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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA PROGRAM APOLLO WORKING PAPER NO. 1321

TWO-GAS ENVIRONMENTAL CONTROL FOR THE APOLLO COMMAND MODULE

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
July 12, 1967

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TWO-GAS ENVIRONMENTAL CONTROL FOR THE APOLLO COMMAND MODULE

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TWO-GAS ENVIRONMENTAL CONTROL FOR THE APOLLO COMMAND MODULE

By Wilbert E. Ellis

1.0 INTRODUCTION

A two-gas atmospheric control system applicable to the Apollo Applications Program has been designed and developed. The hardware is configured to integrate into the Apollo Command Module (CM) but is not flight qualified. This report describes the system selection, design, hardware status, and test results.

2.0 ATMOSPHERE DILUENT SELECTION CONSIDERATIONS

Selection of a two-gas cabin atmosphere must be based on both physiological and engineering factors. In the December 1, 1966, "Position Paper on Spacecraft Atmosphere Selection," the Director of Medical Research and Operations recommended nitrogen as the diluent from a physiological standpoint. Therefore, a two-gas control system with nitrogen will be preferentially selected for implementation if the engineering considerations are not restrictive.

This section develops the engineering factors involved in atmospheric selection. It should be noted that the results of the analysis are strongly influenced by the characteristics of the vehicle (structural considerations, vehicle leakage rate and type of environmental control system), the characteristics of the mission (number of repressurizations, mission duration) and the crew activity (shirt sleeve or suit loop operation). Since the Apollo CM is already designed for pure O_2 at 5 psia, the resulting cabin thermal conditions and system weight increase of an atmospheric substitution must be evaluated to insure neither are prohibitive. To accomplish this objective, both nitrogen and helium will be considered candidate atmospheric diluents.

The primary requirement is to maintain the oxygen partial pressure in the atmosphere above a minimum level to prevent hypoxia, yet below another limit set by the occurrence of oxygen toxicity. This limits the oxygen partial pressure to roughly 2.1 to 5.0 psia (for missions less than 30 days). In the Mercury and Gemini spacecraft a pure oxygen atmosphere at 5 psia was used with an emergency mode of operation of 3.5 psia. For the two-gas atmospheres considered here, a nominal oxygen partial pressure of 3.5 psia was chosen.

The total pressure evaluated here was held at a nominal 5 psia. This value corresponds to the total pressure existing in the current Apollo spacecraft and thus would not cause vehicle structural changes. The actual diluent partial pressure will be less than 1.5 psia, due to the presence of carbon dioxide and water vapor in the atmosphere. Accounting for these constituents complicates the analysis considerably without improving the accuracy of the comparison significantly. For this reason, it was assumed that the diluent partial pressure was 1.5 psia.

The prime engineering factors for comparing atmospheric diluents are:

1. Atmospheric leakage through the vehicle structure

2. Pumping power for atmosphere circulation and conditioning

3. Gas losses due to planned vehicle depressurization

4. Tank weight penalty associated with fluid storage

These factors are reviewed below and an engineering analysis is developed to show the weight penalties associated with the diluents selected for evaluation. The analysis considers two diluent gases, nitrogen and helium, at a total pressure of 5 psia. For comparison purposes, a 5-psia pure oxygen atmosphere is evaluated under the same ground rules.

2.1 LEAKAGE

Atmosphere leakage is an important factor in atmosphere selection, especially as affected by the use of helium as a diluent. The specification leakage rate for the Command Module is 0.2 lb/hr for a pure oxygen atmosphere at 5 psia. This rate serves as the basis for estimating the leakage rate for the two-gas atmosphere. Two models of leakage from a spacecraft can be considered: orifice and capillary leakage. The results obtained from both models follow the same pattern as will be shown later; this is to be expected since the composition of the gas leaking from the vehicle is the same as the cabin atmosphere composition. Therefore, the only difference between the models is a difference in total leakage rate; however, both models show that the helium leakage rate is not excessive.

For orifice leakage an isentropic expansion from cabin pressure to orifice throat pressure is assumed. For orifice leakage the weight flow is essentially proportional to total pressure and the square root of the molecular weight (neglecting differences in specific heat ratios).

In capillary flow, each capillary is assumed to be a long straight cylinder. There exists some controversy concerning the nature of the flow through these capillaries. One theory considers flow near the entrance of the capillary is laminar continuum flow; a transition to free molecule flow takes place in the capillary and flow at the discharge end is molecular. Another theory considers laminar continuous flow throughout the capillary and acoustic exit velocity. The leakage rate for capillary flow is influenced by pressure, molecular weight, viscosity, and capillary length and diameter. Table I summarizes the rates of nitrogen-oxygen to helium-oxygen that would leak from a cabin with a total pressure of 5 psia $\left(PO_2 - 3.5 \text{ psia}\right)$. It can be seen that the particular theory utilized does not have a significant effect on the total atmosphere leakage for the specific total pressure of interest. It can be shown that the most probable capillary diameter is in the range of 1 to 10 microns. Ten microns were used in calculating the data in table I.

Table II compares the equivalent leakage rates for the capillary and orifice flow models. (For comparison purposes, the first described capillary model is used considering a 10-micron hole.) There is a slight difference between the results obtained for each model. It is felt that the capillary model more nearly represents spacecraft leakage than a large single hole (orifice). It should also be noted that both models show identical leakage rates for oxygen. For the pressures and atmosphere composition in a spacecraft, excessive helium leakage should not be a problem.

Tests have been performed at AiResearch Manufacturing Company and Douglas Missiles and Space Division to determine any differences in leakage between oxygen-helium and oxygen-nitrogen atmospheres. Tests show that volumetric leakages were comparable for the two mixtures, and the leakage rates generally verified the capillary leakage model.

TABLE I.- RATIO OF NITROGEN-OXYGEN TO HELIUM-OXYGEN LEAK RATES AS A FUNCTION OF CAPILLARY MODEL

Model	Total pressure, 5 psia
Laminar continuum flow[a] with transition to free molecular flow at exit	1.30
Laminar continuum flow[b] throughout capillary (sonic exit velocity)	1.395

[a]Mason, J. L. et al, "The Two-Gas Spacecraft Cabin Atmosphere Engineering Considerations," IAF Congress, Athens, September 12 to 17, 1963.

[b]Douglas Missile and Space Systems Division, "Engineering Criteria for Spacecraft Cabin Atmosphere" Contract NASW-1371, November, 1966.

TABLE II.- COMPARISON OF CAPILLARY AND ORIFICE LEAKAGE MODELS

Condition	Leakage, lb/day					
	Capillary			Orifice		
	O_2	O_2-He	O_2-N_2	O_2	O_2-He	O_2-N_2
Oxygen	4.8	3.5	3.4	4.8	3.9	3.4
Diluent	---	.2	1.3	---	.2	1.2
Total	4.8	[a]3.7	4.7	4.8	4.1	4.6
Basis: 5 psia total pressure. Capillary leakage model assumed a 10-micron capillary 1 mm long.						

[a]The O_2-He leakage weight is less due to the low molecular weight of helium, not due to a significant difference in volume leakage flow from a pure O_2 or O_2-N_2 atmosphere.

2.2 PUMPING POWER FOR ATMOSPHERE CIRCULATION

Fans and compressors are used to provide atmosphere gas movement for humidity, carbon dioxide and temperature control and for ventilation. All of these functions can influence the pumping power in different ways depending upon the environmental control system (ECS) design.

A computer program developed for the Block II ECS was used to determine system performance. Table III shows the results for typical thermal loads during suit operation. It can be seen that the heat exchanger loads and the suit volumetric flow did not change appreciably for the different gases. However, the power required for the compressor was reduced approximately 15 percent for the oxygen-helium atmosphere.

The operational characteristics of the Command Module cabin blower and heat exchanger for the oxygen and oxygen-helium atmosphere are shown in figure 1. For all practical purposes the oxygen-nitrogen atmosphere characteristics are identical to the pure oxygen atmosphere. The effect of an oxygen-helium atmosphere is to increase volumetric flow through the system and decrease the weight flow. The overall heat exchanger capabilities change only slightly; however, the fan power is reduced. For the conditions shown in figure 1, the blower power is reduced from 34 watts for pure oxygen to 30 watts for the oxygen-helium atmosphere.

The power required for operation of the blowers and suit compressor is shown in table IV. The table includes inverter efficiency. From a performance standpoint all systems operate at essentially the same level.

2.3 TANK WEIGHT PENALTY

The oxygen tank weight penalty utilized assumed that the ECS oxygen is integrated with the cryogenic fuel cell oxygen. A tank weight penalty of 0.27 lb tank/lb usable fluid was used.

For the diluent gases the weight penalties associated with gaseous storage were utilized. A nitrogen tank weight penalty of 3.0 lb tank/lb of usable nitrogen is assumed based on an analysis performed by Douglas.[1] The helium tank weight penalty utilized (i.e., 15 lb tank/lb usable helium) was also obtained from the Douglas reference.

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[1]"Engineering Criteria for Spacecraft Cabin Atmosphere Sélection," prepared by Douglas under NASW-1371.

TABLE III.- COMPARISON OF SUIT CIRCUIT PERFORMANCE

Condition	5 psia, O_2	5 psia, O_2-He	5 psia, O_2-N_2
Number of crewmen in suit	1	1	1
Number of crewmen in cabin	2	2	2
Suited crewmen metabolic load, Btu/hr	518	518	518
Cabin crewmen metabolic load, Btu/hr	896	896	896
Suit flow rate, cfm	34.1	34.7	34.8
Suit heat exchanger latent load, Btu/hr	818	818	816
Suit heat exchanger sensible load, Btu/hr	896	815	887
Total suit heat exchanger load, Btu/hr	1714	1633	1703
Cabin dewpoint, °F	62.8	62.4	62.7
Suit compressor input power, watts	82.9	67.5	80.8

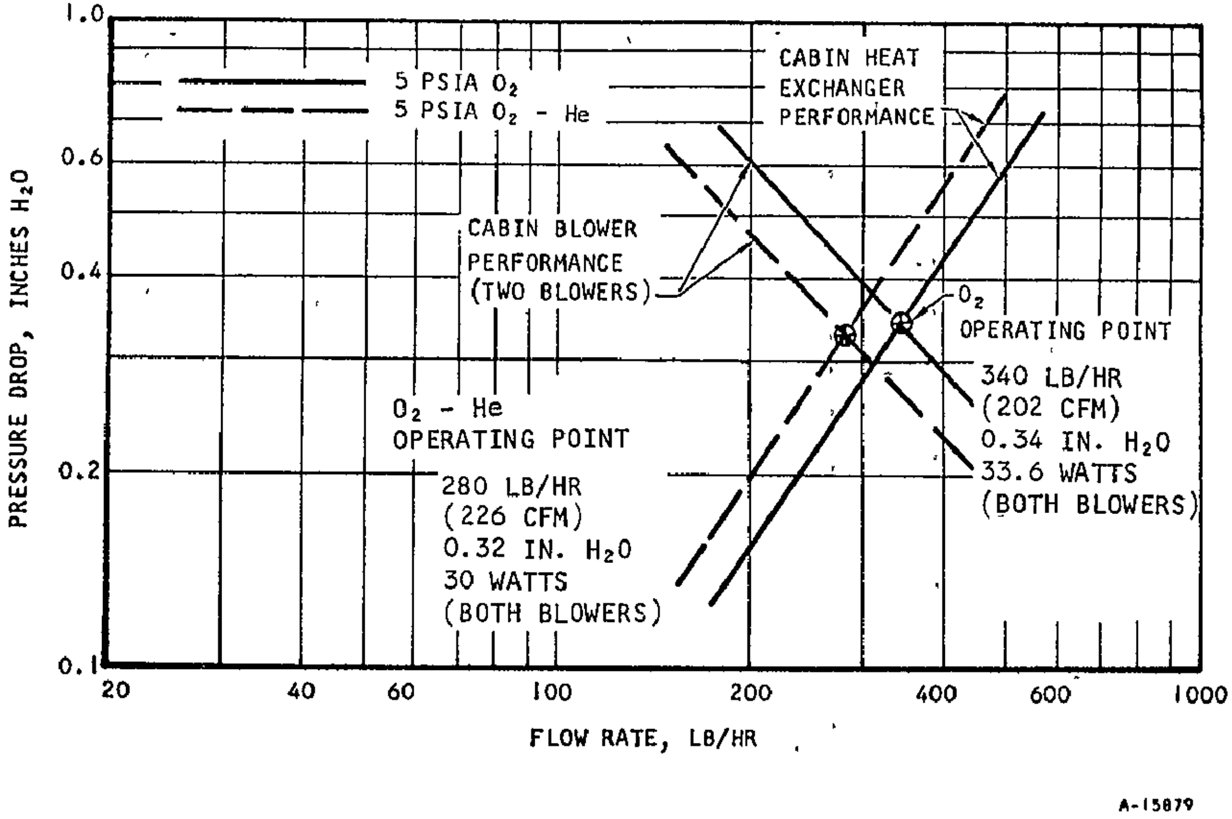


Figure 1.- Cabin blower performance.

TABLE IV.- FAN AND COMPRESSOR POWER REQUIREMENTS

Test article	5 psia, O_2 or O_2-N_2, watts (a)	5 psia, O_2-He, watts (a)
Suit compressor	104	85
Cabin blowers	76	68
TOTAL	180	153

[a]Includes inverter (80 percent efficiency).

2.4 GAS LOSSES

The gas losses are based on a free volume of 306 ft^3 for the Command Module. The number of pressurizations considered is three total vehicle repressurizations.

2.5 ATMOSPHERE WEIGHT COMPARISON

The comparison of the pure oxygen atmosphere with oxygen atmospheres containing helium and nitrogen as a diluent is shown in table V for a 14-day mission. The tabulation is based on the ground rules stated above. In addition the following assumptions were made:

1. The oxygen usage rate is 1.84 lb/man-day.

2. The power penalty is 0.53 lb/watt for 14 days.

3. Inverter efficiency is 80 percent.

It can be seen from table V that the lightest two-gas atmosphere supply system is the oxygen-helium atmosphere at 5 psia. Its atmospheric weight penalty is equal to the pure O_2 atmosphere and it has a weight penalty 48 lb less than an equivalent oxygen-nitrogen atmosphere. From a weight standpoint therefore, an oxygen-helium atmosphere is advantageous over an oxygen-nitrogen atmosphere.

2.6 RECOMMENDATION

The weight equivalency and 15-percent power advantage offered by the oxygen-helium atmosphere is attractive. However, the power equivalency and 15-percent weight penalty of the oxygen-nitrogen atmosphere are not prohibitive; therefore, the preferred oxygen-nitrogen atmosphere is selected.

3.0 TWO-GAS DESIGN CRITERIA

Atmospheric control as referred to in this report is concerned only with the amount of oxygen and nitrogen present in the cabin. Oxygen is controlled so that its partial pressure falls within the range of 3.5 psia and total pressure is maintained at 5.0 ± 0.2 psia. An oxygen

TABLE V.- ATMOSPHERE WEIGHT PENALTY

Atmosphere constituents, total pressure	5 psia	5 psia		5 psia	
	O_2	O_2	He	O_2	N_2
Metabolic	77	77	--	77	--
Leakage	67	49	3	48	18
Repressurization	26	17	.1	17	3
Total fluid required	170	143	3	142	21
Tank weight penalty	46	39	45	38	63
Subtotal	216	182	48	180	84
Power penalty	95	81		95	
Total	311	311		359	

oxygen partial pressure of 3.5 is equivalent to 181 mm Hg. A reasonable control band for the oxygen partial pressure controller is 20 mm Hg. Thus, the oxygen partial pressure in the spacecraft would be maintained at 170 to 190 mm Hg or 3.29 to 3.67 psia (0.38 ΔP). Since the partial pressure of oxygen in sea level air is equal to 160 mm Hg, the selected control pressure range of 170 to 190 mm Hg would keep the spacecraft atmosphere slightly rich in oxygen by comparison.

The reason for the recommended total cabin pressure tolerance of 5.0 ± 0.2 psia is to encompass the current capabilities of the CM cabin pressure regulator.

The hardware equipment designs must meet the Apollo vibration, electromagnetic interference (EMI), and other environmental criteria. Table VI summarizes the design criteria utilized in this effort.

4.0 SYSTEM DESIGN

4.1 POTENTIAL TWO-GAS CONTROL TECHNIQUES

Several methods may be used to control oxygen partial pressure in a two-gas mixture. It is not the purpose of this report to evaluate all possible configurations of two-gas control schemes, but rather to review the basic approaches that appear most promising from the standpoint of utilizing present Apollo components and to point out advantages and disadvantages of each.

In compliance, the following is a brief description of the two-gas control techniques considered competitive.

1. The first, which is referred to as the direct O_2 control system, utilizes the primary constituent sensing signal as the command for supplying oxygen, with the secondary constituent, nitrogen, being supplied on a total-pressure makeup demand basis (see fig. 2(a)). This concept has the advantage of being independent of nitrogen supply system failures or gaseous contaminants buildup in the cabin since the oxygen partial pressure is both the critical parameter (from a crew safety standpoint) and the parameter by which the oxygen supply is controlled.

Repressurizations with the direct system are made operationally easy by the control logic (without astronaut monitoring). The following operational sequence will demonstrate this. In the decompressed mode both the oxygen and the nitrogen supply systems will be isolated with

TABLE VI.- DESIGN CRITERIA

Total pressure	5.0 ± 0.2 psia
Nitrogen diluent	---
Oxygen partial pressure	170 to 190 mm Hg
Apollo environmental criteria utilized	---

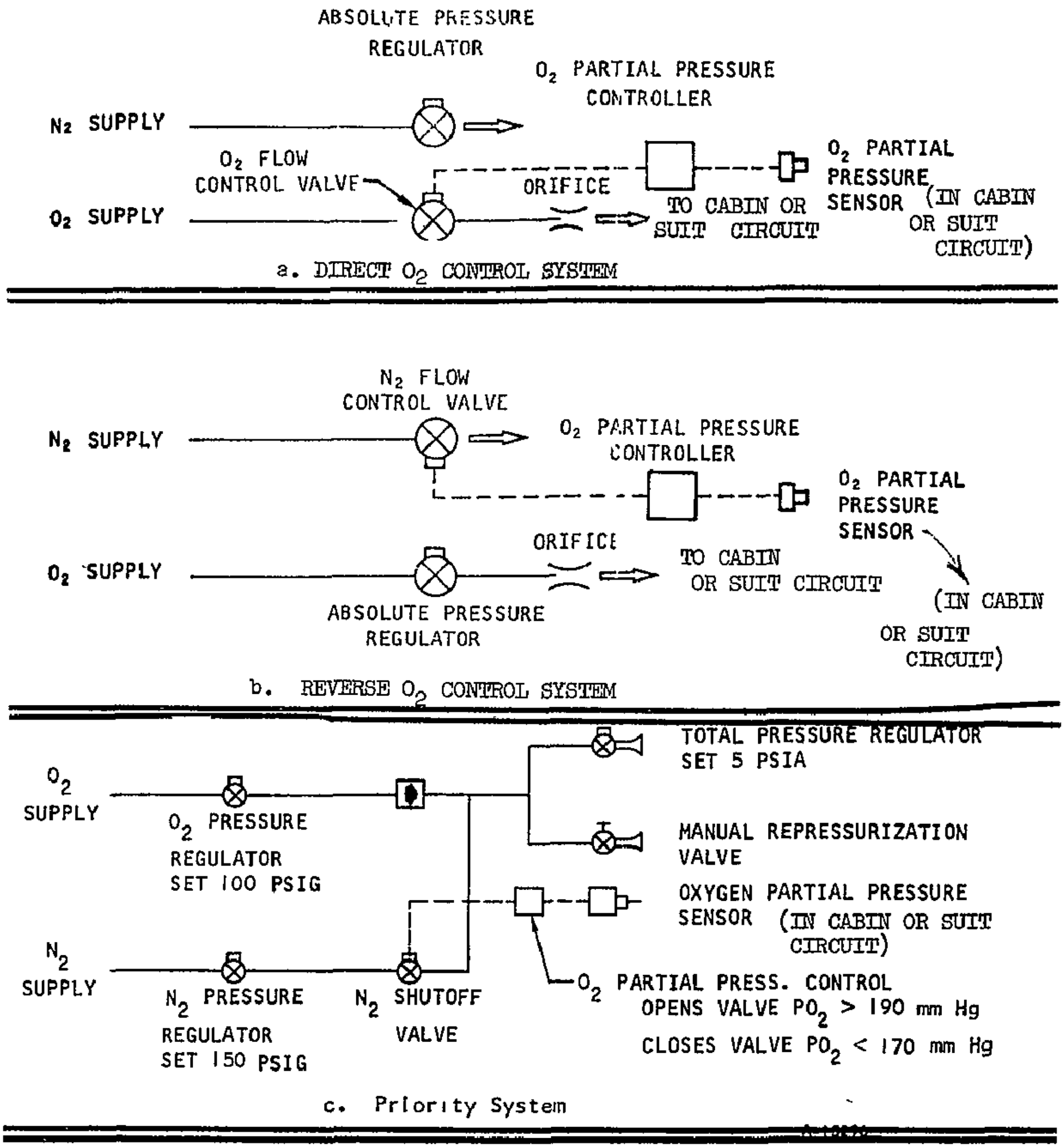


Figure 2.- Basic types of two-gas atmosphere control systems.

shutoff valves. To repressurize, the astronaut would open the oxygen supply valve and permit the control circuit to establish equilibrium (i.e., 3.5-psi pure oxygen within the cabin). At any time thereafter, the astronaut could open the nitrogen supply (which would feed through the total pressure regulator) and bring the cabin pressure to 5 psia where normal operations would resume.

The installation of the direct O_2 control system in the Apollo spacecraft will require the removal of the oxygen supply line which presently goes to the total pressure regulator package. The oxygen supply would then be directed into the cabin through an "on-off" solenoid valve whose command signal is generated by the oxygen partial pressure sensor. The nitrogen supply will require attachment to the existing total pressure regulator package, without change.

The normal failure modes of this system are (1) PO_2 sensor failure, (2) O_2 valve sticking open, (3) O_2 solenoid failing to energize and (4) a power failure. The results of these failures on the operation of the two-gas control system, and thus, the composition of the spacecraft atmosphere are as follows:

a. The expected (and demonstrated) failure mode on the chosen PO_2 sensor is a low (or zero) oxygen reading. With this signal, the O_2 supply valve will remain open and the cabin will eventually purge through the relief valve to a 100-percent O_2 system.

b. If the normally open O_2 valve should stick open, the above described situation would also occur.

c. Should the solenoid fail to energize, the O_2 valve would remain open to again induce the same failure.

d. A power failure has likewise results.

The corrective action for the continuous O_2 supply failure would be to manually override the valve and revert to crew monitoring and control.

Abnormal failures in which O_2 supply will not activate (e.g., the solenoid would not deenergize, etc.) should be accommodated by redundancy.

2. The second control concept, called the reverse oxygen control system, utilizes the primary constituent sensing signal as the command for supplying nitrogen to the cabin atmosphere while the oxygen is supplied on a total-pressure makeup demand basis. (See fig. 2(b).)

The cabin atmosphere is automatically controlled at either 5.0 psia pure oxygen or 5.0 to 5.2 psia total pressure consisting of oxygen plus a nitrogen diluent. In the latter case the oxygen partial pressure is controlled at 3.5 ± 0.2 psia. The oxygen is supplied to the cabin through the Command Module cabin pressure regulator(s) adjusted to maintain the cabin total pressure at 5.0 psia. The nitrogen is supplied to the cabin through a separate cabin pressure regulator adjusted to maintain the total cabin pressure at 5.2 psia. The cabin oxygen partial pressure is measured by the partial pressure sensor which signals the partial pressure control to open or close the nitrogen supply valve in accordance with oxygen partial pressure requirements. The oxygen partial pressure sensor is set to actuate the nitrogen supply valves between the limits of 170 to 190 mm Hg.

When the oxygen partial pressure has reached the upper limit by the addition of oxygen, the partial pressure control valves automatically open. Nitrogen flows into the cabin through a pressure regulator which is adjusted to a higher pressure than the oxygen regulator. This causes the oxygen flow into the cabin to cease. Therefore, during this phase of the cycle, nitrogen will be supplied to replenish lost gases and maintain cabin pressure at 5.2 psia. When metabolic consumption and cabin leakage cause oxygen partial pressure to drop to the lower limit, the sensor circuit will shut off the nitrogen supply. Oxygen will then be supplied through the cabin pressure regulator until the cycle repeats.

The installation of the reverse O_2 control system in the Apollo spacecraft will not require a change in the present O_2 supply system; however, it will require the addition of the N_2 supply system with its attendant regulators, valves, sensors, and controls.

Several potential disadvantages stem from the separation of the oxygen and nitrogen supply systems, the first of which is the necessary variance in cabin total pressure, which is a result of the philosophy of the control technique — that of leaving the primary, 100-percent O_2 control system intact. This control technique does, however, require the addition of a nitrogen cabin pressure control regulator. The total pressure control regulators (one N_2 and O_2) cannot have overlapping control bands if this system is to function properly. This establishes a requirement for matched regulators. The consequence of a flight failure in which the regulator bands overlapped would be the simultaneous activation of both the O_2 and N_2 cabin supply regulators under the oxygen-rich condition. Because of the higher flow rate of the O_2 supply (due to a nitrogen restrictor) the cabin would become more oxygen rich and eventually approach the 5-psia, 100-percent O_2 control. Manual metering of the nitrogen would correct this situation.

The normal failure modes of this system are: (1) PO_2 sensor failure, (2) N_2 valve mechanically failing to open, (3) normally closed solenoid failing to energize and open valves, and (4) power failure. The results of these failures on the operation of the two-gas control system and thus the composition of the spacecraft atmosphere is as follows:

a. The demonstrated failure mode for the chosen PO_2 sensor is a low (or zero) oxygen reading. With this signal to the controller, the nitrogen solenoids will not open. Thus the system would revert to 5-psia, 100-percent oxygen control.

b. If the N_2 valve should stick closed, the system would again revert to 5-psia, 100-percent oxygen control.

c. Should the solenoid valve fail to energize, the valve would remain closed. The oxygen control would again be unaffected.

d. A power failure would deactivate the sensor, controller, and solenoid valve; and would thus return atmospheric control to the mechanical oxygen control system.

Abnormal failures in which N_2 is inadvertently introduced to the cabin would result in popping of the overboard relief valve until cabin atmospheric dilution triggers the low-pressure oxygen warning system. However, this failure result is slow if an N_2 restrictor is used; and manual shutoff of the N_2 supply system will correct the situation and and return the system to 100-percent, 5-psia O_2 control.

3. The third concept considered is called the priority system since gas flow to the cabin is controlled by a single absolute pressure regulator, and a solenoid valve (operated by a signal from the PO_2 sensor) permits either oxygen or nitrogen to be supplied to the regulator. (See fig. 2(c).) The cabin atmosphere is automatically controlled at either 5.0-psia pure oxygen or 5.0-psia total pressure consisting of oxygen plus a nitrogen diluent. In the latter case the oxygen partial pressure is controlled at 3.5 psia. Both the nitrogen and oxygen are supplied to the cabin through the same cabin pressure regulator adjusted to maintain the cabin total pressure at 5.0 psia. The oxygen supply pressure is

regulated at 100 psig. The cabin oxygen partial pressure is measured by the partial pressure sensor which signals the partial pressure control to open or close the nitrogen supply valve in accordance with oxygen partial pressure requirements. The oxygen partial pressure sensor is set to actuate the nitrogen supply valves between the limits of 170 to 190 mm Hg.

When the oxygen partial pressure has reached the upper limit by the addition of oxygen, the partial pressure control valve automatically opens. Nitrogen at a pressure of at least 150 psig causes the oxygen flow to cease by closing the supply check valve. Therefore, during this phase of the cycle, nitrogen will be supplied to replenish lost gases and maintain total cabin pressure at 5.0 psia. When metabolic consumption and cabin leakage cause oxygen partial pressure to drop to the lower limit, the sensor circuit will shut off the nitrogen supply. Oxygen will then be supplied through the cabin pressure regulator until the cycle repeats.

A pure oxygen cabin system may be maintained by deactivating the oxygen partial pressure system which eliminates the opening electrical signal to the nitrogen supply valves. Thus, only oxygen is supplied to the cabin pressure regulator.

The normal failure modes of this system are: (1) PO_2 sensor failure, (2) N_2 valve mechanically failing to open, (3) normally closed solenoid failing to energize an open valve, and (4) power failure. The results of these failures on the operation of the two-gas control system and thus the composition of the spacecraft atmosphere are as follows:

a. The demonstrated failure mode for the PO_2 sensor chosen is a low (or zero) oxygen reading. With this signal to the controller, the nitrogen solenoids will not open. Thus, the system would revert to 5-psia, 100-percent oxygen control.

b. If the N_2 valve should stick closed, the system would again revert to 5-psia, 100-percent oxygen control.

c. Should the solenoid valve fail to energize, the valve would remain closed. The oxygen control would again be unaffected.

d. A power failure would deactivate the sensor, controller and solenoid valve; and would thus return atmospheric control to the mechanical oxygen control system.

Abnormal failures in which N_2 is inadvertently introduced to the cabin would result in popping of the overboard relief valve until cabin atmospheric dilution triggers the low-pressure oxygen wárning system. However, this failure result is slow if an N_2 restrictor is used; and manual shutoff of the N_2 supply system will correct the situation and return the system to 100-percent, 5-psia O_2 control.

