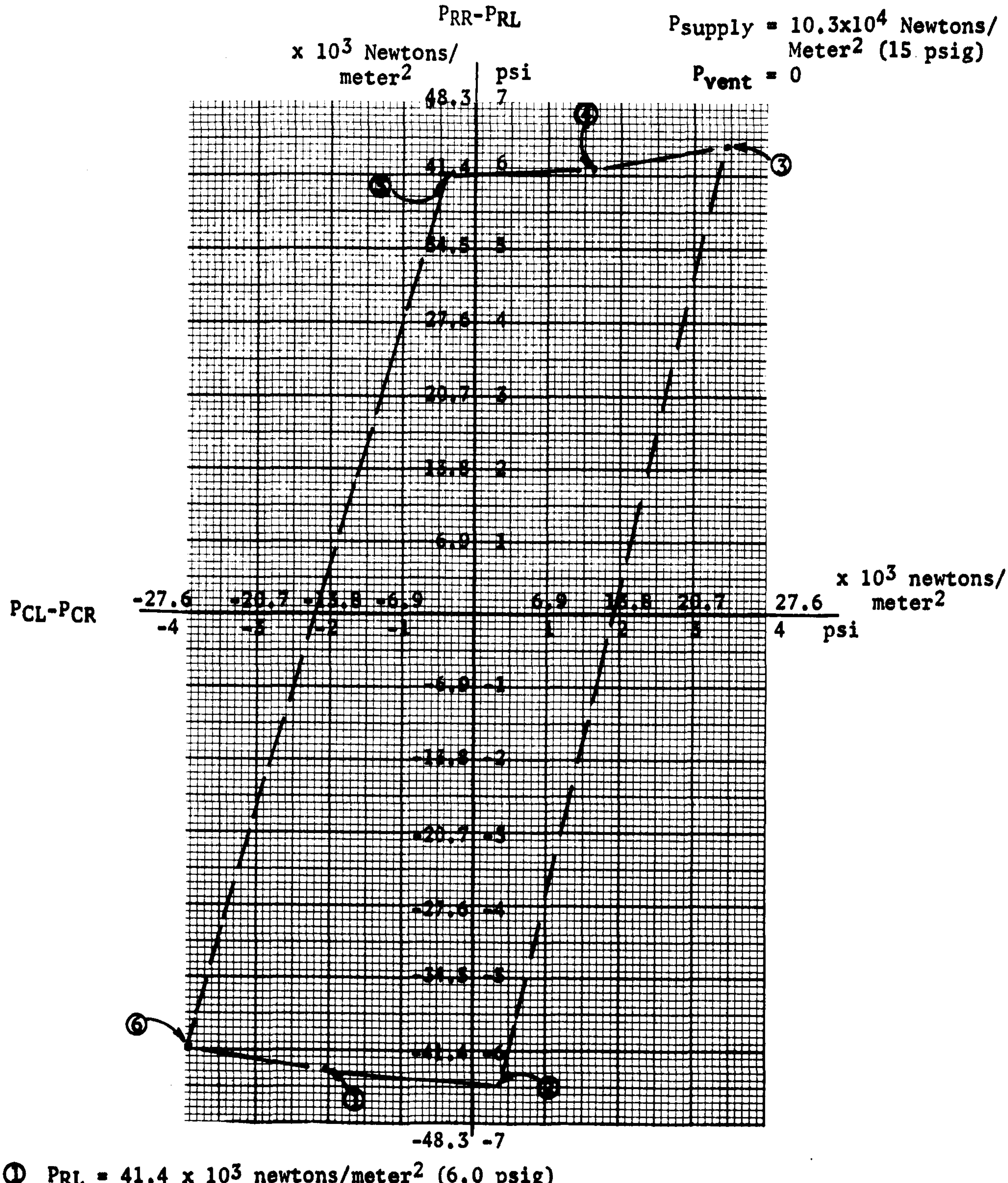
It can be seen from Figure 3-4 that the receiver recovery pressures are 40% of the quantity, supply pressure minus vent pressure. Pressure recovery was determined by slowly increasing both the receiver impedances at the same time until the amplifier began to oscillate. At this point, both impedances were reduced slightly until the amplifier stabilized. The pressures that appear in Figure 3-4 are the maximum stable pressures obtainable.

During the high pressure test, the vents were connected to each other and shut off from the atmosphere so that better pressure recovery could be maintained. Figure 3-5 illustrates the results of this test.

A test run with 138 x 10^4 newtons/meter^2 (200 psig) supply pressure, 121 x 10^4 newtons/meter^2 (175 psig) maximum and 113 x 10^4 newtons/meter^2 (165 psig) minimum receiver pressures was made to check the weight flow rate through the amplifier. The supply flow rate was .000425 kilograms/second (.00094 lb./sec.) GN_2. The high side receiver flow was .000226 kilograms/second (.0005 lb./sec.). The commutation circuit requires a high side flow of approximately .00454 kilograms/second (.01 lb./sec.) GN_2, a weight flow rate twenty times greater than transmitted by the tested amplifier.

