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THE PERKIN-ELMER CORPORATION
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FINAL REPORT
SPACE STATION SIMULATOR
ATMOSPHERE ANALYZER

By
J.H. Stuart

June 1971

Contract NAS1-9618
SPO Number 30007

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Langley Research Center
Langley Station
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ABSTRACT

This report describes the application of a mass spectrometer, as the primary transducer in a two gas atmosphere sensing system, to the monitoring and control of the oxygen and nitrogen partial pressures within a manned spacecraft simulator. The successful application of this system was made in conjunction with the McDonnell-Douglas Ninety-Day Manned Test under Contract NAS1-8997,

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SUMMARY

This Two Gas Atmosphere Sensor System was the second mass spectrometer instrument to have been used in conjunction with the McDonnell-Douglas Space Station Simulator program and, as a whole, must be considered a complete success. The Two Gas Atmosphere Sensor System has been shown to be capable of monitoring the atmosphere of space simulators while being used as the atmosphere control transducer of the experiment. The additional outputs, carbon dioxide (CO_2) and water (H_2O), also provide useful information for other atmosphere control functions, carbon dioxide scrubbers, dehumidifiers, etc. The problems that did occur were entirely attributable to initial system calibration and calibration gas analysis inaccuracy.

INTRODUCTION

Under Contract NAS1-6387, Development of a Two Gas Sensor (Mass Spectrometer), a Two Gas Sensor System was developed that provided for the monitoring of nitrogen, oxygen, water vapor, and carbon dioxide. An Engineering Test Model (ETM) was upgraded to flight prototype status for NASA/Langley Research Center and in early 1968 was tested with the McDonnell-Douglas Space Cabin Simulator for a period of sixty (60) days. The Mass Spectrometer System was mounted externally to the simulator, and sampled the simulator atmosphere via a bypass capillary inlet system (Figure 1). The test demonstrated that the system would function reliably for extended periods of time. The instrument was placed in control of the oxygen and nitrogen partial pressures during this test and functioned satisfactorily in this capacity until the test was completed. The mass spectrometer demonstrates its ability to act as the primary atmosphere monitor and to measure the principal constituents with sufficient accuracy for control purposes. (Refer to NAS1-6387, Final Test Report.)

Continued development resulted in this system being adapted for use in monitoring the atmosphere in elevated pressure environments, such as that for NASA/Langley Research Center on the Tektite undersea experiment. (Refer to NAS1-8631, Tektite 1 Final Report.) For this application the system was coupled with a variable inlet leak and calibration system, integrated with close-coupled ion pumping and suitably packaged for use in an elevated pressure environment of two and one-half (2.5) atmospheres and fifty (50) percent humidity at eighty-five plus or minus five degrees Fahrenheit (85 $\pm$5°F). Additional peripheral equipment to support the system during power shortage was also provided.

The basic Two Gas Sensor System has now been modified for continuous use as the atmospheric monitor and partial pressure controller in the Ninety-Day Space Station Simulator test at McDonnell-Douglas, Huntington Beach, California, under McDonnell-Douglas contract NAS1-8997. This

experiment was similar to the above mentioned sixty-day test insofar as the atmoshpere partial pressure is concerned. The cabin pressure was 10 lbf/in^2 abs (psia), with an oxygen partial pressure of 3.1 lbf/in^2 abs and the balance nitrogen (N_2), with a trace of carbon dioxide (CO_2). The relative humidity ranged from thirty (30) to fifty (50) percent, with the temperature range of seventy-five plus or minus five degrees Fahrenheit ($75 \pm 5°F$). This final report describes the modification effort of the Two Gas Sensor for the Ninety-Day Space Station Simulator application and presents the operational data during the Ninety-Day Space Station Simulator test at McDonnell-Douglas. (See Figures 2 and 3.)

SYSTEM REQUIREMENTS

The requirements of the Ninety-Day Space Station Simulator application was to provide a modified Two Gas Atmosphere Sensor System to monitor the partial pressures of nitrogen, oxygen, carbon dioxide, and water vapor within the simulator. The incorporation of a closed loop emission control system was also provided. The initial preliminary requirements are described briefly in Table 1. The most significant feature of the design requirements was the need to have a relatively compact system with a self-contained calibration system that could sample from and operate within the environment of the Space Station Simulator. Extensive modification of the inlet system was not required, however, the design of an enclosure to house the Mass Spectrometer System was necessary.

SYSTEM DESIGN

Mass Spectrometer

The Mass Spectrometer from the Tektite experiment was evaluated, and then refurbished for application on the Ninety-Day Space Station Simulator test. (See Figures 4 and 5.) The refurbishment included ion source cleaning, filament replacement and realignment of the collectors as required.

Vacuum System

The high vacuum required for mass spectrometer operation was provided by an eight/eleven (8/11) liters per second commercial ion pump (Ultek) D-I shown in Figures 6, 7 and 8) close coupled to the mass spectrometer. The ion pump power supply is described in the Electronics Subsystem Design Section, Page 4. A roughing system is not provided for evacuating the system to ion pump starting pressures from an atmospheric vent because this was not a realistic requirement for operation within the Space Station Simulator. A valve is provided for roughing through, as this was to be done prior to installation of the system.

TABLE 1. PRELIMINARY REQUIREMENTS FOR 90-DAY SPACE STATION SIMULATOR ATMOSHPERIC ANALYZER SYSTEM

Item No.	Program Intent	*Two Gas System*		
1	Monitor and provide outputs for control of crew environment	Air + N_2 at 10.0 lbf/in^2 abs N_2 partial pressure 500 torr full scale O_2 partial pressure 200 torr full scale CO_2 partial pressure 20 torr full scale H_2O partial pressure 20 torr full scale Length of test 90 days, plus 5-day shakedown test		
	General Environment	Required		
2	Ambient pressure Relative humidity	10.0 lbf/in^2 abs 30 to 50% with temperature range of 75 $\pm$5°F		
	General MS System Requirements			
3	Configuration	System Operator Not Required Except For:		
		System Monitoring	Minimum Maintenance	Electrical
	System configuration to be in keeping with weight and volume of present Two Gas Sensor System. Limitation on reduction of weight and volume to be consistent with availability of commercial hardware and economic limitations. Configuration controlled by good design to maintain asthetic value. No military or NASA specifications imposed: good practice should control workmanship and materials. System calibration required: Gas sample equivalent to expected atmosphere.	Calibration monitoring (see Appendix A, Operation Manual; Emission regulator current; Ion pump current output meters; O_2, N_2, CO_2, and H_2O partial pressure	Filter system replacement emergency shutdown in case of power failure	No limitation on power consumption: limited by good design practice Available power: 110 Vac, 60 cycle; Four-channel continuous local voltmeter readout: Accuracy; $\pm$2.0 torr on O_2 and N_2 output, and $\pm$2.0% on CO_2 and H_2O output; Commercially available meters supplied Four channel remote readout: 0 to 5.0 V for each full scale output Anode current and ion pump current readout local Buffer amplifiers will be provided for remote and local readout.
		System Inlet		
		Varian leak modified to include calibration system inlet and valving Heater and temperature controller required Flowmeter required to control inlet pressures, nominal inlet pressure supplied at 3 in H_2O		
	Special System Considerations			
	Ion Pump	Power Supply	Closed Loop Emission Control System	
	Commercially available 8/11 ℓ/sec (Ultek) Magnetic shielding may be required due close coupling with analyzer	Power supply to provide 3.2 kV and operate from 28 Vdc Emergency dc power source for ion pump supply	Summation of partial pressures shall be compared to total pressure transducer. Ionization current changed to keep summation of partial pressures equal to total pressure System to include over pressurization protection for filaments.	

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Sample Inlet System

A Sample Inlet System was designed to interface with the mass spectrometer. The Sample Inlet System consisted of a temperature controlled variable leak (Varian) as shown in Figure 9, a sample flowmeter, various valves, filters, and tubing as shown in Figure 8. A flow schematic is shown in Figure 10. The system interfaced with a one-eight (1/8) inch outside diameter stainless steel transport line that sampled an air conditioning duct with a head pressure of about three (3) inches of water.

The Sample Inlet System is also connected to the calibration verification system, which will admit a calibrated sample gas to the Mass Spectrometer System for calibration verification.

Electronics Subsystem Design

The Electronics Subsystem (Figure 11) for the mass spectrometer was a blend of circuits from the previous Tektite application and new designs recently developed by Perkin-Elmer Aerospace Division (ASD). The analyzer used for the Ninety-Day test was provided with a full set of electronic circuit boards, however, various of these were replaced for the closed loop mode of operation and others were added as new designs to satisfy the requirements of this particular application.

The Tektite units that were used are the electrode bias supply and bias string, electrometers and the electrometer power supply.

The electrode bias supply and bias string were modified as a result of refurbishing of the analyzer assembly. New output voltages from both the supplies and bias string were required. The select-at-test (S.A.T.) resistors in both the supply and string were changed to achieve these new outputs. Additional work was not required on these units.

The Tektite electrometers were modified by changing the feedback resistors to match the expected gas composition of the simulator. Each electrometer was then checked for frequency response to assure a smooth six (6) decibels per octave rolloff. This detail is very necessary for proper operation of the closed loop system. The zero's of each electrometer were checked and, where necessary, readjusted. No other modifications were made to these units.

The electrometer power supply was checked for output regulation with varying line and load parameters. The supply was found to be within specification and no further work was performed.

The following new circuits were incorporated in the instrument:

a. Ion pump power supply

b. Inlet leak heater and controller

c. Battery pack and charger

d. Emission regulator

e. Pressure transducer and amplifier

f. Output buffer and scaling amplifiers

g. Timing oscillator.

The ion pump power supply is a self-excited DC/DC converter which was originally used on NAS8-24712 instruments. This supply is adequate to start the eight (8) liter ion pump at pressures of about 10^{-3} torr. The system is equipped with a pump current monitor to help measure ion pump pressure. The range switch for this meter also controls drive to the chopper transistors in the pump supply to raise the supply efficiency at low pump currents and reduce internal heating of the instrument.

The supply was modified slightly to allow the use of a twenty-eight (28) volt battery pack (Figure 11) in the event of a power line failure. This involved the addition of one terminal on the printed wiring board and rearrangement of the control relay wiring. Otherwise, the supply remains the same as units delivered on previous mass spectrometers.

A special battery pack was designed for this system to sustain ion pump operation during power failures and transportation. During normal operation the battery pack is charged according to the condition of the batteries. Consequently, fresh batteries will be sustained at their peak voltage and batteries partially discharged will be recharged at a rate determined by their condition. This approach allows batteries that have been used for an extended period of time to be charged as rapidly as possible in preparation for the next usage.

