NASA CR 65435

FR-2408-101

FINAL REPORT

DESIGN, DEVELOPMENT, FABRICATION, TESTING, AND DELIVERY OF FIVE (5) CARDIOVASCULAR REFLEX CONDITIONING SYSTEMS

Contract NAS 9-5331

March 14, 1966

Prepared for:

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Beckman® INSTRUMENTS, INC.
ADVANCED TECHNOLOGY OPERATIONS
FULLERTON, CALIFORNIA • 92634

FINAL REPORT

DESIGN, DEVELOPMENT, FABRICATION, TESTING, AND DELIVERY OF FIVE (5) CARDIOVASCULAR REFLEX CONDITIONING SYSTEMS

Contract NAS 9-5331

March 14, 1966

Prepared for:

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Beckman® INSTRUMENTS, INC.
ADVANCED TECHNOLOGY OPERATIONS
FULLERTON, CALIFORNIA • 92634

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

Space flights in both the United States and Russia have confirmed the fact that some form of compensation must be provided in order to minimize the effects of prolonged weightlessness upon the astronaut. As the duration of the flights increases, the problem becomes more critical. Tilt-table and cuffs around the proximal attachment of the lower extremities can have significant benefits in conditioning of the vascular reflex mechanisms and prevent the diuretic effects experienced during prolonged weightlessness.

Periodic inflation of pneumatic cuffs will artifically induce a hydrostatic pressure gradient in the lower venous system causing distention of these vessels and stimulating vascular reflex mechanisms.

Pneumatic cuff inflation, occluding venous return from the lower extremities will increase pooling in these areas and reduce thoracic blood volume. Decreasing thoracic blood volume will deplete the blood volume of the left atrium, thus preventing the stimulation of the Henry-Gauer volume/pressure receptors. This action will reflexly increase renal tubular reabsorption and subsequently inhibit diuresis.

The NASA Manned Spacecraft Center, recognizing the requirement for equipment for the Apollo program, contracted with Beckman Instruments, Inc. for the design, development, fabrication, testing, and delivery of five (5) Cardiovascular Reflex Conditioning Systems. (Contract NAS 9-5331).

1.2 General Description

The Cardiovascular Reflex Conditioning System provides a periodic inflation of pneumatic cuffs around the proximal attachment of the lower extremities. This will artifically induce a hydrostatic pressure gradient in the lower venous system causing distention of these vessels and stimulating venometer reflex mechanisms. In addition, the pneumatic cuff inflation should help prevent the diuretic effect of prolonged weightlessness.

The system is entirely pneumatic in operation and therefore does not require mechanical or electrical power of any kind.

The system is comprised of two basic components:

1. Pneumatic control system
2. Pneumatic oscillator system.

The pneumatic control system includes a two-stage differential pressure regulator for providing power to the oscillator, a single-stage differential pressure regulator for controlling cuff inflation pressure, a high pressure relief valve, and a low pressure relief valve.

The pneumatic oscillator system provides the timing function and the switching logic for the periodic inflation and deflation of the pneumatic cuffs.

1.3 Gemini Program

Beckman instruments, Inc. supplied equipment for the Gemini program (Contract NAS 9-3555) which included a pressurized oxygen storage vessel. The storage vessel was charged with 4500 psig of 100% oxygen. The pneumatic control

system contained, in addition to those components listed in paragraph 1.2, a spring-loaded shutoff valve for actuating the system, provisions for charging the pressurized storage vessel, and porting for installation of a pressure transducer and a reference line to the flight suit. Figure 1 is a photograph of the equipment supplied for the Gemini spacecraft. Figure 2 is a schematic diagram of the Gemini system.

The system was required to pressurize and depressurize one pair of astronaut cuffs on a 2-4 minute cycle to 80 mm mercury differential. In order that the cuff inflation pressure be controlled at 80 mm mercury with relation to the flight suit, a suit reference line was run from the diaphragm of the regulator to the suit.

1.4 Apollo Program

The equipment required for the Apollo program differs from that supplied for the Gemini spacecraft in the following respects:

1. A pressurized storage vessel will not be used. Instead, pressurized oxygen from the spacecraft PLSS supply will be used to operate the equipment.
2. The cuffs will be pressurized and depressurized on a 1-1 minute cycle.
3. The cuffs are pressurized to 90 mm mercury differential.
4. Three pairs of cuffs instead of one must be pressurized.