The installation of the priority O_2 control system will not require a change in the present O_2 supply system and will not require a N_2 regulator since the O_2 and N_2 will be supplied through the present total pressure regulator. The N_2 supply, PO_2 control system, and "on-off" solenoid valve, however, must be installed.

4.2 SYSTEM INTEGRATION CONSIDERATION

This section is concerned with the particular merits of various ways of integrating the two-gas control techniques discussed in 4.1 into the Apollo vehicle to satisfy flight operational modes. It was dictated that the evaluation of the approaches considered be based on (1) minimum changes in the Apollo ECS, and (2) maximum utilization of components from the Gemini and Apollo parts inventory where new components are necessary for system operation. Other évaluation criteria included operation procedures and performance under normal suited and shirt sleeve modes of operation and under emergency modes. Table VII is a list of the detail operational modes considered.

The only diluent considered is nitrogen; cabin total pressure is maintained at 5 psia with an oxygen partial pressure of 3.5 psia.

4.2.1 Candidate System Approaches

Ten systems were considered on the basis of merit, simplicity, and minimum change to the single-gas system. The features and operating modes of these systems are summarized in table VIII.

For all systems, the suit circuit with the cabin depressurized must be essentially purged of nitrogen, so that acceptable oxygen partial pressure is maintained. Also, the provision for oxygen flooding of the cabin should the cabin wall be punctured still applies to all systems.

TABLE VII.- OPERATIONAL MODES CONSIDERED

Launch

Initial orbital operation

Suit closed operation (cabin pressurized)

Suit open operation (cabin pressurized)

Emergency suit operation (cabin depressurized)

Shirtsleeve operation

LM pressurization

Cabin depressurization prior to EVA

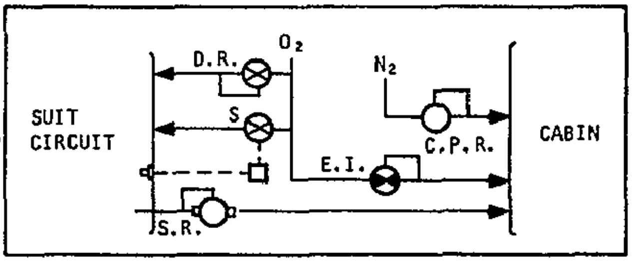
CM repressurization

Emergency depressurization (fire, etc.)

Cabin puncture (cabin depressurizing)

Most of the system features and operational modes are illustrated in table VIII. The short system descriptions below are intended only to supplement table VIII.

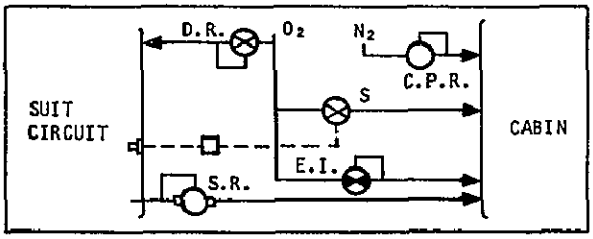
4.2.1.1 System 1 (direct O_2 control).- This system is the only one that provides active oxygen partial pressure control in the suit circuit and consequently provides for automatic oxygen purging of the suit circuit if the cabin depressurizes. After oxygen purging, the oxygen solenoid valve must be shut off manually to conserve the oxygen stores. The demand regulator then supplies oxygen to the suit circuit. During closed-suit operation with a 5-psia pressurized cabin, the cabin atmosphere has no oxygen makeup source. Hence, under this condition, the cabin atmosphere tends to become nitrogen-rich, as illustrated in figure 3. If suited operation is prolonged, say in excess of 20 hr, this could subject the astronauts to an oxygen-lean environment, should shirt sleeve operation be desired or necessary.



System 1

Failure of any of the components in the oxygen partial pressure monitoring or control equipment impairs the environmental control system in maintaining the selected oxygen partial pressure in the cabin atmosphere. This is because, under the failure cited above, the environmental control system lacks an automatic oxygen supply tuned to the oxygen demands of the cabin; thus, component redundancy in the oxygen monitoring and control system is required.

4.2.1.2 System 2 (direct O_2 control).- This system has no positive oxygen partial pressure control in the suit circuit and requires manual purging of the suit circuit with oxygen during cabin depressurization. As in System 1, this system tends to develop a nitrogen-rich cabin atmosphere if the crew remains suited for prolonged periods, because the high suit-circuit oxygen partial pressure required during all suited modes of operation effectively precludes cabin oxygen makeup. Also, as in System 1, and for the same reasons, component redundancy in the oxygen partial pressure monitoring and control system is required.



System 2

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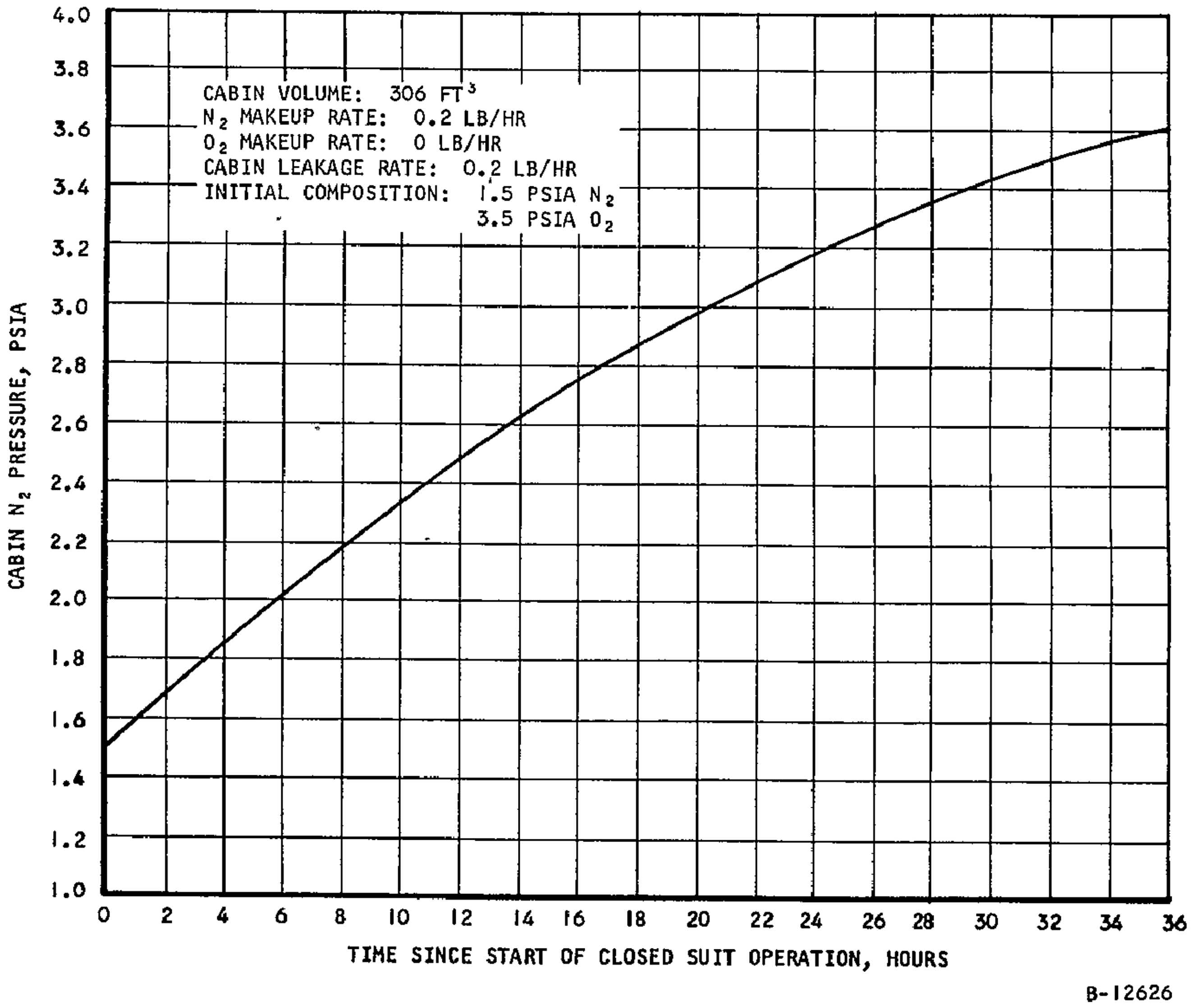
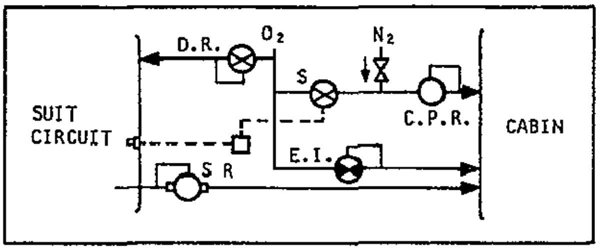


Figure 3.- Cabin atmosphere nitrogen enrichment during closed-suit operation, Systems 1, 2, 3, and 8.

It can be seen that in this system, the oxygen makeup supply is tuned only to the oxygen demands of the suit circuit, while the oxygen makeup stream is directed into the cabin. Thus, in closed-suit operation in a pressurized cabin, with suit oxygen partial pressure less than 3.5 psia, oxygen makeup is bled into the cabin regardless of the cabin total pressure or oxygen partial pressure. If the suit oxygen partial pressure remains less than 3.5 psia long enough, overpressurization of the cabin results. This activates the cabin pressure relief valve (Item 3.1) to relieve the excess pressure, with attendant gas loss.

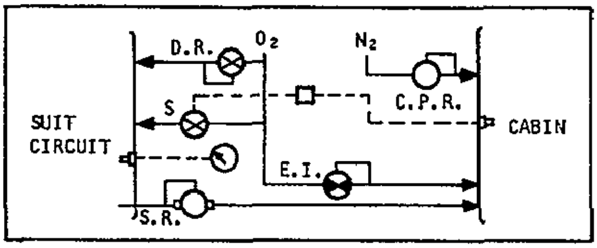
4.2.1.3 System 3 (priority).- This system is identical to System 2, except that it is the priority system version of System 2. In the priority system, oxygen and nitrogen makeup is provided on a priority basis. Oxygen has priority over nitrogen whenever makeup demands for both gases occur simultaneously. Both makeup gases are introduced in the cabin through the cabin pressure regulator, which characterizes the priority systems and maintains cabin total pressure. The priority system, therefore, precludes unnecessary gas expenditure through overpressurization of the cabin; as such, the priority system utilizes less gas in general than the nonpriority systems.



System 3

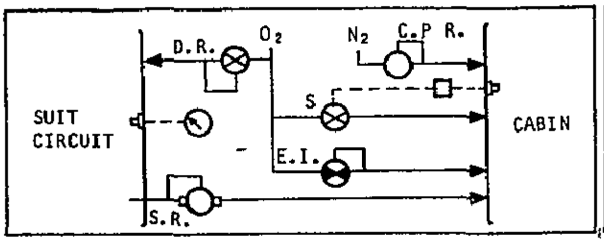
This system is essentially the same as System 2. Oxygen purging of the suit circuit is manual, and a nitrogen-rich cabin atmosphere develops with the crew in the closed-suit mode of operation. As compared with System 2, however, this system would suffer less severely with failure of the oxygen partial pressure monitoring and control system. This is because the system readily reverts to the single-gas (pure oxygen) system, which can be considered a backup system. Component redundancy in the oxygen monitoring and control system, though desirable, is not so important as in the previous systems.

4.2.1.4 System 4 (direct O_2 control).- This system is identical to System 1, except for the placement of the oxygen sensor. This system has many of the features of System 1, such as automatic suit purging. Because of the oxygen sensor placement, however, System 4 does not tend to develop a nitrogen-rich cabin atmosphere during suited operation. As in Systems 1 and 2, and for the same reasons, component redundancy in the oxygen partial pressure monitoring and control system is required.

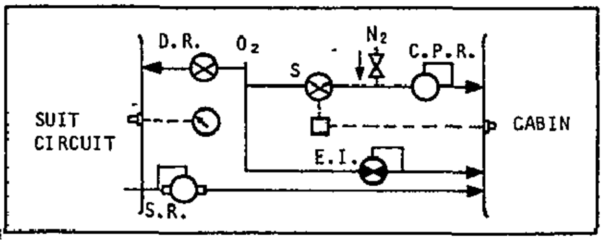


System 4

4.2.1.5 Systems 5 and 6 (direct O_2 control and priority).- These systems are identical, except that System 6 is the priority system version of System 5. Table VIII indicates the similarity of features.



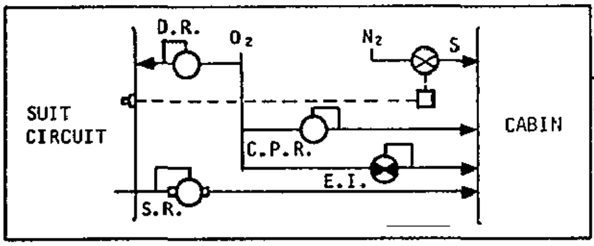
System 5



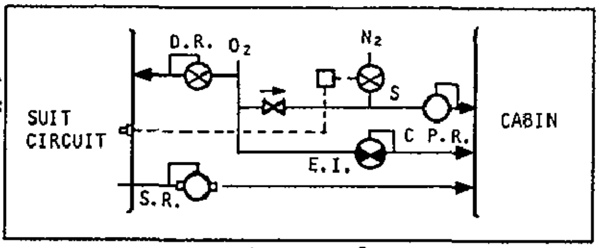
System 6

System 6 readily reverts to the existing single-gas system by closing the nitrogen supply and bypassing the oxygen control solenoid valve. Therefore, as with System 3, component redundancy is desirable but not vital. On the other hand, System 5, like System 1, and for the same reasons, requires component redundancy in the oxygen partial pressure control system. Both systems require manual nitrogen purging from the suit circuits during cabin depressurization.

4.2.1.6 Systems 7 and 8 (reverse O_2 control and priority).- Both systems are identical, except that System 8 is the priority system version of System 7. Both systems tend to develop nitrogen-rich cabin



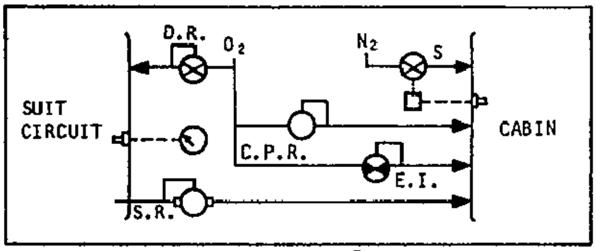
System 7



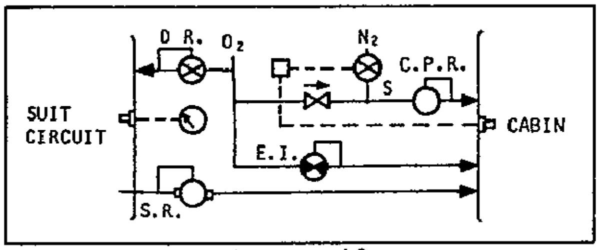
System 8

atmospheres when the crew is in the closed-suit mode. System 7 requires manual shutoff of the nitrogen supply during all-suited mode operation to avoid unnecessary use of nitrogen. Both systems require manual oxygen purging of the suit circuit; they are readily converted to the existing single-gas system by closing the nitrogen supply.

4.2.1.7 Systems 9 and 10 (reverse O_2 control and priority).- These systems are identical, except that System 10 is the priority system version of System 9. Both require manual nitrogen purging from the suit circuit and are readily converted to the existing single-gas system by shutting off the nitrogen supply.



System 9



System 10

A total of 36 hr of suited mode operation in the Command Module was assumed for proper assessment of nitrogen requirements for all the various candidate system configurations in table VIII. It may be seen that nitrogen requirements for the various configurations differ. They are higher for systems that produce a nitrogen-rich atmosphere in the suited operation mode. In these cases cabin total pressure is maintained by nitrogen input to the cabin.

4.2.2 Evaluation of Candidate Approaches

In Systems 4, 5, 6, 9, and 10, there is no means of monitoring the suit circuit oxygen partial pressure in the closed-suit mode of operation. This is because the oxygen sensor is situated in the cabin and is not exposed to the gases in the closed suit circuit. An oxygen partial pressure sensor and readout device should be provided to monitor suit circuit partial pressure for two reasons: (1) the presence of nitrogen in both the suit and cabin atmospheres, and (2) the possibility of nitrogen buildup in the suit circuit through leakage in localized negative-pressure regions of the suit circuit. This oxygen sensor and readout device in the suit circuit could also be used to determine when oxygen has purged enough nitrogen from the suit circuit.

The tendency of the cabin atmosphere to become nitrogen-rich in Systems 1, 2, 3, 7, and 8 during closed-suit operation arises from the oxygen sensors being in the suit circuit. In the closed-suit operational mode, the suit circuit oxygen partial pressure is manually established at a value greater than 3.5 psia and then maintained by means of the demand regulator. This interrupts oxygen makeup in the cabin (Systems 1, 2, 3, and 8) or causes inflow of nitrogen to the cabin (System 7). The net effect is that Systems 1, 2, 3, and 8 have only nitrogen cabin atmosphere makeup (which is sensitive to the cabin total pressure via the cabin pressure regulator), and the cabin atmosphere becomes nitrogen-rich, as illustrated in figure 3. In System 7, the cabin atmosphere also becomes nitrogen-rich, whereas in Systems 1, 2, 3, and 8, the rate of nitrogen enrichment is a function of the cabin atmosphere leakage rate. However, the enrichment rate with System 7 depends upon the makeup nitrogen inflow rate; thus, this enrichment effect could result in overpressurization of the cabin and waste of atmospheric gases.

This tendency toward nitrogen enrichment of the cabin atmosphere during suited operation can be eliminated in Systems 1, 2, 3, and 8 by manually closing off the nitrogen supply. When the cabin pressure decreases to 4.6 psia, the emergency inflow valve admits oxygen as required to maintain this pressure level. In effect, under this condition the emergency inflow valve is used as a cabin pressure regulator valve. It is not desirable, however, to use an emergency valve for a routine function. A better way to maintain cabin total pressure during closed-suit operation with the nitrogen makeup supply closed off would be to use the manual metering valve (Item 4.17) for oxygen makeup via the suit circuit. In System 7, the tendency to develop the nitrogen-rich cabin atmosphere in the closed-suit operational mode is eliminated by manually closing the nitrogen makeup supply.

It should be noted that if suited operation is relatively short, say no more than 3 or 4 hr, there is less possibility of a nitrogen-rich cabin atmosphere. The degree of nitrogen enrichment in 4 hr through the cabin pressure regulator is negligible.

Systems 1 and 4 have automatic oxygen purging of the suit circuit during cabin depressurization, because the controlled oxygen makeup is directed into the suit circuit. With the reduced oxygen partial pressure occurring in any cabin depressurization, the oxygen control solenoid valve is opened, and makeup oxygen flushes nitrogen from the suit circuit. After nitrogen flushing, the oxygen makeup valves are closed to conserve oxygen.

Systems 2, 3, 5, 6, 7, 8, 9, and 10 do not have this automatic suit oxygen-purge feature. With all systems, however, the suits can be oxygen-purged by the manual metering valve (Item 4.17). Also, if, at the onset of cabin depressurization the atmosphere is of the normal composition (3.5-psia oxygen and 1.5-psia nitrogen), minimum suit oxygen partial pressure is approximately 2.45 psia. This partial pressure, corresponding roughly to the oxygen partial pressure level at an altitude of approximately 6500 ft, will sustain the suited astronauts until the suits can be purged manually. Clearly, the automatic purge feature of Systems 1 and 4 is desirable and attractive, but not vital.

In all systems, a low-level, oxygen partial pressure warning feature should be incorporated into the oxygen-monitoring system. This feature is needed to indicate failure of the oxygen partial pressure control system and/or leakage in the nitrogen supply.

The ability to convert the two-gas control system to a single-gas control system is desirable, since the single-gas system can serve as a backup. It is noted that Systems 1, 2, 4, 5, and 9, as shown in table VIII, are not readily converted to the single-gas system. With the addition of a line between the oxygen and nitrogen supplies coupled with appropriate shutoff valves, however, the latter systems could accommodate the single-gas control requirements.

4.3 SYSTEM SELECTION

System selection was made by the process of elimination. Systems 2, 5, 7, and 9 are basically good, sound systems. They were discarded, however, in favor of their priority system counterparts (Systems 3, 6, 8, and 10) for the following reasons.

1. The priority systems have basically all of the features and attributes of their nonpriority counterparts.

2. The priority systems have the automatic cabin gas shutoff feature (for both nitrogen and oxygen) during cabin depressurization, since both gases pass through the cabin pressure regulator. On the nonpriority systems, a makeup gas supply valve must be shut manually.

3. The priority systems conserve gas, since overpressurization is avoided.

4. The priority systems are readily converted to the single-gas system; with the exception of System 7, the nonpriority systems require a line with appropriate manual shutoff valves for this capability.

Systems 1 and 4 have automatic suit purge during cabin depressurization. Offsetting this attraction are certain disadvantages. With System 1 nitrogen enrichment occures when the crew is in closed suits. Since both systems are of the nonpriority type, unnecessary expenditures of the atmosphere gas stores could occur. Also, as in the other nonpriority system, Systems 1 and 4 cannot readily be converted to the single-gas system. System 4 is superior to System 1, and due to the desirability of automatic suit purge, it will be considered in the final selection.

The four priority systems, 3, 6, 8, and 10, remain. Although all have features in common, Systems 3 and 8 have the nitrogen enrichment tendency during closed-suit operation. To avoid this, the nitrogen supply must be shut manually, the oxygen metered into the cabin via the manual metering valve, the cabin total pressure monitored, and the metered oxygen makeup flow adjusted as required. These procedures would require periodic maintenance, which is not desirable. If the nitrogen-enriched cabin atmosphere is tolerated, the nitrogen requirements are increased by 5.25 lb (assuming a total of 36 hr of closed-suit operation), reflecting the higher nitrogen makeup inflow rates during closed-suit operation. Also, depending upon the duration of each closed-suit operation period, a complicated and protracted procedure may be required to reestablish the 3.5-psia oxygen/1.5-psia nitrogen atmosphere in the cabin.

For the above reasons, and because they do not have any advantages over System 6 and 10, priority Systems 3 and 8 are no longer considered.

This leaves only Systems 6 and 10. The slight distinction between these systems is that, in System 6, oxygen makeup is controlled by the oxygen sensing and control system, whereas, in System 10, nitrogen makeup is controlled. In normal operation, they are identical; under failure modes, however, System 10 has superior characteristics. For example, should the power supply to the control system fail, or be intentionally cut off, the makeup gas solenoid control valve would close. In System 6, the system loses its oxygen makeup capability, and unless the system is converted to the single-gas control system, nitrogen enrichment occurs. In System 10, on the other hand, loss of power to the control system results in loss of nitrogen makeup, but the system automatically reverts to the single-gas control system. Further, in System 6, modification to the single-gas control system, if the control system should fail, requires bypassing the makeup gas control solenoid valve and nitrogen supply shutoff. For System 10, only the nitrogen supply shutoff is required. Furthermore, it should be noted that System 10 involves installation of a passive, simple, and compact element (the check valve) into the existing Apollo oxygen control system. System 6, by contrast, requires installation of an active, relatively complex and bulkier element (the solenoid valve). Furthermore, because of the existing layout of the environmental control unit (ECU) control panel, System 10 could be implemented as a Cape retrofit, whereas System 6 would require extensive modification of the ECU. Hence, because of these failure mode characteristics and the required system modification, System 10 is selected over System 6.

System 4 and System 10 are now the only two systems left to compare. System 4 is perhaps a technically superior approach since it results in automatic purging of the suit circuit during closed-suit operation (because the oxygen supply to the cabin is flushed through the suit). The system requires significant plumbing alteration of the current Apollo oxygen supply subsystem. Also, this system does not readily convert to a single-gas system. Therefore, System 10 was selected for integration into the Apollo CM because it is a minimum change approach lending itself very well to a Kennedy Space Center (KSC) modification. The system does not require any internal modification of the Apollo oxygen supply subsystem. The primary disadvantage of this system becomes apparent during the closed-suit mode. Since the PO_2 sensor is located in the cabin and O_2 and N_2 are supplied to the cabin, a buildup of nitrogen could potentially occur if a leak in the suit circuit existed. This can be prevented by manually "cracking" the suit O_2 supply valve such as to maintain a positive suit circuit to cabin pressure differential. This valve must also be utilized during a cabin depressurization to manually purge the suit of nitrogen as the suit total pressure reduces to 3.5 psi.

4.4 SELECTED SYSTEM DYNAMIC OPERATION

Figure 4 shows the schematic of System 10 into which redundant components have been incorporated for high system reliability. Its integration into the Apollo ECS is shown in figure 5. In the automatic mode, the nitrogen solenoid control valves are normally closed and are energized when the oxygen partial pressure in the cabin increases to 190 mm Hg and admits nitrogen to the cabin pressure regulator. At 170 mm Hg oxygen partial pressure, the solenoids are deenergized. The nitrogen supply regulator is set to regulate at 150 psi; thus, whenever the solenoids are energized, nitrogen flows to the cabin pressure regulator. The nitrogen solenoid valve has a three-position manual override which provides the following capabilities:

1. AUTO. Nitrogen is directed through the solenoid valve.

2. MANUAL. Nitrogen can be manually diverted to bypass the solenoid valve.

3. OFF. Positive shutoff precludes flow through either the manual or solenoid sections of the valve.

Provisions are included to (1) switch either control system online; (2) bypass the control system and directly energize the solenoid; (3) switch sensors to the onboard indicator. An alarm circuit provides a low-limit PO_2 signal set at 155 mm Hg.

Estimated operating characteristics of the control system are shown in figure 6. This figure shows the operating pressure ranges of the control valves and partial and total pressure control cycles as a function of usage rate, leakage, and free volume of the CM, all at nominal conditions. The PO_2 control system and nitrogen valves cycle infrequently, with the "on" periods every 14 hr.

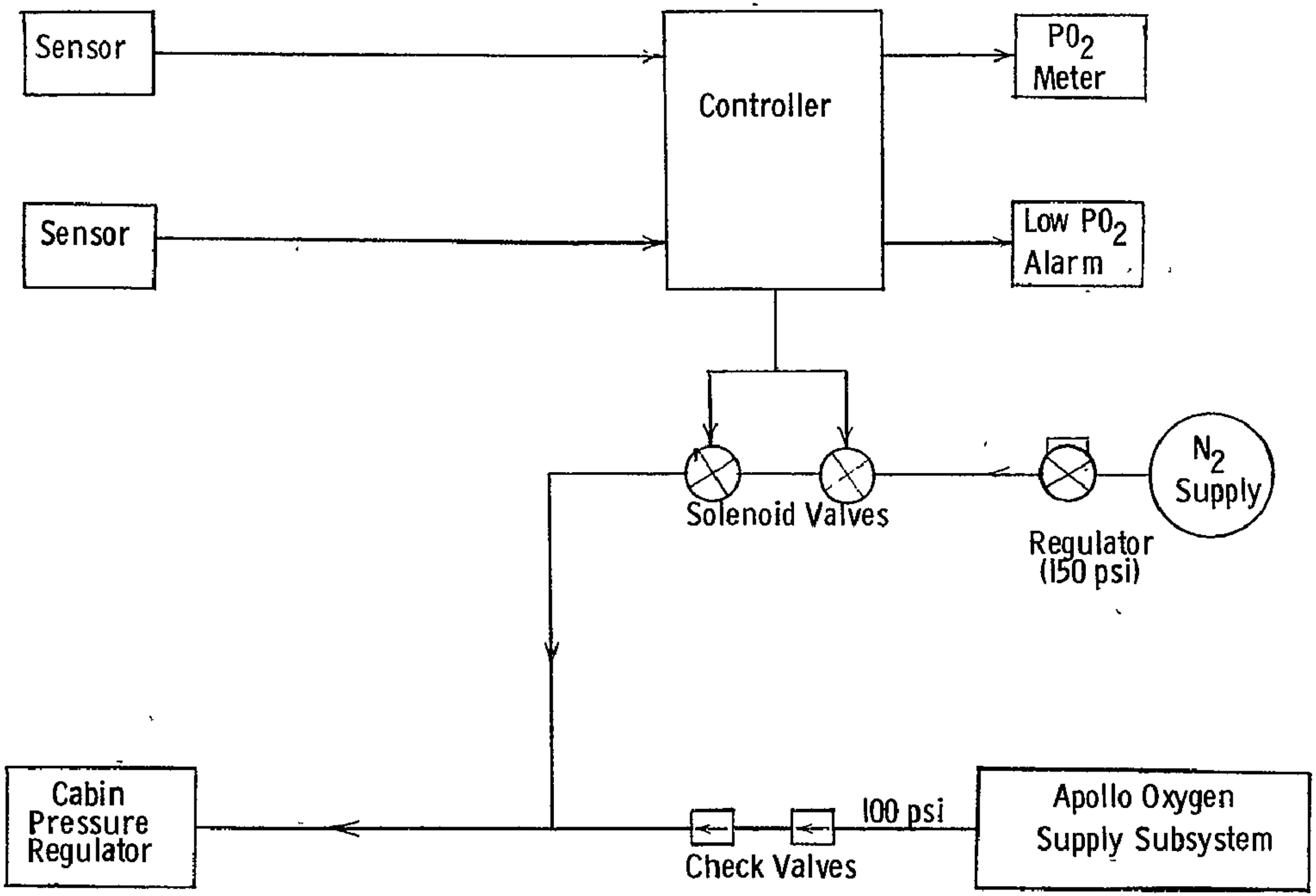


Figure 4.- Minimum modification two-gas system.