Changeover from line operation to battery operation is automatic, with no possibility of shorting the batteries to the twenty-eight volt, direct current (dc) supply. The system was capable of battery operation for at least twelve (12) hours, with a successful recharge, and longer periods of time in emergency situations where system integrity was more important than recharging the batteries.

A heater controller and line heater were incorporated for thermal control of the inlet leak and line between the leak and mass spectrometer. The leak temperature is controlled to some preselected temperature regardless of ambient conditions or power input variations. Temperature sensing

is accomplished with a bead thermistor attached to the valve body. A second thermistor was included for monitoring purposes during system testing. The controller was able to hold the valve temperature constant to within one-tenth of a degree centigrade (0.1°C) under normal laboratory conditions.

The line heater was thermally uncontrolled, the final temperature being set by adjusting a series resistance. The actual temperature of this line is of little consequence as long as the temperature is above the point where water hang-up is eliminated. Temperature variations above this level have no noticeable variation on instrument performance.

The emission regulator circuitry is an adaptation of circuitry developed for the ASD flight mass spectrometer (under contract No. NAS1-6387). This circuit is the heart of the ASD closed loop system. This system is a pressure referenced system where the outputs of the mass spectrometer are weighted and summed together. If the proper weighting for each channel is used, then the sum is an analog of total pressure. A comparison of this analog against the true analog of total pressure is used to create an error signal for the emission regulator. The regulator then drives the mass spectrometer ion source filament to achieve a balance between the two signals. As long as this balance is maintained the electrometer outputs are all related to partial pressures by constants. Consequently, simple scaling of the outputs is all that is required to make the instrument read directly in partial pressure for each measured gas.

The emission regulator is made up of the summing amplifier and a switching system for driving the mass spectrometer filament. The summing amplifier accepts signals from the electrometer outputs and the pressure transducer amplifier. The error signal developed here is used to drive a switching regulator, whose duty cycle is dependent on the error. The output of this regulator is applied to the filament transformer and, consequently, the filament receives a signal that varies according to the error. In this manner, a constant relationship is maintained between the true partial pressure and electrometer outputs.

It is convenient to have the instrument readout calibrated in usable engineering units; consequently, a scaling adjustment is provided for both output meters and remote voltage monitors. This particular instrument was provided with internal meters calibrated directly in torr and a remote voltage readout calibrated for five (5) volts full scale. Separate readouts were provided for each monitored channel.

Various other circuits were provided for the operation of the instrument, but for this report a description of these functions or design is not practical. Generally however, the circuits were of proven design from other successful Mass Spectrometer Systems, and their performance on this application tends to bear this out.

System Packaging

This system has been packaged in a good commercially available bench cabinet, as shown in Figure 12. All packaging of components is to best commercial practice. The system is divided into two modules that are mounted on drawer slides, providing easy access for repair and maintenance.

The mass spectrometer is close-coupled to the eight (8) liter per second ion pump through a bypass manifold and both units are then firmly mounted to a baseplate. The temperature controlled variable leak valve is also attached to the baseplate and connected to the inlet flange of the mass spectrometer. This allows complete testing of the instrument prior to its integration with the total package. The electrometers are plugged into an interface shield connected directly to the collector flange of the instrument.

The instrument and baseplate assembly are mounted to the analyzer module chassis, which has a recessed front panel covered by a hinged door (see Figure 13). On this panel are mounted the flowmeter (1), needle valves (2), shutoff valve (3), and inlet leak valve adjustment (4), for control of the sampled gases to the instrument. There are two bulkhead fittings on the right side of the front panel. One of these permits connection of a one-fourth (1/4) inch sample inlet gas line (5); the other is an exhaust line (6), from the analyzer. The sample select valve (7) is located in the upper center of the panel.

The calibration gas sample bottle and pressure regulator is mounted on the left hand side of the analyzer module chassis and is plumbed into the analyzer sample inlet system for calibration verification.

The analyzer electronics are mounted on printed wiring boards and terminal boards, conformal coated and mounted into connectors and retained by brackets in the analyzer module chassis.

The analyzer control chassis is drawer slide mounted with an attached front panel that provides for mounting of the readout display meters, support electronics control switches and functional indicating meters. A battery pack, trickle charger and twenty-eight (28) volt power supply, plus other support electronics are mounted to the chassis as shown in Figure 14.

There is a connector panel attached to the lower back portion of the cabinet, as shown in Figure 15, with a 115 volt, alternating current (ac) power connector and a connector for external readout. The upper back portion of the cabinet consists of one large removable panel, which completes the total enclosure of the cabinet.

After the project was well underway it was requested that we design, in part, to the Space Station Simulator Phase IV Test requirements 1T33501.

To fulfill flame propogation requirements, all metal joints of the cabinet were designed with overlapping surfaces to create a somewhat sealed package. All painted surfaces are acrylic baked enamel. Internal brackets are aluminum chemical film coated in accordance with MIL-C-5541, Type 1, Grade C, Class 2, or steel cadmium plated in accordance with GQ-P-416, Type 1, Class 2.

A list of all components, electrical and mechanical, their materials and finishes, was generated and submitted to McDonnell-Douglas for approval. Some of the components were questionable, but were approved due to the short delivery date of the finished system. There was not enough time to reorder and wait for suitable replacement parts, some of which would not be interchangeable. This would have necessitated redesign, refabricating, reassembling new parts, and the scrapping of old parts which the schedule and budget could not stand. All wiring used in the system is Teflon sleeved.

The system did not conform to McDonnell-Douglas safety and quality assurance requirements but was approved.

SYSTEM TESTS

Analyzer Tests

The analyzer refurbishment followed the normal procedures that have been followed in earlier tests on the Two Gas Sensor. The analyzer was disassembled, cleaned and new filaments of ninety-seven percent tungsten, three percent rhenium (97% W - 3% Re) were installed. The analyzer was pumped down and the filaments burned in slowly for maximum life. The electron guns were then turned up for maximum electron beam transmission to the anodes. The ion current peaks were measured and after appropriate tuning the peak shape and resolution became acceptable, but the m/e 18 peak was not aligned with respect to the m/e 28, m/e 32, or m/e 44 peaks. After appropriate repositioning of the m/e 18 collector, the alignment was brought to an acceptable degree. (See Figure 16.)

After the peak alignment process was completed, ion focusing was tuned up and the ion source sensitivity was measured and found acceptable. A final set of ion source voltages was obtained, which allowed the proper electrode voltage divider string to be set up.

Ion Pump Tests

The pumping speed of the eight/eleven (8/11) liters per second ion pump (Ultek 220-519-01) was tested to assure its performance on the intended application. Figure 17 shows a schematic of the test setup.

The ion pump power supply was designed to provide 3,200 volts over the operating pressure range of less than 10^{-8} to 10^{-5} torr. The results, as shown in Figure 18, indicate that the speed is above eight (8) liters per second over the pressure range of 3×10^{-7} to 3×10^{-6} torr, which is adequate for this application.

Electronic Subsystem Tests

Electronic Subsystem Tests consisted of each electronic module being carefully tested for adequate performance under expected operating conditions. Units were checked for operation under varying loading conditions, input voltage fluctuations and where critical thermal variations were expected.

Particular attention was paid to the electrometers for proper response and zero stability. Since these units are the heart of the readout and closed loop system, special attention was given to their frequency response rolloff and input zero stability. Special response networks are provided in each electrometer to tailor the frequency characteristics. Each electrometer was adjusted for a band pass of one (1.0) cycle per second and a rolloff of six (6) decibels per octave. Input zero compensation was checked on each unit in an environmental chamber to assure the highest possible accuracy.

The filament emission control system was checked with the use of a dummy diode to simulate the action of the mass spectrometer ion source. Ionization current regulation was of prime importance here, as well as stability of electron current with thermal changes.

The remainder of the circuits were checked on test equipment normally used to check production equipment. These tests were mainly functional in nature.

System Integration Tests

The analyzer, ion pump and inlet system were assembled and leak checked prior to pumpdown. After the systems vacuum integrity was verified the ion pump was started and the system allowed to pump down prior to a final bakeout.

A two day bakeout at 250 degrees centigrade was accomplished with complete success, i.e., no leaks. The mechanical assembly of the balance of the system proceeded with no major problems. The system was then operated and a recheck of the analyzer parameters performed and found acceptable. An alignment check was made, Figure 19, due to the possibility of misalignment that could be caused by the mechanical assembly. The alignment check showed that no further alignment was necessary and, therefore, the full electronic subsystem integration testing could begin.

After the integration of the electronics with the mass spectrometer, tests were run to establish the values of the closed loop summing resistors and scaling resistors on the outputs. These values were then checked by exercising the instrument with various calibration gasses. Such cross checking verified the correct values of these selected components.

As a final system test, various expected operational conditions were simulated to check overall instrument performance. These included power failure to verify battery changeover operation, opening and closing of the electronic bay drawers to check thermal regulation of the sample inlet valve and varying line voltages, etc. The instrument was able to cope with the simulated conditions affecting overall operation or accuracy.

INSTALLATION AND CHECKOUT DURING FIVE-DAY RUN

On 24 March 1970 the system was delivered to McDonnell-Douglas, Huntington Beach. The system was set up and an operational checkout performed. McDonnell-Douglas performed an electrical and mechanical inspection and nothing of major consequence turned up.

The first Space Station Simulator crew and standby crew were instructed in the principals of operation and the operating procedures (see Appendix A) of the instrument.

On 15 April 1970 the system was installed into the Space Station Simulator in preparation for the initial five-day shakedown run. Except for a few minor interface problems, the checkout was performed without incident.

The five-day run started on 29 April 1970. The outputs of the Atmospheric Sensor System are shown in Figure 20.

OPERATION DURING NINETY-DAY MISSION

From the end of the five-day run until two days before the beginning of the ninety-day run the system was shut down, however, the ion pump remained on. Two days before the ninety-day mission started a quick operational checkout of the system was made, primarily to check some changes that were made in the interfacing data acquisition equipment.

On 13 June 1970 at 0935, the ninety-day mission was started and at 1102 the Atmospheric Sensor System was turned on. At 1230 the first calibration verification was made. The results indicated that the Σpp were within one (1.0) percent of the total pressure as read on the primary cabin pressure gauge. Several calibration verifications were made during the

first few weeks of the mission and they all indicate that the Σpp was within one (1.0) percent of the total pressure. All the system calibration verifications are summarized in Table 2.

A complete curve of the system performance is shown in Figure 21. The data for these curves was taken from the data reduction of the McDonnell-Douglas Low Speed Data Acquisition System at 1800 hours. This time was chosen because it was considered the most normal, with the least unprogrammed activity, and should give a more representative picture of the cabin atmosphere from day to day.