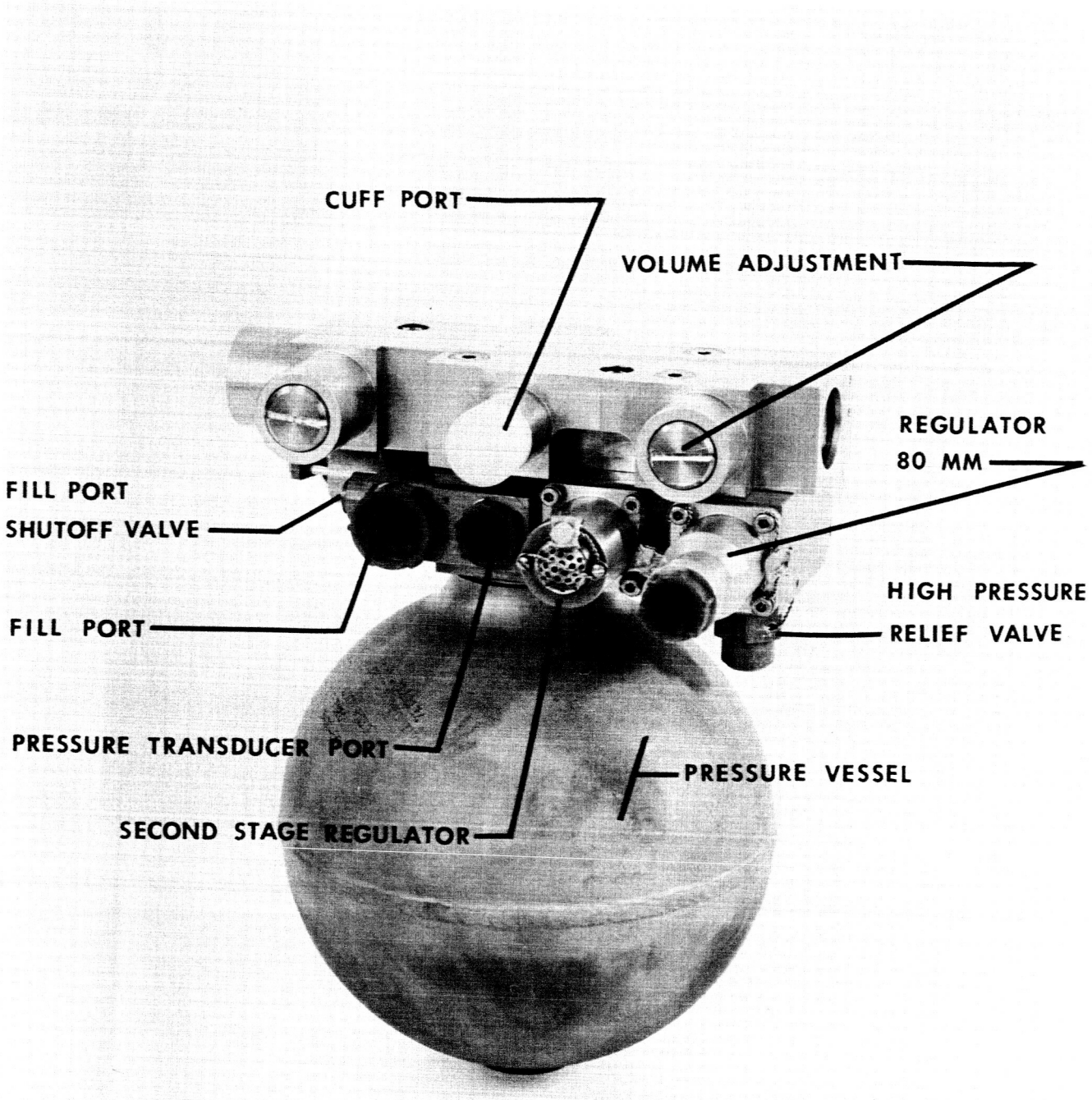


Figure 1. Photograph of Gemini System

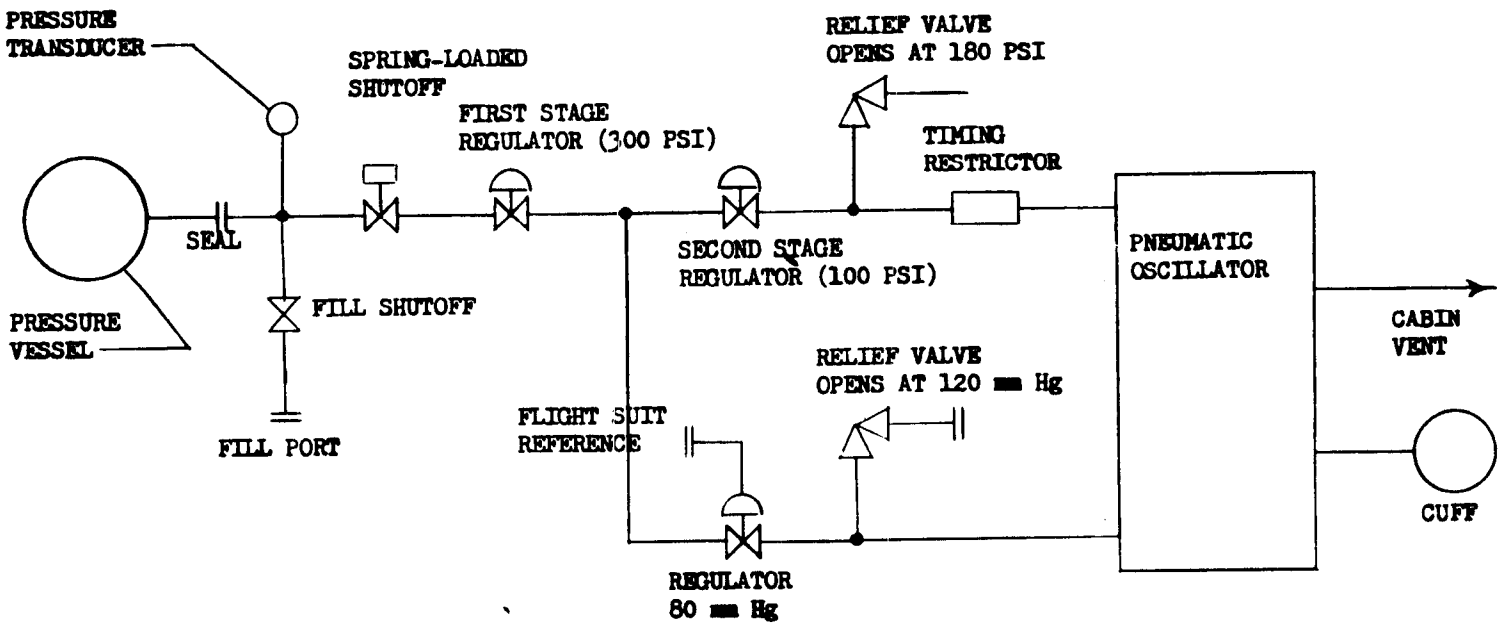


Figure 2. Cardiovascular Reflex Conditioner-Gemini, Schematic Diagram

As with the Gemini system, operation of the equipment is completely automatic once it is turned on. By deleting the pressurized storage vessel and operating the equipment instead from the main spacecraft oxygen supply, longer operation is assured. Also, system reliability is greatly increased because the number and complexity of components have been reduced to a minimum.

2.0 PRINCIPLES OF OPERATION

2.1 General Description

The necessary components less interconnecting tubing and cuffs (supplied by NASA-MSC) are mounted on a frame measuring 6.87 inches wide, 5.00 inches deep, and 3.06 inches high. The entire assembly weighs less than 2.5 pounds and mounts in the Apollo lower equipment bay. Figure 3, is a diagram of the system showing proper orientation with the spacecraft longitudinal axis.

2.1.1 Input

Input to the system is oxygen at 900 $\pm$35 psia supplied by the Apollo Portable Life Support System (PLSS). Connection is made by means of a specially fabricated MS fitting supplied by Beckman Instruments, Inc., which is similar to MS 33656-4, except for thread length. Input on the front of the mounting frame is clearly labeled as INLET.

2.1.2 Output

The output from the system is directed to the astronaut cuffs via connecting flexible tubing supplied by NASA-MSC. Connection is made through a standard MS 24392-4 fitting supplied by Beckman Instruments, Inc. Maximum pressure at this fitting is 90 +5, -10 mm mercury differential. This connector is labeled on the mounting frame as CUFF.

2.1.3 Cycling Times

The astronaut cuffs, when connected to the Cardiovascular Reflex Conditioning System, will alternately pressurize and depressurize to approximately 90 mm mercury differential over a two-minute cycle. That is, the cuffs are pressurized during the first minute, and bled down to ambient during the second

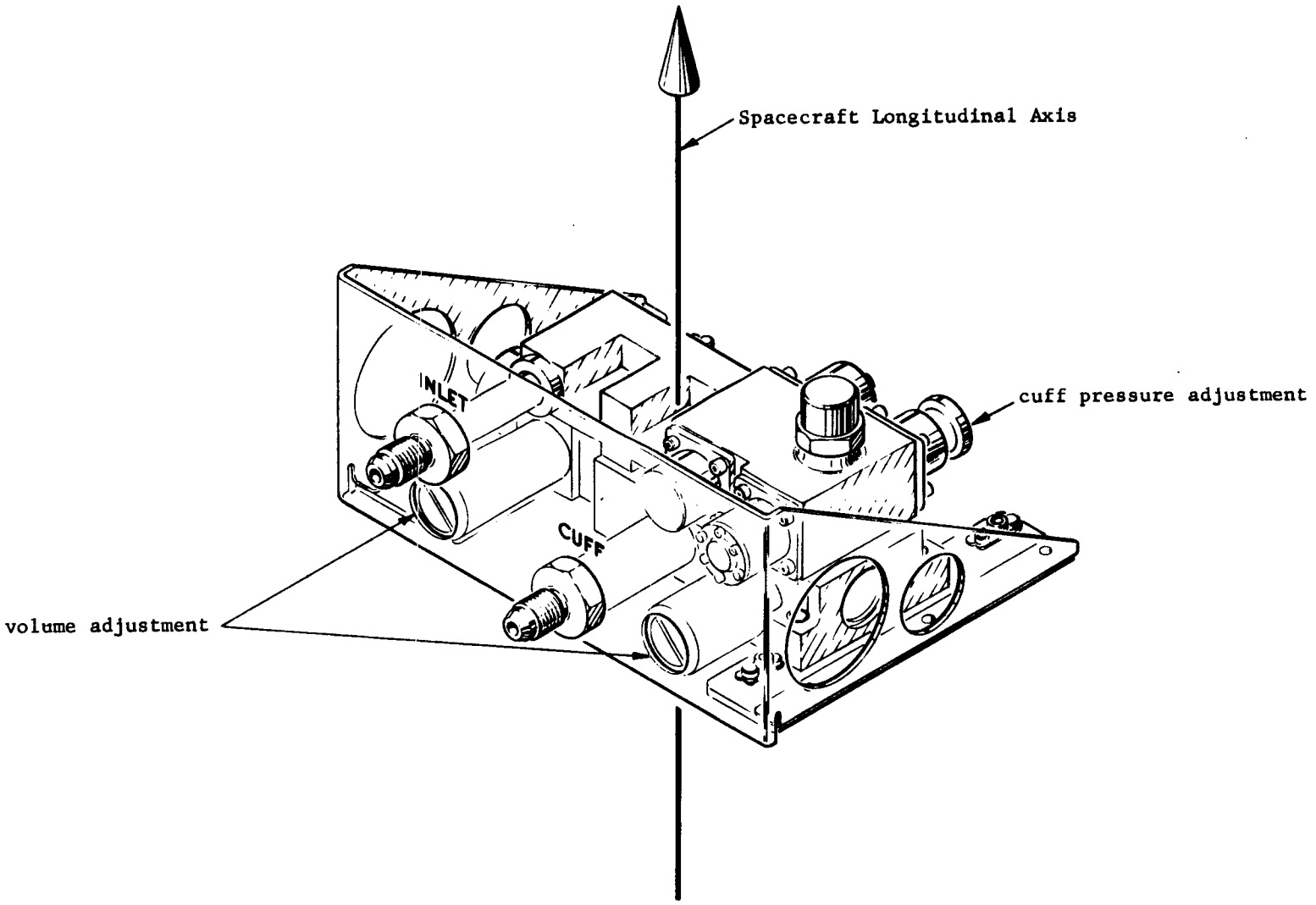


Figure 3. Apollo Diagram showing Spacecraft Longitudinal Axis

minute (for a 5.0 psia ambient atmosphere). Cycle times will be slightly shorter if the system is operated at ambient pressures higher than 5.0 psia. The system will operate according to the contract, Statement of Work, if the total displaced cuff volume is less than 60 cubic inches.

2.1.4 Pneumatic Circuit

Figure 4 is the pneumatic circuit for the Cardiovascular Reflex Conditioning System - Apollo. Operation of each of the components is more fully explained in subsequent paragraphs.

2.2 Pneumatic Control System

2.2.1 Two-Stage Regulator and Relief Valve

A two-stage regulator reduces the inlet pressure from 900 $\pm$35 psia to 100 $\pm$2 psig. Both stages consist of constant differential pressure regulators referenced to cabin atmosphere. As a protection against failure of the two-stage regulator, a relief valve is provided to assure the output pressure from the second stage does not become excessive. This relief valve actuates at 180 $\pm$20 psig.