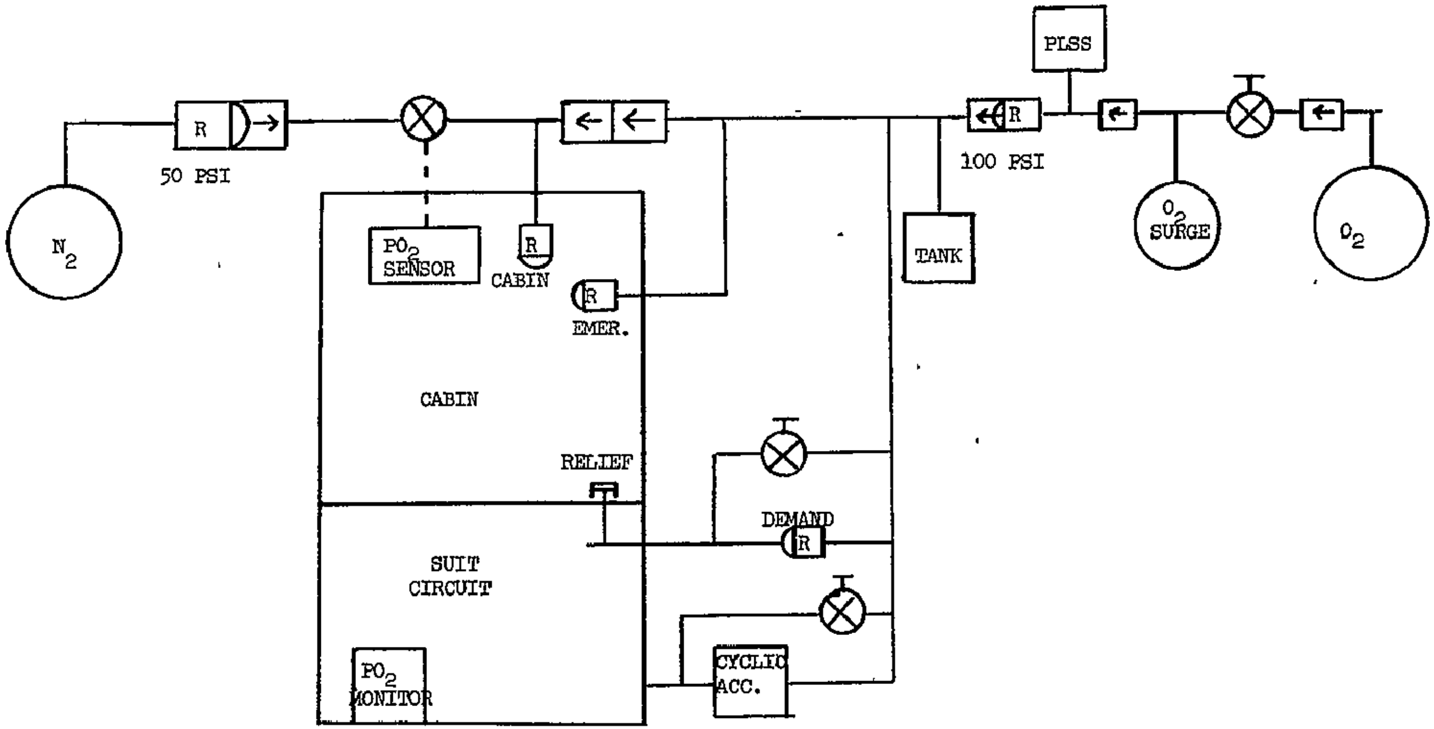


Figure 5.- Integrated minimum modification two-gas system.

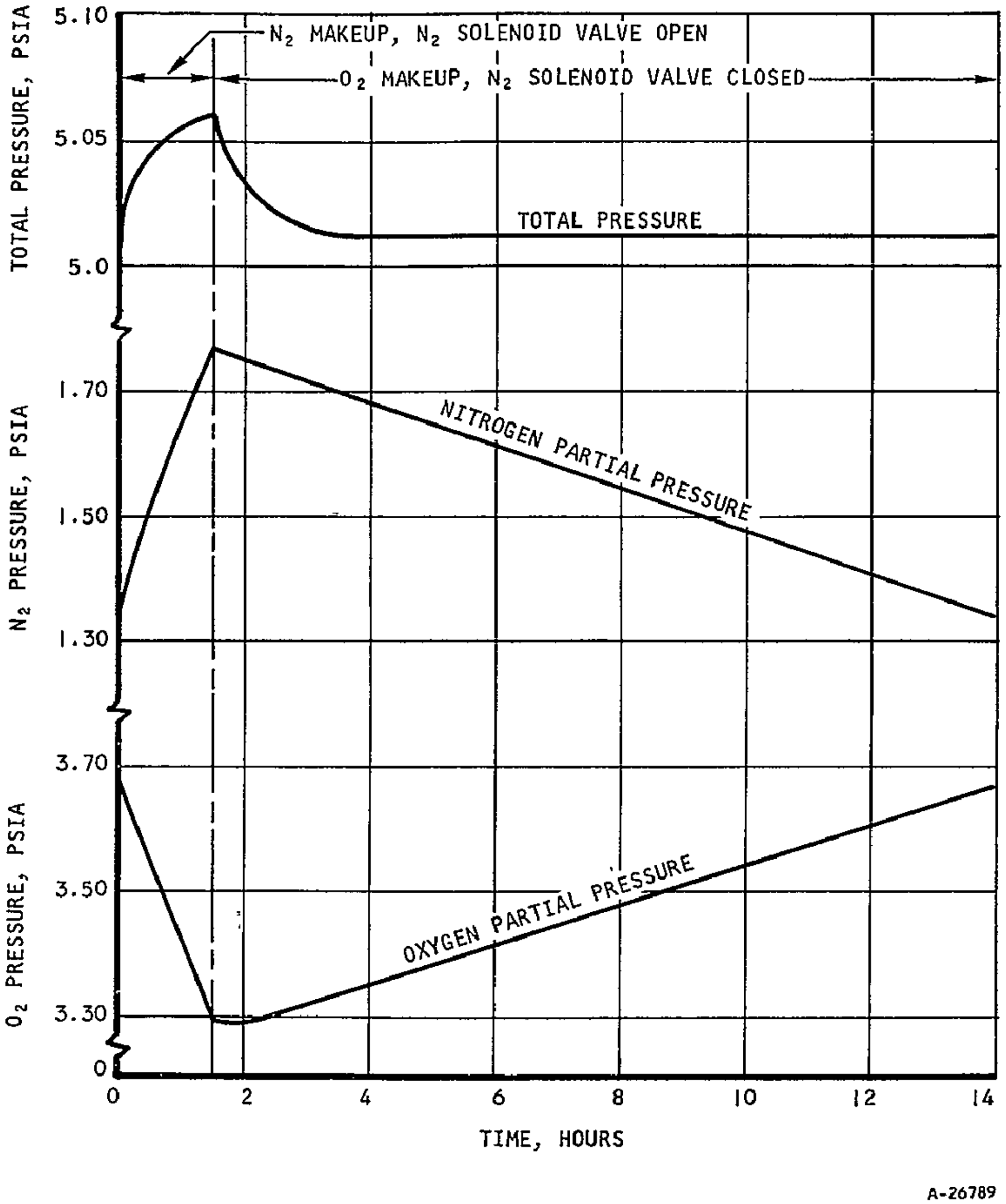


Figure 6.- Estimated minimum modification two-gas system performance.

The decay rates of partial pressures and total pressures shown in figure 6 were determined on the basis of 306 ft^3 CM free volume, nominal leakage of 0.2 lb per hr $\left(0.145\ O_2 + 0.055\ N_2\right)$, and metabolic oxygen consumption of 0.23 lb per hr. The supply rates were determined from the cabin pressure regulator performance shown in figure 7 using 100-psig oxygen supply pressure and 150-psig nitrogen supply pressure.

Starting with a total pressure of 5.01 psia, oxygen partial pressure of 3.67 psia (190 mm Hg) and nitrogen partial pressure of 1.34 psia, the nitrogen solenoid valve opens, feeding nitrogen to the cabin through the total pressure regulator. It will take approximately 1.5 hr for the oxygen partial pressure to reach the lower control point of 3.29 psia (170 mm Hg), where the control system deenergizes the nitrogen solenoids. During this time, the nitrogen partial pressure has increased to 1.77 psia, producing a cabin total pressure of 5.06 psia.

When the nitrogen solenoids are energized, nitrogen inflow to the cabin starts at 0.75 lb per hr (fig. 7: 5.01-psia cabin; 150-psig nitrogen supply). During the next 1.5 hr, the nitrogen partial pressure and cabin total pressure increase according to figure 6. During this time, the nitrogen inflow decreases according to figure 7 as cabin pressure increases. At the end of 1.5 hr, when the solenoid is deenergized, the nitrogen inflow to the cabin has reduced to 0.43 lb per hr. Switchover to 100-psig oxygen provides an oxygen inflow of 0.2 lb per hr (fig. 7: 5.03 psia; 100-psig oxygen supply). Since this is less than the total usage of 0.43 lb per hr (metabolic + leakage), cabin pressure decreases for 1.5 hr with a corresponding increase of oxygen inflow until equilibrium is reached at 5.01 and oxygen inflow is constant at 0.43 lb per hr.

At this point, with 0.43 lb per hr oxygen inflow, 0.23 lb per hr metabolic oxygen usage, 0.145 lb per hr oxygen leakage, and 0.055 lb per hr nitrogen leakage, an oxygen unbalance occurs, causing oxygen partial pressure to gradually increase until the high PO_2 limit of 190 mm Hg is reached at 14 hr, when the cycle repeats.

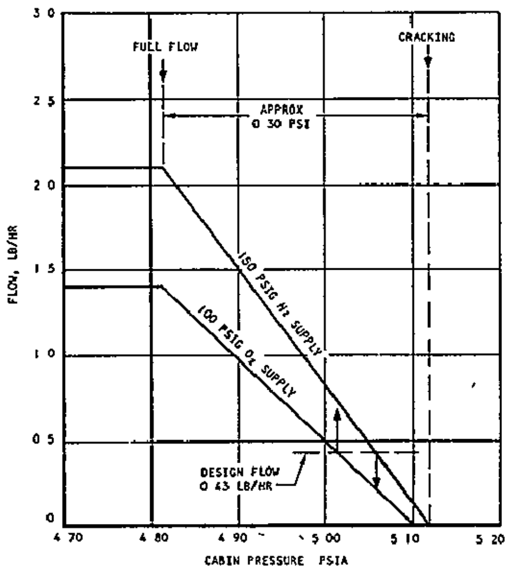


Figure 7.- Cabin pressure regulator characteristics.

Oxygen purging of the suits to flush out nitrogen is required whenever closed-suit mode operation is commenced. At present, little is known of the dynamics of this operation, but analysis indicates that a 30-second oxygen purge (based on current CM oxygen valve flow capacity) is required to obtain a 98-percent oxygen suit circuit environment. It has been determined that no crew denitrogenation time is required in transferring from a 5-psia $\left(3.5\ PO_2 - 1.5\ PN_2\right)$ to a 3.5-psia pure oxygen atmosphere if more than 24 hours have elapsed from being in a sea level atmosphere.[2]

5.0 OXYGEN PARTIAL PRESSURE SENSOR SELECTION

For the measurement of oxygen partial pressure, a considerable number of devices based on a variety of physical and chemical processes have been devised. They include:

1. Acoustic
2. Conductivity
3. Chromatography
4. Miniature fuel cell
5. Mass spectrometry
6. Paramagnetic
7. Polarographic

A special sensing problem exists when the diluent gas is nitrogen, because of the small difference between the molecular weights of the constituents of the two-gas atmosphere (oxygen 32, nitrogen 28) and their similar thermodynamic and transport properties. Measuring methods must either be sophisticated (such as mass spectrometry or gas chromatography) or depend upon differences in chemical activity (polarography or fuel cell) or upon some unique physical parameter (paramagnetism).

The proposed oxygen partial pressure sensor for an Apollo oxygen-nitrogen atmosphere is of the polarographic cell type. This device,

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[2] Edward Michel, Biomedical Research, Space Physiology Branch.

together with the other types of sensors considered for this application, are described below and their development status summarized in table IX.

1. Polarographic cell. Polarographic sensing of oxygen partial pressure is used presently in airborne hypoxia sensing systems and appears to be the most advanced method available (see fig. 8). A polarographic oxygen sensor is essentially a small battery in which oxygen, permeating through a membrane, is reduced at the cathode. At the anode, silver, cadmium, or other metals are simultaneously oxidized. The reaction at the cathode can be represented by

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$$

and at the anode by

$$4\ Ag \longrightarrow 4\ Ag^+ + 4e^-$$

The rate of reduction of oxygen at the cathode is influenced by the electrochemical potential between the dissimilar metals used at the cathode and anode, overvoltages at the electrodes, resistance of the electrolyte, and impressed potentials as in electrochemical cells. The cathodic reduction of oxygen must be more rapid than the diffusion of oxygen through the membrane covering the cathode, so that the rate of diffusion, which is proportional to partial pressure, is limiting. The current flow is then directly proportional to the partial pressure of oxygen.

The polarographic cell is available in at least two variations, both depending upon the reduction of a gel-type electrolyte by oxygen, which produces a current flow proportional to oxygen partial pressure between electrodes. The two polarographic sensors presently developed are described below.

a. Beckman Instruments: Silver anode, gold cathode type, potassium chloride (KCl) electrolyte, temperature-compensated. (Requires 0.8-volt cathode voltage.) Typical range: 0 to 800 mm (0- to 300-mm linear). Accuracy, ±2 percent over linear portion, ±5 percent over full range. Outputs from solid-state Beckman amplifier and power supply may include 0- to 5-volt readout, alarm signals, and/or "on-off" control of oxygen supply. The unit being used on military aircraft weighs 2.7 lb,

TABLE IX.- POTENTIAL PARTIAL PRESSURE SENSORS

DEVELOPMENT STATUS

Acoustic - Undeveloped (not promising for O_2-N_2 but is for O_2-He)

Conductivity - Laboratory device undeveloped for flight (large size and water vapor concentration sensitive)

Polarographic - Most developed (aircraft, suit monitoring, Bios)

Miniature fuel cell - Undeveloped (required H_2 supply)

Chromatography - Laboratory device undeveloped for flight (requires carrier gas or expendable absorbent)

Paramagnetic - Laboratory device undeveloped for flight (mechanically complicated)

Mass spectrometer - Under development for flight (capable of multiple trace gas analysis, sophisticated, large weight, volume and power instrument)

Conclusion: The polarographic sensor was chosen for Apollo due to its advanced state of development

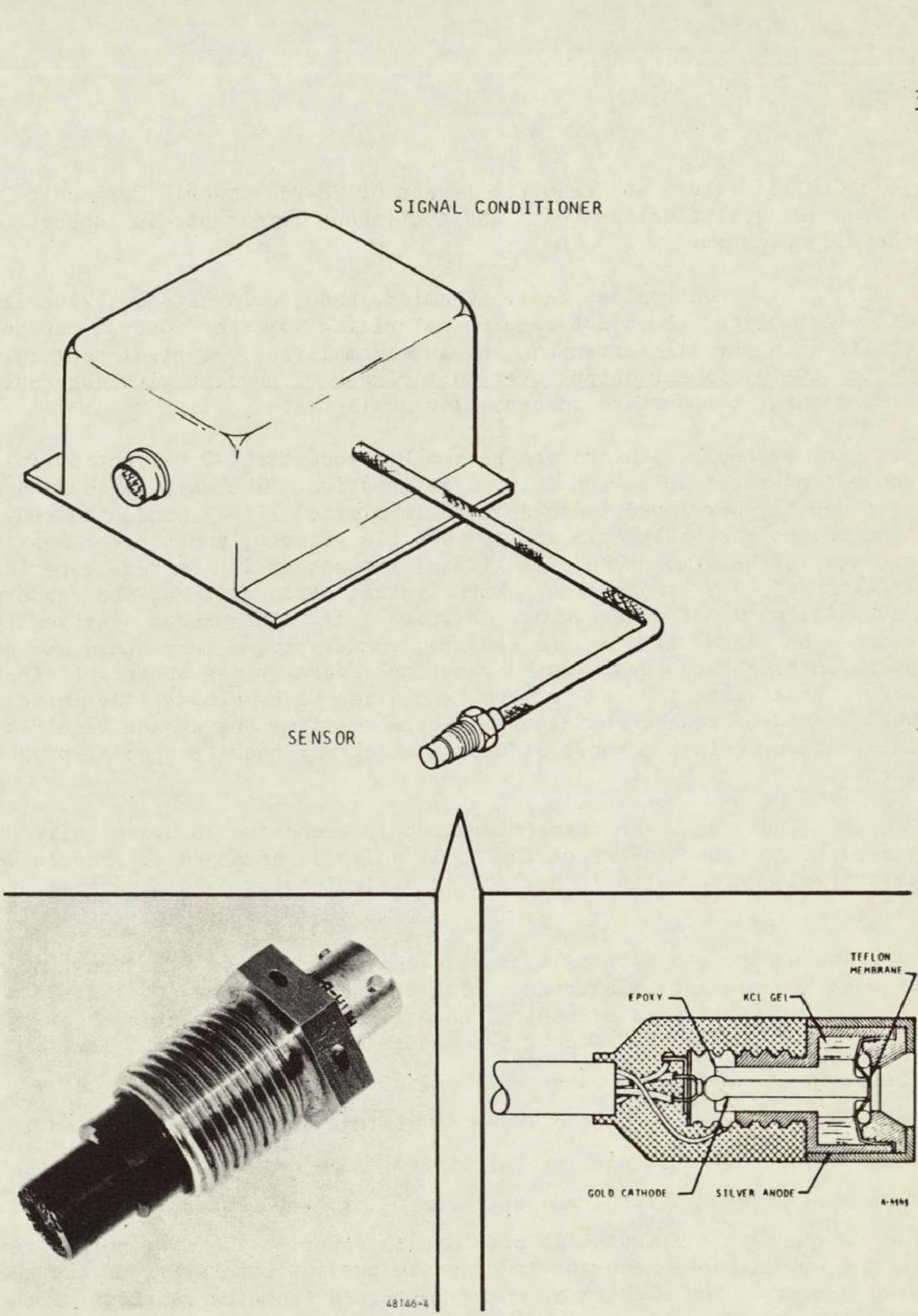

Figure 8.- Oxygen partial pressure sensor.

is 30 in^3 in volume and requires 1 watt of 28-Vdc power. This unit has passed qualification tests and continuous life tests in support of the Bios program.

b. Chemtronics, Inc.: Cadmium anode, gold cathode, with liquid electrolyte. Does not require polarizing voltage. Output may be utilized in any high-impedance low-level amplifier. Typical range: 0- to 800-mm, linear output over full range, ±1 percent with constant temperature; temperature compensation available.

Polarographic sensors are reasonably accurate (±2 percent of full scale) and repeatable with initial calibration. The main disadvantage of presently developed sensors is their limited life. Since the reduction of the electrolyte is an irreversible process, and the gel must be exposed to the atmosphere, the life of the sensor is limited, especially in extremely dry atmospheres. With typical cabin systems, the sensors have a lifetime of a few weeks. Extremely dry atmospheres drastically reduce the useful life of the sensors; conversely, a very humid atmosphere enables the sensors to operate for several times their anticipated life. Shelf life for the sensors is claimed to be almost indefinite when stored in sealed containers. Replacement of the sensor requires calibration against a known standard, which may require special procedures.

2. Fuel cell. Another polarographic technique is essentially an ion-exchange hydrogen-oxygen fuel cell which is arranged to produce an output voltage across a load which is variable with oxygen partial pressure.

The sensor consists of a plastic ion-exchange membrane sandwiched between two platinum electrodes. The electrodes act as catalysts, in addition to serving as electrical conductors. Small quantities of hydrogen, flowing on one side of the membrane, pick up OH ions from an electrolyte, to produce water and free electrons ($H + XOH \rightarrow X^{+}OH^{-} + H_2O + e^{-}$). Oxygen is then allowed to diffuse through a gas-permeable membrane to the water and free electrons. The oxygen reacts with the water and free electrons, and releases OH^{-} ions ($O + H_2O + e^{-} \rightarrow 2OH^{-}$). The gas-permeable membrane is provided to restrict the oxygen flow rate to the ion-exchange membrane in order to prevent saturation of the sensing element. The electrical energy obtained from the reaction of the hydrogen and oxygen is proportional to the partial pressure of the oxygen in the atmosphere. The sensor requires no externally applied voltage and, if properly sized, may provide the electrical energy required to drive a low-power oxygen partial pressure controller.

This unit, which is being developed by General Electric, Union Carbide, and others, requires an extremely small supply of hydrogen and gives promise of relatively high output voltage, accuracy, and (depending upon hydrogen supply) long life without drift or special calibration. The obvious disadvantage is the necessity for supplying and controlling hydrogen flow to the cell, together with any associated hazard.

3. Chromatography. A suggested method of oxygen partial pressure control in conjunction with two-gas atmospheres is the two-gas chromatograph, which could be designed to provide continuous analysis of both oxygen and nitrogen (or other diluent gas), indicating and controlling the partial pressure of both. There is no known development activity on this type of instrument; like other chromatographs, it would probably require a supply of carrier gas or an adsorbent system, which would limit its life.

4. Acoustic. An acoustic sensor is a possible approach to two-gas control in an oxygen-helium atmosphere; it is less attractive in an oxygen-nitrogen atmosphere, however, since the acoustic velocity of oxygen and nitrogen differ by less than 10 percent.

5. Paramagnetic. Many laboratory oxygen analyzers utilize the magnetic susceptibility of oxygen for measurement of oxygen concentration. Oxygen gas is unique compared to other gases (particularly carbon dioxide, water vapor, nitrogen, and helium) in its magnetic properties in that it is strongly paramagnetic (attracted into a magnetic field). Other gases are, with few exceptions, slightly diamagnetic (repelled out of a magnetic field). Thus, measurement of the magnetic susceptibility of a gas can be used as a means of accurate determination of oxygen content.

A typical instrument for detecting and measuring oxygen content by means of paramagnetism consists of a small glass dumbbell suspended on a taut, durable, quartz fiber in a nonuniform magnetic field. When no oxygen is present, the magnetic force exactly balances the torque of the quartz fiber, and the dumbbell remains stationary. When a gas sample containing oxygen is drawn into the test chamber surrounding the dumbbell, the magnetic force is altered. This causes the dumbbell to rotate. The degree of rotation is proportional to the change in force, which is in turn proportional to the oxygen concentration in the sample. A small mirror attached to the dumbbell reflects a beam of light onto a scale.

The principal disadvantages of this type of control are that it is mechanically more complicated than the polarographic type, has not been developed in miniature sizes, is susceptible to damage due to high mechanical loads, and is affected by total pressure and gas flow velocity in the sampling chamber.

6. Thermal or electrical conductivity. Gas comparator types of instruments are used in laboratories for measurement of component concentrations of gases in a mixture utilizing differences in thermal or electrical conductivity of the gases. Typical instruments of this type utilize a sensitive bridge circuit to measure the difference in conductivity between a sealed chamber containing a pure gas and a similar chamber into which the sample gas is introduced. The disadvantages of this instrument are lack of simplicity, large size, gas sampling problems, and sensitivity to water vapor concentration in oxygen-nitrogen and oxygen-helium atmospheres.

7. Mass spectrometer. The spectrographic device most applicable to measurement of oxygen partial pressure is the mass spectrometer. This instrument converts the sample gas constituents to ions by electron bombardment, accelerates the ions to their characteristic velocities, and determines their characteristic mass-to-charge ratio, thereby identifying them. There are basically two types of mass spectrometers: (1) that which electrostatically accelerates the ions through a magnetic or radio-frequency field that causes the ions to deflect according to their mass-to-charge ratio; and (2) that which electrostatically accelerates the ions and allows them to drift through a field-free drift tube and measures their time of flight over a preset distance. The time of flight is directly proportional to the mass-to-charge ratio of the ion. Types employing magnetic devices have undesirable EMI producing characteristics. The time-of-flight type utilizing no magnetic devices may be of interest: (1) because it has no EMI-producing characteristics, and (2) because it has been developed into a flight weight and size version. In conjunction with its associated digital data-processing equipment, it can provide direct indication of the primary gas quantities, plus digital counts or traces of the selected mass spectrum. In the spacecraft configuration, the coincidence mass spectrometer occupies a volume of 864 in^3, is approximately 18 in. long by 6 in. wide by 8 in. high, weighs 14 lb, and requires 30 watts of power (including its data-processing equipment requirements) for operation.

This instrument was designed for use on a spacecraft for detection and analysis of trace gases. The instrument is also capable, however, of monitoring oxygen partial pressure and of providing a signal for a controller. Such a sophisticated instrument is probably not warranted as an oxygen partial pressure sensor alone. If it is carried onboard the vehicle for trace gas analysis, however, its use as a sensor for oxygen partial pressure control may be considered as a byproduct.

6.0 SYSTEM DEVELOPMENT

6.1 SCHEDULE

The schedule followed in the development of the Apollo applicable two-gas control system is shown in figure 9. A sensor Research and Development (R&D) task was conducted between September 1965 and July 1966 to determine the applicability of available polarographic sensors to long-term spacecraft missions. During the final phases of this R&D task, the selected sensors were purchased from the manufacturer and a controller to interpret the PO_2 sensor signal was designed and fabricated. Also, at this time, applicable Apollo CM developed valves were purchased. Once the former tasks were complete system assembly was accomplished. Two-gas system performance and design verification tests were then conducted to insure an adequate design before final vehicle installation. The developed prototype two-gas system designed to integrate into the Apollo CM will be delivered to Manned Spacecraft Center (MSC) in about August 1967.

The following parts of this section of the report will give the detail results of each of the scheduled development tasks.

6.2 SENSOR DEVELOPMENT TEST

6.2.1 Description of Oxygen Sensors Tested

Beckman 78340V, 76365 (Commercial Model 778), and 78411V (hypoxia) and Chemtronics Model GP10S sensors were used in testing and for experimental purposes. In addition, an older version of the Chemtronics unit having a larger cathode of 1/8-in. diameter was available. Table X lists the principal features of these sensors.

Gold is presently used for cathodes by both Beckman and Chemtronics. The potential (1.7-V theory) between cadmium and gold (Chemtronics) is sufficient to overcome the overvoltage required for reduction of oxygen on gold, so no potential need be impressed across the electrodes. The potential (0.56-V theory) between silver and gold is too low to insure reduction of oxygen, and an impressed potential of 0.7- to 0.8-V is maintained between the electrodes used for Beckman sensors. Both Beckman and Chemtronics use essentially a neutral (pH 6-8) potassium chloride solution as an electrolyte.

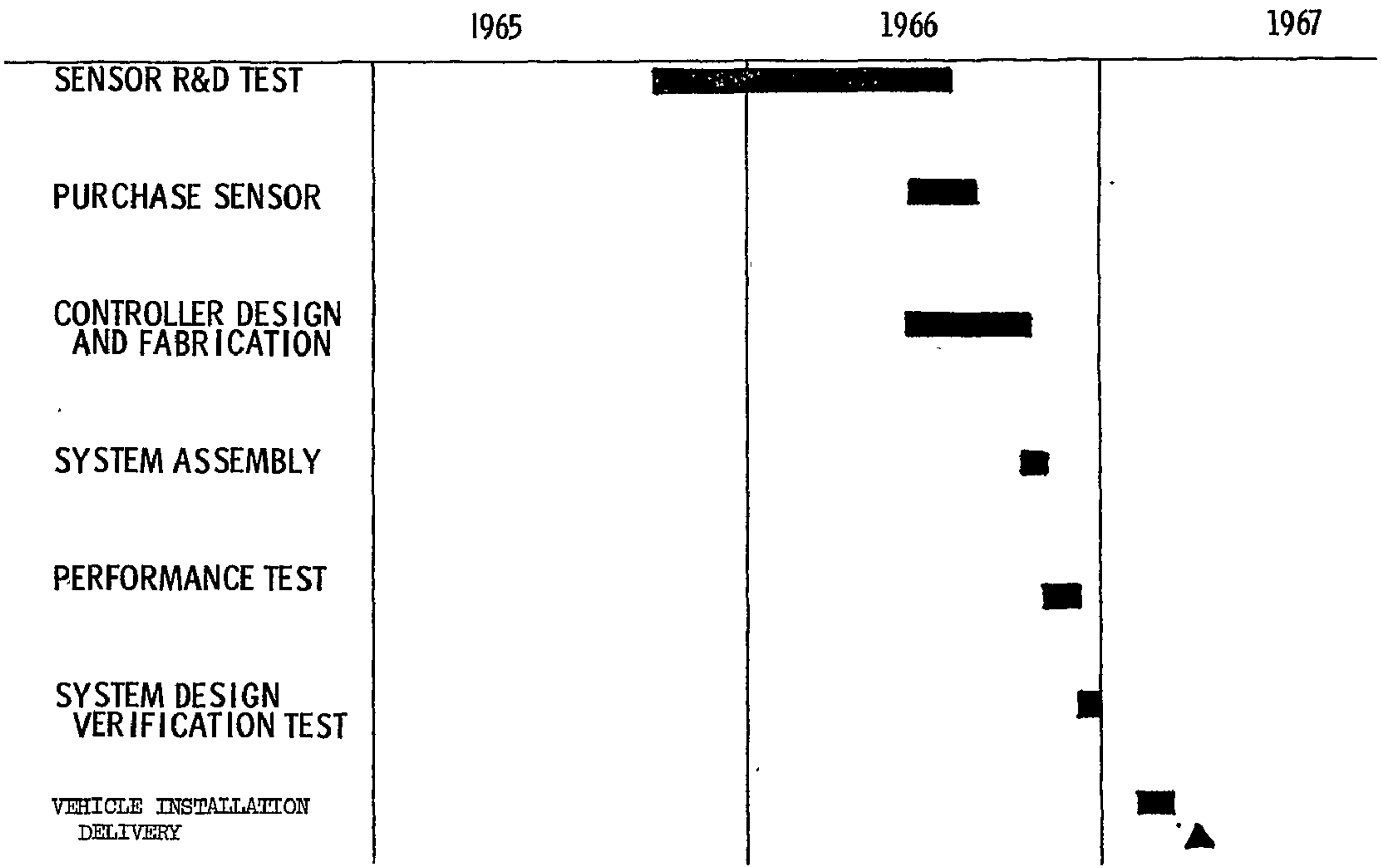

Figure 9.- Development schedule.