A few comments have been added to the ninety-day test curves at points where definite correlation to known activities have occurred.

CONCLUSIONS

Five-Day Run

The purpose of the five-day run was to operationally check out all systems under actual operating pressures (10.0 lbf/in^2 abs). The Atmosphere Sensor System performed very well during the five-day run, but there were several interface problems in the electrical readout systems (i.e., open leads, crossed leads, and ground loops) which were corrected prior to the ninety-day test. Therefore, the plot (Figure 21) of the Atmospheric Sensor System performance is from manually taken data, off the instrument metered outputs, from inside of the Space Station Simulator.

Ninety-Day Run

A review of the data in Figure 20 shows that the summation of the partial pressures, as measured by the Atmosphere Sensor System, agrees with the cabin pressure to about minus two and one-half (-2.5) percent, constantly over the entire ninety-days. This constant minus two and one-half (-2.5) percent error can be attributed primarily to the carbon dioxide and water vapor channels. A detailed discussion of the error attributable to the water vapor channel is given in Appendices B and C and will not be presented here. The error caused by the carbon dioxide channel was due to an error in the calibration gas analysis by West Coast Technical. The original analysis (Appendix D) was used to set up the instrument and at the end of the Ninety-Day test, McDonnell-Douglas sent the gas back for reanalysis because they had also used it for calibration. The second analysis (Appendix E) showed a plus twenty-five (+25) percent difference in the carbon dioxide content. The evaluation of a Four Gas Mass Spectrometer, used for atmospheric control during the ninety-day test, is presented in Appendix F and, the results of the 180-day test at ASD are presented in Appendix G.

TABLE 2.- CALIBRATION VERIFICATION

Date	Time	Cabin Press	O_2	N_2	CO_2	H_2O	Σpp	Remarks
6-13-70	1232	519.5 T	149 T	352 T	3.05 T	8.1 T	512.15	-1.4% error in Σpp CABIN
6-13-70	1315	521.9	171 T	340 T	12.9 T	1.86 T	525.76	+1.0% error in Σpp - CAL MIX N_2 - 65.2% = 340 T ∿ 0% error O_2 - 32.4% - 169 ∿ -1.0% error CO_2 - 2.45% = 12.8 T ∿ 1% error
6-14-70	1405	525 T	153 T	348 T	5.06 T	9.22 T	515.28	-2.0% error in Σpp - CABIN
6-18-70	1814	512.5 T	144 T	342 T	5.72 T	10.3 T	502.02 T	-2.0 % error in Σpp - CABIN
6-18-70	1902	514.2 T	167.8 T	334 T	12.6 T	2.38 T	516.78 T	+1.0% error in Σpp - CAL MIX N_2 - 65.2% = 334 T ∿ 0% error O_2 - 32.4% = 166 T ∿ +1.0% error CO_2 - 2.45% = 12.5 T ∿ +1.0% error
6-20-70	0322	519 T	155.8 T	340 T	5.14 T	9.0 T	509.44 T	-2% error in Σpp - CABIN
6-26-70	0510	518 T	155.3 T	325.5 T	10.0 T	12.3 T	503.1 T	-3% error in Σpp - CABIN
7-8-70	1059	521.5 T	154 T	337 T	7.46 T	10.5 T	509.0 T	-2.5% error in Σpp - CABIN
7-8-70	1135	521.5 T	170.5 T	338 T	12.9 T	20.5 T	521.5	0% error in Σpp - CAL MIX N_2 = 65.2% = 340 T ∿ +0.6% error O_2 = 32.4% = 169 T ∿ +1.0% error CO_2 = 2.45% = 12.8 T ∿ +1.0% error
7-11-70	0450	516.5 T	154.8 T	322.2 T	5.10 T	14.4 T	496.5	-4% error in Σpp - CABIN
7-13-70	1245	516 T	155 T	328 T	6.7 T	12.3 T	502.0	-3% error in Σpp - CABIN
7-13-70	1346	515 T	169 T	334 T	12.7 T	2 T	517.7 T	+1% error in Σpp - CAL MIX N_2 - 65.2% = 336 T ∿ -1% error O_2 - 32.4% = 167 T ∿ +1% error CO_2 - 2.45% = 12.6 T ∿ 1% error
7-18-70	1853	526 T	156 T	337 T	4.41 T	13.0 T	510 T	-2.5% error in Σpp - CABIN (meters)
7-25-70	1430	514.5 T	155.6 T	331.5 T	4.88 T	10.46 T	502.44 T	-2.5% error in Σpp - CABIN
9-9-70	0205	513.3 T	155.4 T	334 T	6.98 T	10.1 T	508.48 T	-1% error in Σpp - CABIN
9-9-70	0250	512.5 T	169.6 T	333 T	12.9 T	∿	515.5 T	+1% error in Σpp - CAL MIX N_2 - 65.2% = 334 T ∿ -0.4% error O_2 - 32.9% = 169 T ∿ 0.3% error CO_2 - 2.45% = 12.6 T ∿ 2.3% error

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The close liaison between ASD and McDonnell-Douglas greatly contributed to smooth installation, operation and data acquisition. This was the first operational application of the closed loop mode of operation and the results show that no calibration verification at all would lead to as good, if not better, results since this mode of operation will automatically correct for the majority of variations within the system, provided that the initial calibration is carried out correctly using a reliable analysis of the calibration gas to be used.

The Two Gas Atmosphere Sensor System has demonstrated that mass spectrometer instrumentation has a definite place in the field of closed environment atmosphere monitoring and control, where a life-support atmosphere is essential. The operation of a mass spectrometer within a closed environment was demonstrated, as well as the ability to sample continuously from within such a closed environment. Long term operation of a mass spectrometer atmospheric analyzer, under relatively unattended conditions, was also shown to be feasible. The continuous and simultaneous monitoring of the major atmospheric constituents, which could then be displayed within the habitat and at a remote location, was also demonstrated. The feasibility of periodic calibration of a multichannel mass spectrometer, using a calibrated gas mixture, was proved and it was shown that relatively untrained personnel could carry out this task.

The flexibility of the Two Gas Atmosphere Sensor would allow it to be applied to a wide range of potential closed environment applications. The monitoring and control of the major atmospheric constituents within many types of habitats, at various pressures, could be carried out. By increasing the number of ion current collectors other lower level constituents such as hydrogen, methane, Freons, and total hydrocarbons can be monitored and with the addition of an accumulator cell inlet system, which is now under development for NASA/Langley Research Center, carbon monoxide monitoring can be incorporated. In addition to atmospheric monitoring, the Two Gas Sensor can be applied to biological measurements, such as, measuring the metabolic rate of crewmen under various conditions of stress. It is evident that many possibilities exist for the application of the Two Gas Atmosphere Sensor in closed environments.

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APPENDICES

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B. Water (H_2O) Analysis

C. Analysis of a Closed Loop Mass Spectrometer System With an Incorrectly Calibrated Channel

D. ASD Calibration Gas Test Report

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APPENDIX A

OPERATION MANUAL
ATMOSPHERE ANALYZER SYSTEM

APPENDIX A

OPERATION MANUAL

ATMOSPHERE ANALYZER SYSTEM

SPO 30007

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Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Langley Research Center
Hampton, Virginia

APPENDIX A

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APPENDIX A

1. PRINCIPLE OF OPERATION

The Atmosphere Analyzer System can be divided roughly into four parts. These are: 1) the inlet system; 2) the calibration system; 3) the mass spectrometer, and 4) necessary support equipment for the above.

The inlet system performs several functions, the most important of which is the reduction of the pressure of sample gas from an ambient of ten lbf/in^2 abs to 2×10^{-4} torr. This pressure reduction is accomplished with a special valve which has a precisely adjustable leak rate. The balance of the inlet system consists of filters to extract all dust particles and other contamination from the air of larger size than approximately one micron, and metering valves and a flowmeter to control the sample gas flowing through the leak valve. A schematic of the inlet and vacuum systems is shown in Figure 22.

The calibration system provides a gas mixture of precisely known composition which makes possible the absolute calibration of the instrument. The calibration system consists of a pressure bottle containing calibration gas, a pressure regulator, and a metering valve.

The mass spectrometer is the central part of this atmosphere analyzing system. A mass spectrometer is an instrument which analyzes a chemical compound or mixture according to its atomic mass number. The mass spectrometer used in the Atmosphere Analyzer is a single focusing magnetic sector instrument. The mass spectrometer consists basically of three parts. These are: 1) the ion source; 2) the analyzer section; and 3) the collector and readout electronics. The ion source takes the incoming low pressure gas mixture and passes an electron beam through it causing ionization. Ions are charged molecules or atoms and are sensitive to electric and magnetic fields. The ions are accelerated by fields of several hundred volts to fairly high velocity at which point they enter the analyzer section of the mass spectrometer which, reduced to its basic function, consists of nothing more than a magnet. This magnet deflects the ions from their normal straight paths into paths describing arcs of various radii of curvature. The heavier the ion, or the higher the mass number of the ion, the less it will be deflected by the magnetic field, therefore, ions of large mass will move in arcs of large radius while ions of low mass will move in small radius arcs. This will produce separation of the various ions produced by ionizing the given gas mixture. The ions now proceed to a series of collectors which are positioned to intercept the different masses. In the Atmosphere Analyzer, there are four collectors which are used to detect four particle masses. These are m/e 18, or water, m/e 28, or nitrogen, m/e 32, or oxygen, and m/e 44, or carbon dioxide. The ions,

upon hitting the collectors, will cause an electric current to flow through an external circuit. These currents are extremely small, on the order of 10^{-12} amperes, therefore, very sensitive electrometer amplifiers are used to amplify these currents for further processing. The outputs of these amplifiers are then proportional to the currents that pass through the collectors, which in turn are proportional to the relative partial pressures of the particular constituent in the incoming gas mixture.

The fourth section of the Analyzer System is the support equipment required for the other three sections; this includes the ion pump that maintains a low pressure in the analyzer, power supplies, and various other auxillary equipment.