2.2.2 Single-Stage Regulator and Relief Valve

The single-stage regulator (3rd stage) will operate from 100 psig supplied by the output from the second stage of the two-stage regulator described in 2.2.1. The output from the single-stage regulator is adjustable over the approximate range of 70-120 mm mercury differential; however, prior to testing and delivery, it is set at 90 mm mercury differential.

As a protection against failure of the single-stage regulator, a relief valve is provided to assure that the outlet pressure does not become excessive.

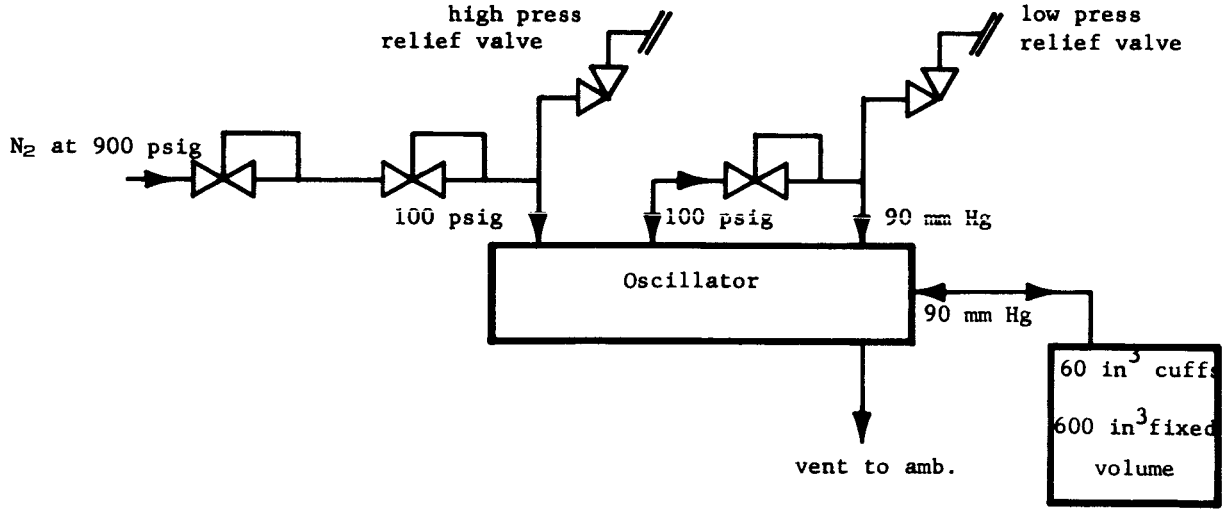


Figure 4. Cardiovascular Reflex Conditioner
Apollo, Pneumatic Diagram
(External to Oscillator)

This relief valve actuates at 120 $\pm$12 mm mercury differential.

2.3 Pneumatic Oscillator

The pneumatic oscillator is the heart of the Cardiovascular Reflex Conditioner. It provides the pneumatic RC timing functions as well as the necessary porting logic for directing the flow of gaseous oxygen to the pneumatic cuffs. A unique snap-action oscillator was designed at Beckman to meet the stringent requirements of long-cycle time and precise repeatability. A simple diagram of the pneumatic system is shown in Figure 5 to illustrate the principle of operation.

The oscillator is comprised of a piston of magnetic material which moves in a nonmagnetic cylinder. Ceramic magnets are located as stops at each end of the cylinder. The piston always rests in either the right-hand or the left-hand position in the cylinder, with the end of the piston pulled firmly against a ceramic magnet. The piston is provided with O-rings, and ports are drilled at right angles into the cylinder housing. Two different patterns of gas through the system can be traced out, depending on whether the piston is in the right-hand or the left-hand position.

As shown in Figure 5, the piston is in the right-hand position. Gas from the restrictor is deadended at port No. 1, but can flow into the right-hand magnet chamber through port No. 2. The high pressure side of the 90 mm mercury regulator is vented to ambient, as is the left-hand magnet chamber, and cuff port No. 3. The time the piston remains in the right-hand position is dependent on the gas flowing into the magnet chamber, as well as the size of the chamber itself. As gas fills the chamber, the pressure will rise until the net force

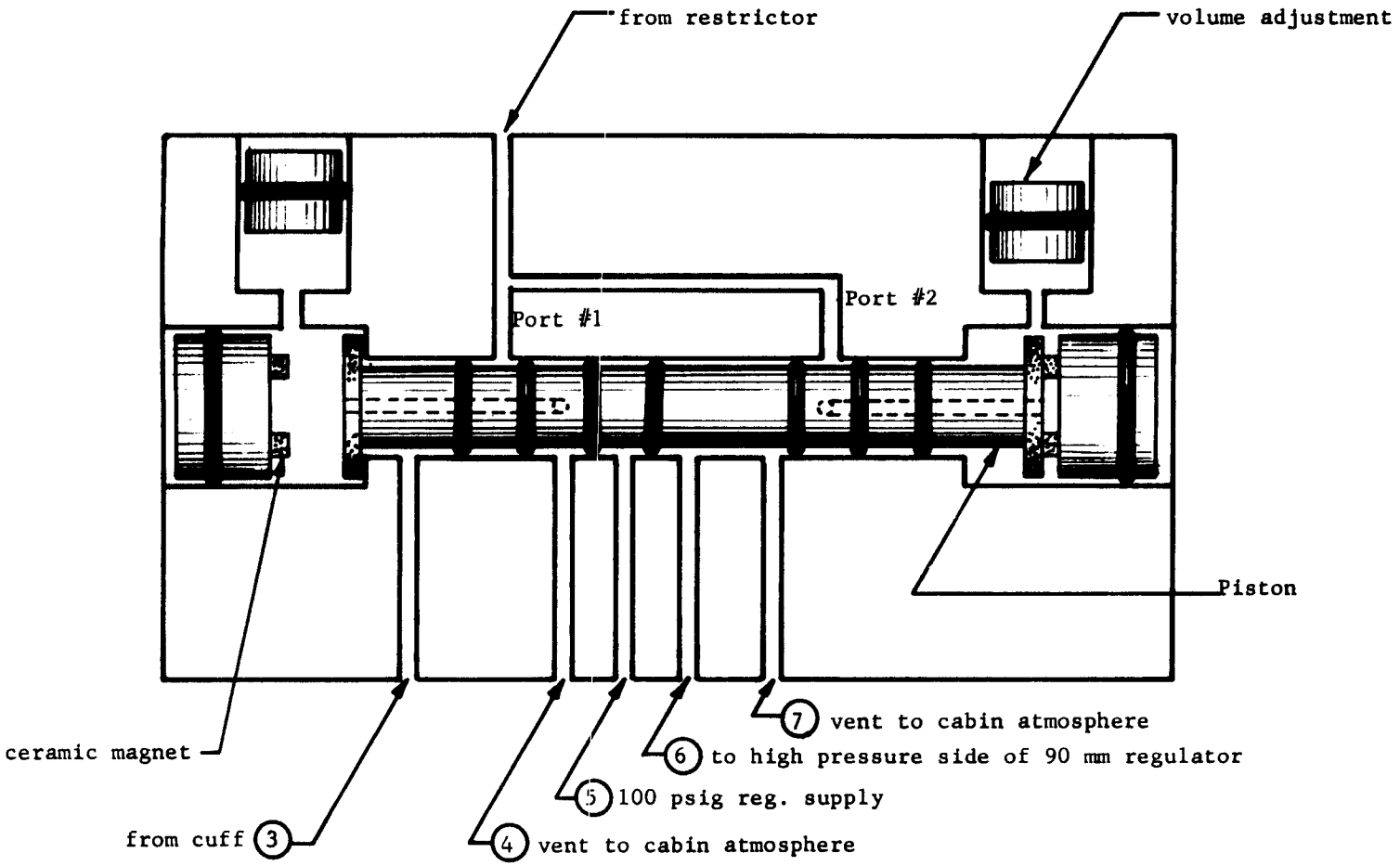


Figure 5. Pneumatic Oscillator, Schematic Diagram, Apollo

exerted against the right end of the piston exceeds the restraining force of the magnet; whereupon the piston will move swiftly and positively to the left-hand position. When the piston is in the left-hand position, gas from the restrictor is directed into the left-hand magnet chamber (port No. 2 is blocked) and the right-hand magnet chamber is vented to ambient. Ports No. 5 and No. 6 are cummuted so as to pressurize the 90 mm mercury regulator, and thus fill the cuffs (porting not shown since the output from the 90 mm mercury regulator is fed directly to the cuffs). Cuff port No. 3 is blocked, as is vent port No. 4.