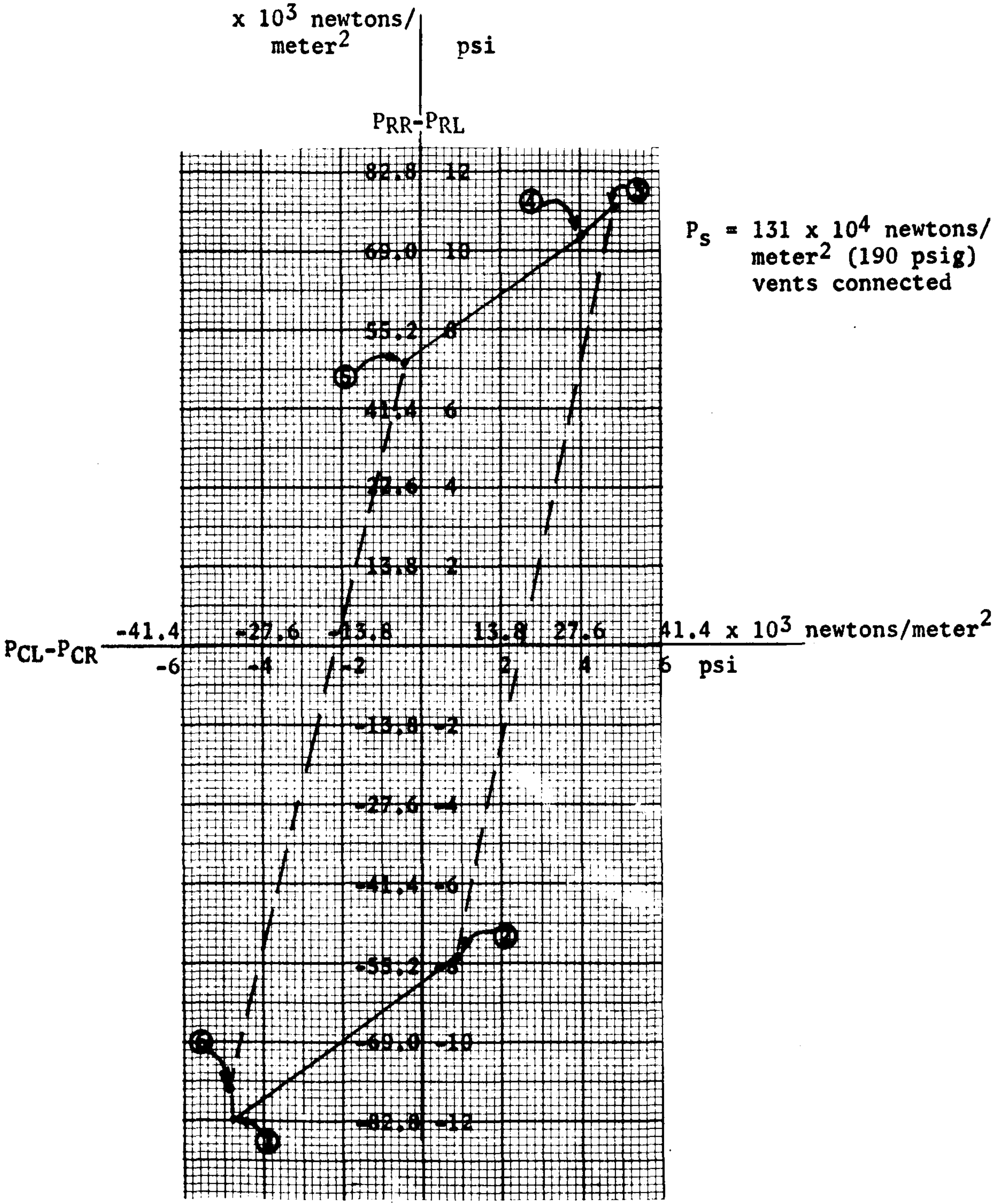
It is believed the amplifier can be scaled to meet the higher flow requirements and yet maintain the 121 x 10^4 newtons/meter^2 (175 psig) high side, 113 x 10^4 newtons/meter^2 (165 psig) low side pressures with a supply pressure of 138 x 10^4 newtons/meter^2 (200 psig).

The pressure-flow characteristics of the directional signal in the actual commutation will be measured to determine more precisely the requirements before a bistable unit is fabricated.



① P_{RL} = 41.4 x 10^3 newtons/meter^2 (6.0 psig)
P_{CR} = 2.76 x 10^3 newtons/meter^2 (-0.4 psig)
④ P_{RR} = 41.4 x 10^3 newtons/meter^2 (6.0 psig)
P_{CL} = -2.76 x 10^3 newtons/meter^2(-0.4 psig)

FIGURE 3-4 LOW PRESSURE PRESSURE RECOVERY



1 P_{RL} = 121 x 10^4 newtons/meter^2 (176 psig)
1 P_{CR} = 113.2 x 10^4 newtons/meter^2 (164.8 psig)
4 P_{RR} = 121 x 10^4 newtons/meter^2 (176 psig)
P_{CL} = 112.9 x 10^4 newtons/meter^2 (164 psig)

FIGURE 3-5 HIGH PRESSURE PRESSURE RECOVERY

SECTION 4

FOURTH QUARTER GOALS

The integration of the commutation circuit and the actuator motor will be made early in the fourth quarter. The nutation angle and the pick-off positions will then be adjusted to obtain optimum performance. Once the completed system is optimized, flow measurements will be made to determine the requirements of the pressure error valve and the directional flip-flop. These units will then be fabricated, tested and incorporated with the actuator motor system.

An electromechanical torque motor of the NERVA drum actuator design will be used to provide the input signal. Upon completion of the commutation circuitry, dynamic response measurements will be made.

The complete actuator motor will be connected to the NERVA drum fixture and operated on hydrogen gas at a gas and environmental temperature down to -280°F. Operation of the scram mechanism will be demonstrated at the cryogenic temperatures.

Due to the fabrication lead time, it is not anticipated that the directional amplifier or pressure error valve will be evaluated at cryogenic conditions. The operation of the remaining components of the commutation logic should, however, indicate the feasibility of the entire system.

An analytical study of the comparison between this actuator motor and more conventional concepts has been started. The performance data obtained during the fourth quarter will be incorporated in this study.

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