TABLE X.- OXYGEN SENSORS USED FOR TESTING AND EVALUATION

Manufacturer	Part No.	Model No.	Self Loading	Anode Material	Cathode Material	Cathode Diameter	Electrolyte
Beckman	78340V	(Old style)	Yes	Silver	Platinum	1 mm	Buffered Gelled KCL
Beckman	76365	778	Yes	Silver	Gold	1 mm	Buffered Gelled KCL
Beckman	78411V	Hypoxia	No	Silver	Gold	1 mm	Buffered Gelled KCL
Chemtronics, Inc.	---	(Old style)	Yes	Cadmium	Gold	1/8 in.	KCL solution with wetting agent
Chemtronics, Inc.	---	GPIOS	Yes	Cadmium	Gold	1/16 in.	KCL solution with wetting agent

Beckman supplies teflon (1 mil) as the membrane material. Chemtronics sensors are supplied with polyethylene membranes (black, 0.75 mil) having a lower oxygen permeability than teflon. For the self-loading models of both suppliers, membranes of various other materials could be used for test purposes, if desired. Normally experiments were conducted with teflon membranes (1 mil) fabricated from teflon film available in the laboratory. Problems were encountered with loading the Chemtronics sensor if the black polyethylene was used, because entrapped air under the membrane could not be detected and could influence the experimental results. The principal sensors used are shown in figure 10.

The Chemtronics sensor is reported to have a life span of 40 days or more. The Beckman hypoxia sensor is claimed to be operable for 70 to 100 days. In order to investigate these claims, an extended test of these sensors was undertaken to determine the operating characteristics, stability, and degradation of the sensors when subjected to simulated space conditions. Since it is necessary that the oxygen sensor be the primary standard in space, adjustments during the test were not permitted.

6.2.2 Test Equipment and Procedure

The test apparatus used for the extended (60-day) test is shown in figures 11 and 12. Three sensors exposed to laboratory air were permanently mounted and sealed so that they could be enclosed in a bell jar and periodically subjected to partial vacuum. The amplifier of the Beckman hypoxia sensor was modified to control a relay which opened a solenoid valve when the partial pressure of the oxygen fell below a preset level. Opening this valve simulated an input of oxygen to a space cabin, but for test purposes a nitrogen pressure was maintained upstream of the valve and the nitrogen was bled into the atmosphere. Following completion of the vacuum tests, the bell jar was refilled with laboratory air. A calibrated Beckman paramagnetic oxygen sensor (F-3) was used to determine the actual concentration of oxygen in the laboratory atmosphere, for comparison with sensor performance. Because of calibration difficulties with the F-3 oxygen analyzer, this item could not be used reliably until the last 40 days of the test period.

Amplifier readings of the three sensors were taken in the morning and afternoon of each working day. The barometric pressure, temperature, and relative humidity were also noted. The current output of each sensor was semicontinuously recorded (Brown Electronik, 24 point) at 10-minute intervals so that sensor performance during unattended periods could be evaluated. Once during each working day the absolute pressure in the bell jar was reduced until the hypoxia sensor reached 139 mm Hg oxygen pressure.

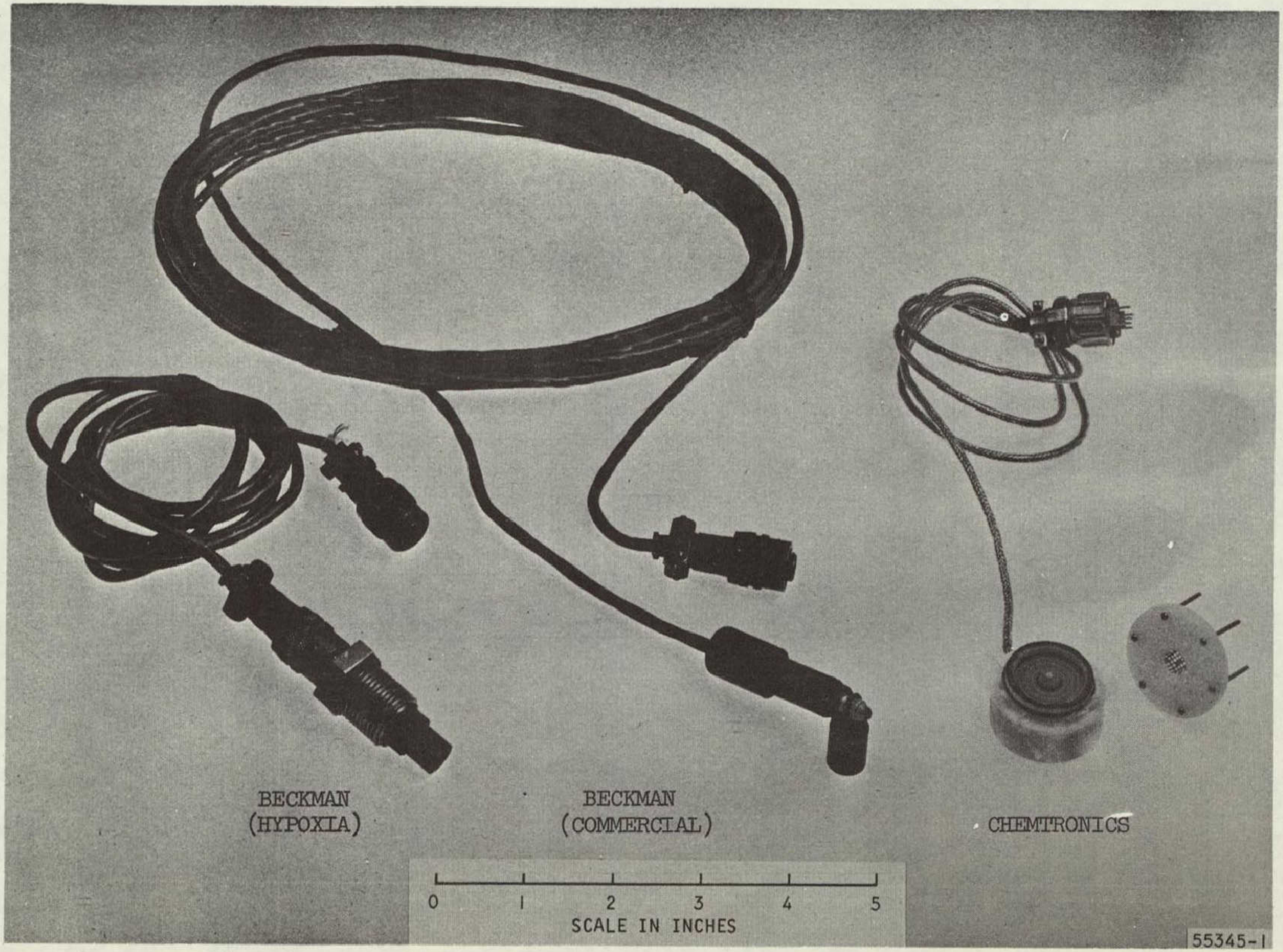

Figure 10.- Polarographic oxygen sensors.

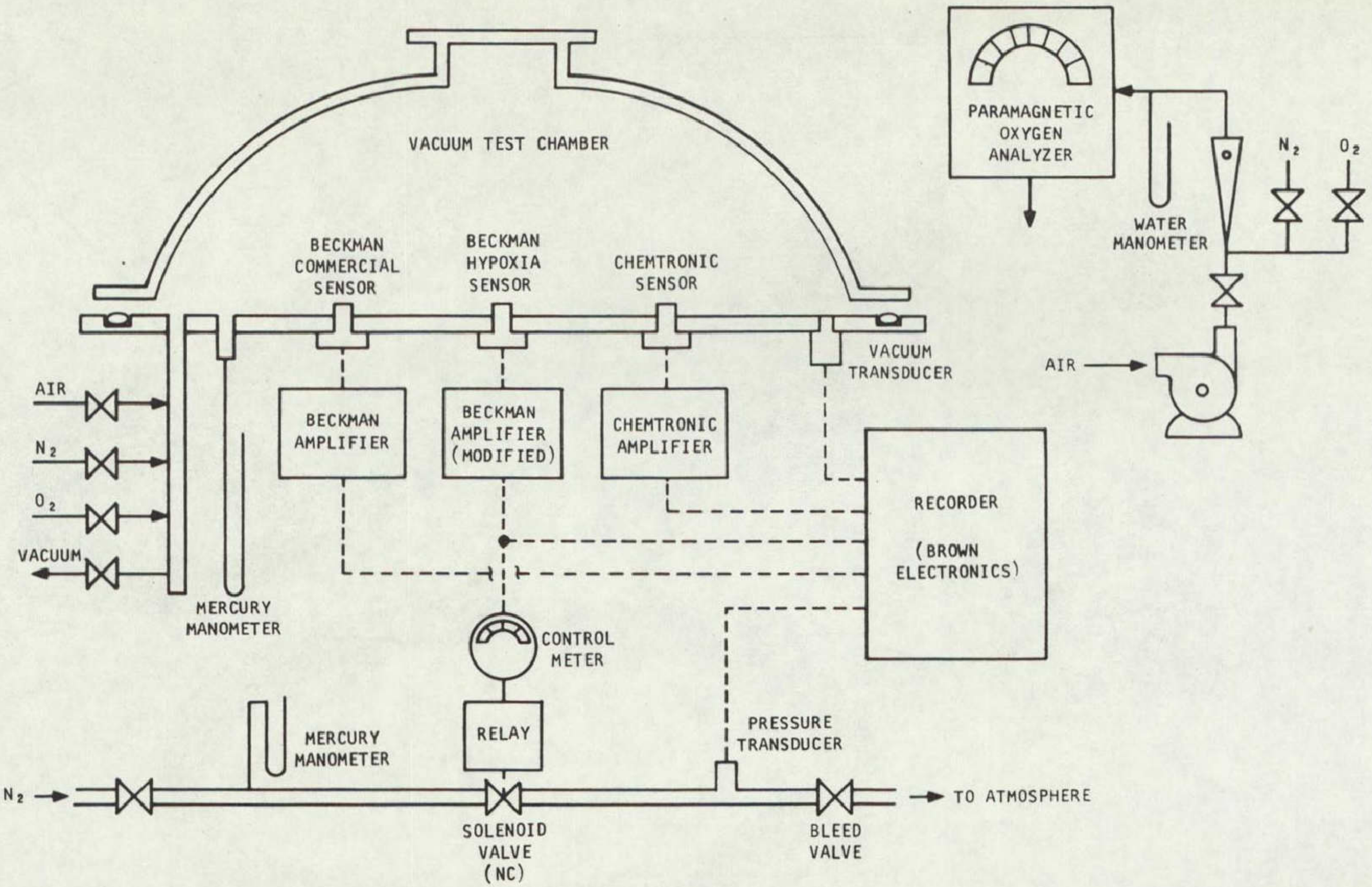

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Figure 11.- Schematic of test apparatus for evaluation of oxygen sensors.

Figure 12.- Test apparatus for evaluation of polarographic oxygen sensors.

The three sensors chosen for evaluation of extended duration performance included a Beckman hypoxia sensor, a Beckman commercial sensor (Model 778), and a Chemtronics sensor (Model GP10A). The hypoxia sensor was as received, since it was not rechargeable. The Beckman Model 778 sensor was charged with an acidified lithium chloride (LiCl) solution. The Chemtronics sensor had been used for previous tests of electrolytes and had been returned to Chemtronics, Incorporated, for charging with potassium chloride electrolyte (covered by a polyethylene membrane) prior to the start of the extended test.

Since vacuum tests were being conducted, it was necessary to seal the sensors into the base of the test apparatus to prevent air leaks. The Chemtronics unit suffered in this respect since it was difficult to provide an adequate seal without removing the cover which normally provided pressure against the membrane. As installed, the Chemtronics unit had an exposed membrane without a cover. An O-ring was used to seal the edge of the membrane to prevent gas leakage.

During a portion of the test period, response measurements were made on the hypoxia sensor. Response was measured by blowing a nitrogen stream over the face of the membrane until the amplifier reading was reduced to the lowest possible value (1 to 2 mm Hg O_2 pressure). The nitrogen was then removed, and the rapidity with which the amplifier would return to 90 percent of the original reading (140 mm) was measured with a stopwatch. Response times of 6 sec or less were common for this sensor. Since these tests apparently disturbed the membrane face (due to velocity of the nitrogen) and possibly affected the electrolytic layer under the membrane, they were subsequently discontinued until the 60-day test was completed.

Following completion of the 60-day test, additional tests were run in which the hypoxia sensor was subjected to complete vacuum; the amplifier was shut off and started after a lengthy interval; and the sensor was removed, stored, and replaced. These tests were designed to determine the ability of a sensor to return to its original value under conditions which might be encountered in a space vehicle.

6.2.3 Initial Test of Sensors with Failure Discussion

Tests on the three sensors, as previously described, were started on January 25, 1966. Figure 13 gives the performance data, daily readings, adjustments, and incidental information for the period up to March 3, 1966.

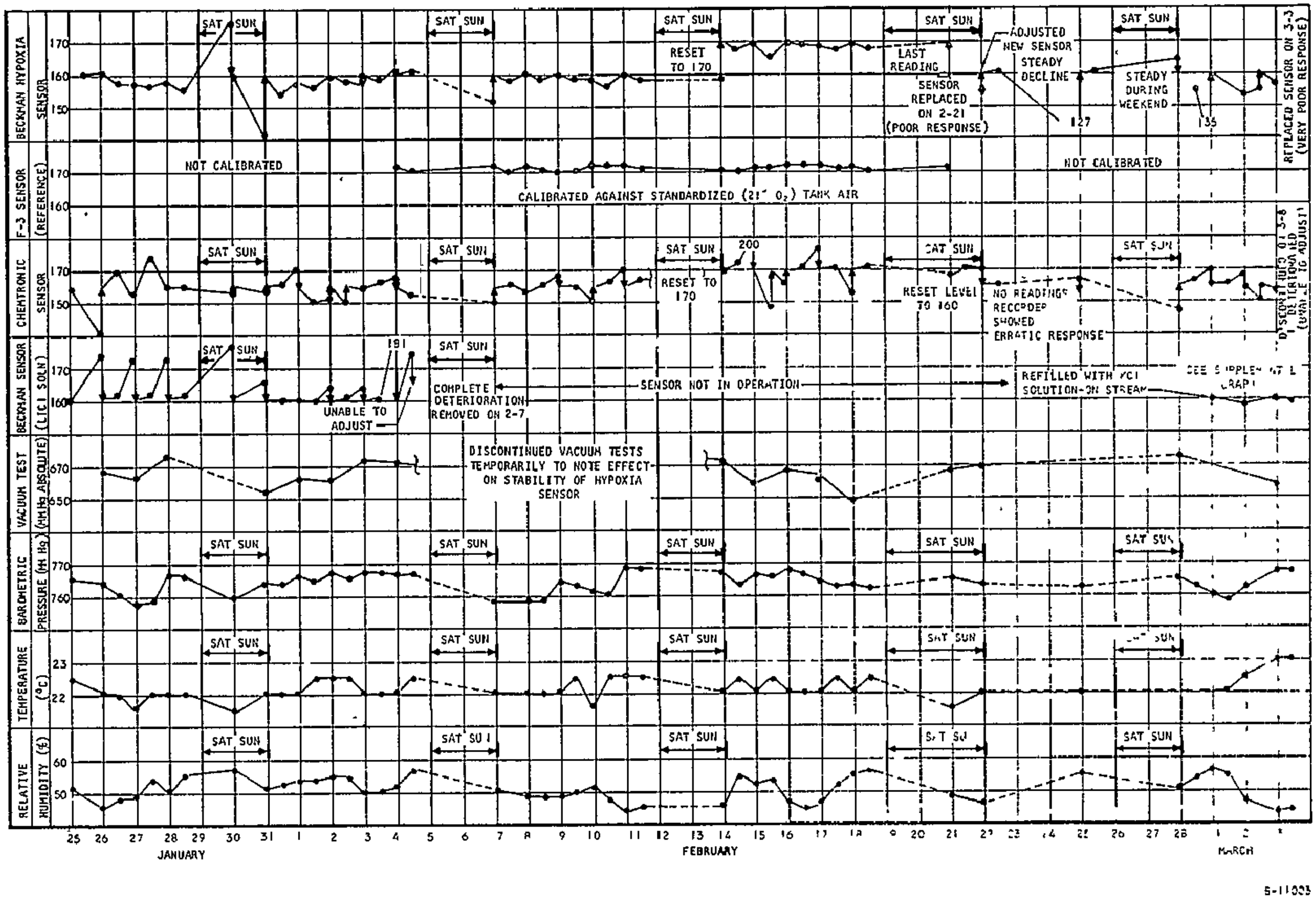

Figure 13.- Preliminary tests of polarographic oxygen sensors.

The current output from the Beckman sensor (Model 778) using acidified LiCl electrolyte was found to increase steadily with continued operation requiring daily adjustment. During vacuum tests this sensor responded more rapidly to pressure changes than did the hypoxia sensor. This sensor shorted out in less than 2 weeks due to the formation of silver crystals extending from the cathode to the silver anode. Before starting the test, the sensor had been modified by cutting microscopic grooves in the epoxy insulator supporting the cathode. The crystals were found to occupy these grooves. The increase in current output was apparently related to an increase in cathodic area as plating of silver continued. The sensor was refilled with potassium chloride electrolyte (using wicking material for a reservoir) and returned to operation on March 1, 1966. After 30 days of operation 6-percent degradation occurred, and after 38 days, complete degradation occurred.

Data for the Chemtronic sensor were very erratic. The sensor required daily adjustment of the zero control on the amplifier as well as adjustment of the amplifier reading. Response during vacuum tests was relatively good in the initial stages but was highly unreliable after about 3 weeks. The sensor deteriorated rapidly after 6 weeks and was removed from the system.

Two Beckman hypoxia sensors were used between the period of January 25, 1966, to March 3, 1966. The first sensor used being somewhat erratic, particularly in the initial period, required adjustment, and its response was poor. When response was measured on Feburary 21, 1966, (date of replacement), it was found that residual currents were present which prevented the sensor from reading less that 50 mm Hg O_2 pressure. During vacuum tests it had been observed that the sensor apparently lagged behind the calculated pressure and that vacuum had to be applied very slowly, in order to allow the sensor to respond. On returning to atmospheric pressure, the same effect was noted. This sensor was replaced on February 21, 1966, with a new hypoxia sensor supplied by Beckman. This second sensor had a response time of less than 6 sec initially but was erratic and required numerous adjustments. After 8 days of operation, response time increased to above 10 sec. This sensor was replaced on March 3, 1966, with a third hypoxia sensor. Therefore, the first two Beckman hypoxia-type sensors used in the extended 60-day test failed to function as planned. Beckman attributed the first failure to poisoning of the electrolyte by a curing agent used in the epoxy insulator which supports the gold cathode. Use of other materials of construction might provide a higher reliability factor. It was suggested by Beckman that the second sensor may have had a loose membrane.

6.2.4 Subsequent Replacement and Retest of Sensor for Extended Period

A new Beckman hypoxia sensor, placed in operation on March 3, 1966, operated steadily for the required 60-day period with degradation estimated at less than 2 percent (3 mm Hg O_2 pressure). Data are shown in figures 14 to 17. Initially, the sensor was set at 160 mm Hg because the F-3 oxygen analyzer was not calibrated. After calibration of the F-3 unit, the hypoxia sensor was adjusted by 6 mm Hg on March 23, 1966, to correspond to the reference oxygen analysis. This was the only adjustment made throughout the 60-day period.

Vacuum test data are given in figure 18. In figure 18 the oxygen pressure observed by the hypoxia sensor is given along with the oxygen pressure calculated from the mercury manometer, the barometric pressure, and the initial pressure. Recognizing the expanded scale and errors introduced in the reading of a mercury manometer (± 3 mm Hg), the scatter appears to be within the limits of accuracy (except for the 58th day of test). The sensor responded readily to changes in oxygen concentration throughout the 60-day period.

Initially, response measurements were made on a daily basis from March 3 to March 17, 1966. During this period, a 90-percent response time of 6 sec or less was obtainable. These measurements were discontinued when they appeared to upset sensor stability and an increased current output was noted. After the 60-day period, the response time was again measured at 6 sec or less.

The partial pressure of the oxygen in the atmosphere is a function of the barometric pressure, temperature, and relative humidity. Barometric pressure would have to vary by 5 mm Hg for the sensor to vary 1 mm. The relative humidity and temperature are a measure of the partial pressure of water vapor in the atmosphere. This must be subtracted from the barometric pressure to obtain the true partial pressure of oxygen. It has been calculated from the observed maximum and minimum values for relative humidity and temperature during the test period that the maximum deviation due to water vapor would not exceed 3 mm Hg O_2 pressure. Deviations from the initial adjustment which could be attributed to changes in barometric pressure, temperature, and relative humidity might be expected for long periods of time over several days. However, a daily drop in the oxygen partial pressure of 3 to 5 mm or more was observed with the test sensor from the 26th day to the end of the test. These fluctuations apparently occurred only during the normal working days, as the recorder did not reflect similar decreases during periods when the laboratory was relatively quiet. The sensor would recover each evening. The reason for these fluctuations has not been determined, but may be related either to the daily vacuum tests or to the fact that the

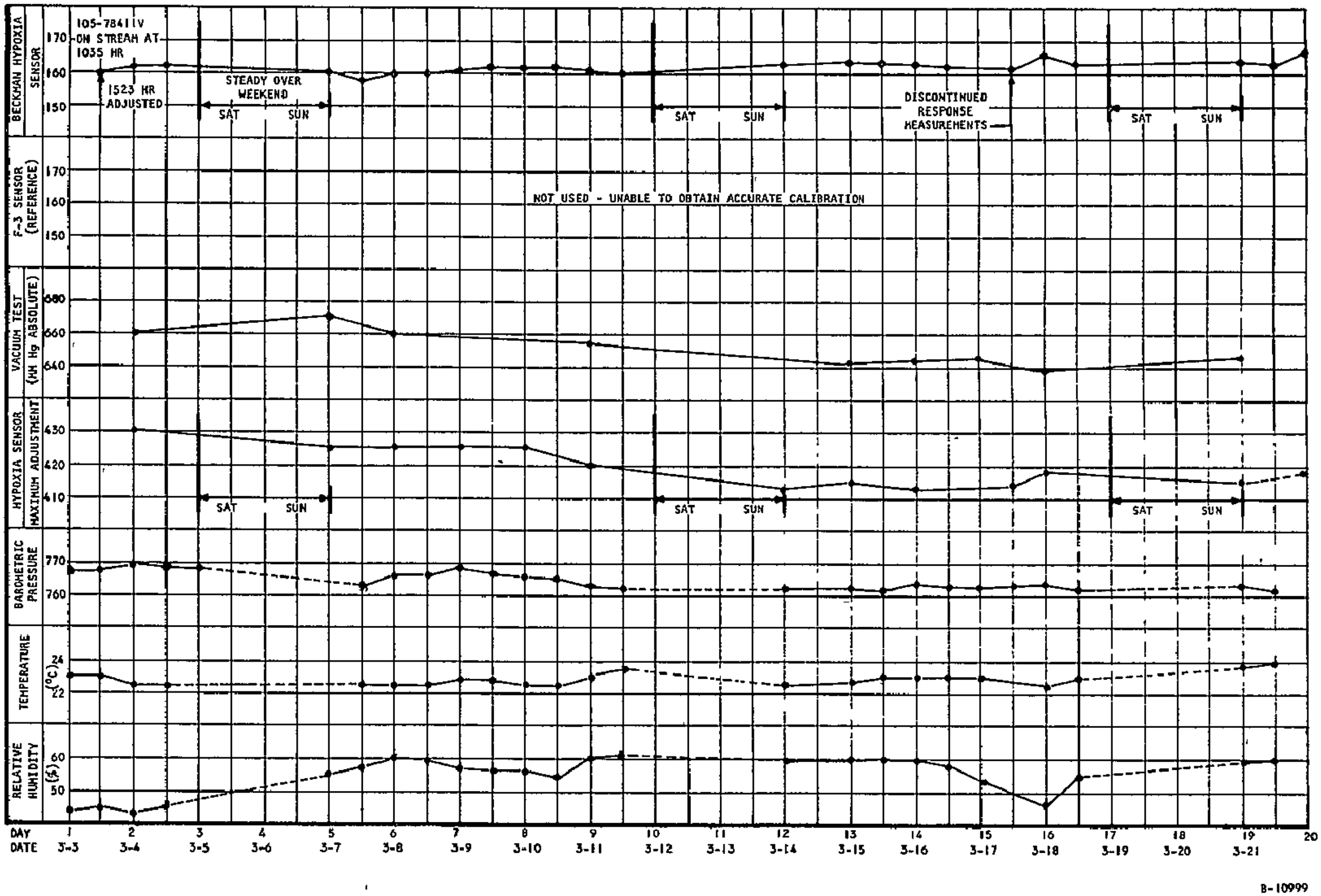

Figure 14.- Performance data for Beckman hypoxia sensor (Part 1).

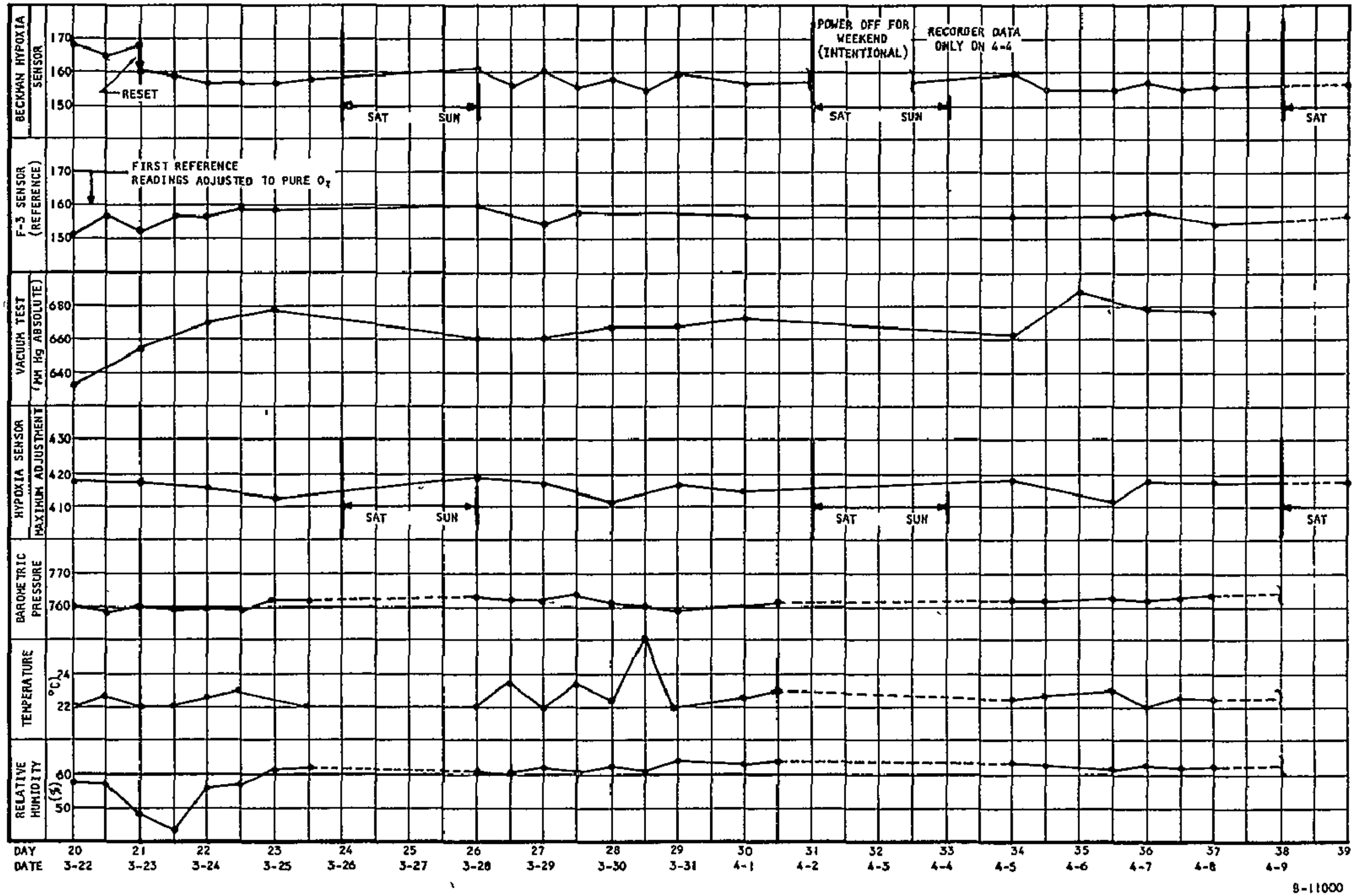

Figure 15.- Performance data for Beckman hypoxia sensor (Part 2).