3.0 PRELIMINARY TESTING AND EVALUATION

During the month of November, 1965, a prototype oscillator assembly was constructed and tested to determine the following:

1. Cycle time reproducibility
2. Cuff fill and dump times.

The system was connected according to Figure 6 and allowed to operate unattended for sixteen days. For this test, the Leonard Penumatic Control System, which was not yet available, was simulated by the use of two bottle gas pressure regulators. These regulators supplied the necessary pressure to operate the oscillator assembly and alternately pressurize and depressurize a 60-cubic-inch volume which was used to approximate the cuff response. Observed daily averaged cycle times are plotted and shown in Figure 7.

At the conclusion of the test, the unit was disassembled and carefully examined for signs of wear and other deterioration.

3.1 Cycle Time Repeatability

In examining the plotted cycle time data (Figure 7), it will be noticed that, allowing one day for system stabilization, a trend of gradually increasing times was established for seven days in a row. During this period, both the fill and dump cycle times increased from approximately 62 seconds to 68 seconds. Thereafter, the fill time leveled out at 70 seconds, but the dump times showed a long-period response for the remainder of the test.

Disassembly of the unit after the test revealed the following:

1. O-rings showed no signs of wear (dynamic or static)

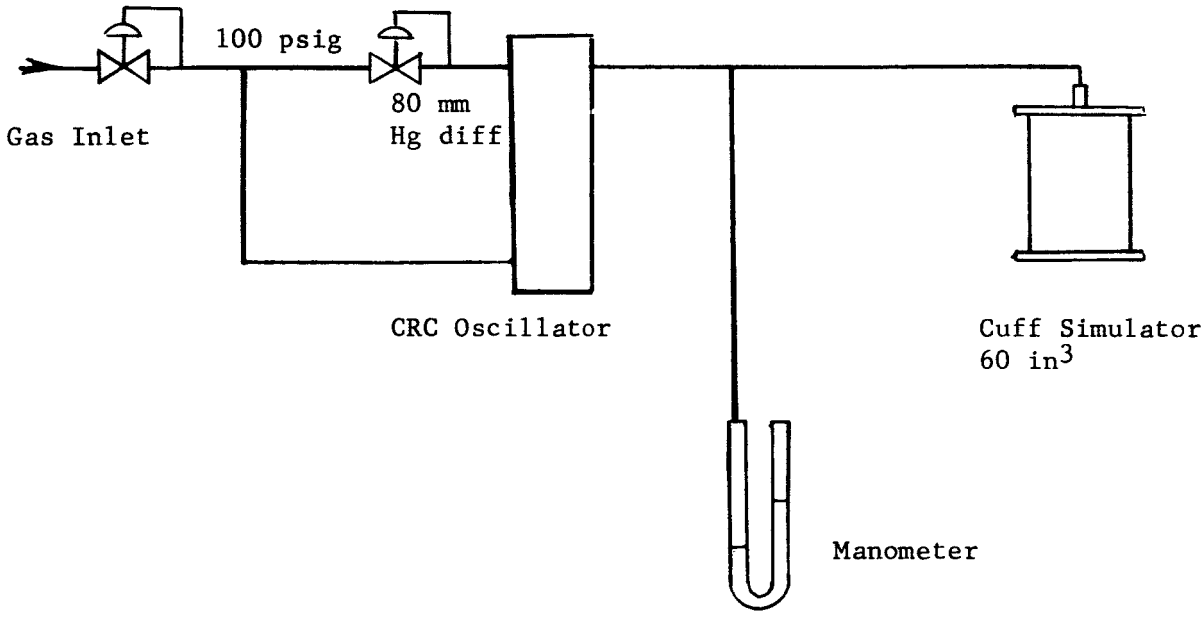


Figure 6. Functional Test System

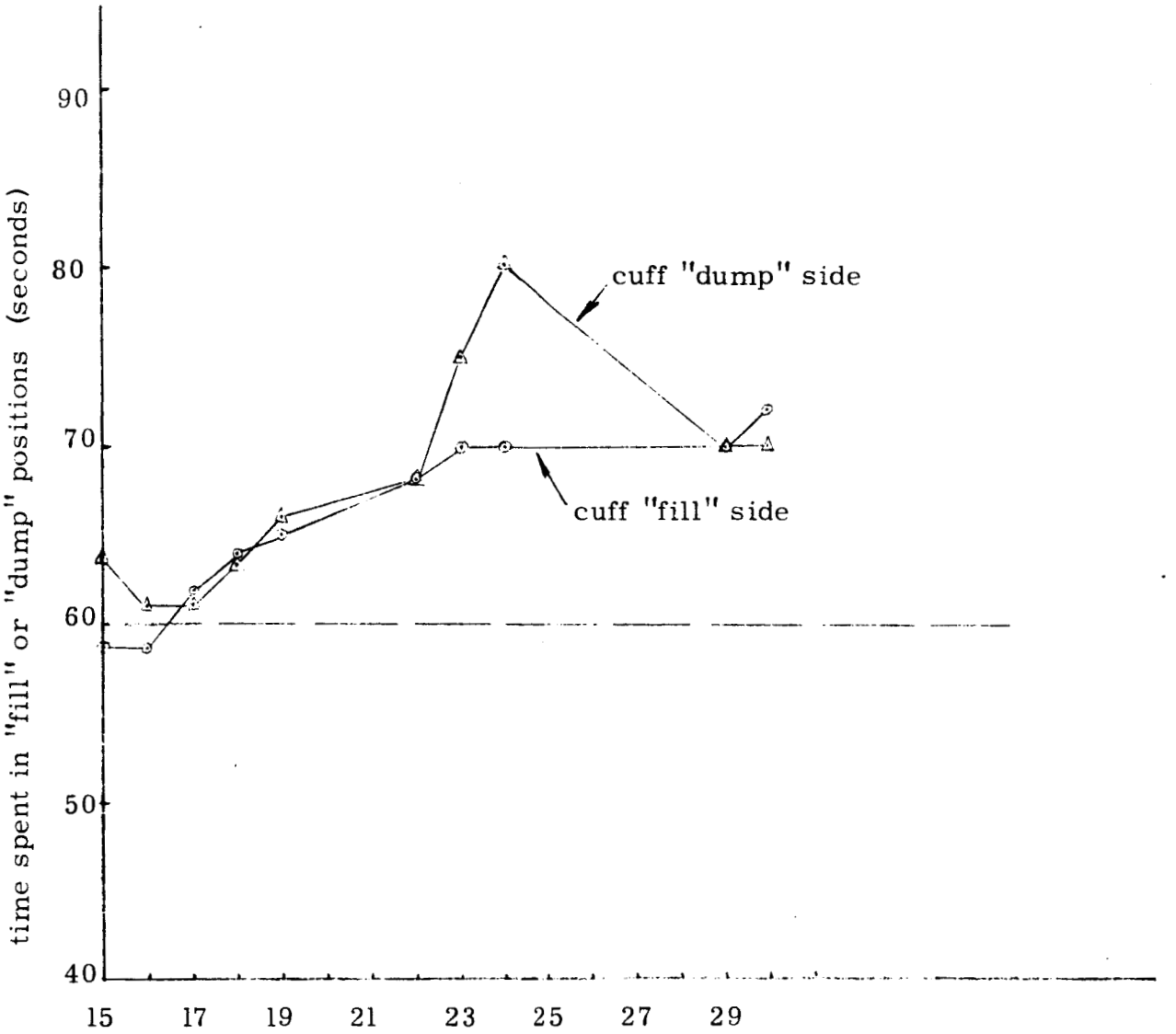


Figure 7. Cycle Times

Cardiovascular Reflex Conditioner -- Apollo
Prototype Test
"FILL" AND "DUMP" TIMES

Note: The data represent the times during which the oscillator slider valve is first in one position, then the other (corresponding to cuff "fill" and cuff "dump" modes of operation).

2. Magnet assemblies showed no distortion as a result of the continual hammering by the slider pole pieces.
3. One minute axial (longitudinal) scratch was noticed on one magnet assembly which could possible have created an extremely small leakage path.

Beckman's approach to improving cycle time repeatability will be fully explained in paragraph 4.1.

3.2 Fill and Dump Times

Tests conducted at Beckman Instruments, Inc., with the system as shown in Figure 6 indicated that the time required to fill and dump a simulated cuff of volume equal to 60 cubic inches was approximately 5 seconds. It was noted that this time was well within the stipulated 10 seconds of the contract, so no further attention was focused on this aspect of the Statement of Work, pending a test with NASA-furnished cuffs at the end of November.

During the month of December, tests with actual astronaut cuffs demonstrated conclusively that the use of a 60-cubic-inch, fixed-volume cuff simulator did not properly duplicate the operation of the actual astronaut cuffs. It was experimentally determined that the inflatable cuff and tubing volume at standard conditions was approximately 51.7 cubic inches, and that fill and dump times were of the order, 30-40 seconds. By using the perfect gas law, an equivalent fixed volume could be calculated which, if alternately pressurized and depressurized at ambient conditions, would yield results equivalent to actual cuffs. For the data just quoted, this volume is approximately 550 cubic inches. From this information, an aluminum container of 600 cubic

inches was fabricated and tested in lieu of the astronaut cuffs. The effect upon system operation was as expected in that cuff action was properly simulated.