2. SYSTEM DESCRIPTION

The following is a brief functional description of the Atmosphere Analyzer. To simplify the system description, each part of the system referred to has been assigned an index number as shown in Figures 23 and 24. Sample gases enter the inlet system from the one-eighth sample line at the sample inlet point (1). The sample gas then passes through a needle flow control valve on the front panel of the instrument (2). After passing through the flow controlling valve, the sample gas goes to the mode selector valve (3) which determines the mode of operation, that is, operating in the calibration mode or the normally operating sample mode. After passing through the mode selector valve, the gas is filtered by a two stage inline filter (4). On the sample outlet, corresponding sets of filters (5) are present. The gas mixture then passes through a sample flowmeter (6) which measures the rate of gas flow through the instrument and therefore allowing the pressure drops through the inlet system to be checked. After passing through the flowmeter the sample travels past a total pressure transducer (16) and out the sample vent (17). Between the double filters the gas passes through the variable leak valve (7). This variable leak valve is fitted with a temperature control system. The heater switch (8) controls the heater for the inlet valve. The calibration gas mixture is stored in a pressure tank (9) with regulator (10). Passing through the regulator, the sample gas goes to a protection shutoff valve (14) and then to a needle flow control valve (15) then to the selector valve (3). Part of the gas to be sampled (either the sample gas or the calibration gas), passes through the restriction in the leak valve and through a small diameter line (11) into the mass spectrometer (12) located within the analyer chassis for initially pumping down the instrument. THIS SHOULD NEVER BE TOUCHED BY OPERATING PERSONNEL. The conductance of the variable leak valve can be adjusted by means of a slotted screw adjustment (28) on the front panel. The ion currents coming out of the mass spectrometer

are detected and amplified by four electrometers. The electrometer outputs go to the output meters (26) and also to buffered outputs. The zero levels of the electrometers can be checked by pressing the press-to-test button (27) which cuts off the ion beams. The main power to the mass spectrometer is provided by a 28 Vdc power supply, requiring a 115 volt ac input.

There is a front panel switch (18) that controls the operation of the 28 volt power supply. Other items on the front panel are the ion pump meter switch (19), and the ion pump current meter (20). These monitor the current flowing to the ion pump from the high voltage supply and, therefore, indirectly monitor the analyzer pressure. There are two other meters on the front panel of the Analyzer Control Module. One of these is the battery voltage indicator (21). This indicates the stage of readiness of the emergency batteries, which are used for powering the ion pump in a power off situation. The other front panel meter is the anode current meter (22). This meter measures the anode current and gives an indication of the sensitivity at which the source is being operated. The anode current may be adjusted only in the open loop mode by the anode current adjustor potentiometer (23). The mode of operation, open or closed loop, is controlled by a selector switch (24) on the front panel.

3. NORMAL OPERATING INSTRUCTIONS

3.1 START-UP PROCEDURE

a. With 115 Vac applied to unit check that the ION PUMP CONTROL switch (19) is in the 0.1 mA position. Reading should be nominally < 10 μA (the first division).

b. Check BATTERY VOLTAGE (21). The voltage should be 27 V or above.

c. Check positions of the following controls prior to any further changes:

(1) ION PUMP CONTROL SWITCH (19) to 0.1 mA.

(2) SAMPLE/CLOSED/CALIBRATE valve (3) to CLOSED position, FLOWMETER (6) at zero.

(3) SYSTEM POWER switch (18) to OFF.

(4) FIL 1/FIL 2 switch (29) to FIL 1.

(5) ANODE CURRENT ADJUST (23) to zero (full CCW).

(6) HEATER switch (8) to OFF.

(7) VARIABLE LEAK ADJUST (28) to OFF position (full CW).

(8) LOOP MODE switch (24) to OPEN.

d. Set HEATER POWER switch (8) to ON. It takes about one hour for the inlet leak valve to reach the final temperature.

e. Set SYSTEM POWER switch (18) to ON.

f. Output meters (26) will show some deflections at this time, however, they should all drop to zero or low levels after a minute or two. Do not adjust any of the meters at this time.

g. Release lock on ANODE CURRENT ADJUST knob (23) by turning outer ring CCW. The ANODE CURRENT ADJUST is turned slowly clockwise until the ANODE CURRENT meter reads 10 μA. The output meters will show some deflections, expecially on H_2O and CO_2 channels, due to background.

h. Wait 90 minutes for warm-up of valve heater, electrometers, and ion source.

NOTE

Air conditioner blower must be on
in order to obtain sample.

i. Admit sample of atmosphere by turning SAMPLE/CLOSED/CALIBRATE valve to SAMPLE. Open sample needle valve (2) until flow is maximum for at least 30 seconds then adjust flow until a reading of 0.015 is obtained on the flowmeter (observing black ball through flowmeter).

j. Hold the ANALYZER in this condition for a one hour stabilization period. At the end of this time some nominal readout for each gas will be noted, for example, 1.5 to 2 torr for N_2 and O_2 respectively and about 0.5 torr for H_2O and CO_2.

k. A sample may now be admitted to the ATMOSPHERIC ANALYZER.

The sample is introduced by turning the inlet leak (28) adjust screw CCW looking from the front. About 2-1/4 revolutions will be required with the last revolution very carefully applied. The ION PUMP CURRENT (20) should be carefully watched during this process. The ION PUMP CONTROL switch (18) must be in the 1 mA position. At about 2-1/8 turns, the ION PUMP CURRENT will increase. Carefully adjust the INLET LEAK valve until the sum of the outputs (in torr) equals the inlet pressure.

ℓ. The system may now be switched to CLOSED loop operation with the LOOP MODE switch and the final adjustment of the leak made until the anode current is 10.0 μA.

3.2 VERIFICATION PROCEDURE

a. Turn SAMPLE/CLOSED/CALIBRATE flow-switching valve from SAMPLE to CALIBRATE. Open CAL GAS SHUTOFF valve (14). Adjust needle control valve (15) on this panel until the ball is about full scale, hold for 15 to 30 seconds then slowly close needle control valve until a flow of 0.015 on the black ball is obtained.

b. Leave ANALYZER in this condition for 15 to 30 minutes for stabilization.

c. In particular note the drop in the H_2O output.

d. While waiting, note and record the cabin pressure. Compute the true partial pressure of the N_2, O_2 and CO_2 in the particular calibration gas sample being used. H_2O is a minute value and can be disregarded.

e. Before making any further calibration adjustment, note and record all meter outputs as well as the CABIN total pressure.

f. If the outputs do not agree within $\pm$2% of the calculated composition, the Perkin-Elmer representative should be contacted for further instructions.

4. MAINTENANCE

The only maintenance required for the Atmosphere Analyzer is the verification check, as outlined in Paragraph 3.2 above, once every 14 days and a once a day reading of all meters, i.e., anode current (2 mA/div), ion pump current (.05 mA/div, in 1 mA position), battery voltage (2 V/div), O_2 output, N_2 output, CO_2 output and H_2O output.

APPENDIX A

5. EMERGENCY PROCEDURES

5.1 EXTERNAL EMERGENCIES

External emergencies are those relating to abnormalities outside the instrument proper. These include power failure and power shortage. In a power failure situation, the analyzer will shut off and the ion pump will automatically switch over to battery operation, preventing contamination of the vacuum system. The leak valve should be closed in any prolonged power failure, as this will reduce the pressure in the analyzer and extend the life of the emergency batteries.

5.2 INTERNAL EMERGENCIES

Internal emergencies are those relating to abnormal operation of the instrument itself.

If, for some reason, the ion pump current goes past 0.5 mA in the 1 mA position and remains there for more than five minutes, the leak valve should be closed. If the ion pump current goes off-scale in the start position for more than one minute, the pump should be shut down. Restart of the system after shutdown will require a sorption roughing pump. Perkin-Elmer Aerospace Division should be consulted, if necessary, to restart the pump.

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APPENDIX B

WATER (H_2O) ANALYSIS

APPENDIX B

WATER (H_2O) ANALYSIS

By Michael R. Ruecker
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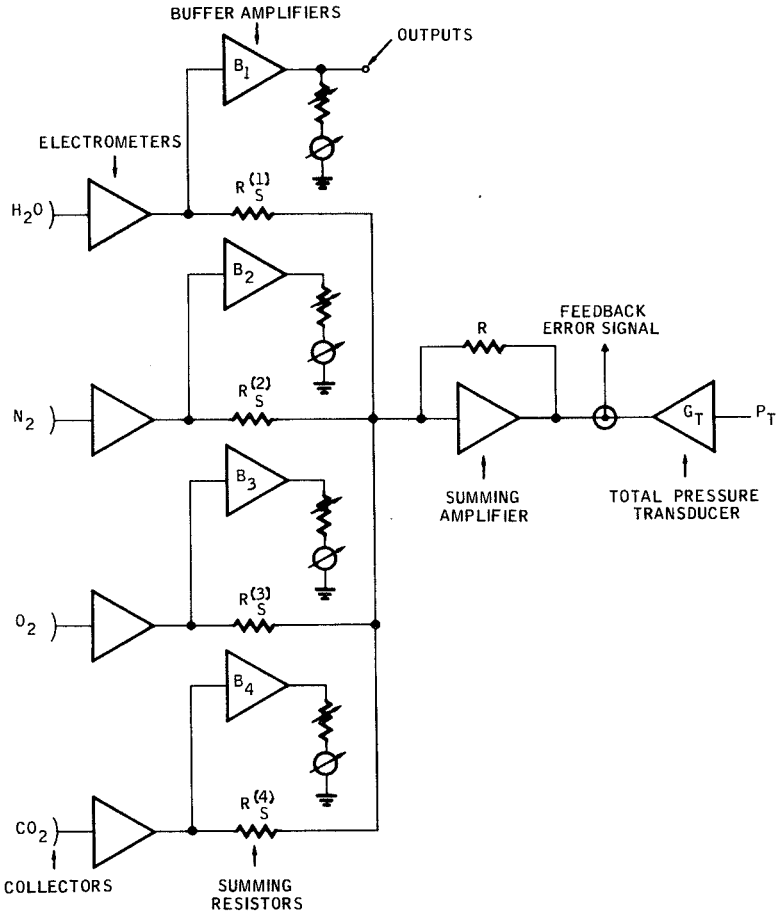
The output region of the Mass Spectrometer Atmospheric Sensor is shown below:



APPENDIX B

In a normal calibration, which occurs at the time the system is initially tuned up, the summing resistors are adjusted so that the gain of each channel is the same. If G_1, G_2, G_3, and G_4 are the gains of the mass spectrometer (includes inlet leak conductance, ion source sensitivity, analyzer transmission efficiency, and electrometer gain) for H_2O, N_2, O_2, and CO_2, respectively, then the above stated condition is given by:

$$\frac{G_1}{R_S^{(1)}} = \frac{G_2}{R_S^{(2)}} = \frac{G_3}{R_S^{(3)}} = \frac{G_4}{R_S^{(4)}} \tag{1}$$

Furthermore, the individual channel gains are also matched to the gain of the total pressure transducer, as is shown by the following expression:

$$\frac{R_S}{R_S^{(1)}} G_i = G_T = \text{constant} \tag{2}$$

This equation must be satisfied in order to have the closed loop operate in a manner that produces outputs such that the sum of the partial pressures is equal to the total pressure. When these adjustments are made the instrument can be operated in the closed loop mode.