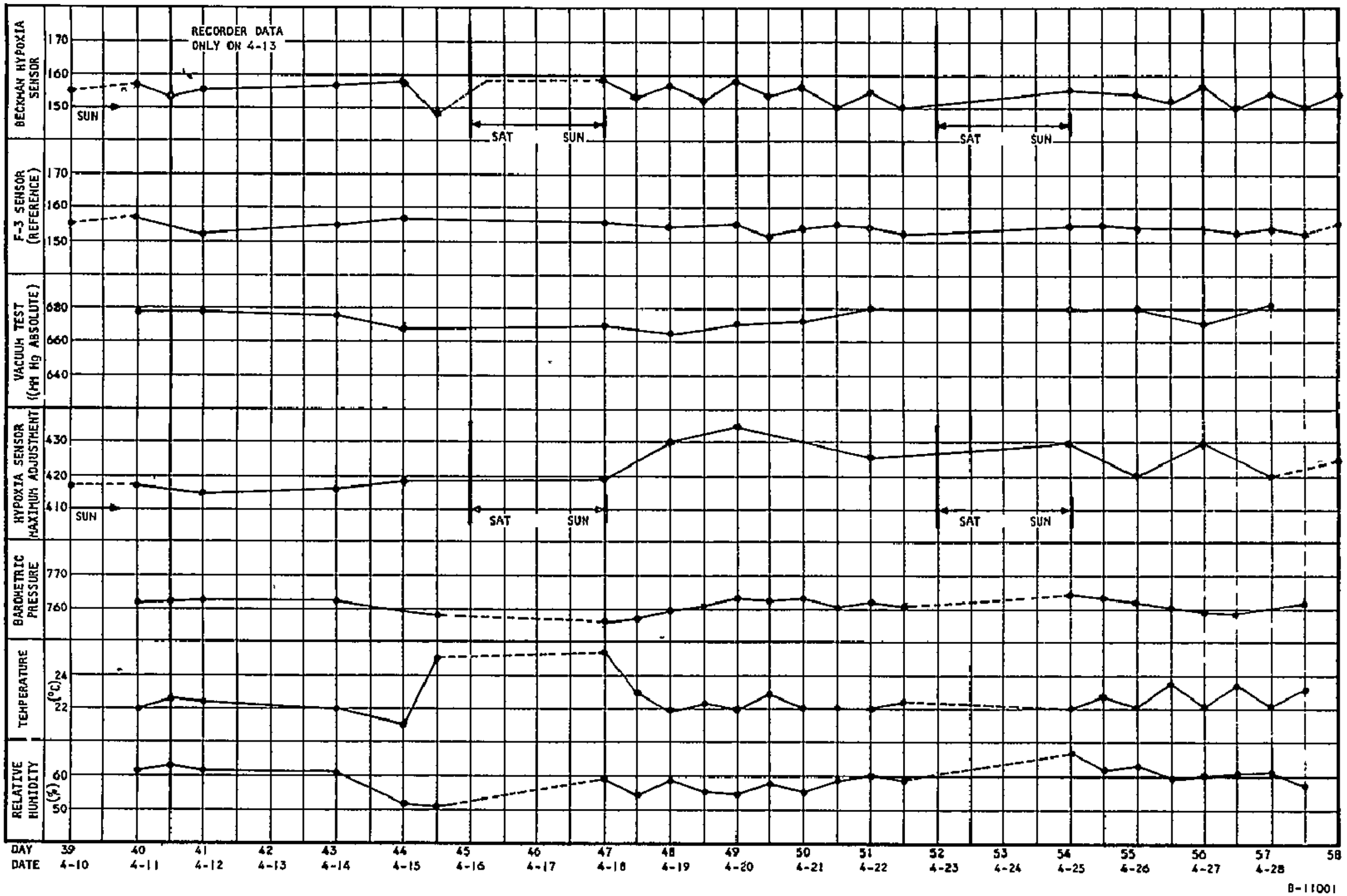

Figure 16.- Performance data for Beckman hypoxia sensor (Part 3).

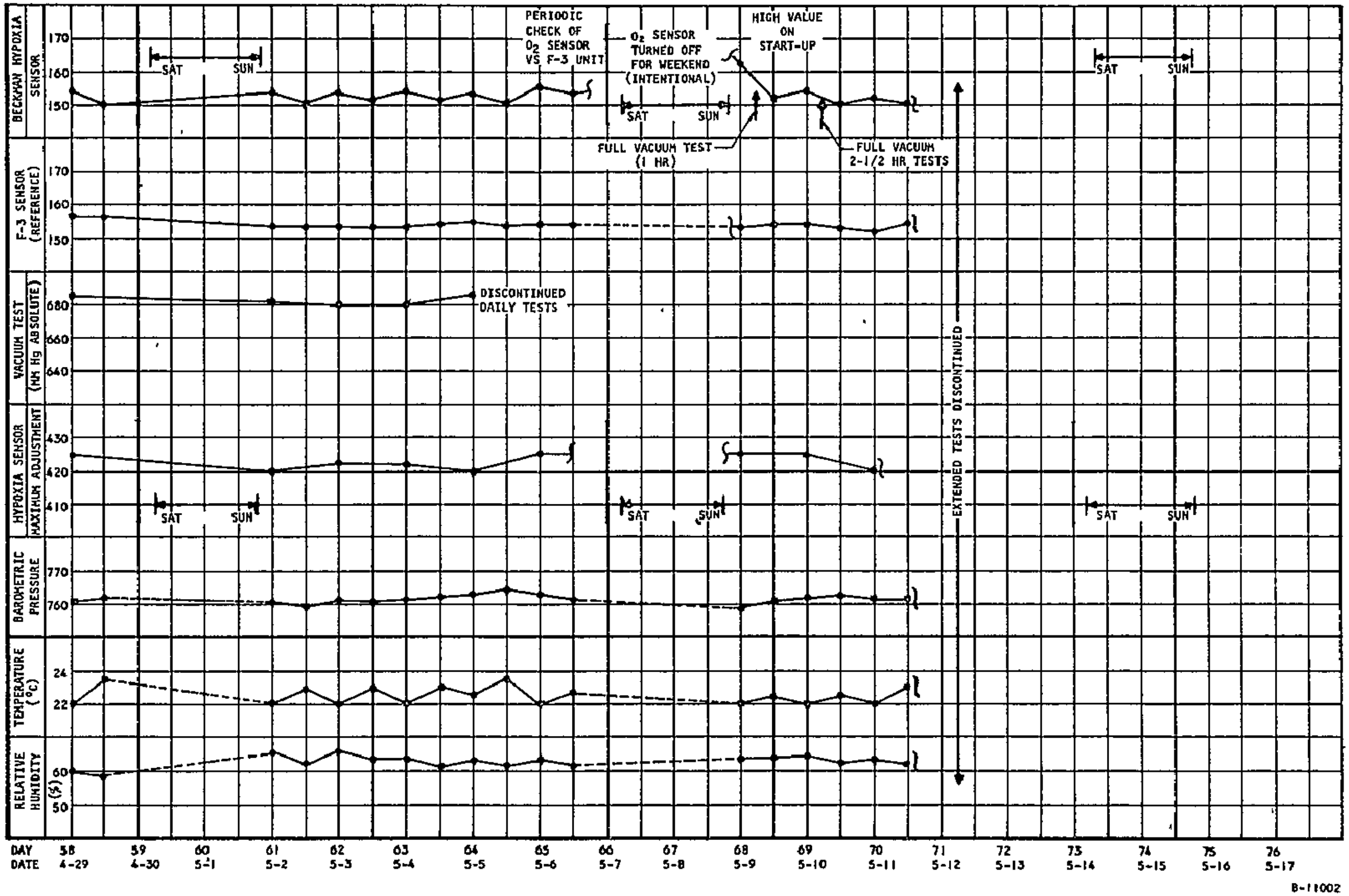

Figure 17.- Performance data for Beckman hypoxia sensor (Part 4).

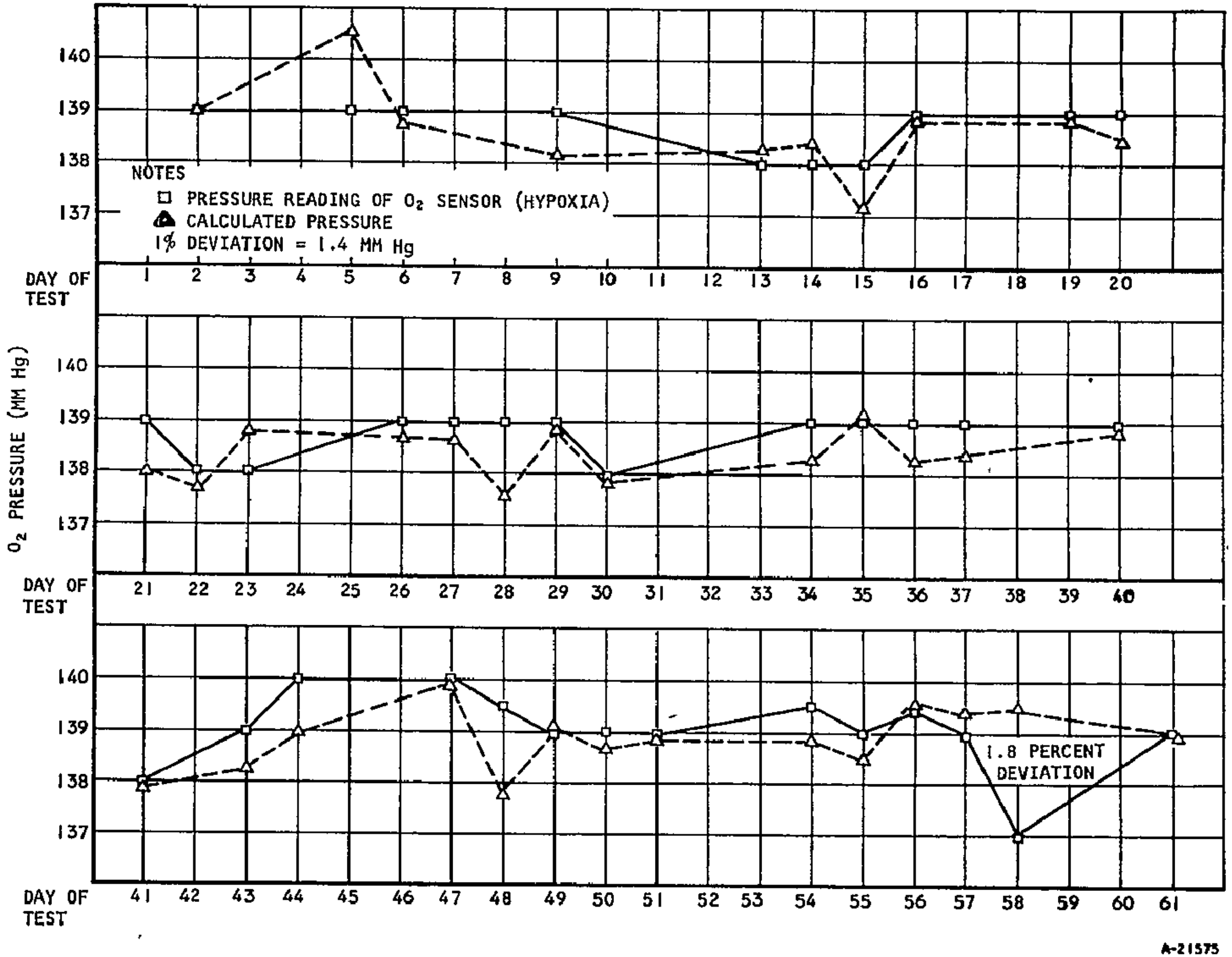

Figure 18.- Comparison of observed oxygen pressure with calculated pressure under vacuum conditions (Beckman hypoxia sensor, 60-day test).

sensors were ordinarily kept covered by the bell jar raised about 1-1/2 in. above the sensor. This provided a quiescent zone which possibly did not reflect the true atmospheric oxygen concentration. Relatively large quantities of inert gases (such as helium and nitrogen) are liberated in the laboratory at various times and, although purged by a continual flow of fresh air, could possibly have settled under the bell jar. The F-3 analyzer did not reflect any appreciable change in oxygen concentration during the day. After completion of the 60-day test, a tube was mounted near the hypoxia sensor, and air was pumped into the F-3 unit from the hypoxia sensor for analysis. A record of readings of both the reference sensor, hypoxia sensor, barometric pressure, temperature, and relative humidity was maintained through the day. A decrease of only 1.5 mm of O_2 pressure, noted for the hypoxia sensor on this date (May 6, 1966) was probably due to the increased air flow. It can be seen that the hypoxia sensor and reference sensor (F-3) corresponded on this date within the limits of accuracy of measurements.

6.2.5 Tests to Determine Stability of the Acceptable Sensor

Following completion of the 60-day test (May 3, 1966), the Beckman hypoxia sensor was subjected to a series of additional tests to determine its performance and ability to recover from adverse conditions. These tests included subjecting the sensor to complete vacuum; removing the sensor and returning the sensor to simulate replacement; and turning off the amplifier for extended periods to discover if the sensor would return to its original value. During this period, the response time of the sensor was measured periodically with practically no variance (i.e., 6 sec or less for 90-percent response).

The amplifier was off on three separate occasions for periods up to 64 hr during the weekends of April 2, May 7, and May 14, 1966. When reactivated, the sensor returned to approximately 4 percent of its original value within 4 hr and approximately 2 percent after 8 hr. After amplifier reactivation, sensor readings were always high (above 200 mm) but fell off relatively rapidly. The recorder was not programmed to record the initial rates of decrease, so exact rate equations were not calculated. Such rates may be a function of the length of time the sensor is not under power. Possibly the electrolyte becomes saturated with oxygen when not in use, and this oxygen contributes to the initial high value. The rate of consumption of dissolved oxygen would be dependent on the rate of diffusion from the electrolyte to the cathode. In one test (May 11) the sensor was removed from the holder (amplifier was under power) and returned after 1/2 hr. The sensor returned to within 1.5 percent of the initial reading within 15 min, indicating it had adsorbed relatively little oxygen. This suggests that if spare sensors are carried for space applications, it might be preferable to store the sensor prior to installation in an atmosphere (relative humidity of 100 percent) having an oxygen concentration less than that which will be measured.

The sensor was subjected to complete vacuum on four separate occasions. Data for three of these vacuum tests are given in figures 19 and 20. In the first figure the sensor was subjected to two vacuum tests, each of 1/2-hr duration. An overall degradation from 155 to 150.5 mm (3 percent) was found but the sensor partially recovered overnight, attaining 152.5 mm at 0800 on May 11. Starting on May 12 the sensor was subjected to full vacuum for 24 hr (see fig. 20). After completing this test on May 13, the sensor returned to 146 mm, giving an overall degradation of about 6 percent based on 155 mm initial. The amplifier was off for the period of May 14 to 15, and when reactivated on May 16 at 0800 hr, the sensor equilibrated at 150 mm at 1600 hr indicating partial recovery. On May 17, the sensor reading had decreased to 149, but by May 20 it had returned to 153 and was completely equilibrated at the original value of 155 mm by May 23 (10-day period required for complete recovery). These vacuum experiments indicated that the sensor is affected by a reduction in total pressure (although not necessarily by simply a reduction in the partial pressure of oxygen) but that degradation is limited and the sensor is capable of rejuvenation. The results from these vacuum tests were obtained at the end of sensor life, and may not be indicative of performance of a fresh sensor under vacuum when less degradation could be expected.

The oxygen pressure observed by the sensor closely approximated the calculated pressure in the two 1/2-hr tests. Readings obtained as the pressure decreased tended to be somewhat higher than calculated pressures (possibly due to dissolved oxygen in the electrolyte) but somewhat lower on return. This deviation is more apparent in figure 20 for the 24-hr test. It should be recognized that calculated pressures are more subjected to error at lower pressures. The pressure observed by the sensor depended on the scale used; the Beckman amplifier has a 250-mm scale and a 50-mm scale. Observed pressures in the lower region depended on which scale was used.

Response measurements before and after the vacuum tests were identical (6 sec for 90-percent response), and no degradation was indicated.

As of May 26, 1966, the sensor completed 84 days of onstream, and readings were essentially normal (i.e., 155 mm Hg O_2 pressure). The Beckman hypoxia sensor can therefore be expected to have a lifetime well in excess of 60 days.

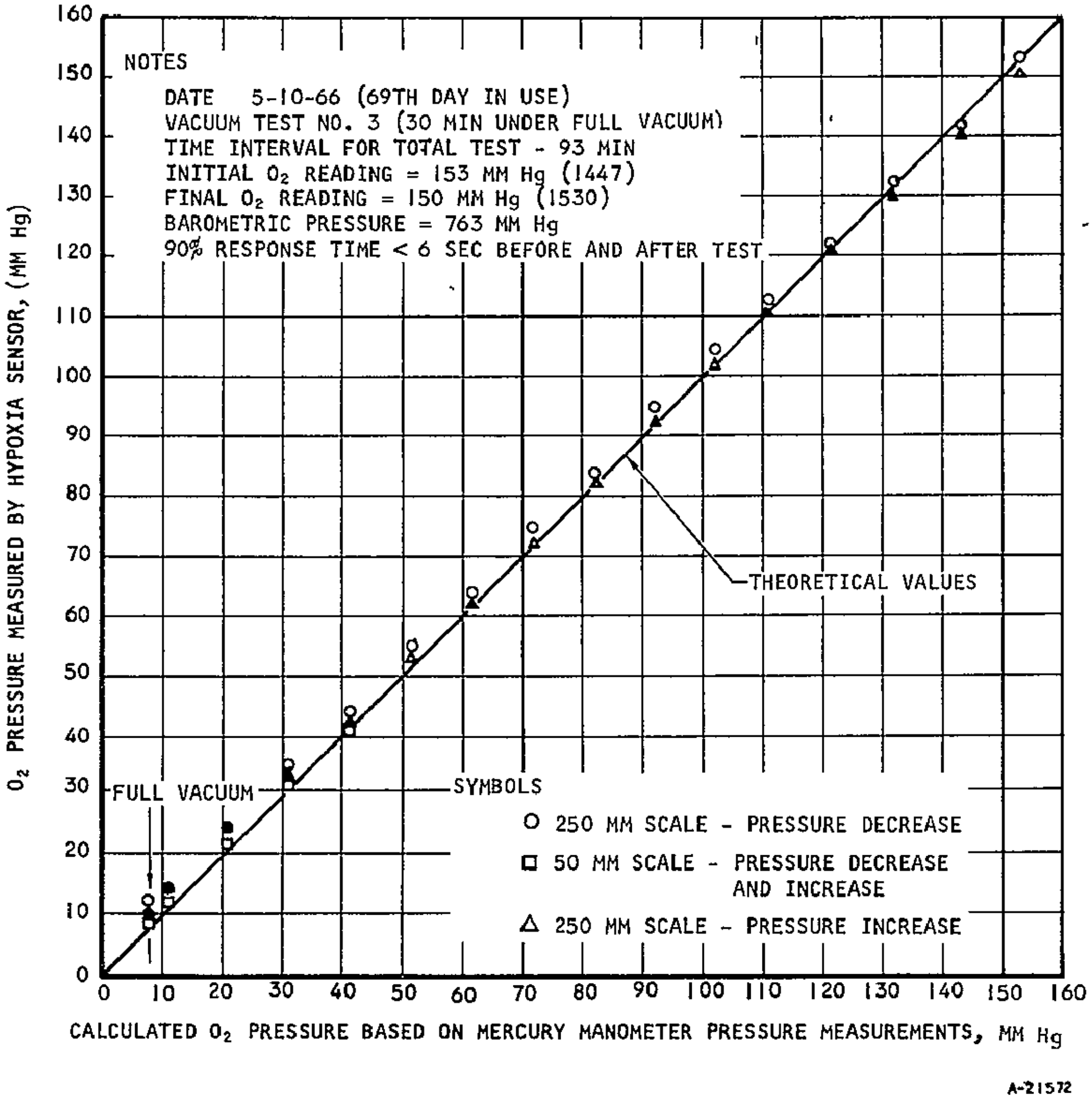

Figure 19.- Comparison of observed with calculated oxygen pressure (one-half hr vacuum).

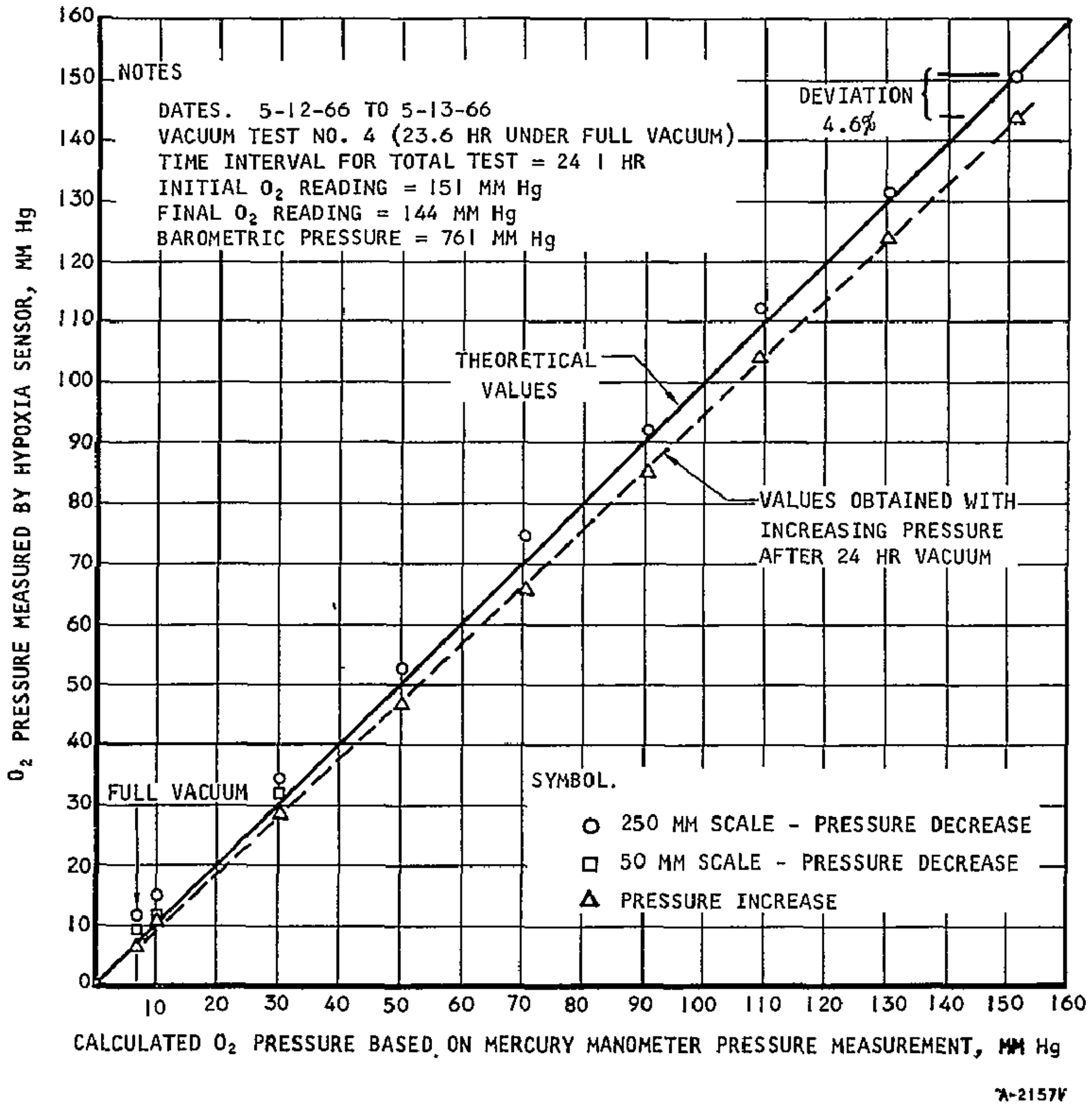

Figure 20.- Comparison of observed with calculated oxygen pressure (24-hr vacuum).

6.2.6 Summary of Sensor Development Test

Polarographic oxygen sensors 76365 and 78411V (hypoxia), Beckman Instruments, Inc., and Model GP10S, Chemtronics, Inc., were evaluated to determine their applicability as a primary standard in the measurement of the oxygen content of two-gas space cabin atmospheres for space missions extending to 60 days.

Electrolyte dehydration by evaporation of water through the membrane cover was considered to be a major factor contributing to sensor degradation. Sensor design was found to influence the expected life span.

A Beckman sensor 78411V (hypoxia) successfully passed a 60-day test with degradation estimated at less than 2 percent. During this period, it was subjected periodically to partial vacuum (139 mm Hg) to simulate space cabin conditions. After the 60-day test, the sensor was subjected to complete vacuum, on four separate occasions, for a total of 28 hr. Total degradation was estimated at 6 percent following these tests. A 10- to 14-week (70 to 80 days) life is claimed for this sensor under normal temperature, humidity, and pressure conditions.

The sensor development test results are summarized in table 11.

6.3 DESCRIPTION OF HARDWARE COMPONENT

Hardware additions to the current Apollo system to allow two-gas operation consist of equipment for positive oxygen partial pressure measurement, monitoring, and control. Modification of the existing Apollo hardware beyond minor modifications to the ECU control panel and requalification of valves at new operating pressures is not contemplated. The two-gas control system hardware requirements are as follows:

1. An oxygen partial pressure measuring, monitoring, and control signal generator system. This can be similar to the Bios two-gas system polarographic oxygen sensor, amplifier, and controller.

2. A gas-flow control solenoid valve (Apollo Item 1.36) to control oxygen or nitrogen supply. This valve has three operating modes: AUTOMATIC (controlled by the oxygen partial pressure sensor and control system), MANUAL (valve solenoid section bypassed, valve fully open) and OFF (valve acts as a shutoff valve).

3. Check valves (Apollo Item 4.25). These valves insure unidirectional flow of either oxygen or nitrogen.

TABLE XI.- SUMMARY — SENSOR DEVELOPMENT TEST RESULTS

Dehydration of electrolyte in the immediate vicinity of cathode appears to be primary life limitation

First two Beckman hypoxia type sensors failed within week after life tests

Reasons — according to Beckman

(1) First - poisoning of electrolyte by a curing agent used in epoxy insulator

(2) Second - sensor had loose membrane

A Beckman hypoxia type sensor was successfully life tested for 60 days (without recalibration) with less than 2 percent degradation

Some degradation of sensors occurs after short exposures to vacuum (1.5 percent in 30 minutes). Longer periods of vacuum exposure can significantly effect sensor performance (6 percent in 24 hours).

Sensors should be tested for periods up to a week to ensure absense of construction defects before being used in spacecraft.

4. Pressure regulators and relief valves, pressure gauges, and check valves to control nitrogen delivery pressure to the control system.

6.3.1 Control System Description

The two-gas atmosphere control subsystem is shown schematically in figure 21. The components of the subsystem are listed in table XII. Component redundancy incorporated into the system design provides two control channels; each channel is individually capable of providing the two-gas atmosphere control function, thus guarding against system failure.

The primary purpose of the two-gas atmosphere control system is the maintenance of a selected range of oxygen partial pressure in the Apollo vehicle during flight. The system functions as described in the following (see fig. 22). The cabin total pressure is maintained by the cabin pressure regulator (Item 3.28). The cabin pressure regulator is connected to both the nitrogen and oxygen supply lines downstream of their respective pressure regulators. Oxygen is supplied to the cabin pressure regulator through redundant check valves (4.25) at 100 psia; nitrogen is supplied at 150 psia. The nitrogen supply is cycled ON-OFF by redundant, normally closed, solenoid valves (4.62), which are controlled by the oxygen partial pressure sensing system. The oxygen partial pressure is measured by the oxygen sensor assembly (4.66), which produces a signal received by the controller (4.67). The signal causes the controller to energize (open) or deenergize (close) the nitrogen solenoid shutoff valve. When the oxygen partial pressure reaches 190 mm Hg, the controller energizes the nitrogen solenoid valve, allowing nitrogen to enter the cabin through the cabin pressure regulator in preference to oxygen. The nitrogen solenoid then remains opened until the oxygen partial pressure decays to 170 mm Hg, at which time the nitrogen solenoid is deenergized, allowing only oxygen makeup gas to flow to the cabin via the cabin pressure regulator. The nitrogen solenoid remains closed until 190 mm Hg oxygen partial pressure is reached again.

Incorporated into the design is a warning system that energizes a warning device whenever the oxygen partial pressure decays below 155 mm Hg. The warning device stays on as long as the oxygen partial pressure is below 155 mm Hg.