Tests conducted at NASA-MSC were for the purpose of verifying the system operation at an ambient pressure of 5.0 psia. The results of these tests are summarized in Figure 8. Six cuffs were tied around simulated thighs (which simply consisted of a length of large-diameter rigid tubing covered by one or more layers of soft rubber).

It was noted that the type of mount and method of application yielded differences in data of a significant nature. A generalization which can be made is that a cuff mounted on a soft thigh, and/or laced loosely, will show long fill and dump times, as compared against the same cuff hard mounted and laced firmly.

The fill time profiles shown in Figure 8 do not follow an exponential function, as would be expected if the cuffs were of fixed volume pressurized from a source of infinite capacity. The flatness in the curves (linear response) could result from the balloon action of the cuff, the resiliency of the mount, the nonideal action of the regulator, or any combination of these effects. Also to be noted from the curves is the fact that the fill time or time to rise to a value of 75 mm mercury differential is approximately 30 seconds. The time for the pressurized cuffs to deflate to a differential pressure of approximately 5 mm mercury is about 25 seconds.

Because the use of a 60-cubic-inch, fixed-volume cuff simulator did not

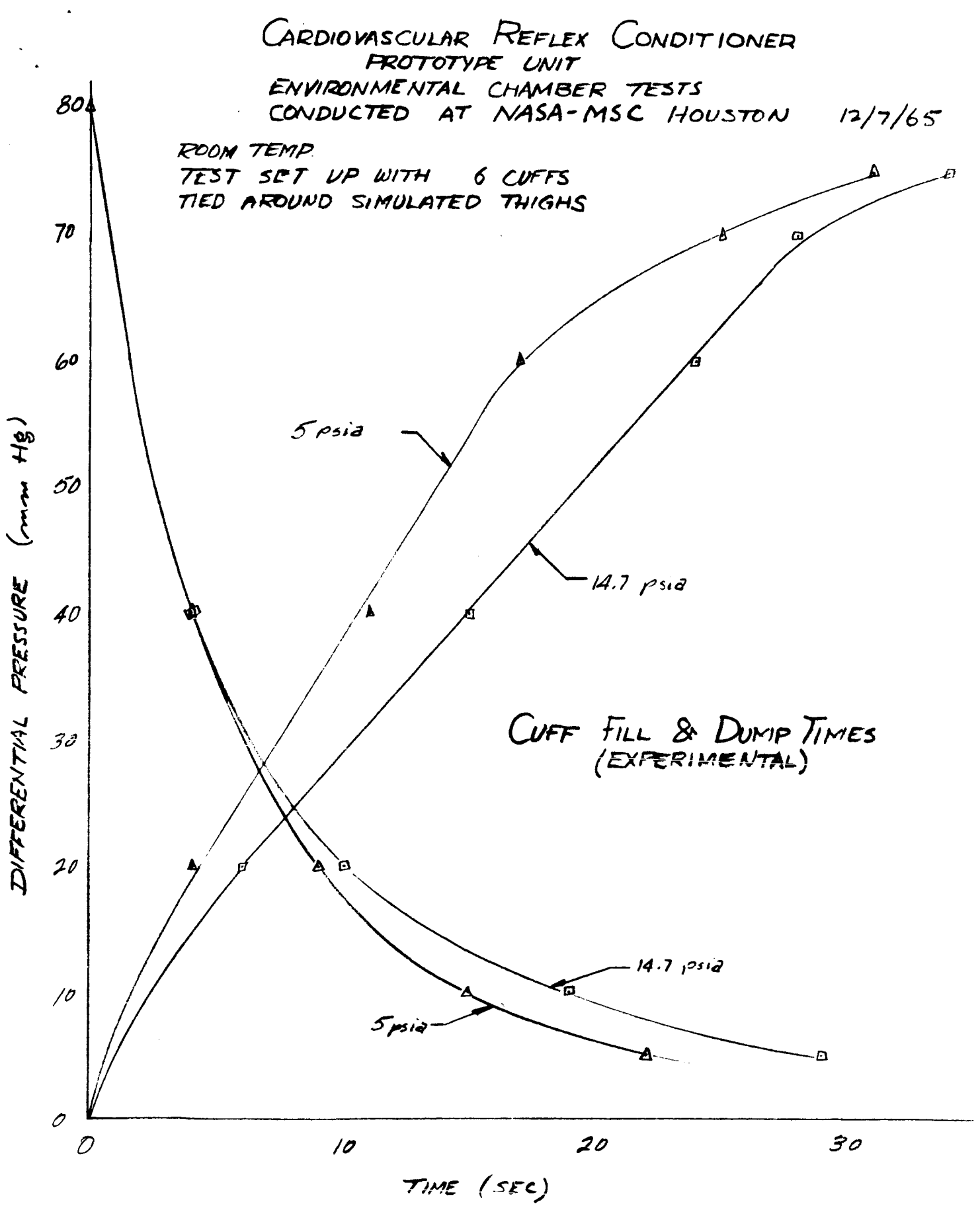


Figure 8. Cuff Fill and Dump Time Profiles

DJS 12/8/65

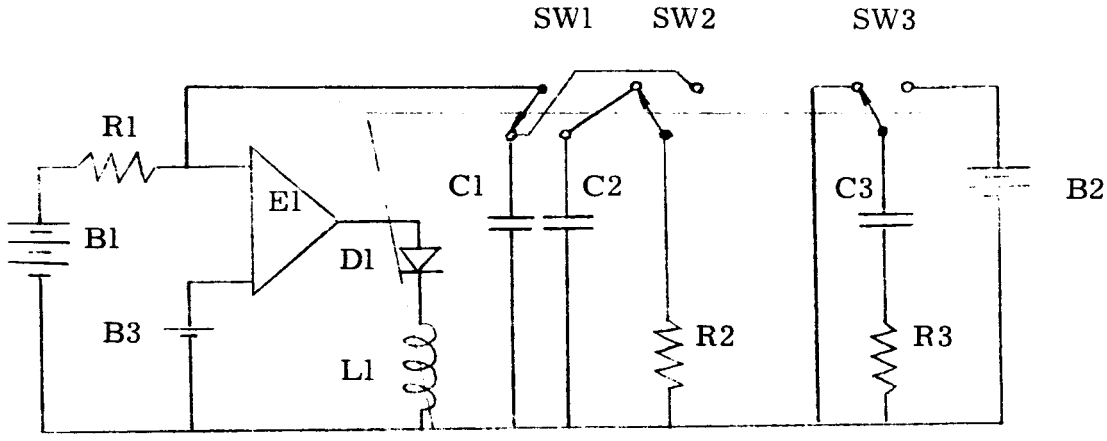
properly duplicate the action of actual astronaut cuffs, it was necessary to redesign the Cardiovascular Reflex Conditioning System - Apollo as explained in paragraph 4.2.

4.0 DESIGN MODIFICATION AND EVALUATION

4.1 Cycle Time Repeatability

As explained previously in 2.3, the oscillator is simply a pneumatically operated shuttle valve which alternately commutes various ports in the housing assembly. It operates from a steady source of 100 psig oxygen.
An end chamber is gradually pressurized by restricting the flow of gas into it until the restraining force of the magnet is overcome, and the slider (the slider end forms one wall of the chamber) is forced to move to the other bi-stable position. In so doing, the pressurized chamber is bled down to ambient, and the gas source is directed to the other end of the chamber. (See Figure 5.)

When reviewing the operation of the oscillator assembly, it is helpful to think in terms of a simplified electrical analog shown in Figure 9. The resistance R1 in series with the battery B1 allows a small current to flow and charge capacitor C1 (all this corresponds to a small volume flow of gas into the oscillator magnet chamber). When the voltage across the capacitor equals the battery voltage B3, the error amplifier turns on and energizes the stepper switch relay coil causing switches SW1, SW2, and SW3 to operate. When this switching operation is completed (corresponding to the slider moving between the two magnets and commutating various internal ports), the amplifier turns off since C2 was originally at ground potential, and the cycle begins again; this time with battery B1, charging C2.