The outputs of the electrometers are attached to buffer amplifiers that have adjustable gains. These outputs go to the atmosphere control system. They also go through variable resistances to output voltmeters, which are scaled to read pressure in torr. The buffer amplifier gains are adjusted to give output levels that are compatible with the electronic interface, and finally, the variable resistor is adjusted to give the correct meter readings.

Once this complete calibration process has been accomplished it should not be disturbed. Calibration verification may be run, but if the instrument is found to be in error no adjustments can be made in the output electronics without adjusting the summing resistors. As will be shown, the violation of this rule resulted in the errors experienced in the atmospheric analyzer that was operated at McDonnell-Douglas in the Space Station Simulator.

During calibration at ASD before the 90 day test, the N_2, O_2, and CO_2 channels were calibrated utilizing an analyzed gas mixture and an inlet system which allowed a pressure of 517 torr (10 lbf/in^2 abs) to be established. The instrument was operated in the open loop mode with a nominal anode current of ten microamperes, and all outputs were allowed to stabilize for several hours to insure that the correct values were obtained. The inlet

system was not capable of handling water vapor in a quantitative manner, and therefore the water calibration was accomplished by sampling laboratory air at ambient pressure and closing down the variable inlet leak valve to give the proper output value for nitrogen. After waiting for a period of two hours for the H_2O channel to stabilize the m/e 18 electrometer output was read, the ambient relative humidity was read with a laboratory dry bulb - wet bulb R.H. indicator, and the ambient H_2O partial pressure was computed. From this data the mass spectrometer gain for the H_2O channel was computed and the input resistor was selected. No further tests on the water vapor channel were conducted.

The summing resistor values resulting from the calibrations are reviewed below. The correctness of their values can be checked approximately by applying the constraint:

$$C = \frac{R_f^i}{R_S^i} \quad \frac{1}{S_R^i} = \text{constant for all } i \qquad (3)$$

where:

R_f^i = Electrometer feedback resistor for i^{th} channel

R_S^i = Summing resistor for i^{th} channel

S_R^i = Relative sensitivity for the i^{th} channel

The table below shows the application of this relationship:

Constituent	R_f^i	R_S^i	S_R^i	C
N_2	2×10^{10} Ω	50.0 k	1.0	400
O_2	1×10^{11} Ω	229 k	1.18 †	370

† Measured

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Constituent	R_f^i	R_S^i	S_R^i	C
CO_2	5×10^{11} Ω	1.37 M	0.89 *	382
H_2O	1×10^{12} Ω	607 k	1.3 *	1270

From this data, note that the value of C for N_2, O_2, and CO_2 is within ten percent, while the value for H_2O is different by a factor of three. Had this computation been done at the time the H_2O channel was calibrated, it would have been questioned, and perhaps a better calibration would have resulted.

The water calibration and the associated computations has been reviewed with the following results. Plotting the data revealed that the water output had not fully stabilized at the end of the two-hour period; however, it appeared that the output was not far from a stable value, perhaps ten percent low. The data is shown in Figure 22. This would not account for the observed factor of three error. The calculations were also checked and found to be substantially correct. The following equation was utilized:

$$R_S^{H_2O} = R_S^{N_2} \frac{V_{H_2O}}{V_{N_2}} \frac{\%N_2}{\%H_2O} \qquad (4)$$

The percent N_2 that was used for the H_2O calibration was found to be incorrect, a calibration gas valve being used instead of the percentage for air. Using a correct valve would have increased the water channel summing resistor by a factor of $\frac{0.6617}{0.7803}$, giving a value of 1080 for C.

This is still a factor of two and one-half high. Apparently the water channel output was low during the calibration. This caused too small a value of $R_S^{H_2O}$ to be selected, and this caused too high a value for the feedback gain, H.

The reason for the low water output is not now understood. Water is known to hang up on surfaces, but the data in Figure 25 shows that the output appeared to be stabilizing. Further, there was no apparent effect of water on the other channel sensitivities. Data taken on the system at McDonnell-Douglas shows that the water output stabilizes almost fully in approximately one hour.

* CEC data

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Examining the data from the four to five day test, the following is observed. At the calibration where the buffer amplifiers were set the sum of the outputs agrees with the observed total pressure within 0.2 percent. On a later calibration the agreement is worse, 0.8 percent. (This data is tabulated in Table 3.) In both cases, however, there is a water background from the cabin atmosphere, which was previously sampled. A water background will have the effect of making the other channels read low when sampling a dry calibration gas in the closed loop mode, provided that this background is in the mass spectrometer high vacuum region and not in the inlet system, i.e., the sample transport lines and inlet leak valve. Sufficient information is not presently available to make this determination; however, the fact that the sum of the indicated partial pressures is low when the water background is higher indicates that the background is inside the mass spectrometer. If this is true,

TABLE 3.- FOUR TO FIVE DAY CALIBRATION DATA

p	523.7 torr	525
V_{O_2}	4.43	4.40
	-.18	-.18
$V_{O_2}\Big\|_{\text{correct}}$	4.25	4.22
S_{O_2}	40 torr/volt →	
p_{O_2}	170	169
p_{O_2} correct	169.4	
V_{N_2}	3.60	3.57
	-.18	-.18
$V_{N_2}\Big\|_{\text{correct}}$	3.42	3.39
S_{N_2}	100 torr/volt →	

APPENDIX B

TABLE 3.- (Concluded)

p_{N_2}	342	339
p_{N_2} correct		
V_{CO_2}	3.40	3.37
	-.18	-.18
$\lvert V_{CO_2} \rvert$ correct	3.22	3.19
S_{CO_2}	4 torr/volt →	
p_{CO_2}	12.9	12.8
p_{CO_2} correct	12.8	
V_{H_2O}	0.68	1.24
	-.18	-.18
	0.50	1.06
S_{H_2O}		
p_{H_2O}	2.5	5.3
p_{H_2O} correct	0	0
$\sum p_i$	524.9	520.8
Δp	+1.2	-4.2
$\Delta p/p$	+0.229%	-0.80%

then the fact that there was a 0.5 volt output on the water channel at the time the buffer amplifiers were set indicates that the outputs on the other channels were set too high. They should have been set low by a combined total of about 2.5 torr. Since it was not, subsequent readings will be in error by this amount.

There is another problem with the data, in that when the mass spectrometer outputs read zero the telemetered outputs read between +0.15 and +0.19 volts. While zero levels were corrected for by subtracting a nominal 0.18 volts from the outputs, there is still an uncertainty of $\pm$0.02 volts in this level, which corresponds to a $\pm$2 torr error in the nitrogen channel (less in the other channels). This represents about a half percent effect.

When the system was run on the cabin atmosphere the outputs read low by about three-quarters of a percent, although the exact value varied from this average. The data is shown in Figure 26. The reason for the low summation of partial pressures is not fully understood. It is possible that the buffer amplifier for the water channel was not properly set at the time of calibration. In fact, comparing the H_2O meter outputs to the corresponding buffer outputs it appears that it was set for five torr/volt instead of four torr/volt as was planned. Adjustments were made on the other buffer amplifiers while the instrument was inside the SCS and it is possible that the H_2O buffer was erroneously adjusted. In other words, the H_2O buffer may not have properly compensated for the incorrect value of the H_2O electrometer output. Since the electrometer outputs are not available, it is possible that both the water channel buffer and its output meter were in error, so that the apparent value of four torr/volt is not correct. In any event, the error in the sum of the partial pressures is always less than one percent (except for one apparently spurious point near the beginning of the test, and the last point which shall be discussed presently).

During the five-day test at McDonnell-Douglas it was found that the water vapor channel was reading high compared with the Cambridge Dewpoint Indicator. The Dewpoint indicator was reading 11.3 torr while the mass spectrometer was reading 23.1 torr, with a buffer amplifier output of 4.68 volts. Mcdonnell-Douglas personnel adjusted the buffer amplifier to give an output of 2.82 volts based upon an 11.3 torr partial pressure and a desired system gain of 20 torr/five volts. This correction gave the proper water output, but it did <u>not</u> correct the fact that the summing resistor for the water channel was apparently in error. One effect of this adjustment is seen in the data presented in Figure 23. This shows the error between the sum of the partial pressures as indicated by the mass spectrometer, and the total cabin pressure as measured by the Wallace-Tiernan gauge. Referring to the lower set of data, which is computed from the digital outputs, note that during the five-day run the sum of the partial pressures agreed with the total pressure within one percent or better except for the final

reading, which was 2.9 percent low. This additional two percent error amounts to an error of 10.5 torr at 525 torr total pressure, which is very nearly equal to the 11.8 torr error that existed in the water output prior to adjustment of the buffer amplifier.

From the analysis in Appendix C, Page 39, note that the error in the water channel is given by Equation (26), Page 43. Assuming that there may be an additional error in the buffer amplifier (since it was only set once and never rechecked), the expression for the water output error is:

$$\left.\frac{\Delta O}{O}\right|_{H_2O} = \left(1 - \frac{p_{H_2O}}{p_T}\right)\frac{\Delta H}{H} + \frac{\Delta B'}{B} \tag{5}$$

Looking at the derivation of Equation (30) of Appendix C, Page 44, observe that the inclusion of the added buffer error produces an error in the total pressure, which is given by:

$$\left.\frac{\Delta p_T^I}{p_T}\right|_i = \frac{p_{H_2O}}{p_T}\ \frac{\Delta B'}{B} \tag{6}$$

where T = total pressure, I = indicated, and i = initial (i.e., before the adjustment of the buffer amplifier).

After the adjustment of the buffer amplifier to give the correct water output, the total pressure will be in error as given by Equation (33) of Appendix C, Page 44.

$$\left.\frac{\Delta p_T^I}{p_T}\right|_f = -\frac{p_{H_2O}}{p_T}\ \frac{\Delta H}{H} \tag{7}$$

where f = find (i.e., after tweeking the buffer).

Combining these three equations to find $(\Delta p_T^I/p_T)_f$, the result is:

$$\left.\frac{\Delta p_T^I}{p_T}\right|_f = \frac{-\frac{p_{H_2O}}{p_T}\left[\frac{\Delta O_{H_2O}}{O_{H_2O}} - \frac{\left(\Delta p_T^I\right)_i}{p_{H_2O}}\right]}{\left[1 - \frac{p_{H_2O}}{p_T}\right]} \tag{8}$$

The observed values for these parameters are:

$$\frac{\Delta O_{H_2O}}{O_{H_2O}} = \frac{11.8}{11.3} \qquad \frac{p_{H_2O}}{p_T} = \frac{11.3}{525}$$

$$\left.\frac{\Delta p_T^I}{p_T}\right|_i = -\frac{4}{11.3}$$

The results of the computation are:

$$\left.\frac{\Delta p_T^I}{p_T}\right|_f = -3.1\%$$

$$\frac{\Delta H}{H} = 1.43$$

$$\frac{\Delta B}{B}' = 0.353'$$

The observed value for the error in the total pressure was -2.9 percent, which is in better agreement than should be expected.