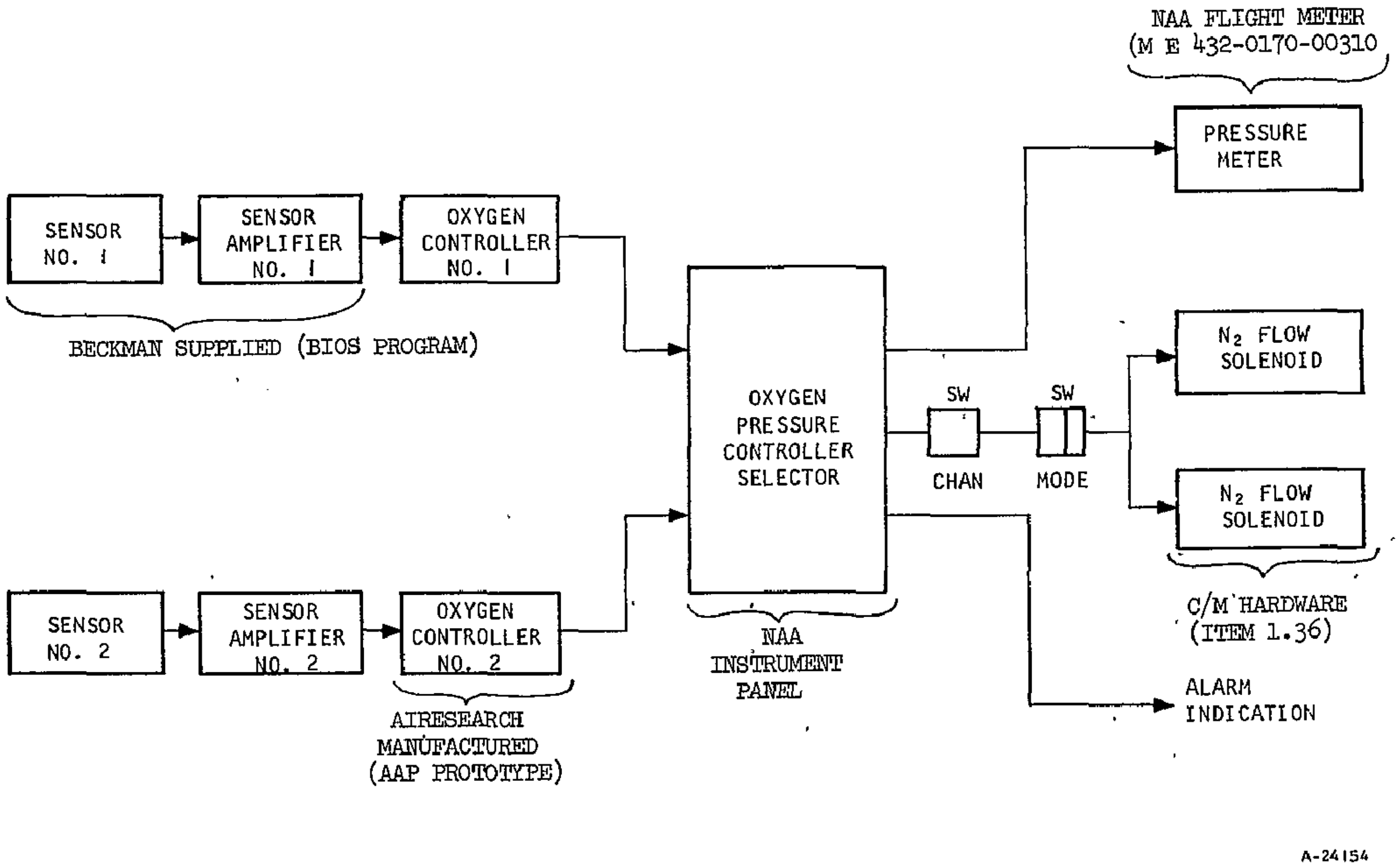

Figure 21.- Hardware design.

TABLE XII.- PO_2 SUBSYSTEM COMPONENTS

Item no.	Title	Quantity required
3.28	Cabin pressure regulator	1
4.25	Oxygen check valve	2
4.62	Nitrogen shutoff valve	2
4.66	Transducer assembly	2
---	Amplifier, PO_2 control	2
---	Sensor, PO_2 control	2
4.67	Partial pressure control	2
---	Indicator and alarm	1

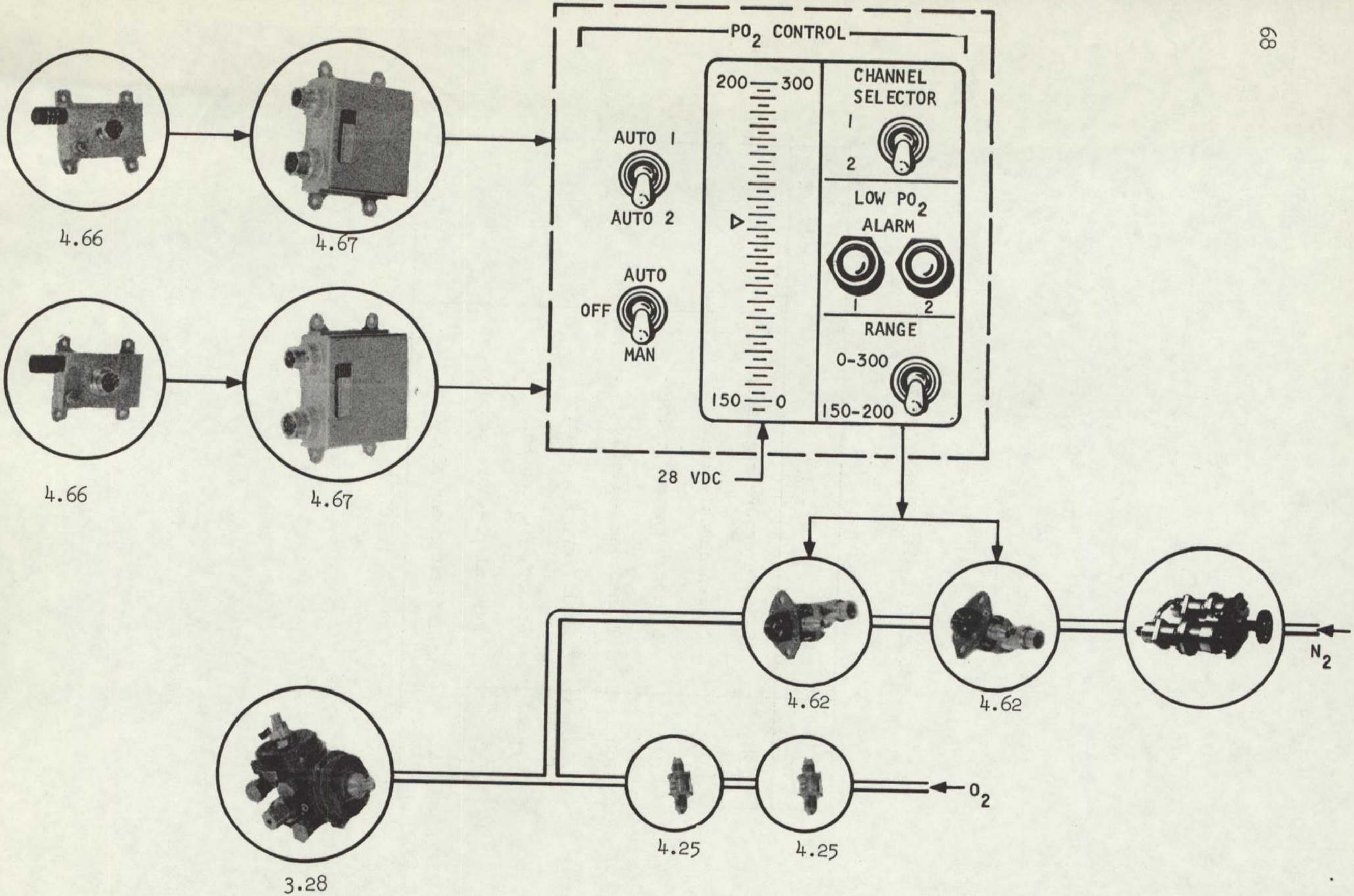

Figure 22.- Hardware schematic.

6.3.2 Component Descriptions

6.3.2.1 Oxygen sensor and sensor amplifier.- The Beckman oxygen sensor and sensor amplifier couple together to form the oxygen partial pressure transducer (4.66). The transducer (see fig. 23) produces a linear output voltage of 0 to 3 Vdc corresponding to 9 to 300 mm Hg oxygen pressure. Excitation of the transducer is received from the power supply in the oxygen controller (4.67). For a more detailed description of the sensor refer to section 5.0 of this report.

6.3.2.2 Oxygen controller.- Figure 24 shows a block diagram of the oxygen controller. The input signal to the controller is received from the O_2 transducer and is supplied to the control circuitry and the alarm circuitry. A photograph of the controller is presented in figure 25.

In the control circuitry, the input signal is fed to the amplifier, which drives the hysteresis circuit. The hysteresis circuit drives the switch circuit and also produces a feedback signal to the amplifier. Control of the output relay is provided by the switch circuit.

Operation of the control circuit is as follows. When the oxygen pressure reaches 190 mm Hg, the control circuitry output is switched to the ON position, where it remains while the pressure reduces from 190 to 170 mm Hg. This signal will remain ON until 170 mm Hg pressure is reached, at which time the output signal is turned OFF. This constitutes a cycle of operation and is repeated as a function of the partial oxygen pressure level.

Should a condition exist where the oxygen partial pressure level drops to 155 mm Hg, the alarm circuitry is activated and produces an alarm output signal. The input signal is fed to the alarm circuitry comparator amplifier, which is set to turn on at 155 mm Hg oxygen pressure. When the input signal reaches 155 mm Hg pressure, the comparator amplifier turns on the switch circuit. The switch circuit drives the relay, producing an output signal for alarm indication. Alarm indication will remain ON below 155 mm Hg and remain OFF whenever the O_2 partial pressure level exceeds 155 mm Hg.

An internal power supply converts the externally supplied unregulated +28-Vdc power to regulated ±dc power for use by the control and alarm circuitry.

6.3.2.3 Oxygen pressure controller selector.- The oxygen pressure controller selector is a junction box for feedthrough, selection, and display of control and alarm outputs.

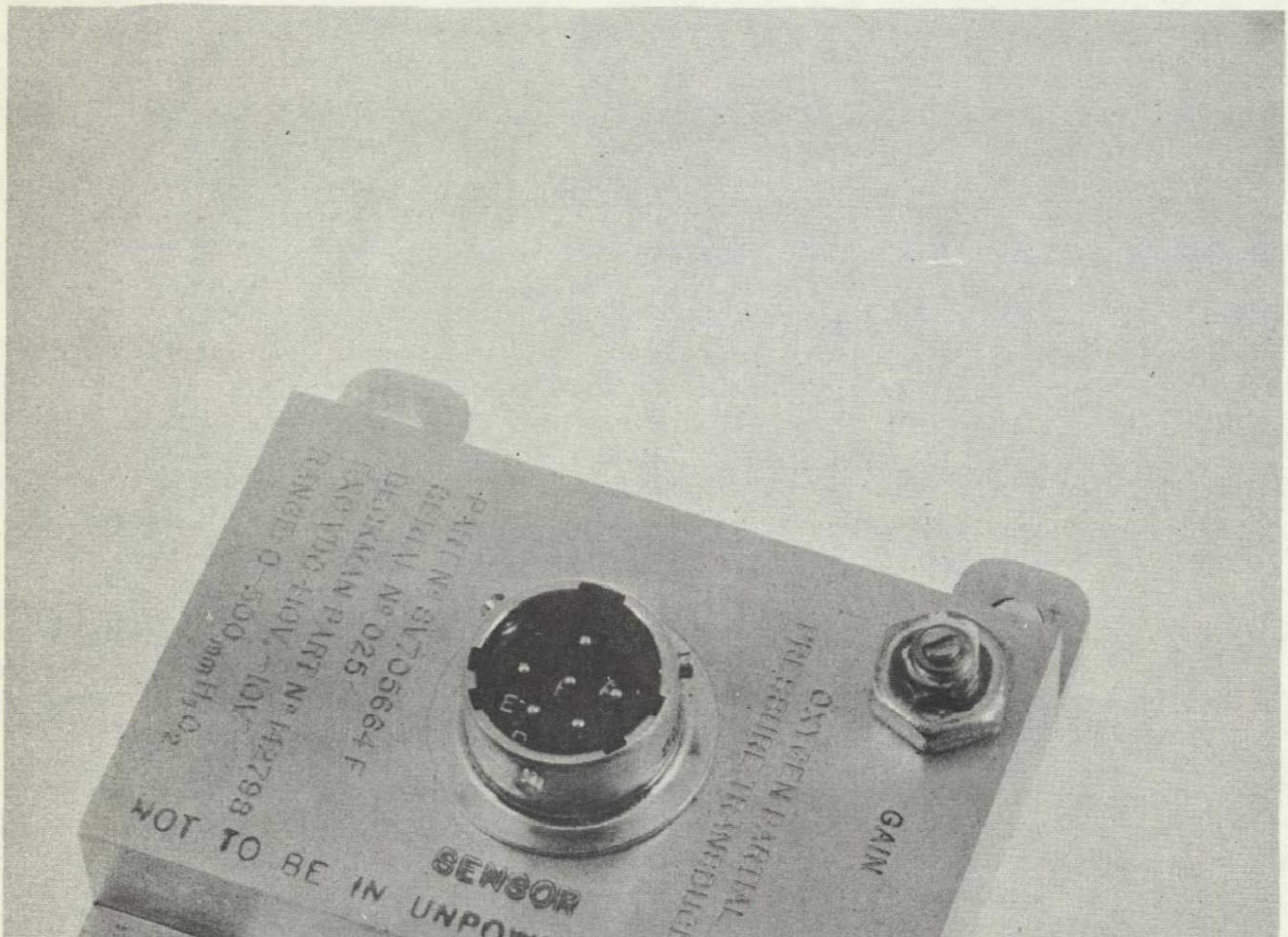

Figure 23.- Oxygen partial pressure transducer.

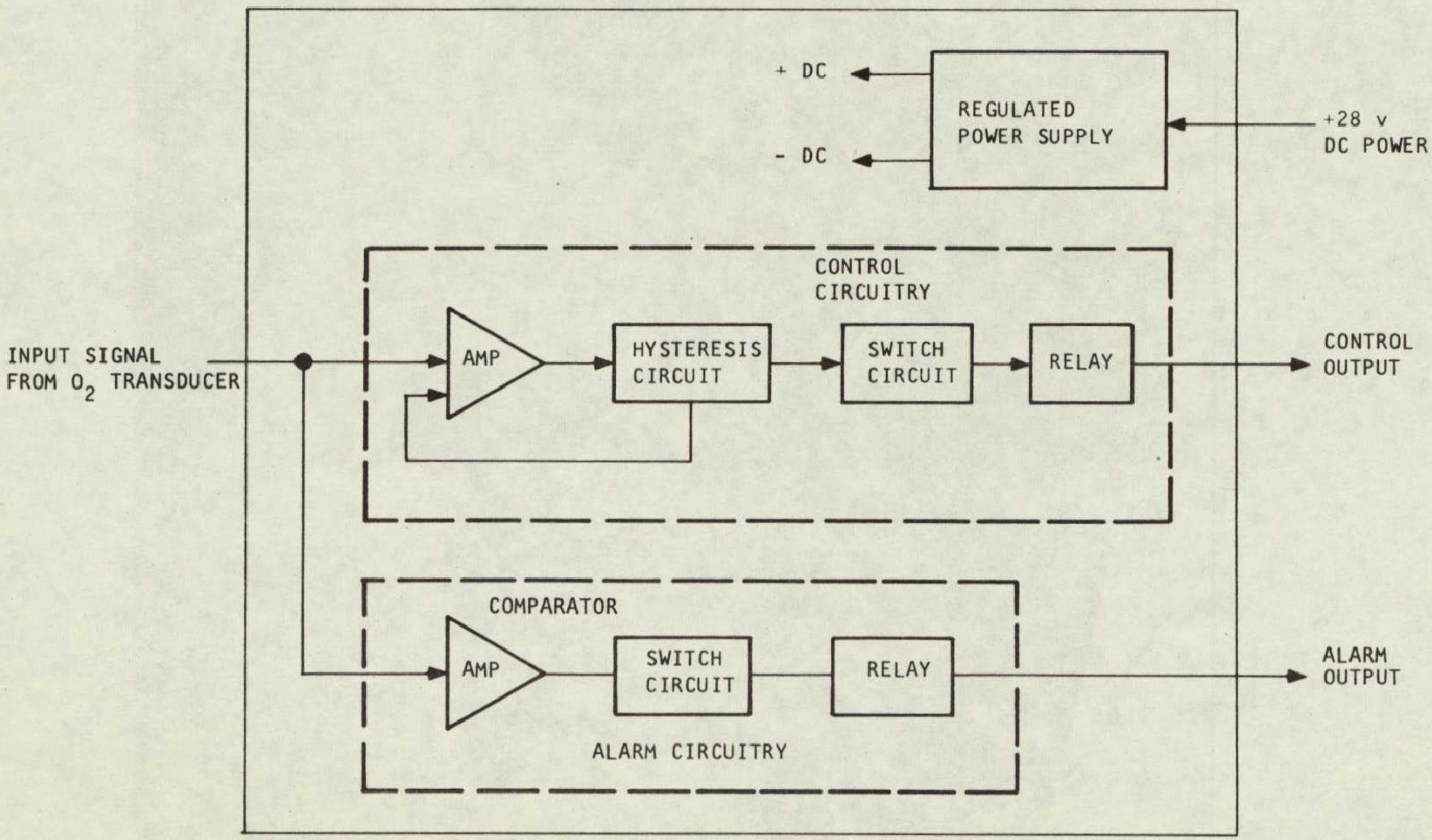

Figure 24.- Controller design.

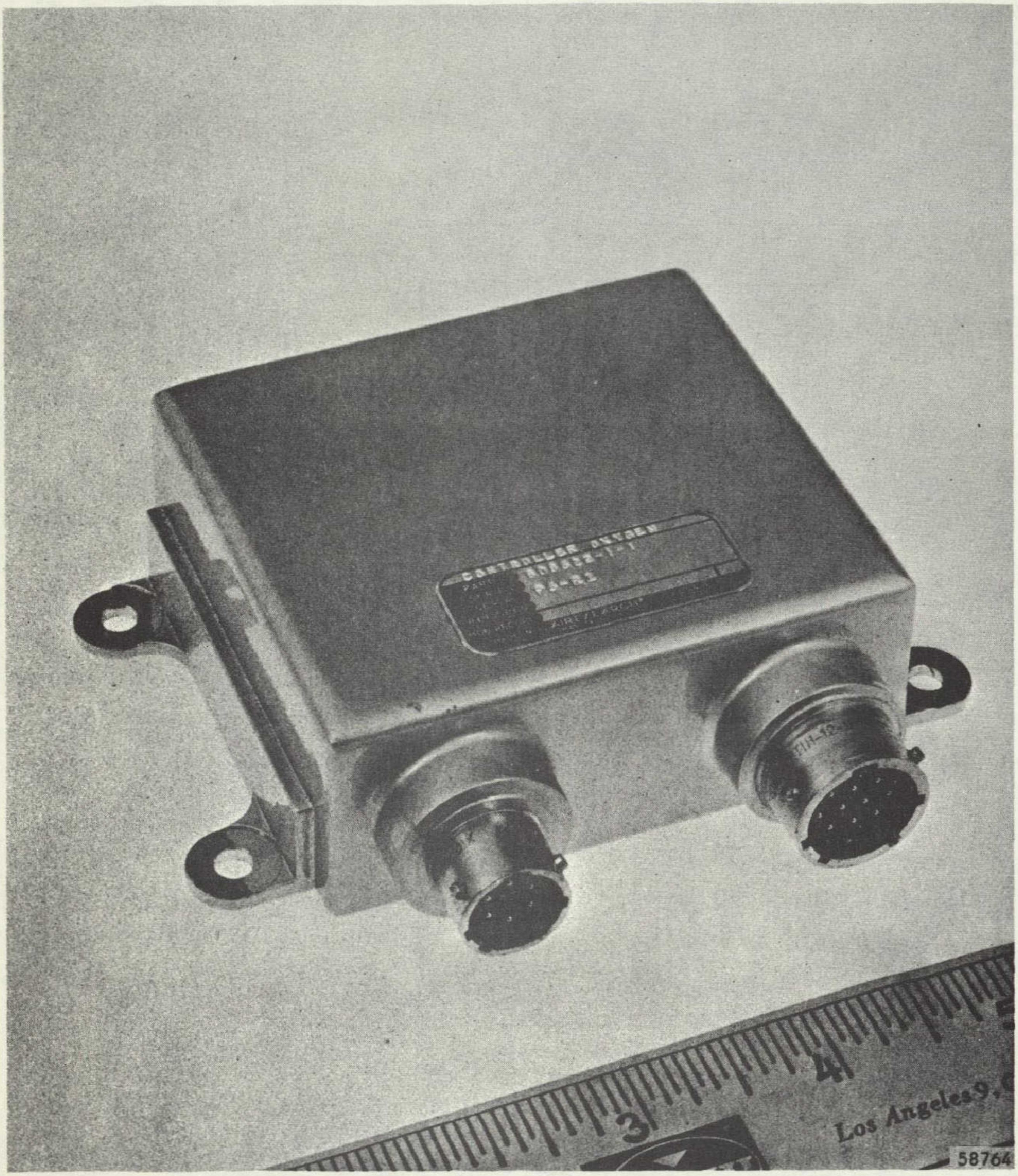

Figure 25.- Oxygen partial pressure controller.

Two switches and two lights are located on the front panel of the selector, as shown in figure 26. One switch allows selection of channel No. 1 or No. 2; this permits the output of the sensor amplifier to be observed on the pressure meter. The other switch allows selection of an expanded scale on the pressure meter when the oxygen level is between 150 and 200 mm Hg. The two alarm lights provide continuous monitoring of system operation. Both lights work independent of each other, with each light providing monitoring of one channel. As previously discussed, the alarm lights turn on whenever the oxygen pressure level drops below 155 mm Hg.

Outputs from the oxygen pressure controller selector are provided to the pressure meter, to the N_2 flow solenoids, and to an external alarm indication. Signals to the pressure meter come from the sensor amplifier, that is, the oxygen controller input. The control circuitry output of +28-Vdc signals supplied to the alarm lights are also supplied for external alarm indication, such as a buzzer.

6.3.2.4 Pressure meter.- A pressure meter (fig. 27) is provided for a visual indication of partial oxygen pressure level. The input is received from the sensor amplifier. The meter is a 0 to 100 amp dc ammeter; the dial face is inscribed with two pressure ranges. One range is 0 to 300 mm Hg oxygen pressure, and the other range is an expanded range of 150 to 200 mm Hg. The expanded range is provided for increased accuracy in the normal operating range.

6.3.2.5 Cabin pressure regulator.- The cabin pressure regulator (fig. 28) controls the flow of nitrogen and oxygen into the cabin during space operation to make up for cabin gas depletion due to metabolic consumption and normal leakage or depressurization. The regulator maintains total cabin pressure at 5.0 psia.

The unit consists of two absolute-pressure regulator sections and a manual repressurization rate control. The regulator sections are redundant, aneroid-operated controls which function simultaneously. Failure of an aneroid element will close the malfunctioning regulator section.

6.3.2.6 Nitrogen shutoff valve.- This unit (fig. 29) serves to automatically cycle, ON-OFF, the nitrogen supply to the Apollo vehicle atmosphere. The solenoid selector valve consists of two valves in one housing; one is a three-position selector valve and the other a solenoid shutoff valve. The three positions of the selector valve are AUTOMATIC, MANUAL, and OFF. In the AUTOMATIC position, 150-psig nitrogen is supplied to the solenoid shutoff valve portions of the selector valve, which is periodically opened by the oxygen partial pressure sensor and controller. In the MANUAL position, the solenoid portion of the valve is bypassed. In the OFF position, the valve acts as a shutoff valve.

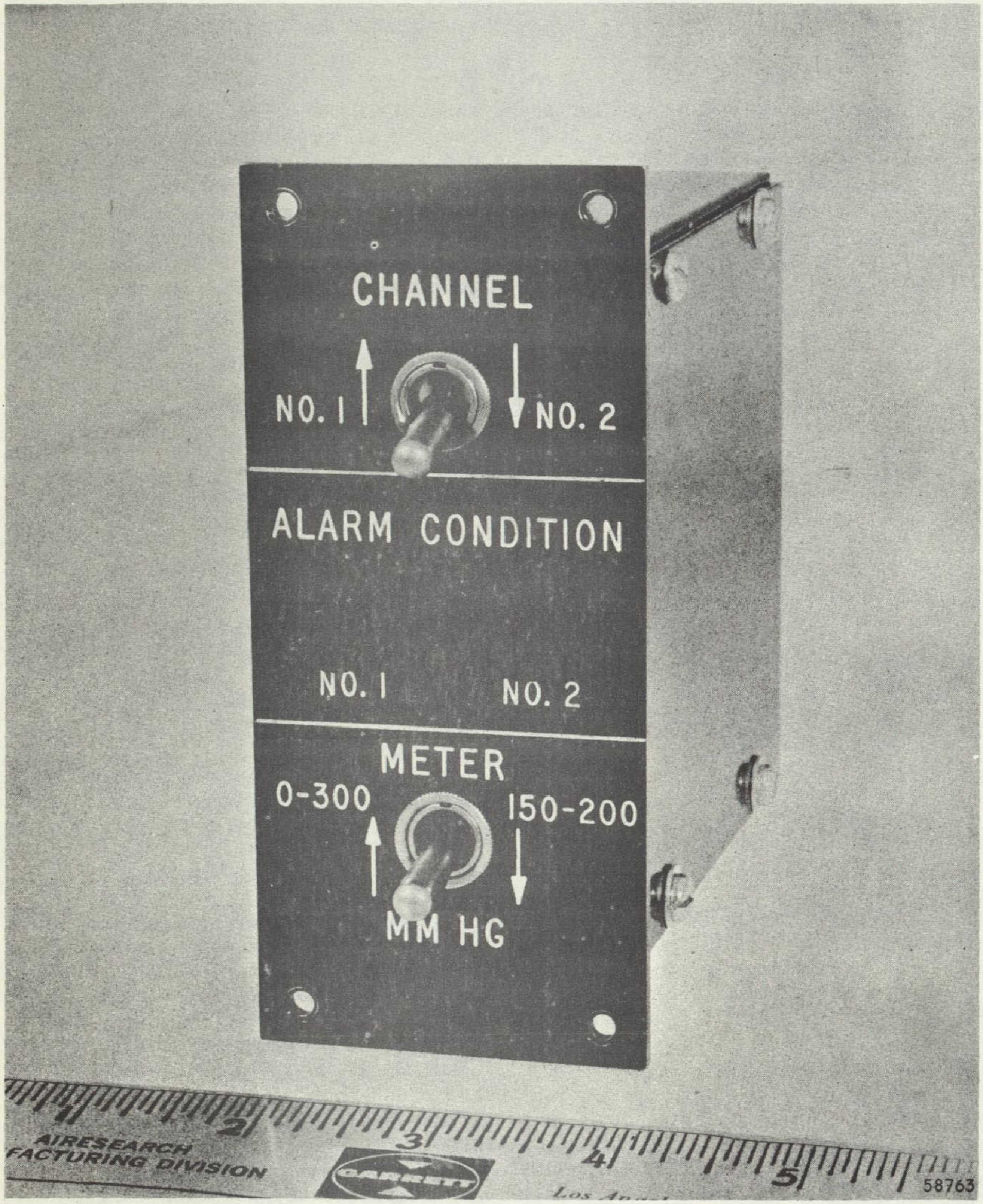

Figure 26.- Oxygen pressure controller selector.

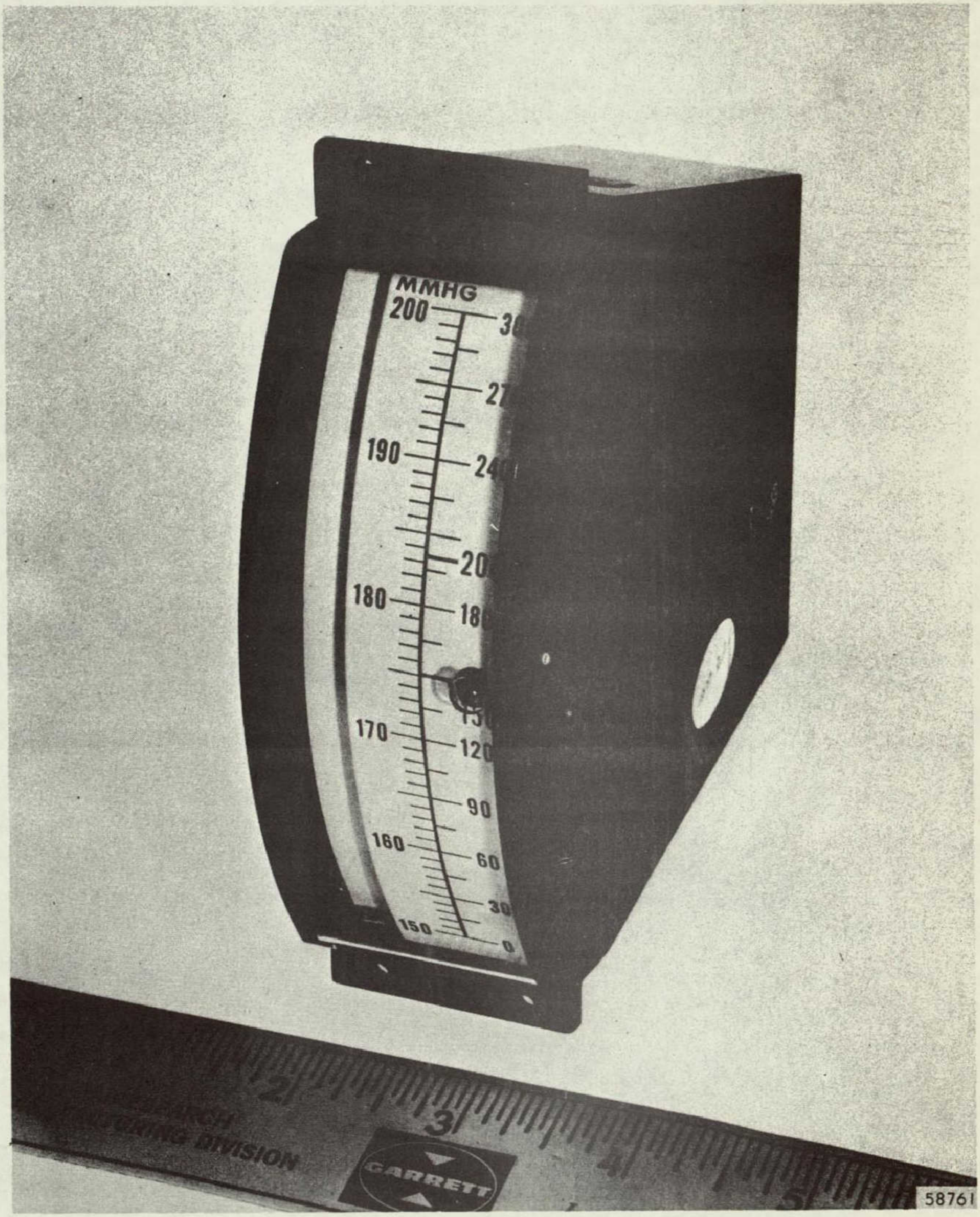

Figure 27.- Oxygen partial pressure meter.