Cardiovascular Reflex Conditioner -- Apollo
SIMPLIFIED ELECTRICAL ANALOG

B1 ------- Regulated pneumatic supply @ 100 psig
B2 ------- Regulated pneumatic supply @ 80 mm Hg diff.
B3 ------- Magnet restraining force
R1 ------- Capillary restrictor
R2 ------- Passage restrictions in oscillator housing
R3 ------- Passage restrictions in oscillator housing and cuff assembly
C1 ------- Volume around magnet (dump side)
C2 ------- Volume around magnet (fill side)
C3 ------- Cuff volume
SW1, SW2, SW3 ------ Port commutation of slider valve
E1, D1, L1 -------- Electrical duplication of slider action

Figure 9. Electrical Analog

This idealization of the pneumatic circuit allows the prediction of changes in operation if certain parameters are perturbed. It will be noted that the time required to pressurize the end chamber to the magnet breakaway force is a function of three basic parameters (supply pressure being held constant): (1) Magnet strength, (2) Restrictor size, and (3) Chamber size. Speaking in analogous fashion, a gradual increase in cycle time can occur if either B1 or R1 increases. This effect will also be noted if B3 increases. On the other hand, an erratic response of one of the cycle times can only be caused by a variable impedance across one of the capacitors (leakage path).

Examination of each of the internal parts of the oscillator assembly after the sixteen day test, plus theoretical considerations lead to the conclusion that day to day repeatability could be substantially improved if magnet breakaway force were reduced. That is, if the value of B3 in the analog circuit were reduced, so that the voltage appearing across C1 or C2 (corresponding to actuation pressure) would cause the error amplifier to turn on and actuate L1 at a lower value. Figures 10 and 11 can be used to verify the fact that at the original prototype test actuation pressure (90 psig) minor changes in supply pressure cause large changes in cycle times; whereas, if the actuation pressure were reduced to 1/2 its original value, supply pressure variations have much smaller effect on cycle time.

In order to reduce the susceptability of the oscillator system to minor variations in magnet strength and in restrictor and chamber sizes, the ceramic magnet pole pieces were machined down until the breakaway force as measured with bench top test apparatus was exactly 8 pounds. Corresponding actuation pressure then became approximately 40 psig.

Governing equation for pressure rise in the oscillator magnet chamber:

$$P = P_o(1 - e^{-\frac{1}{RC}t})$$

where:

P_o = supply pressure, psig

P = actuation pressure

RC = system time constant, $seconds^{-1}$

t = time in seconds

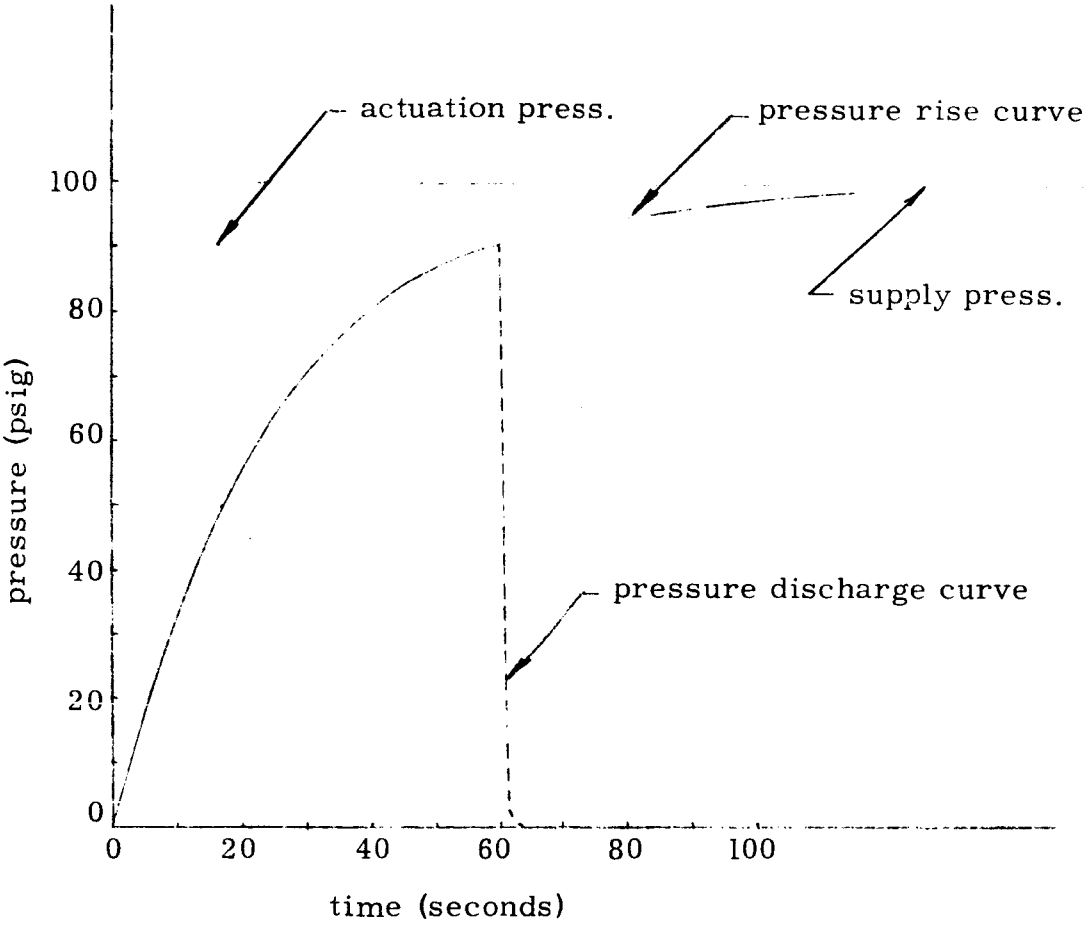
If P = 90 psig, and RC = 26.1 sec^{-1}, the following table can be constructed to demonstrate the effect of changing P_o on actuation time:

P_o	t
95	76.7
100	60.0
110	44.3

If P = 40 psig, and RC = 117.5 sec^{-1},

P_o	t
95	64.3
100	60.0
110	52.8

Figure 10. Equation for Pressure Rise in Magnet Chamber



Cardiovascular Reflex Conditioner
MAGNET CHAMBER PRESSURE HISTORY

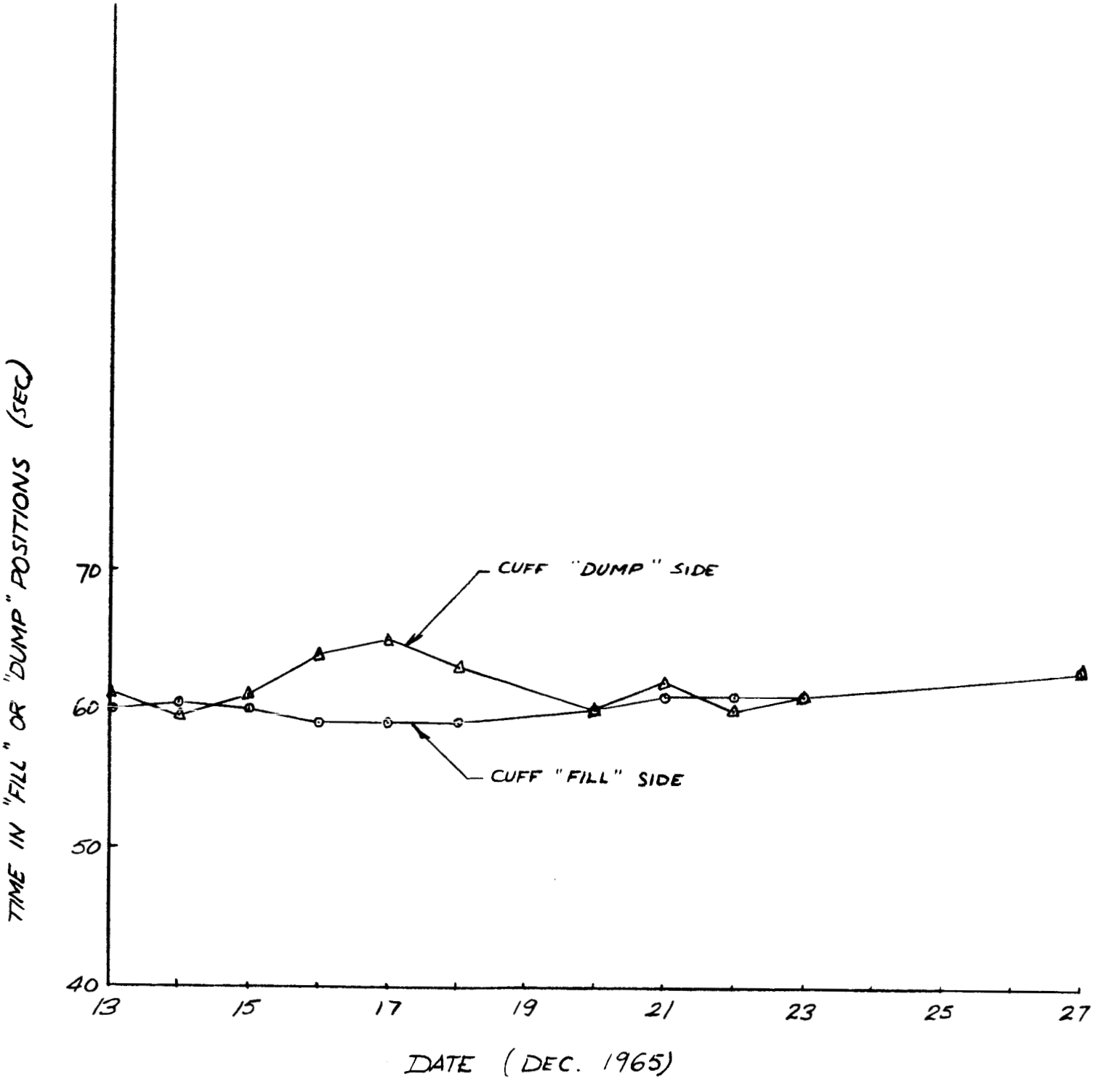
Figure 11. Chamber Pressure History

Another two week test was initiated after effecting this modification. The results are plotted in Figure 12. Note that day-to-day repeatability is greatly improved, and thus substantiates conclusions based upon theoretical considerations. An outgrowth from this effort is a standardization of restrictor assemblies, since minor differences in magnet strength from unit to unit were heretofore compensated by restrictor tube lengths. Also, care had to be exercised in the selection of matched pairs of magnets for use in the same unit since gross differences in strength could not be adjusted out with the chamber adjusting screws intended for that purpose.