SUMMARY AND CONCLUSIONS

While there were some assumptions made in this analysis they are very likely valid, since the fact remains that the instrument calibrates well on a dry calibration gas, but has an error when monitoring a wet cabin gas. It should be noted that the value of $\Delta H/H$ predicted by the last calculation does not fully agree with the value predicted by the comparison in Table 3. This may suggest that although the mass spectrometer was registering more nearly correct electrometer output levels at McDonnell-Douglas, it is still not giving values that should be expected from relative ion source sensitivity data. The buffer amplifier was adjusted from 4.87 volts to 3.01 volts. Part of this change was to go from an assumed five torr/volt gain factor (based upon output meter information) to four torr/volt, which was the original goal. Taking this into account, the change in the buffer amplifier for other reasons was 0.495, which indicates it was originally a factor of 2.02 high. Looking at the values of $\Delta H/H$ and $\Delta B'B$, the predicted value for $\Delta B/B$ is 1.78, which is in fair agreement.

In conclusion, it appears that the incorrect calibration of the water channel accounts for the fact that the sum of the partial pressures is reading low. In order to correct the readings note from Equation (35) of Appendix C, Page 45, that it is only necessary to multiply each of the outputs by the ratio of the correct total pressure to the sum of the incorrectly indicated partial pressures. While other variations also exist in the data, these are somewhat smaller. Fully analyzing the performance of the mass spectrometer will not be possible until it is returned to ASD.

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APPENDIX C

ANALYSIS OF A CLOSED LOOP MASS SPECTROMETER SYSTEM WITH AN INCORRECTLY CALIBRATED CHANNEL

APPENDIX C

ANALYSIS OF A CLOSED LOOP MASS SPECTROMETER SYSTEM WITH AN INCORRECTLY CALIBRATED CHANNEL

By Michael R. Ruecker
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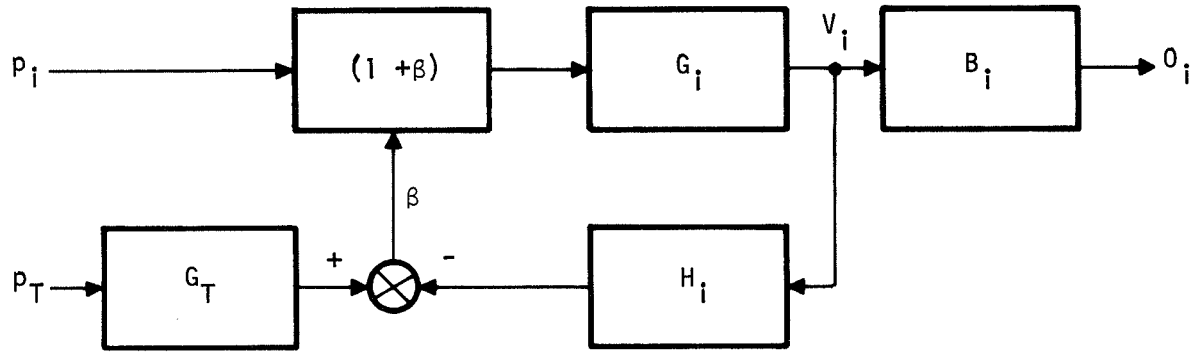
The closed loop operation of the mass spectrometer may be modeled as shown below.



A single channel system is shown but other channels would appear similarly and sum at the summation point. The symbols are:

P_i = Inlet partial pressure of the i^{th} channel

β = Variable gain factor in the emission regulator

G_i = Mass spectrometer gain for the i^{th} channel

B_i = Buffer amplifier gain for the i^{th} channel

P_T = Total pressure

G_T = Total pressure transducer gain

H_i = Feedback element gain for the i^{th} channel

V_i = Electrometer amplifier output of the i^{th} channel

O_i = Mass spectrometer output of the i^{th} channel.

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When the gains are balanced:

$$G_i H_i = G_T \text{ and } \beta = 0 \tag{9}$$

By definition:

$$p_T = \sum_i p_i \tag{10}$$

The equations of operation for a two channel system are:

$$p_1(1 + \beta)\ G_1 = V_1 \qquad p_2(1 + \beta)\ G_2 = V_2 \tag{11}$$

$$\beta = G_T P_T - (V_1 H_1 + V_2 H_2) \tag{12}$$

Combining Equations (3) and (4):

$$\begin{bmatrix} (1 + p_1 G_1 H_1) & p_1 G_1 H_2 \\ p_2 G_2 H_1 & (1 + p_2 G_2 H_2) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} p_1 G_1 (1 + G_T p_T) \\ p_2 G_2 (1 + G_T p_T) \end{bmatrix} \tag{13}$$

Solving these equations gives:

$$V_1 = p_1 G_1 \left[\frac{1 + p_T G_T}{1 + p_1 G_1 H_1 + p_2 G_2 H_2} \right] \ ; \ V_2 = p_2 G_2 \left[\frac{1 + p_T G_T}{1 + p_1 G_1 H_1 + p_2 G_2 H_2} \right] \tag{14}$$

These results may be extended to a system with n channels:

$$V_i = p_i G_i \ \frac{1 + p_T G_T}{1 + \sum_{j=1}^{n} p_j G_j H_j} \tag{15}$$

Assume that there is an error in the gain of the feedback element of the k^{th} channel, i.e.,

$$H_k^c = H_k + \Delta H_k \tag{16}$$

where the 'c' superscript refers to a value established during calibration. Then substituting Equation (16) into Equation (15) and making use of Equations (9) and (10) gives:

$$V_i = \frac{p_i G_i \ (1 + p_T G_T)}{1 + p_T G_T + p_k G_k \Delta H_k} \tag{17}$$

In order for the closed loop system to properly compensate for common mode errors it is required that $P_T G_T >> 1$. Assuming that $p_k G_k \Delta H_k << p_T G_T$ then:

$$V_i \approx p_i G_i \left(1 - \frac{p_k G_k \Delta H_k}{p_T G_T} \right) \tag{18}$$

which by the use of Equation (9) may be written as:

$$\frac{\Delta V_i}{V_i} = - \frac{p_k}{p_T} \frac{\Delta H_k}{H_k} \tag{19}$$

The above expression is valid for all i including i = k, since the only error is presumed to be in the feedback element. However, there will be an additional error in the k channel because the buffer amplifier for this channel is scaled incorrectly.

During calibration the gain of the mass spectrometer is determined:

$$G_k^c = V_k^c / p_k^c \tag{20}$$

and the gain for the feedback element is established from Equation (9):

$$H_k^c = p_k^c \ G_T \ / \ V_k^c = G_T \ / \ G_k^c \tag{21}$$

The buffer amplifier is then set to give a specified full scale output:

$$B_k^c = \frac{1}{G_k^c} \frac{O_k^f}{p_k^f} = \frac{p_k^c}{V_k^c} \frac{O_k^f}{p_k^f} \tag{22}$$

This assumes that B_k^c is determined while the instrument is in the open loop mode. The errors in h_k^c and B_k^c may then be related from Equations (21) and (22) since both are due to an error in G_k^c.

$$\frac{\Delta H_k}{H_k} = \frac{\Delta B_k}{B_k} \tag{23}$$

where Equation (16) and $B_k^c = B_k + \Delta B_k$ have been utilized. The resulting error in the mass spectrometer outputs is the combination of the errors at the electrometer outputs and the error in the gain of the buffer amplifiers:

$$\frac{\Delta O}{O} = \frac{\Delta V}{V} + \frac{\Delta B}{B} \tag{24}$$

Utilizing the above results:

$$\frac{\Delta O_i}{O_i} = \frac{p_k}{p_T} \frac{\Delta H_k}{H_k} \qquad i \neq k \tag{25}$$

$$\frac{\Delta O_k}{O_k} = \left(1 - \frac{p_k}{p_T}\right) \frac{\Delta H_k}{H_k} \qquad i = k \tag{26}$$

The result shows that the output of the channel with the feedback gain error will be high and the outputs of the other channels will be low (assuming $\Delta H_k > 0$). The foregoing analysis assumes that the calibration has been carried out open loop, i.e., that the calibration error in the k channel does not cause a calibration error in the other channels. It will, however, cause an error in the subsequent readings as indicated.

The indicated partial pressures are then:

$$p_i^I = p_i \left(1 + \frac{\Delta O_i}{O_i}\right) \tag{27}$$

and this is valid for all channels including i = k. It might not be expected that the above expression would be valid for i = k but it is due to Equation (23), i.e., the error in the gain, G_k^c is corrected for by B_k^c so that there is no net error in the data reduction. That is solving the equation:

$$p_i^I = \frac{O_i}{G_i^c B_i^c} \tag{28}$$

does not give an additional error due to the denominator when i = k.

APPENDIX C

When the indicated partial pressures are summed the result is:

$$p_T^I = \sum_{i=1}^{n} p_i^I = p_T + \sum_{i \neq k} p_i \frac{\Delta O_i}{O_i} + p_k \frac{\Delta O_k}{O_k} \tag{29}$$

Substituting Equations (25) and (26) into Equation (29) gives:

$$p_T^I = p_T - (p_T - p_k) \frac{p_k}{p_T} \frac{\Delta H_k}{H_k} + p_k \left(1 - \frac{p_k}{p_T}\right) \frac{\Delta H_k}{H_k}$$

$$= p_T - \left(1 - \frac{p_k}{p_T}\right) p_k \frac{\Delta H_k}{H_k} + p_k \left(1 - \frac{p_k}{p_T}\right) \frac{\Delta H_k}{H_k}$$

$$p_T^I = p_T \tag{30}$$

which says that in spite of the errors in the indicated partial pressure, there will be no error in the indicated total pressure.