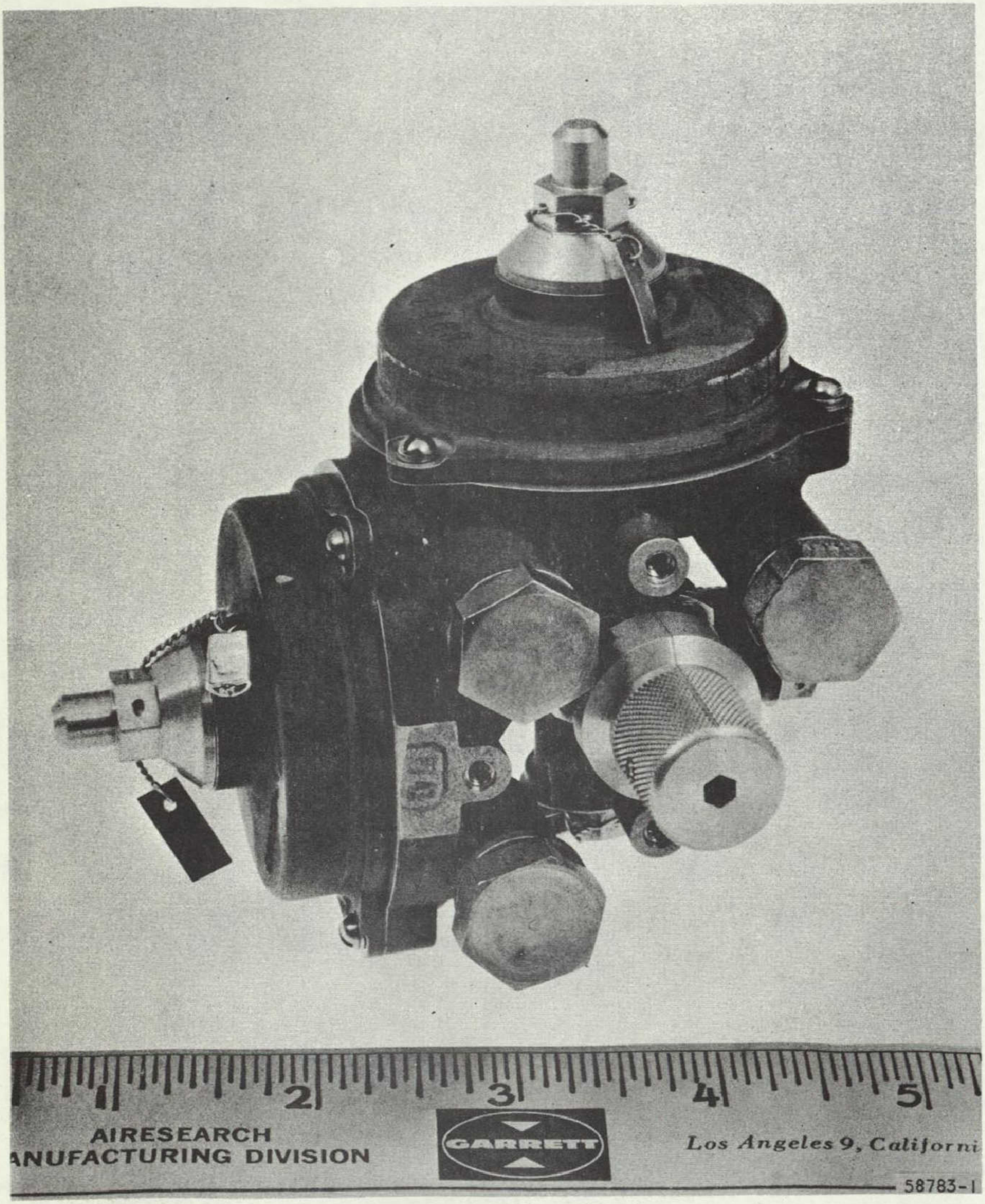

Figure 28.- Cabin pressure regulator.

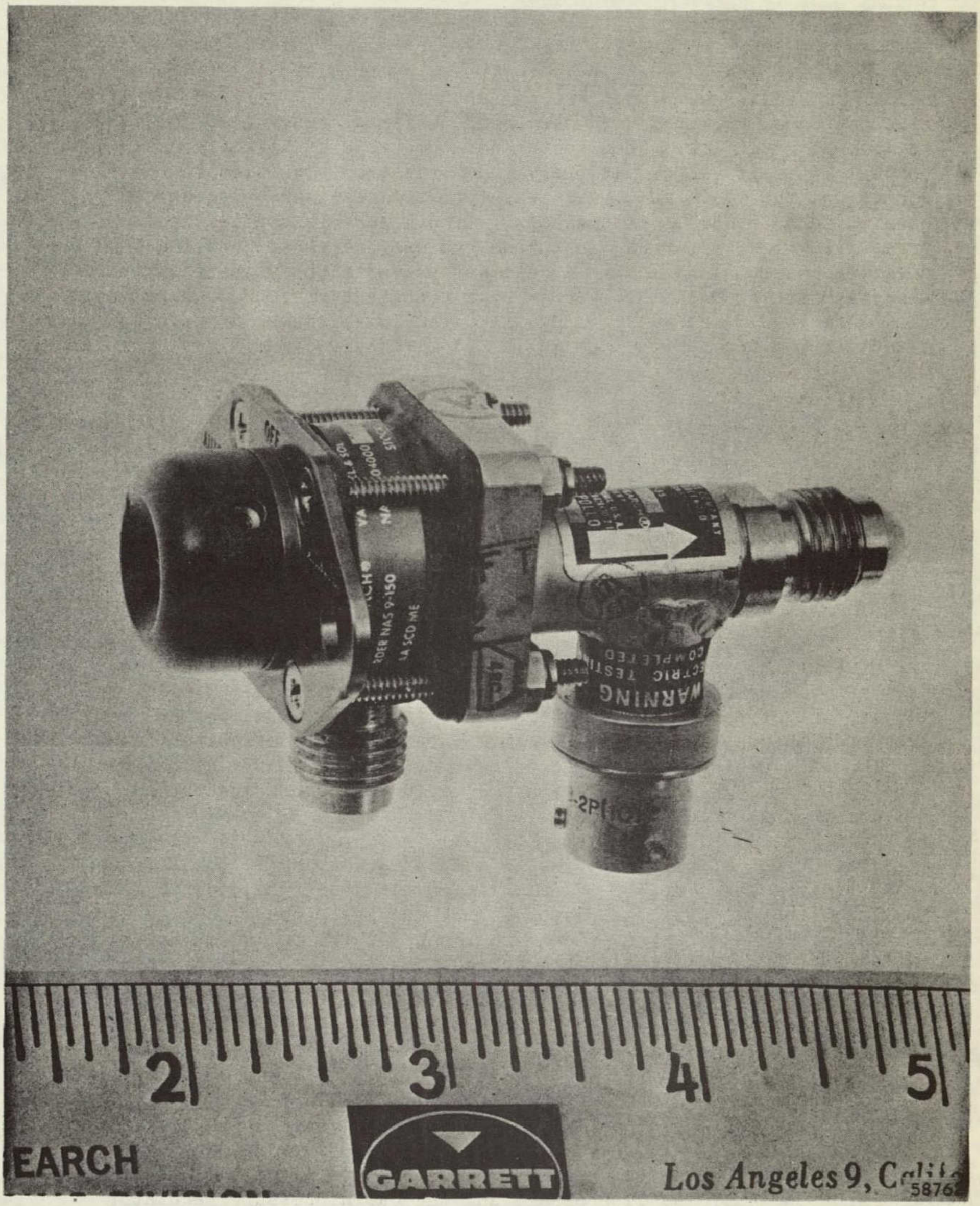

Figure 29.- Nitrogen shutoff solenoid.

6.3.2.7 <u>Oxygen check valve</u>.- The valve (fig. 30) consists of a rubber umbrella-shaped seal and a flat metal seat. The seat has a series of holes, arranged in a circle of lesser diameter than the valve, to allow throughflow. When installed, the valve is slightly preloaded to seal it at its outer periphery. If pressure is applied in the flow direction, the valve is forced away from the seat, allowing oxygen to pass through the holes in the seat. If pressure is applied in the reverse direction, the valve is forced against the seat, checking flow by covering holes in the seat. A retainer prevents the valve from tearing away from its seat in the event a high transient pressure occurs in the flow direction. The valve is designed for low-pressure drop in the flow direction and negligible leakage in the check direction.

6.4 SYSTEM DESIGN VERIFICATION TEST

This section describes the results of a life cycle test conducted on the complete two-gas atmosphere control subsystem.

6.4.1 Test Description

The test was conducted in an altitude chamber approximately one-sixth the volume of the Apollo vehicle to reduce system cycle time. The test was conducted at a chamber pressure of nominally 5 psia; the oxygen partial pressure was controlled by the two-gas atmosphere control subsystem between 170 and 190 mm Hg. The tests were conducted on a single-shift basis. At the end of each shift the sensor was removed and stored in a glass bottle with the cap on. At test resumption, the F-3 analyzer was recalibrated.

The object of this test was to demonstrate that (1) the components of the system were capable of maintaining the specified accuracy during cycling, (2) the subsystem response rate was fast enough to keep the partial pressure of oxygen within the range of 170 to 190 mm Hg and, (3) no performance degradation occurred over 150 test cycles. Additionally, the alarm feature of the system, warning of oxygen partial pressure below 155 mm Hg, was tested.

The test setup is shown schematically in figure 31. Figure 32 is a photograph of the test setup. An altitude chamber of approximately 50 ft^3 volume was used to simulate the cabin. A Beckman F-3 oxygen analyzer was used to monitor the oxygen partial pressure and was used for comparison with the system readout. Two pressure gages are provided to determine the cabin total pressure and the cabin pressure regulator

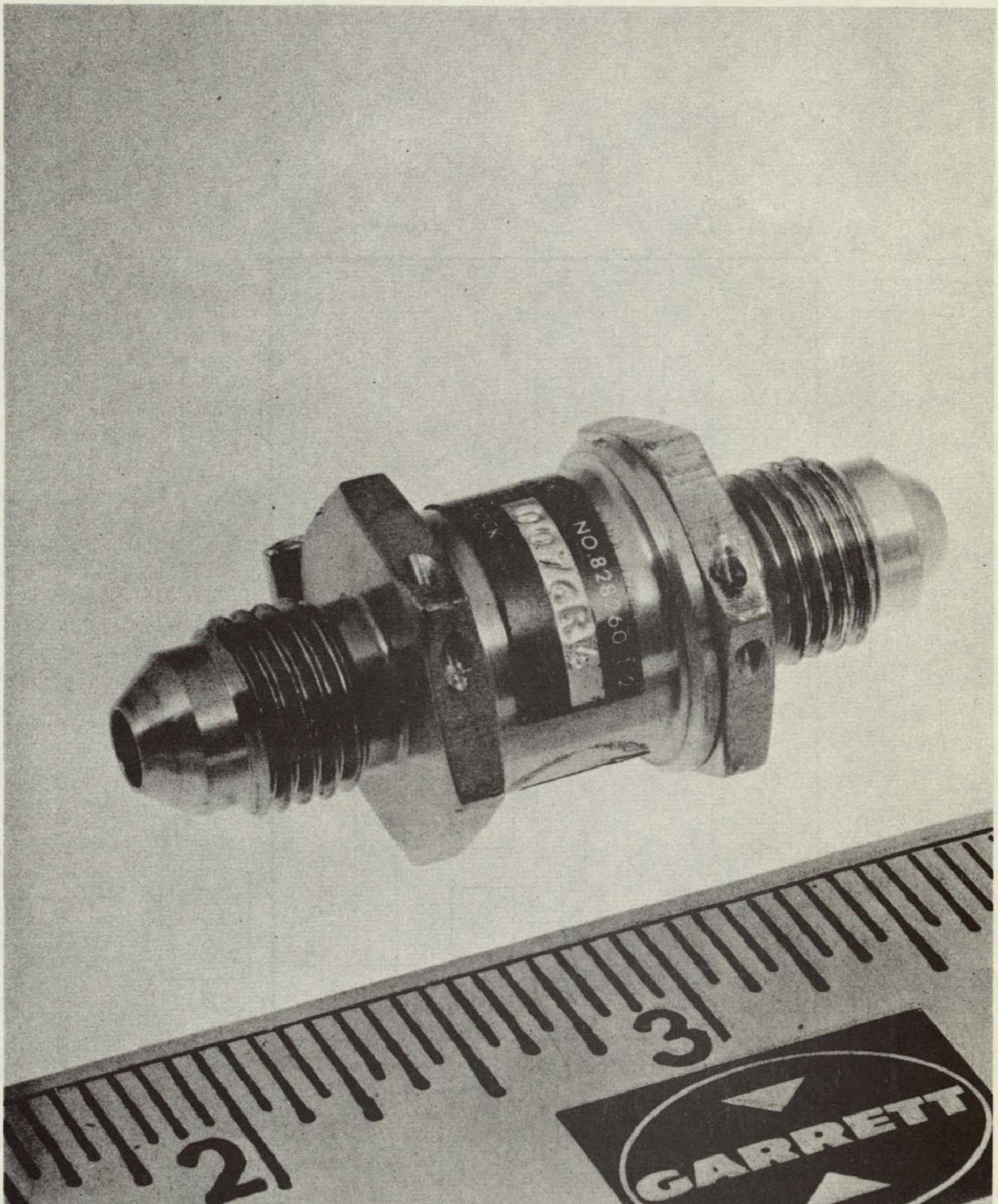

Figure 30.- Oxygen check valve.

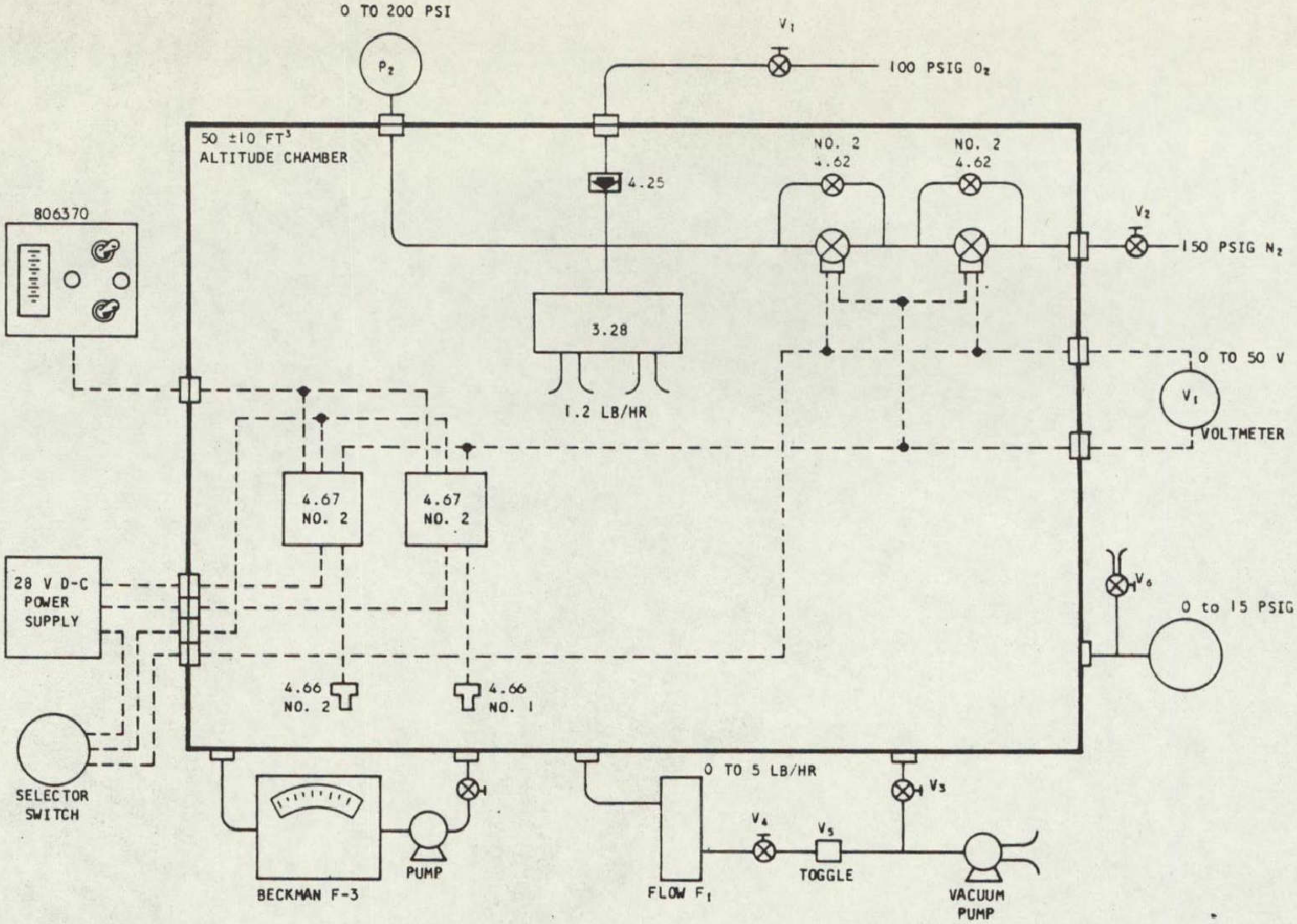

Figure 31.- Oxygen partial pressure control subsystem cycle test schematic.

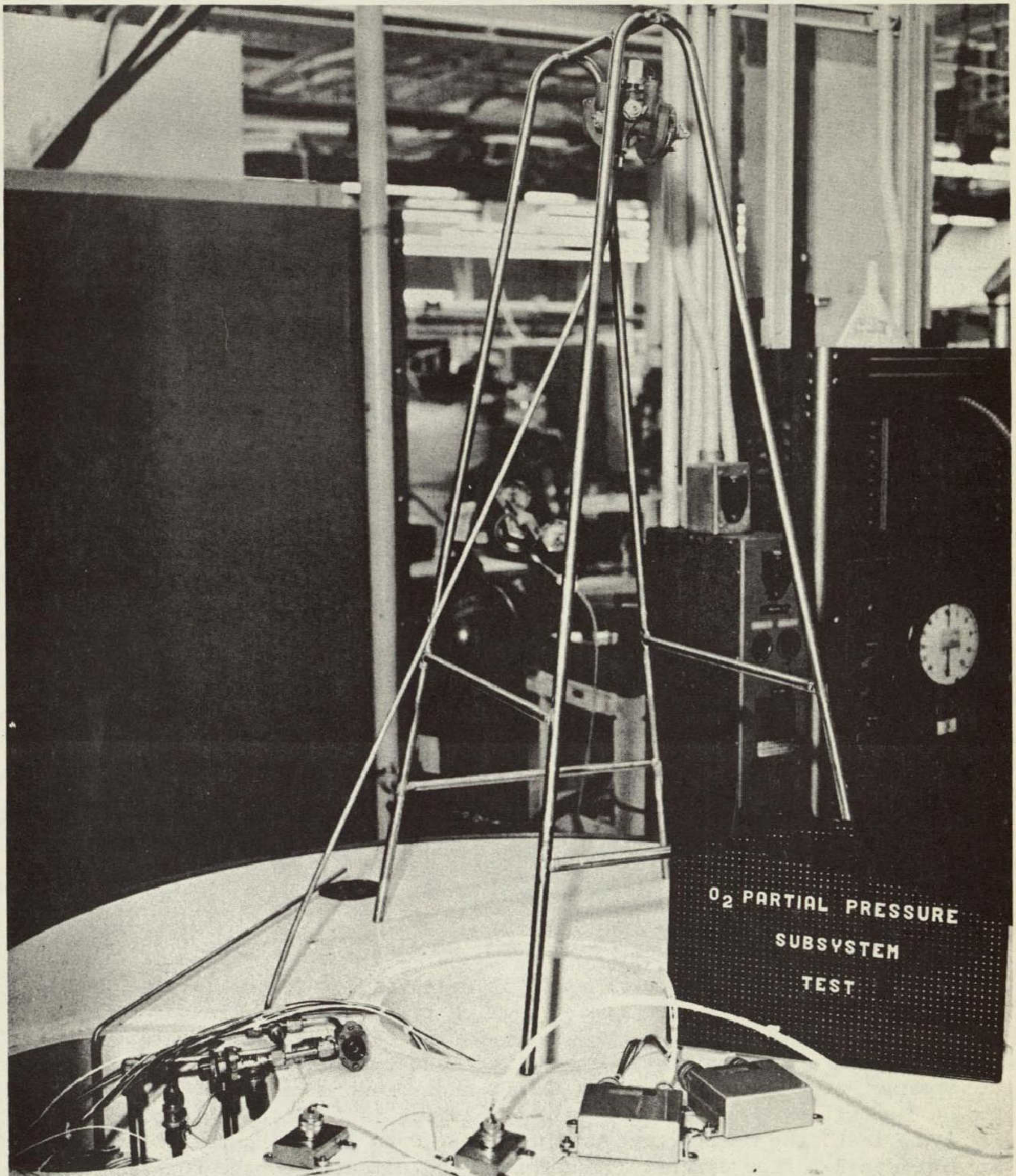

Figure 32.- Test setup — two-gas system design verification test.

supply pressure. A voltmeter was incorporated in the nitrogen solenoid-valve control circuit to indicate energizing of these valves. An Offner eight-channel recorder provided continuous records of:

1. Cabin O_2 partial pressure as measured by the O_2 sensor

2. Cabin total pressure

3. Alarm circuit energization

4. Nitrogen solenoid valve energization

5. Cabin O_2 partial pressure as measured by the Beckman F-3 analyzer

6.4.2 Test Setup

The equipment shown schematically in figure 31 was installed in an altitude chamber approximately 4 ft in diameter by 4 ft tall. A 100 ± 10 psig oxygen pressure source via shutoff valve V_1 and a 150 ± 10 psig nitrogen pressure source via valve V_2 was connected to the check valve (Item 4.25) and the solenoid valves (Item 4.62) respectively. A Beckman F-3 oxygen analyzer was calibrated and connected to the chamber with a pump and a precalibrated needle valve to provide a flow rate of approximately 400 scc per min. Flowmeter F_1 was calibrated for 5.0-psia air and connected to the chamber with a needle valve, a toggle valve, and a vacuum pump. A voltmeter V_1, a total pressure gage P_1, a supply pressure gage P_2, and a 28 ± 2 Vdc power source was provided.

6.4.3 Test Procedure

The PO_2 controllers (Item 4.67) and the manual selector switch are applied a power of 28 Vdc. Manual ON is selected for solenoid valves (Item 4.62) and proper performance verified by an audible click of each solenoid valve. This is repeated several times and then position No. 1 for automatic operation is selected. The manual selector of the solenoid valve No. 2 is positioned in BYPASS and solenoid valve No. 1 in the AUTO position. The channel selector switch is positioned in position No. 1 and the meter range switch in the 0 to 300 mm Hg position. The Beckman F-3 flow circuit is energized and compared to the PO_2 readings of the F-3 and the meter. Both readings indicate a PO_2 of 160 mm Hg.

The pressure source supply valves V_1 and V_2 are closed and altitude chamber pumped to 4.6 psia by means of valve V_3. The PO_2 readings of the F-3 and the meter versus total pressure P_1 in increments of 1.0 psi are recorded. The PO_2 reading when the alarm light goes on is recorded. This reading must be 155 mm Hg.

The oxygen and nitrogen pressure source valves V_1 and V_2 are opened, valve V_3 is closed, and a total pressure P_1 of 4.6 psia is maintained by adjustment of a vacuum valve V_4. The PO_2 control subsystem should oscillate between 170 mm Hg (3.29 psia) and 190 mm Hg (3.67 psia). Each excursion from 170 to 190 mm Hg and back to 170 mm Hg will be taken as one cycle. PO_2 of the F-3 and meter versus time and the PO_2 reading are recorded at the time when the solenoid valve (Item 4.62) is energized or deenergized, as indicated by the voltmeter V_1 reading. Sixty cycles are conducted with the channel selector switch in position No. 1. Each cycle takes approximately 10 min. The interval between recordings will be 1 min.

After 65 cycles are completed, vacuum valves V_3 and V_5 are closed and the total pressure P_1 recorded after stabilization is noted. The stabilized pressure should be in the range of $5.0 \begin{smallmatrix} +0.3 \\ -0.4 \end{smallmatrix}$ and will indicate the upper control pressure setting of the cabin pressure regulator (Item 3.28).

The altitude chamber is allowed to return to sea level by means of valve V_6. The manual selector of solenoid valve No. 1 is positioned in BYPASS and the selector of solenoid valve No. 2 in the AUTO position. The rotary selector switch is placed in position No. 2 and the channel selector switch in position No. 2. Sixty cycles with the selector switch in the No. 2 position are conducted, noting what the PO_2 is at the time when the alarm light goes on and the PO_2 at the time when voltmeter V_1 indicates that the solenoid valve (Item 4.62) becomes energized or deenergized. Recording intervals and parameters will be identical with those recorded for the first 60 cycles.

Thirty additional cycles are conducted with the solenoid valves (Item 4.62) in the AUTO position.

6.4.4 Test Data

Sixty operational test cycles of channel 1 were performed, as specified by the test procedure followed by 15 additional test cycles in the AUTO position. The above procedure was then repeated for channel 2. The calibration of the Beckman F-3 oxygen analyzer was checked and adjusted, as required, each morning.

Data traces showing performances of channels 1 and 2 are shown in figures 33 and 34. These are representative cyclic performances of the total 150 test cycles conducted. The traces are self-explanatory. Twenty-eight Vdc on the N_2 valves and alarm traces indicate periods during which the solenoids and alarms are energized. These data traces clearly demonstrate satisfactory control of the oxygen partial pressure and proper cycling of the nitrogen solenoid shutoff valves.

Figures 35 and 36 show performance data traces of the subsystem low oxygen partial pressure warning provision. To test this warning provision, a nitrogen leak into the cabin was simulated to drive the oxygen partial pressure down until the alarm device was energized. These traces again demonstrate proper functioning of the warning system. Figures 35 and 36 also demonstrate the rapid recovery from the low oxygen partial pressure condition.

6.4.5 Summary of Design Verification Test Results

The test conducted on the Apollo applicable two-gas atmosphere control subsystem demonstrates that it provides excellent control of a two-gas atmosphere. All facets of the subsystem performance were as anticipated. Control of the oxygen partial pressure within the specified range of 170 to 190 mm Hg was maintained throughout the test. The low oxygen partial pressure warning provision of the system produced a warning signal when the oxygen partial pressure went below 155 mm Hg. (This low partial pressure was intentionally obtained by introduction of large quantities of nitrogen in the test chamber.) System recovery from the low oxygen-concentration condition was excellent. The test results are summarized in table XIII.