4.2 Fill and Dump Times

Beckman devoted a great deal of effort to the study of a new prototype that would meet anticipated fill and dump requirements of actual astronaut cuffs. Subsequent work involved design changes in both the oscillator and regulator assemblies for the primary purpose of substantially increasing the gas flow rate to the cuffs. Beckman fabricated and tested a new prototype to the pneumatic circuit diagram shown in Figure 4.

It was expected that by locating the low pressure regulated output immediately upstream from the cuffs (not switching it through the oscillator), the cuffs would fill in less time. A preliminary test performed at Beckman Instruments, Inc., including the substance of Figure 4 into the first prototype system gave very encouraging results. The Leonard Regulator was not yet available, so with bottle gas regulators connected to the oscillator assembly, it was found possible to pressurize a 600 cubic inch cuff volume simulator in about 7 seconds.



OSCILLATOR REPEATABILITY TEST
PROTOTYPE

Figure 12. Cycle Time

The feasibility of the revised pneumatic circuit was thus proved - it remained to test the system with the Leonard Regulator in order to verify the practicality of the design changes.

Porting in both the regulator and the oscillator housings was modified to incorporate the revised pneumatic circuit into the experimental prototype. It is fortuitous that both the regulator and oscillator assemblies could be revised without scrapping either housing. Additional holes and plugs were placed where it was necessary to effect the modification, and all passage-ways downstream from the low pressure regulator were increased in diameter from .062 inches to 0.10 inches and larger. Porting into the slider chamber was increased from .015 inches diameter to .030 inches diameter (which affects the cuff dump time since exhausting gas must pass around the slider valve to ambient).

Another series of equipment tests was conducted at NASA Houston on January 18, 1966. The tests were conducted in an environmental chamber located on the premises of NASA-MSC and with actual astronaut cuffs laced to simulated thigh. The results of the test are shown in Figures 13 and 14.

In order to effect the faster rise time to 75 mm Hg differential pressure in the cuffs, NASA directed the output from the low pressure regulator to be changed from 80 mm Hg differential to 90 $\pm$ 5, - 10 mm Hg differential.