To carry the analysis further, suppose that a later calibration of the instrument is performed which results in the detection of the earlier error. Let it be assumed that this calibration is done in the closed loop mode of operation, and that only the erronious channel is recalibrated. When the error is found the buffer amplifier of the k^{th} channel is adjusted to give the correct output:

$$\frac{O_k^f}{p_k^f} = \frac{O_k'}{p_k'} = \frac{V_k' B_k'}{p_k'} \tag{31}$$

where the primes refer to the values obtained at the recalibration. From Equation (19)

$$\frac{\Delta B_k}{B_k} = \frac{p_k'}{p_T} \frac{\Delta H_k}{H_k} \tag{32}$$

Then from (32) and (24):

$$\frac{\Delta O_k}{O_k} = -\left(\frac{p_k}{p_T} - \frac{p_k'}{p_T}\right) \frac{\Delta H_k}{H_k} \tag{33}$$

and Equation (25) is still valid for $i \neq k$ since no adjustment has been made inside of the loop or to the buffer amplifiers of the other channels. Note that when $p_k = p_k'$, $\Delta O_k = 0$, which says that the correct value for the k channel output will be obtained at this point as it should be. Utilizing Equations (25), (27) and (33) the summation of the indicated partial pressures is found to be:

$$p_T^I = p_T \left[1 - \frac{p_k}{p_T} \frac{\Delta H_k}{H_k} + \frac{p_k p_k'}{p_T^2} \frac{\Delta H_k}{H_k} \right]$$

but

$p_k'/p_T << 1$ giving:

$$p_T^I \simeq p_T \left[1 - \frac{p_k}{p_T} \frac{\Delta H_k}{H_k} \right] \tag{34}$$

which says that although the closed loop is in balance insofar as total pressure is concerned, the sum of the indicated partial pressures is no longer equal to the correct total pressure due to the adjustment of the k channel buffer amplifier.

Comparing Equation (34) and Equations (25) and (27) (which are still valid for all channels where $i \neq k$) note that the outputs of the channels $i \neq k$ may be corrected to give correct values by multiplying them by p_T/p_T^I. In other words:

$$p_i = p_i^I \frac{p_T}{p_T^I} \tag{35}$$

Therefore, the outputs may be readily corrected to give correct values. In the case of channel k itself, so long as the partial pressure remains near the calibration valve, the error will not be large.

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APPENDIX D

ASD CALIBRATION GAS TEST REPORT

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APPENDIX D

ASD CALIBRATION GAS TEST REPORT

WEST COAST TECHNICAL SERVICE INC.

1049 SOUTH SAN GABRIEL BLVD. SAN GABRIEL, CALIF. 91776 (213) 287-0926

REPORT

PREPARED FOR: The Perkin-Elmer Corporation
2855 Metropolitan Place
Pomona, California 91767
Attn: Mr. Bill Hartman

DATE: 1/30/70

JOB NO: 1821

PURCHASE ORDER NO: 09740-H

The contents of the two cylinders of gas submitted by you have been analyzed by mass spectrometry. The composition of the gases was found to be as follows:

Constituent	7130P	DL27742
Nitrogen	66.166	65.154
Oxygen	31.271	32.376
Argon	0.019	0.022
Carbon dioxide	2.544	2.448

If we can be of further assistance, please do not hesitate to contact us.

Respectfully submitted,

WEST COAST TECHNICAL SERVICE INC.

H. Dwight Fisher, Ph.D.
Vice President-Technical Director

HDF/bcw

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APPENDIX E

McDONNELL-DOUGLAS CALIBRATION GAS TEST REPORT

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APPENDIX E

McDONNELL-DOUGLASS CALIBRATION GAS TEST REPORT

WEST COAST TECHNICAL SERVICE INC.

1049 SOUTH SAN GABRIEL BLVD. SAN GABRIEL, CALIF. 91776 (213) 287-0926

REPORT

PREPARED FOR: McDonnell Douglas Astronautics Co.
5301 Bolsa Avenue
Huntington Beach, Calif.
Attn: G. Hart CB-A3-275 x3614

DATE: 8-21-70

JOB NO: 2206

PURCHASE ORDER NO: 91-OH-994909-K

The three gas cylinders submitted by you have been analyzed to determine their compositions. The results of these analyses are as follows:

	Low Span	H/C Span	P.E. Gas O_2 Span
		Cylinder	
	#1	#2	#3
Water	0.00	3 ppm	15 ppm
Oxygen	0.005	28.843	31.632
Argon	0.002	0.059	0.020
Carbon Dioxide	0.784	5 ppm	2.012
Carbon Monoxide	161 ppm	0	0
Heptane	0	280 ppm	0
Nitrogen	Balance	Balance	Balance

If we can be of further assistance please contact us.

Respectfully submitted,

WEST COAST TECHNICAL SERVICE INC.

H. Dwight Fisher, Ph.D.
Vice President-Technical Director

HDF:dee

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APPENDIX F

EVALUATION OF A FOUR GAS MASS SPECTROMETER USED FOR ATMOSPHERIC CONTROL DURING THE NINETY DAY TEST

APPENDIX F

EVALUATION OF A FOUR GAS MASS SPECTROMETER USED FOR ATMOSPHERIC CONTROL DURING THE NINETY DAY TEST

By Michael R. Ruecker
Perkin-Elmer Corporation
Aerospace Division
Pomona, California

SUMMARY

The design and performance of a Mass Spectrometer Atmospheric Sensor System (M.A.S.S.), which was utilized for monitoring and control of the manned Space Station Simulator (SSS) atmosphere during a Ninety-Day Test, is reviewed. The instrument was a modified Two Gas Atmosphere Sensor System, which was operated with a new closed loop electronics control system for improved long term stability. Based upon calibration verification data, taken during the five-day and ninety-day runs, the instrument demonstrated that it could hold its calibration within one percent for nitrogen, two percent for oxygen and three percent for carbon dioxide for a period of 132 days. The instrument also monitored water vapor partial pressure during these tests. The output signal from the oxygen channel was employed as the input to the atmospheric control system for maintaining the oxygen partial pressure of the SSS. The instrument demonstrated its ability to perform reliably and its potential value as equipment for Environmental Control System (ECS) applications.

INTRODUCTION

In 1965 a phased program was initiated with Langley Research Center aimed at the development of a mass spectrometer system for monitoring the major constituents of a buffered two gas atmosphere as well as the primary metabolic products of respiration. The Two Gas Atmosphere Sensor System, a single focusing magnetic sector mass spectrometer, evolved from this program, which was capable of continuously monitoring nitrogen, oxygen, carbon dioxide, and water vapor. An engineering test model and four prototype units were fabricated on this program. One of these units is shown in Figure 4. These instruments have been employed in several applications for atmospheric and respiratory measurements in various laboratories, a space station simulator and two undersea habitats. One of these applications was in conjunction with

the Sixty-Day Manned Space Cabin Simulator Test in 1968. At that time, the Two Gas Atmosphere Sensor System was operated externally to the Space Cabin Simulator with a laboratory vacuum system, and sampled the cabin atmosphere through a capillary-bypass inlet system.

In the most recent application, the subject of this paper, one of the original instruments was refurbished, equipped with updated electronics, repackaged with a close-coupled ion pump and a direct entry sample inlet system, and mounted inside the SSS where it monitored the partial pressures of oxygen, nitrogen, carbon dioxide, and water vapor. The output signal of the mass spectrometer's oxygen channel was provided as the input to the atmospheric control system, which controlled the oxygen partial pressure. The performance of the combined system was more than adequate to hold the oxygen partial pressure within the limits required for constant physiological functioning of the crew.

PRINCIPLES OF OPERATION

The Two Gas Atmosphere Sensor System is a singel focusing magnetic sector mass spectrometer that is designed to provide four simultaneous outputs which are proportional to the partial pressures of nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), and water vapor (H_2O). The fundamentals of mass spectrometer operation are shown in Figure 27. A small quantity of the gas sample to be analyzed is continuously introduced to the mass spectrometer through a molecular inlet leak. The characteristics of this leak allow each constituent of the sample to flow through the leak independent of the other components. The resulting partial pressures within the ion source are proportional to the corresponding partial pressures in the sample environment.

The function of the ion source is to ionize part of the gas to form charged particles, which are then acted upon by the electrostatic and magnetic fields within the instrument. Ionization is accomplished by bombardment of an electron beam, which is derived from a hot wire filament. The ions are repelled from the ionizing region, focused by an electrostatic lens and passed through the ion source exit slit into the magnetic sector. A permanent magnet provides a uniform magnetic field through which the ion beam passes within the vacuum envelope. The ions are deflected into circular arcs by the magnetic field, their radii being proportional to the square root of the mass-to-charge ratios of the ions. Since all of the ions of interest are singly charged, the radii are proportional to $m^{\frac{1}{2}}$. Consequently, the ions are dispersed as they leave the magnetic field and collected

by four Faraday cage type collectors located along a focal plane. The collectors are attached to single pin feedthroughs that pass the current through the vacuum envelope to four electrometer amplifiers which amplify the small currents to provide output voltages that are proportional to the ion currents. The output signals are therefore proportional to their respective partial pressures. The internal vacuum necessary for operation of the analyzer is maintained by a suitable high vacuum pump, which is connected to the mass spectrometer by means of a pump tube.

The Two Gas Atmosphere Sensor mass spectrometer analyzer assembly is shown in Figure 28. The vacuum envelope, permanent magnet, single pin feedthroughs and the pump tube are clearly visible. The multipin feedthroughs, which are visible in the ion source housing, provide the voltages that operate the ion source filament and focusing electrodes.

REQUIREMENTS FOR THE NINETY-DAY TEST

The requirements for the Ninety-Day Space Station Simulator (SSS) application were to monitor the partial pressures of nitrogen, oxygem, carbon dioxide, and water vapor using a modified Two Gas Atmosphere Sensor. The principal requirements are summarized in Table 4.

The instrument was to be located within a specified volume within the SSS and was to provide continuous outputs within a specified tolerance for the entire ninety-day period without requiring recalibration. In order to provide information for engineering evaluation of the instrument's performance, a method of making calibration verification was required. The instrument was to be provided with the necessary support equipment to maintain its internal vacuum through a power failure. Dual outputs were necessary for internal signal monitoring by meters as well as voltage outputs to be monitored by the computer system external to the SSS.