7.0 TWO-GAS SYSTEM WEIGHT PENALTY DETERMINATION

The oxygen presently carried by the Apollo vehicle for the single-gas atmosphere exceeds the oxygen requirements for the two-gas atmosphere. This is because the two-gas atmosphere is approximately

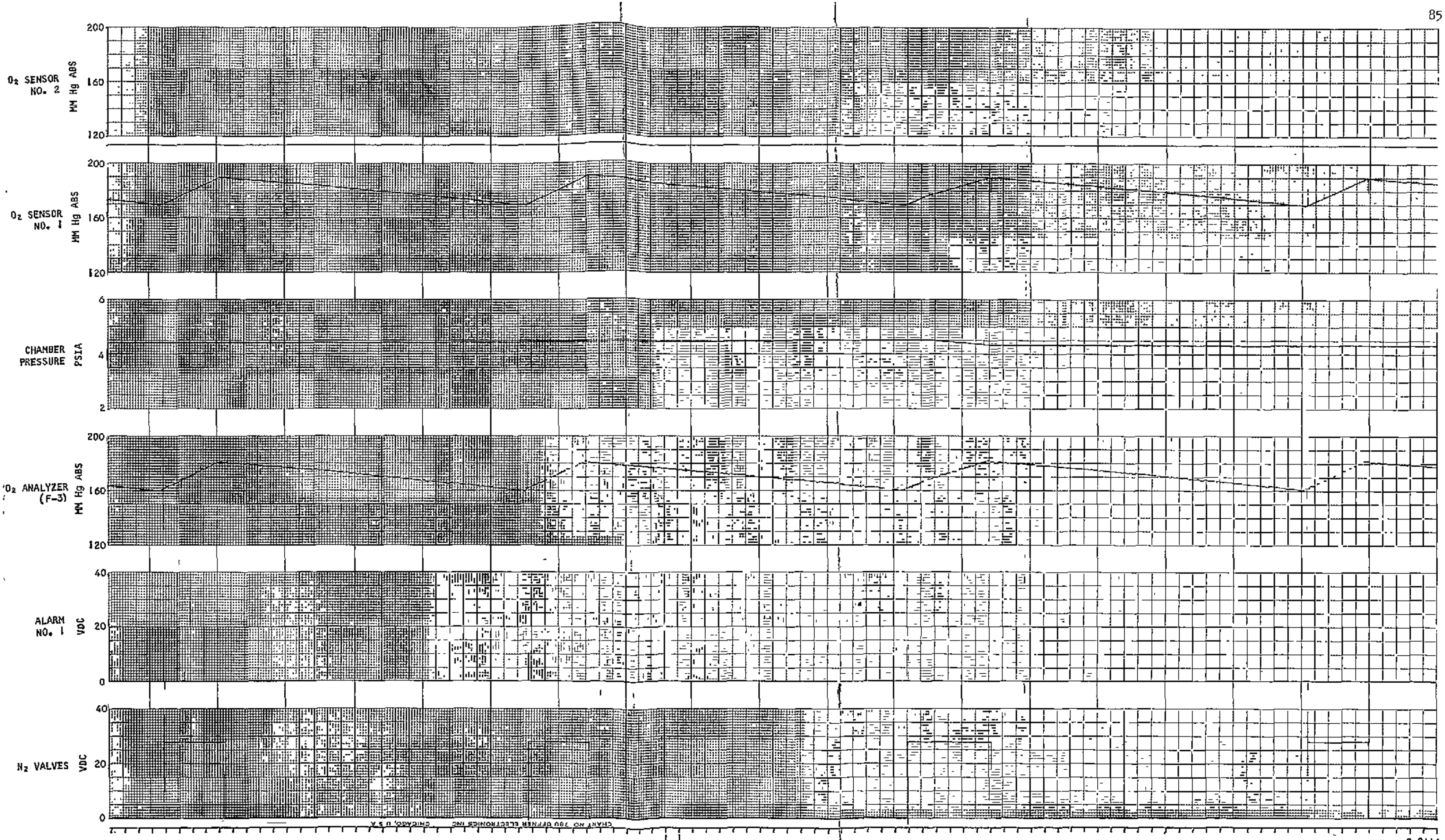

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Figure 33.- Channel 1 test results.

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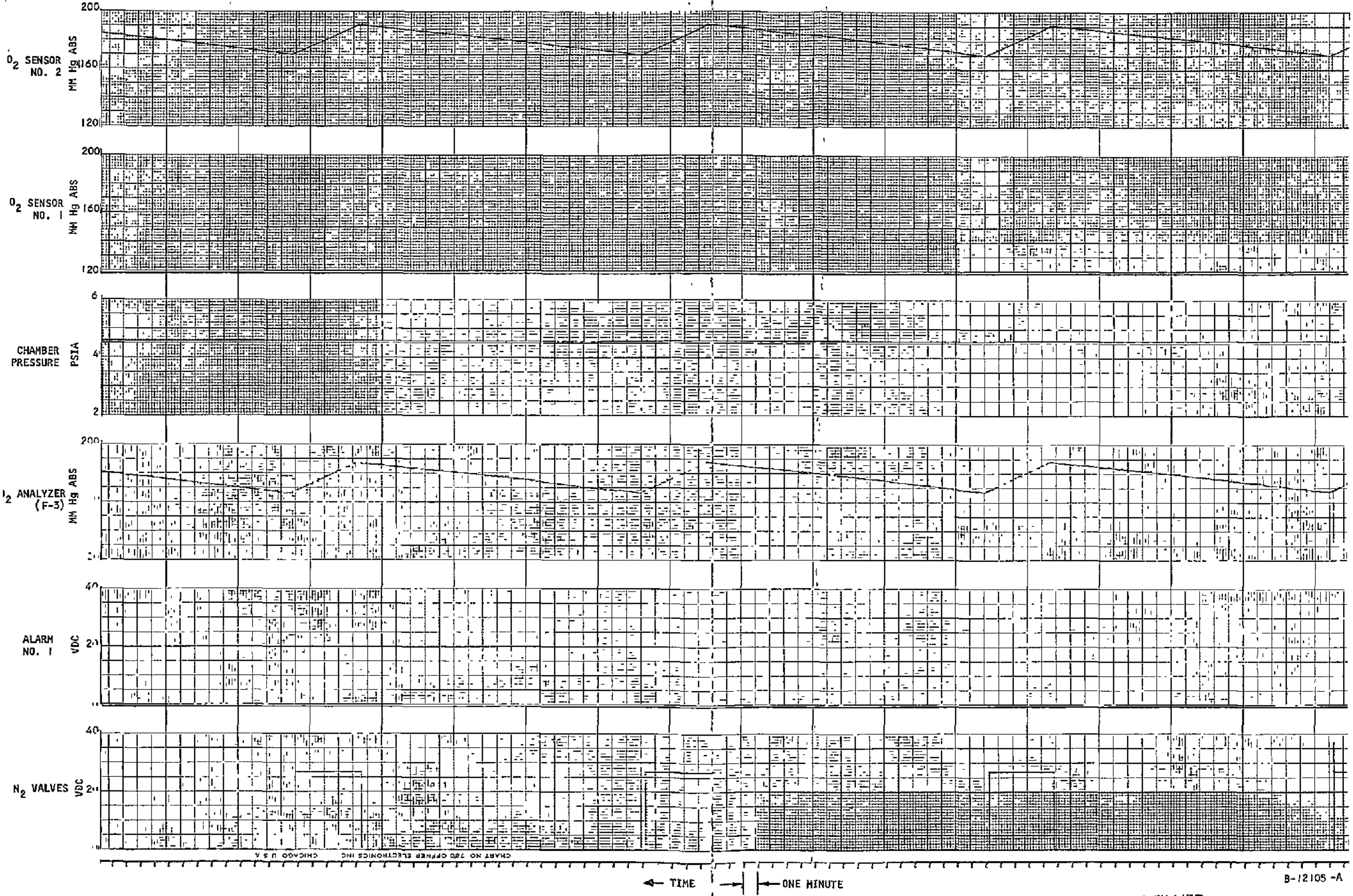

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Figure 34.- Channel 2 test results.

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TABLE XIII.- SUMMARY — DESIGN VERIFICATION TEST RESULTS

An accelerated cyclic test of the entire two-gas system (excluding flight storage tanks) in a 5 psia chamber has been successfully completed.

The components of the system were capable of maintaining the specified accuracy during cycling.

The subsystem response rate was fast enough to keep the partial pressure of oxygen within the range of 170 to 190 mm Hg.

No performance degradation occurred over 150 test cycles.

The alarm feature of the system was successfully tested.

30-percent nitrogen; the oxygen makeup necessary to compensate for cabin atmospheric leakage is therefore proportionally reduced (assuming that the metabolic and fuel cell requirements are unchanged). The resulting net oxygen demand rates and total oxygen requirement of the two-gas systems are less than those of the single-gas system; the Apollo oxygen storage tanks can therefore be applied unmodified to the two-gas atmosphere system.

The nitrogen requirements are established by the Apollo vehicle leakage rate and pressurization demands. For this study, it was assumed that the total gas leakage rate would be 0.2 lb per hr; at the desired 3.5-psia oxygen/1.5-psia nitrogen composition, nitrogen leakage would be 0.0546 lb per hr. One full repressurization of the Command Module and a full pressurization (the initial pressurization) of the Lunar Module (LM) with the 3.5-psia oxygen/1.5-psia nitrogen atmosphere was assumed. A total of 36 hr of suited mode operation in the Command Module was assumed in assessing nitrogen purging losses. Other than the initial LM pressurization, the LM atmosphere demands were not considered; the LM is a totally suited mode vehicle having its own atmosphere conditioning and supply system. Table XIV shows the Apollo N_2 requirements based on these assumptions.

Table XV is a tabulation of the available storage tanks from the Gemini and Apollo Programs which are potentially applicable for Apollo CM nitrogen storage. Analysis has shown that the small (2-day) Gemini ECS and reactant supply system (RSS) cryogenic storage tanks are not thermally adequate for nitrogen storage at the Apollo usage rate for longer than 1 to 2 days. The 14-day Gemini ECS and RSS tanks are adequate but have weight and volume penalties approaching the available gox tanks. Either one LM descent gox tank or five Gemini secondary gox tanks can be used. It is recommended that the LM descent tank be utilized since it offers a 34-lb weight advantage, exclusive of mounting brackets and manifolding. The Gemini bottles offer greater flexibility in packaging due to their smaller size, but could offer significant problems when applied to the Apollo vehicle since five tanks would have to be plumbed into the vehicle.

Table XVI is a tabulation of the weight penalties involved in incorporating a two-gas control system and nitrogen supply in the CM. The introduction of the system on the spacecraft results in a total weight penalty of about 70 lb, including the nitrogen gas storage tanks (from the LM program).

TABLE XIV.- APOLLO N_2 REQUIREMENT

Leakage	18.4
CM repressurizations	3.2
Initial LM pressurization	2.5
Suit circuit N_2 purge loss	1.0
Total	25.1 lb

TABLE XV.- AVAILABLE TANKS

Tank		Operating pressure, psi	Usable N_2, 14 days, lb	Weight, lb	Diameter
Gemini secondary ECS gox		5000	6.5	19	Cylinder 7-in. outer diameter, 17-in. length
LM descent gox		3000	35	58	21-in.
Gemini cryo tanks	2-day ECS	Cryo 1000	0 (1.5 days) heat leak limited	13.0	12.1-in. outer diameter, $\left(V = 0.264\ ft^3\right)$
	14-day ECS	Cryo 1000	35.6	38.8	20.55-in. outer diameter, $\left(V = 1.65\ ft^3\right)$
	2-day RSS	Cryo 1000	0 (1 day) heat leak limited	20.5	15.6-in. outer diameter, $\left(V = 0.72\ ft^3\right)$
	14-day RSS	Cryo 1000	60.0	55.9	23-in. outer diameter, $\left(V = 2.636\ ft^3\right)$

TABLE XVI.- APOLLO CSM TWO-GAS WEIGHT DELTA

Component	Weight
Nitrogen	
Leakage	18
CM repressurizations	3
Initial LM pressurization	3
Suit circuit N_2 purge loss	1
Tank (LM descent gox)	58
PO_2 sensor and controls	4
Miscellaneous plumbing	10
Subtotal	97
CSM oxygen off load	26
Net penalty	71

8.0 FLIGHT HARDWARE DEVELOPMENT REQUIREMENTS

The status of the primary two-gas control system hardware with respect to its flight qualification is shown in table XVII. It will be noted that the design of all of the hardware is complete, but a thorough reliability and failure modes analysis (including EMI) has not been conducted on the controller, and the applicability of the oxygen regulator analysis conducted on the mainstream Apollo effort to the nitrogen regulator must be reviewed.

Prototype or flight hardware of all of the components is available. The oxygen controller is the only component in the prototype stage of development. It should be noted that the control panel PO_2 meter(s) and the nitrogen regulator require minor modifications to existing CM-developed hardware.

Qualification tests have been completed on the sensor and amplifier in support of the Bios program. The applicability of these tests to the Apollo CM have been tentatively reviewed and seem to support the major Apollo requirements. Since the flow solenoid valves and the control panel switches will be utilized for somewhat different functions in the two-gas system, it is anticipated that some of the required Apollo qualification tests will have to be repeated. No requalification requirements are anticipated for the Apollo-developed control panel meters applied to the two-gas system. Of course, a full qualification program must be conducted on the new oxygen controller developed. Also, since the nitrogen regulator is a modified version of a qualified Apollo component, some requalification tests are expected.

In summary, it can be stated that flight hardware is available for all of the two-gas control system components except for the oxygen controller. A projected flight hardware two-gas control system development schedule is shown in figure 37. The 6-month projected schedule is dependent on the use of the current available prototype hardware for confirmation of the proposed design through extensive testing that can be initiated immediately.

9.0 VEHICLE INSTALLATION

The purpose of this portion of the report is to investigate methods of installing the two-gas system into the Block II CSM. It is desired that these additions be designed so that they may be installed at KSC.

TABLE XVII.- HARDWARE STATUS

Hardware		Design	Reliability and failure modes analysis	Prototype fabrication	Flight hardware modification	Qualification test	Flight hardware developed
Sensor and amplifier (Beckman)		Complete	Complete	N/A	N/A	Complete For Bios	Complete For Bios
Controller (AiResearch)		Complete	Preliminary effort only	Complete	N/A	Must be conducted	Must be developed
Control panel (NAA)	Switches	Complete	Complete	N/A	N/A	Apollo effort must be reviewed	Complete
	Meters	Complete	Complete	N/A	Scales on flight hardware to be modified	Complete	Complete
Flow solenoid (1.36) (NAA)		Complete	Complete	N/A	N/A	Portion of previous Apollo test applicable	Complete
Nitrogen Regulator (NAA)		Complete	Must review Apollo CM effort for applicability	N/A	Complete	Portion of previous Apollo test applicable	Complete

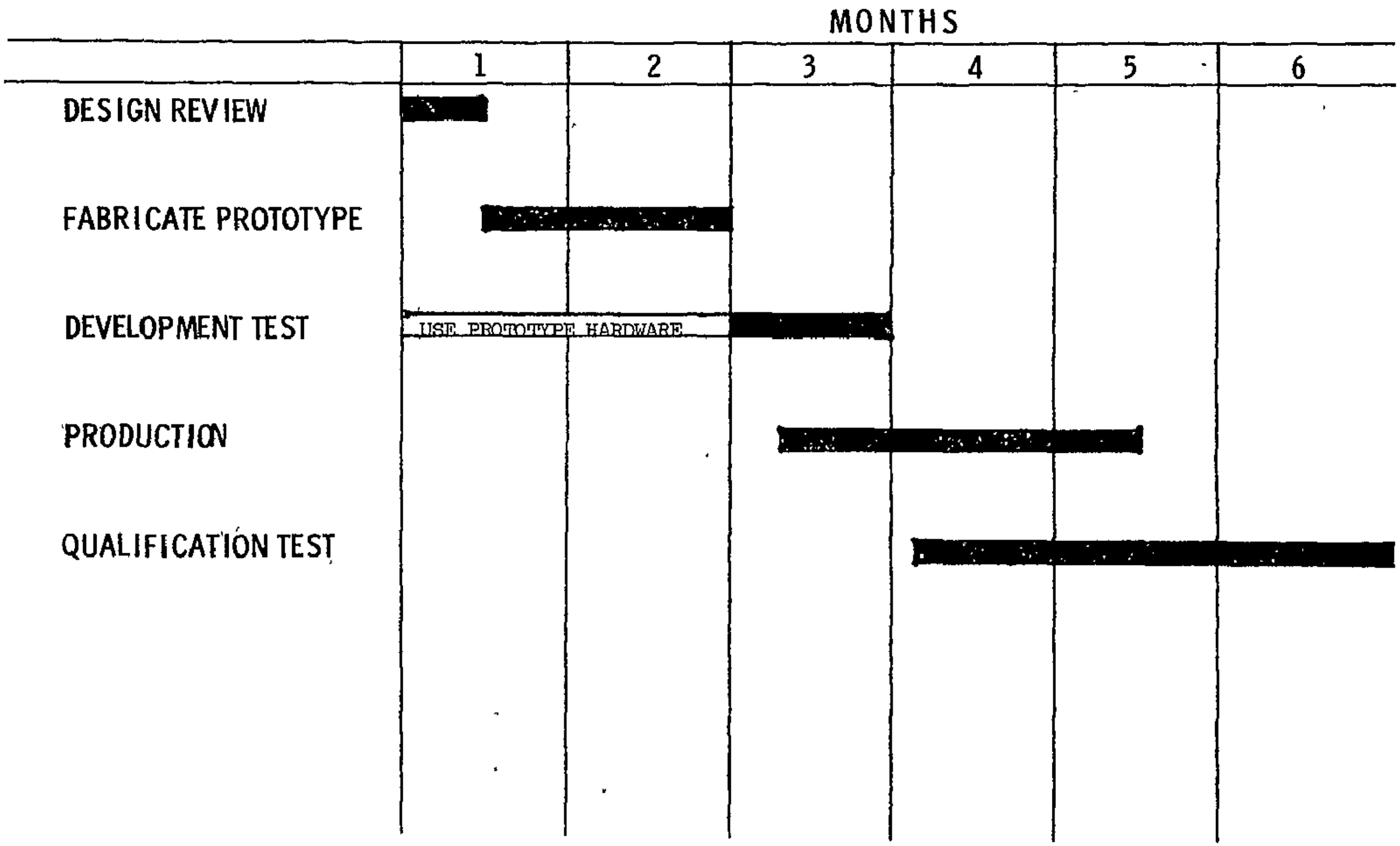


Figure 37.- Projected flight hardware schedule.

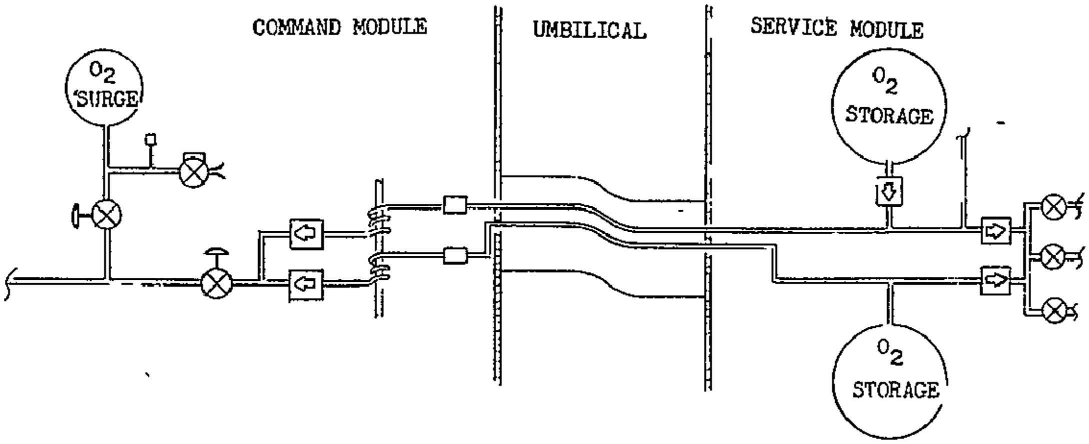
The two-gas system consists of a nitrogen tank, feed line, and pressure reducer regulator and control valves suitable for operation with oxygen.

9.1 NITROGEN TANK AND SUPPLY LINE

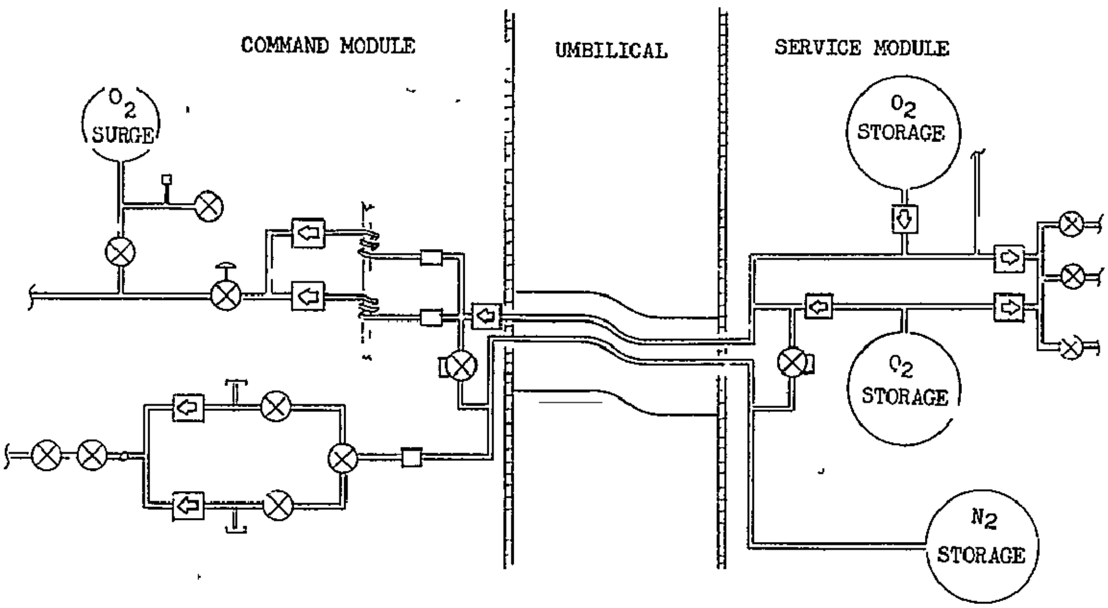
The installation of a nitrogen tank and the associated lines, valves, and controls necessary to provide a two-gas environment, is discussed as a KSC modification kit installation. Essentially, the same installation would apply if it were a production-line vehicle change. A nitrogen tank (a LM descent gox tank as defined in Section 7.0) would be installed in Bay I of the Service Module. A Gemini-type mounting structure was assumed and appears compatible with the structure.

Figure 38 illustrates the nitrogen system installation. The figure shows the tank mounted to the Service Module (SM) forward bulkhead in Bay I. In a typical Block II SM configuration, Bay I contains no major equipment and, except for rerouting of lines near the attach points, nothing will be moved. The complete Bay I outer panel is removable to provide access. The tank mounts could be bolted to the honeycomb forward bulkhead with use of doublers and spacers. A service panel could be attached providing the fill and vent valves and lines. The main panel could be reworked to provide opening for access to the service panel. If required, the flyaway umbilical could be modified to incorporate the nitrogen tank service provisions. Routing of the nitrogen feed line through the SM can be accomplished without difficulty; additional access into Bay IV is available.

Routing the nitrogen line through the SM-CM umbilical does not lend itself to kit modification. To meet heat shield requirements after the umbilical is guillotined, a portion of the line and wire bundle is potted-in solid. This precludes rework of the umbilical to include the added nitrogen line. Spare wiring through the umbilical can be used for controls and displays required by the tank. The CM and umbilical are mated and checked out before delivery of the vehicle, and to replace the umbilical would also require a continuity check of all systems affected. Investigation of the current Command and Service Module (CSM) oxygen supply system reveals another possibility. The existing Apollo oxygen system has two storage tanks, each of which is connected to an individual supply line passing through the umbilical into the CM, as shown in the upper half of figure 39. It is proposed to use one of the two oxygen lines in the umbilical as the nitrogen feed line, by incorporating the piping revisions shown in the lower half of figure 39. This scheme permits the addition of the nitrogen system, and makes it amenable to a KSC installation.



BLOCK II OXYGEN SYSTEM SCHEMATIC



TWO-GAS OXYGEN & NITROGEN SCHEMATIC

Figure 39 - Atmosphere supply system

9.2 CONTROL VALVES

The nitrogen line after entering the CM must connect to a pressure reducing regulator, then to two solenoid-operated "on-off" control valves, and finally, to the existing cabin pressure regulator. To make this type of nitrogen control compatible with the oxygen controls, redundant check valves must be added to the 100-psig oxygen supply line just upstream of the point at which the nitrogen line connects to the cabin pressure regulator. Investigation of detailed drawings indicates that there is sufficient room behind the oxygen control panel for the check valve (see fig. 40).

The CM installation is shown in figure 41. An existing pressure bulkhead penetration fitting can be utilized for the nitrogen feed line entry into the cabin by drilling and installing a bulkhead fitting as shown. This entry is located behind the oxygen control panel which keeps the line short and simplifies the mounting. As shown in the drawing, the high pressure nitrogen line enters the CM behind the oxygen control panel in the left-hand equipment bay, passes between the oxygen and water control panels, then to the small nitrogen control panel on the lower equipment bay. This panel contains the nitrogen pressure reducer and the two control valves. The line containing nitrogen at a reduced pressure goes from the nitrogen control panel to the back of the oxygen control panel, connecting to the oxygen system between the new check valves and the existing cabin pressure regulator.

10.0 GSE AND GROUND PROCEDURES REQUIRED

Implementing the two-gas atmosphere control system for the Apollo spacecraft would entail several new preflight ground procedures and items of ground support equipment. Additional ground procedures required would be to check the calibration of the oxygen sensors and to insure proper functioning of the control system. For the cabin oxygen sensor, this would require a portable plenum (a new GSE item) to form an airtight chamber enclosing the sensor, so that the sensor could be exposed to controlled oxygen-nitrogen mixtures. A calibrated Beckman F-3 oxygen analyzer, or equivalent, would be required to establish the test plenum atmosphere. The test atmosphere in the plenum would be varied, to demonstrate proper activation and deactivation of the solenoid valves and to show that the low-level oxygen partial pressure warning system is in order.

For the suit circuit oxygen sensor, hoses with appropriate nitrogen and oxygen connections (new ground support equipment (GSE)) are needed

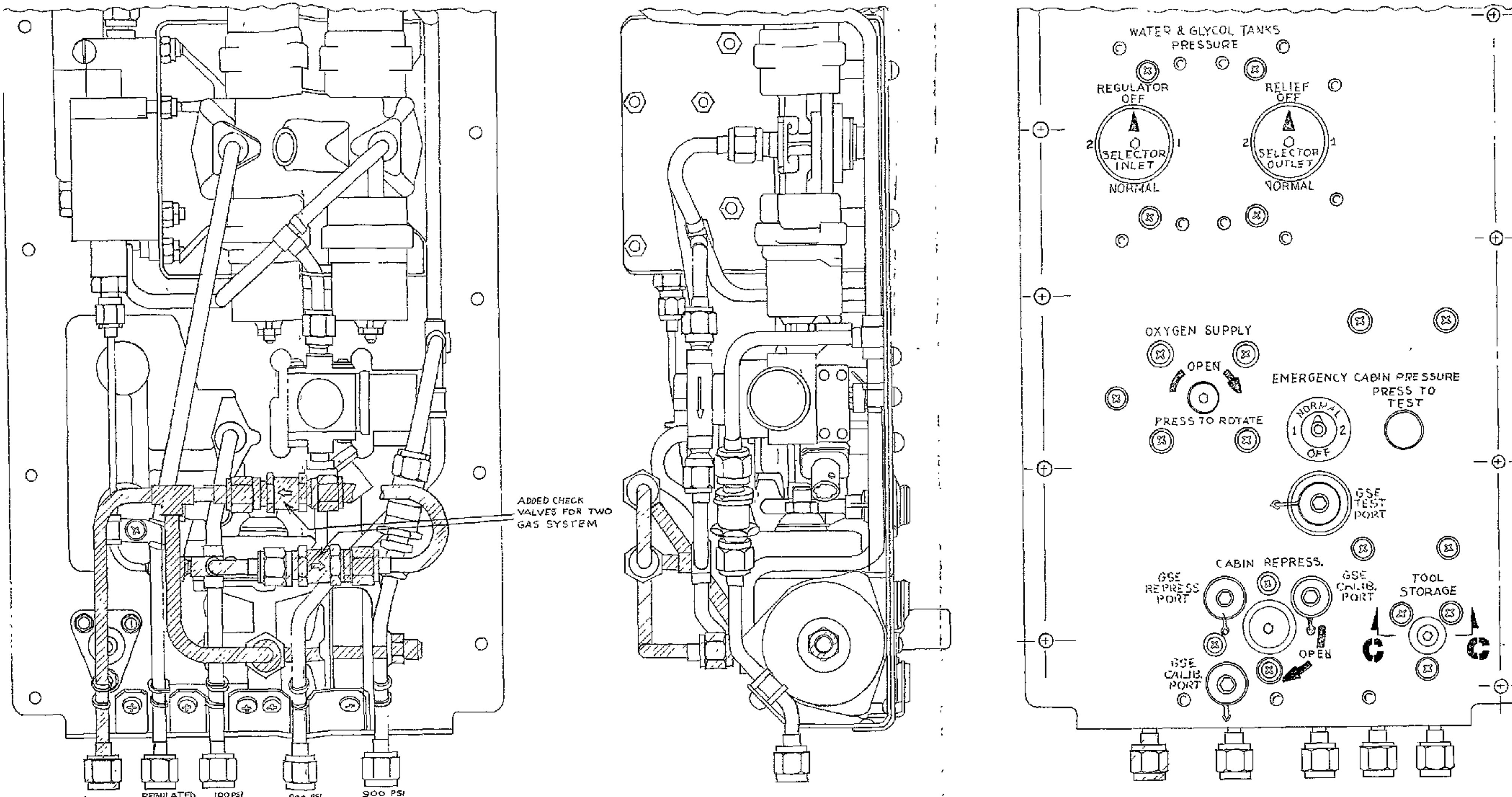


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Figure 40. - Panel outline, two gas control.

to close the suit circuit, and thus control the closed suit circuit gas composition. The oxygen sensor and readout can then be checked against the Beckman F-3 oxygen analyzer.

A 3000-psi nitrogen cart (new GSE) would be required to charge the nitrogen storage bottle.

REFERENCES

1. Work conducted under contract NAS 9-3541 "Environmental Control and Life Support System for Apollo Applications" by AiResearch Manufacturing Company. Pertinent reports consisted of:

   SS-3414 (January 10, 1966)
   66-0714 (July 18, 1966)
   67-1706 (February 13, 1967)
   67-1884 (April 6, 1967)

2. Work conducted under contract NAS 9-5017 "Apollo Applications Program Engineering Tasks" by North American Aviation, Inc. Reports number SID 66-1361 (August 8, 1966) and SID 66-1555 (September 30, 1966).