DJS 1/28/66

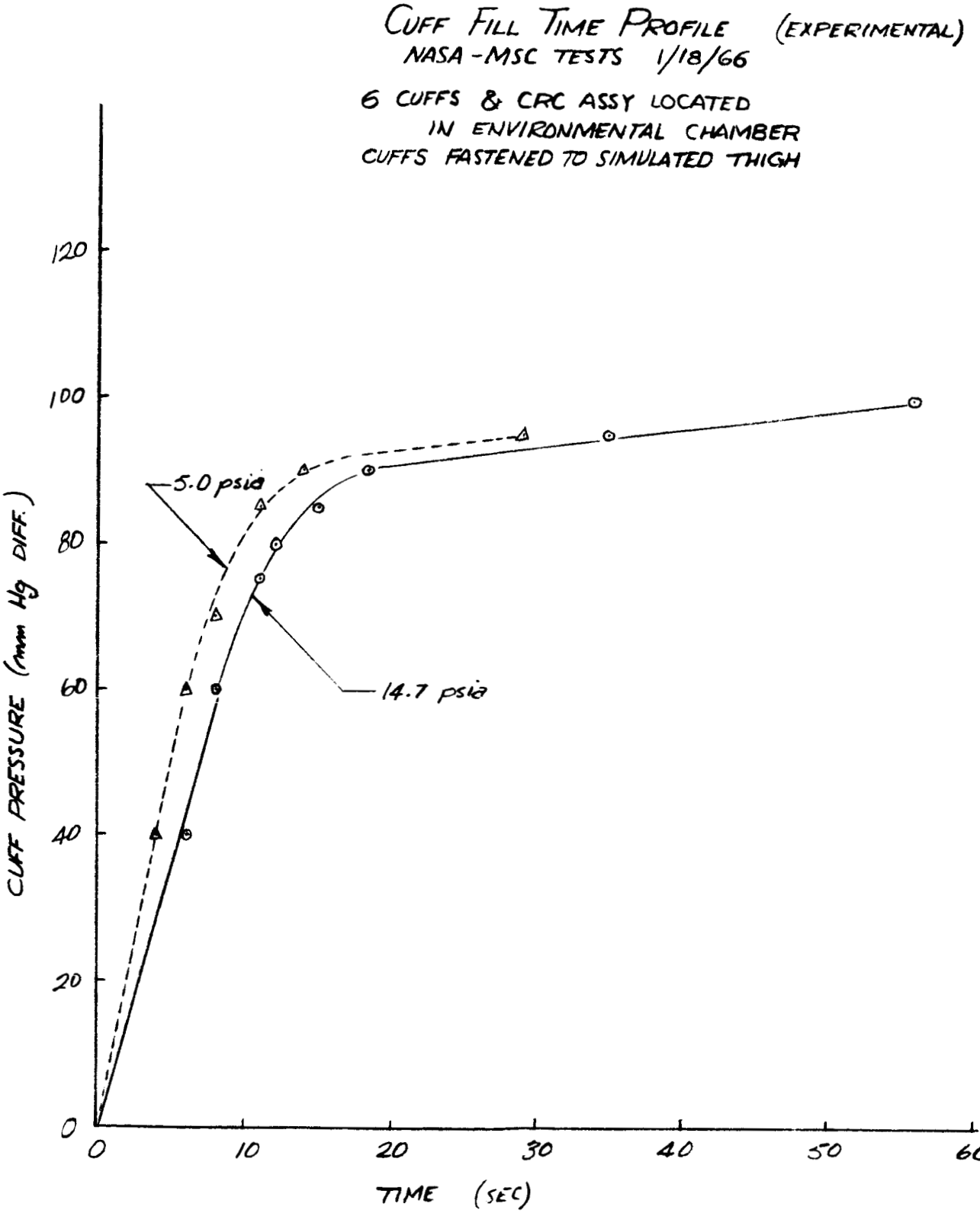


Figure 13. Cuff Fill Time Profiles

TJS 1/28/66

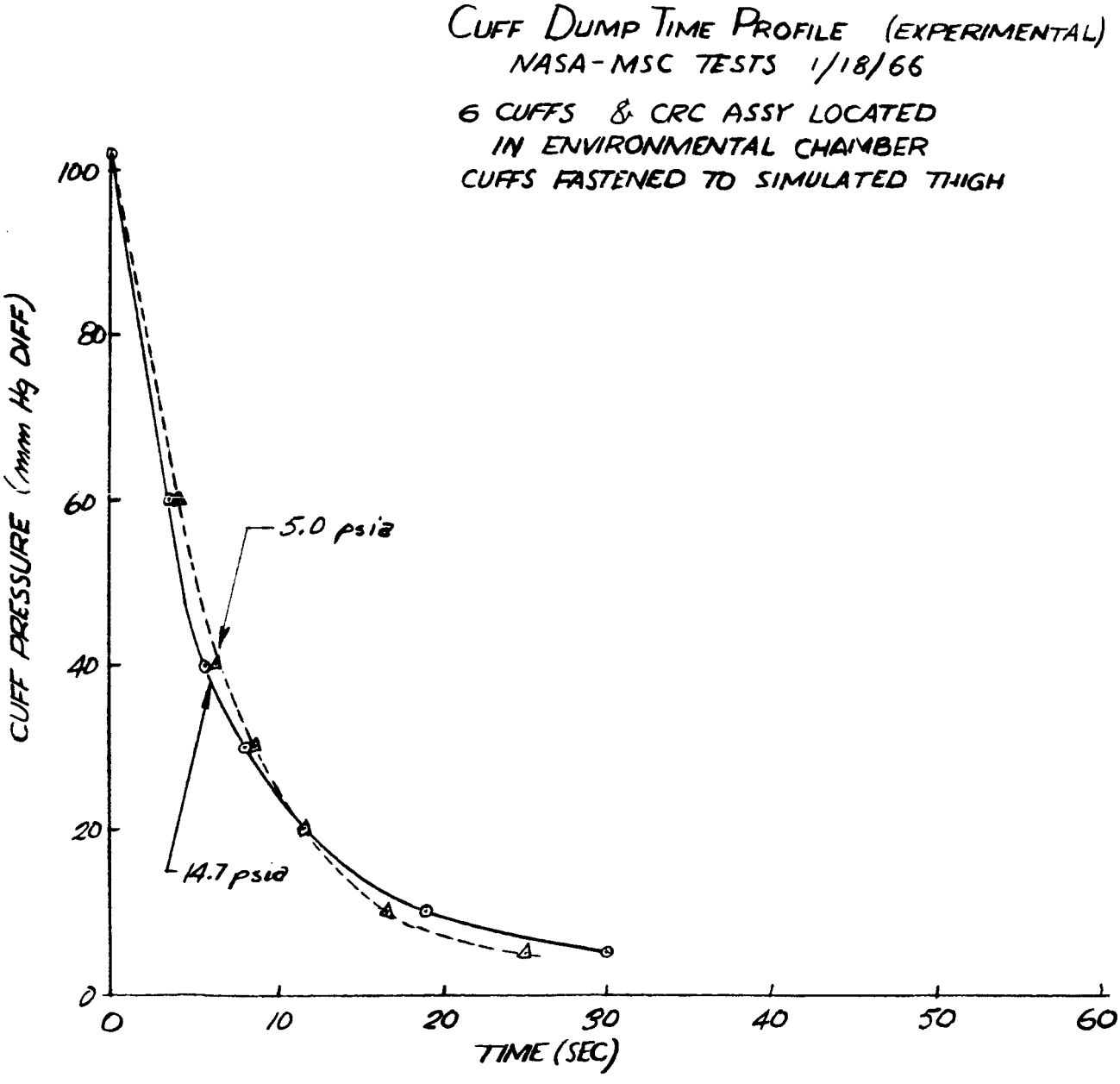


Figure 14. Cuff Dump Time Profiles

igure

5.0 QUALIFICATION TESTING

The qualification test procedures for the Cardiovascular Reflex Conditioning System for Apollo, experiment MI-A were submitted to NASA-MSC for approval on November 12, 1965. Approval was tendered by NASA by letter communication on March 15, 1966, subject to incorporation of some changes. Further communications from NASA on May 6, 1966 directed Beckman Instruments to make additional changes to the original qualification procedures.

5.1 Description of Tests

The test schedule required the use of two test speciments. It was planned to subject each unit to the test itemized on page 2 of qualification test procedures. Unit serial number 102 was subjected to high temperature and oxygen atmosphere, low temperate, humidity, and oxygen atmosphere. Unit serial number 103 was subjected to high temperature (decompression), temperature pressure, acceleration, vibration, acoustic noise, and shock. All testing was handled through the facilities of Corporate Reliability Engineering, Beckman Instruments, Inc., Fullerton, California. Some required test equipment was not available at the Beckman facility, so the tests required for unit serial number 103 were subcontracted to American Laboratories, Fullerton, California.

5.2 Summary of Test Failures

Three types of failures were noted during the course of qualification testing. In each case, the cause of failure was identified, and corrective action taken.

The failures described were not apparent during the testing of the CRC systems on the Gemini Spacecraft. It is believed that the underlying reason for these failures was the inclusion of design changes effected in the Apollo units. These design changes resulted in the oscillator assembly being required to switch oxygen at 100 psig instead of 1.5 psig, and relatively high gas-flow rates as compared to the Gemini units.

5.2.1 High Cuff Pressure (High Temperature Test)

This type of failure is manifested by out-of-specification cuff-pressure readings at ambient conditons. It was noted that after several hours running time, that the cuff pressure would increase to a high value, usually about 140 to 150 mm mercury differential. Subsequent examination of the low-pressure regulator revealed the fact that when both sides of the regulator were vented to atmosphere, and then the high-pressure side repressurized with 100 psig oxygen, it was possible to contaminate the poppet-seat assembly. The source of this contamination was probably the interconnecting tubing and fittings. It seems improbable that the contamination would have originated within the unit since caution was exercised in properly cleaning it in the clean-room facilities located at W. O. Leonard Company, Pasadena, California. When the failure was noted, and before repeating the test, the unit was thoroughly cleaned once again at W. O. Leonard Company, and interconnecting tubing and fittings were cleaned in the facilities at Beckman Instruments.

5.2.2 Slider Hang-Up (High Temperature)

It was observed that during the 200^{o}F portion of the high temperature tests, the unit operated in a proper manner. However, at the conclusion of this test, the temperature was reduced to ambient and during the course of this

temperature decrease, the outer housing, by virtue of the temperature difference between it and the slider, caused the slider to stop midway in its travel from one bi-stable position to the other. The unit was taken out of test, disassembled, and inspected to determine the cause of failure. Both the bore diameter and slider diameter were measured. Although the dimensions obtained were within the tolerance called for in the manufacturing drawings, they were such that a sudden decrease in temperature of the housing would cause an interference fit. Before the unit was put back into test, the slider was turned down in diameter to obviate this source of difficulty.

It was later established by communication from NASA-MSC of May 6, 1966, that the operational requirement of the 200°F portion of the high temperature test was to be eliminated. Since the conditioner would never be required to operate during the spacecraft conditions which this 200°F exposure was intended to simulate, operation during this test period was eliminated.

5.2.3 Slider Hang-Up (Humidity Test)

The failure occurred during the humidity test, again due to slider hang-up midway in its travel between the two bi-stable states. Upon disassembly, it was noted that both the O-rings and slider were practically dry. The O-rings were examined under a microscope and it was determined that the roughness noted on the sides of the O-rings was caused by gaulling within the cylinder bore. This obvious loss of lubricant was attributed to atomization and bulk carry over caused by the relatively high gas flow rate.

The oil used for lubrication was Dow Corning No. 200 with a viscosity of 50 centistokes. It was reasoned that oil of higher viscosity, with the attendant

greater surface tension, would adhere more strongly to the surfaces which should be lubricated during the course of the test. Therefore, the solution to this problem was to use the same type of oil having a viscosity of 200 centistrokes. The O-rings were replaced with new ones which were examined under the microscope for flaws, and the whole assembly was generously lubricated with the higher viscosity oil prior to the start of the test.

5.3 Discussion of Tests

All details of the Qualification Test Program are included in the final test report prepared by the Beckman Corporate Reliability Engineering Laboratory.

The care in assembly and changing to a heavier lubricant occasioned by failures during Qualification Tests have resulted in a unit which can successfully pass all environmental conditions which may be obtained inside the Apollo Spacecarft. It is significant to note that no mechanical design changes were required to correct faults of the system.

6.0 ACCEPTANCE TESTING

Acceptance inspection and test procedures for the Cardiovascular Reflex Conditioning Systems for Apollo, experiment M1A were submitted to NASA-MSC for approval February 4, 1966. Approval was obtained on March 15, 1966, and additional revisions were obtained May 6, 1966.

The fundamental purpose of the Acceptance Test is to ascertain proper operation of the instruments, and adherence to the specifications as laid down by NASA in contract NAS 9-5331. It is not the purpose of these tests to subject the units to any severe environmental tests which, by their nature, might impair the proper functioning of the units at a later date. Details of the Acceptance Inspection and Test Procedures can be obtained from Beckman Report IR-2408-101 (revised).

All five Cardiovascular Reflex Conditioning Assemblies were required to pass the acceptance tests. Additionally, the two units which were subjected to qualification testing were refurbished and tested according to the acceptance inspection test procedures before shipment to NASA.

Certain changes to the original operating specifications, and to the qualification acceptance test plans were effected as a result of the testing:

1. Maximum fill time was increased from 13 seconds to 16 seconds.
2. The rigid simulator cuff volume of 600 $\pm$10 cubic inches used at 14.7 psia was changed to 225 $\pm$5 cubic inches when the system was operated at 5 psia ambient pressure.
3. The operational requirement for the Qual Test Unit Serial No. 102 during the 200^{o}F portion of the high temperature and oxygen atmosphere test was deleted.

7.0 RECOMMENDATIONS

The Cardiovascular Reflex Conditioner for the Apollo vehicle has met all the basic performance requirements of Contract NAS 9-5331.

During the course of testing and evaluation, it was observed that some minor modifications might be made to future units so as to improve overall performance and reliability:

1. Increase the third stage regulator sensitivity, and at the same time reduce the effects of temperature, hysteresis, friction, etc., by enlarging the sensitive area of the diaphragm.
2. Minimize the possibility of third-stage, regulator-seat contamination by including a filter between the oscillator and regulator inlet.