TABLE 4

Requirements For Ninety-Day SSS Atmospheric Sensor

Monitored Species:	H_2O, N_2, O_2, and CO_2
Monitored Masses:	m/e 18, m/e 28, m/e 32, and m/e 44
Full Scale Ranges:	20 torr, 500 torr, 200 torr and 120 torr respectively

APPENDIX F

TABLE 4 (Concluded)

Total Pressure:	Nominally 10 lbf/in^2 abs (psia) or 517 torr
Configuration:	Limited size consistent with available space and commercial support components
Operating Controls:	None for normal operation. Inlet system valving for initial setup and calibration verification. Power on-off, ion pump and emission current adjusts.
Maintenance:	None
Outputs:	Internal: four meters Remote: four buffered, linear, zero to 5 volts
Performance Monitors:	Anode current, ion pump current, and battery voltage
Sample Inlet:	Sample transport line w/3 inch H_2O head
Nominal Accuracy:	$\pm$2% of full scale for N_2 and O_2 $\pm$3% of full scale for CO_2 $\pm$5% of full scale for H_2O
Environment:	Compatible with operation in the SSS

SYSTEM DESCRIPTION

The description of the Ninety-Day SSS Atmospheric Sensor is facilitated by considering its major system components which are: first, the sample inlet and calibration inlet system; second, the mass spectrometer subsystem, including its vacuum pump; and third, the support electronics subsystem, which includes the electronics required to operate the analyzer and ion pump as well as the output circuits. A block diagram of the system is shown in Figure 22 and can be used for reference in the following discussion. The sample and calibration inlet system, shown in the upper left hand corner of Figure 22, is shown in greater detail in Figure 23 and the front panel of the system is shown in Figure 24.

APPENDIX F

To simplify the system description, each part of the system referred to has been assigned an index number as shown in Figures 23 and 24. Sample gases enter the inlet system from the one-eighth inch sample line at the sample inlet point (1). The sample gas then passes through a needle flow control valve on the front panel of the instrument (2). After passing through the flow controlling valve the sample gas goes to the mode selector valve (3) which determines the mode of operation, that is, operating in the calibration mode or the normally operating sample mode. After passing through the mode selector valve the gas is filtered by a two stage inline filter (4). On the sample outlet corresponding sets of filters (5) are present. The gas mixture then passes through a sample flowmeter (6), which measures the rate of gas flow through the instrument, and therefore, allowing the pressure drops through the inlet system to be checked. After passing through the flowmeter the sample travels past a total pressure transducer (16) and out the sample vent (17). Between the double filters the gas passes through the variable leak valve (7). This variable leak valve is fitted with a temperature control system. The heater switch (8) controls the heater for the inlet valve. The calibration gas mixture is stored in a pressure tank (9) with regulator (10). Passing through the regulator the sample gas goes to a protection shutoff valve (14), and then to a needle flow control valve (15), then to the selector valve (3). Part of the gas to be sampled (either in the sample gas or the calibration gas) passes through the restriction in the leak valve and through a small diameter line (11) into the mass spectrometer (12), and finally to the ion pump (13). There is a roughing valve (25) located within the analyzer chassis for initially pumping down the instrument. The conductance of the variable leak valve can be adjusted by means of a slotted screw adjustment (28) on the front panel. The ion currents coming out of the mass spectrometer are detected and amplified by four electrometers. The electrometer outputs go to the output meters (26) and also to buffered outputs. The zero levels of the electrometers can be checked by pressing the press-to-test button (27) which cuts off the ion beams. The main power to the mass spectrometer is provided by a twenty-eight (28) volt, direct current (dc) power supply, requiring a 115 volt, alternating current (ac) input.

There is a front panel switch (18) that controls the operation of the twenty-eight volt power supply. Other items on the front panel are the ion pump meter switch (19) and the ion pump current meter (20), which monitor the current flowing to the ion pump from the high voltage supply, and therefore, indirectly monitor the analyzer pressure. There are two other meters on the front panel of the Analyzer Control Module. One of these is the battery voltage indicator (21), which indicates the stage of readiness of the emergency batteries that are used for powering the ion pump in a power off situation. The other front panel meter is the anode current meter (22), which

measures the anode current and provides an indication of the sensitivity at which the source is being operated. The anode current may be adjusted only in the open loop mode by the anode current adjustor potentiometer (23). The mode of operation, open or closed loop, is controlled by a selector switch (24) on the front panel.

An important feature of the system is the closed loop mode of operation, which automatically compensates for any common mode variations. The four electrometer outputs are scaled to provide signals that are all proportional to pressure with the same volt per torr sensitivity and are summed to give a "total pressure" signal. Since the four components of interest comprise essentially all of the atmosphere this signal can be compared with the output of a total pressure transducer, which is reflecting the true pressure seen by the sample inlet system. The resulting error signal represents the sensitivity error of the mass spectrometer. This signal is fed back to the emission regulator that controls the level of ionizing electron current in the ion source and, thereby, the levels of the ion currents which are detected at the collectors. In this way the summation of the partial pressures is held at the prevailing ambient pressure level and, consequently, common mode variations due to such factors as changes in the inlet leak conductance or ion source sensitivity are eliminated. This method of operation represents a significant improvement in mass spectrometer design and allows a high level of accuracy to be maintained for a long period of time.

Other elements of the system, which are shown in Figure 22, are the power supplies that provide voltages to the ion source, the ion pump and its high voltage power supply, the power supply system, the front panel control and monitoring functions, and the output buffer amplifiers.

The complete Ninety-Day SSS Atmospheric Sensor is shown in Figure 12 and the internal construction of the upper and lower bays is shown in Figures 8 and 11 respectively. The upper bay contains the mass spectrometer, ion pump, their support electronics, the sample inlet and calibration inlet systems, and the calibration gas supply. The lower module houses the main power supply, the battery pack and charger, the buffer amplifiers, output and monitoring meters, and the buffer amplifiers and pressure transducer power supplies.

APPENDIX F

CALIBRATION

The Atmospheric Sensor was calibrated using a calibrated gas mixture of nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2). In order to calibrate the instrument as close as possible to the expected operating conditions the calibration gas was admitted to a laboratory inlet system in which the pressure was held at 10 lbf/in^2 abs (psia) (517 torr) and, from this reservoir, it was introduced into the mass spectrometer inlet system. The volt per torr sensitivity, at the electrometer amplifier output of each channel, was computed and this information was utilized to adjust the summing resistors so that the current arriving at the summing junction of the summing operational amplifier from each channel has the same ampere per torr sensitivity. Then the gains of the buffer amplifiers are set so that the proper full scale value for each channel is achieved at five volts. During the dry gas calibration the pressure was exercized between 400 and 634 torr to verify that the channels were tracking pressure. This is a plus or minus twenty-two and six-tenths ($\pm$22.6) percent pressure variation, which is much greater than the expected variation of the SSS atmospheric pressure. The final calibration data over this pressure range is shown in Table 5.

TABLE 5

Table of Calibration Errors at Final Calibration

Pressure	Error		
	N_2	O_2	CO_2
400 torr	+0.37%	-0.85%	-2.86%
517 torr	-0.01%	+0.01%	+0.31%
634 torr	-0.29%	+0.58%	+2.87%

The water vapor channel was calibrated by allowing the inlet system to sample laboratory air and comparing the water vapor electrometer output with the partial pressure, as computed from the relative humidity indicated by a wet bulb - dry bulb Mason's form hygrometer. Since the instrument was sampling at one atmosphere during this test, the variable inlet leak valve was closed down to maintain the normal internal partial pressures. The water sensitivity was compared with the nitrogen sensitivity, as determined from the air composition, and this data was utilized to set the water vapor channel summing resistor and buffer amplifier gain.

APPENDIX F

OPERATIONAL RESULTS

During the five-day test run the calibration of the Atmospheric Sensor was verified twice by admitting a calibration gas sample. During the first verification the gains of the buffer amplifiers for the dry gas channels were reset. At this time it was discovered that the oxygen buffer amplifier gain had somehow shifted during the process of shipment, inspection and installation, however, the other buffer amplifiers were very close to their proper values. The data from this calibration verification and a second one taken later during the run is shown in Table 6. In both cases the error is less than one percent on all dry channels.

During the five-day test it was found that the water vapor channel was reading high compared with the Cambridge Dew Point Hygrometer. The dew point indicator was reading 11.3 torr, while the mass spectrometer was reading 23.1 torr, with a buffer amplifier output of 4.68 volts. Just prior to the end of the run the buffer amplifier was adjusted to provide an output of 2.82 volts based upon an 11.3 torr partial pressure and a desired system gain of 20 torr/five volts. This correction provided the proper water output, but it did not correct the summing resistor for the water channel, which was also apparently in error. One effect of this adjustment is seen in the data presented in Figure 26, which shows the error between the sum of the partial pressures, as indicated by the mass spectrometer, and the total cabin pressure, as measured by the Wallace-Tiernan gauge. During the five-day run the sum of the partial pressures agreed with the total pressure within one percent or better except for the final reading, which was 2.9 percent low. This final value was taken after the water vapor channel was readjusted and the additional two percent error amounts to an error of 10.5 torr at 525 torr total pressure, which is very nearly equal to the 11.8 torr error that existed in the water output prior to adjustment of the buffer amplifier.

This error results from the action of the closed loop, which makes up for the erroneously high water vapor electrometer amplifier output by dropping the ionizing current to achieve the correct total pressure. Reduction of the water vapor buffer gain led to a low value for the summation of the partial pressures.

TABLE 6

Results of Calibration Verification During the Five-Day Test

	ERRORS, PERCENT			
	N_2	O_2	CO_2	pp
INITIAL	+0.23	+0.23	+0.47	+0.23
FINAL	-0.91	-0.71	-0.70	-0.84

During the ninety-day test the Atmospheric Sensor performed without malfunction. Five calibration verifications were run during the course of the test and the data from these is presented in Table 7. This data shows that the mass spectrometer maintained its calibration within very close tolerances. The last adjustment of the instrument was made on 30 April 1970. Therefore, the analyzer maintained its calibration on nitrogen, oxygen, and carbon dioxide within 0.9. 2.1 and 2.7 percent, respectively, for a period of 132 days. The sum of the dry gas partial pressures remained within 0.84 percent during the same period. It is difficult to evaluate the performance of the instrument by any means other than the calibration verification data. Typical output data for the instrument is shown in Figure 21, Sheets 1, 2 and 3. This data was taken from the computer reduced data obtained on the MDAC Low Speed Data Acquisition System at 1800 hours on each day of the test. This time was selected because it was considered the most "normal", with the least unprogrammed activity, and should give a more representative picture of the cabin atmosphere from day to day.

Figure 21, Sheet 1 of 3, shows the variations in the oxygen and nitrogen partial pressures; Figure 21, Sheet 2 of 3, the variations in the carbon dioxide and water vapor partial pressures; and Figure 21, Sheet 3 of 3, the variation in the cabin pressure, the sum of the partial pressures and the difference between these two values. A cursory review of the data has indicated that the fluctuations in the partial pressures are usually accounted for by specific known events that occurred within the SSS. The oxygen partial pressure was controlled within a total variation of 2.9 torr or better than $\pm$1.0 percent. The total pressure variations are much wider, primarily due to a lower gain in the nitrogen make up portion of the atmospheric control system. The variations in the carbon dioxide and water vapor partial pressures reflect changes in the status of the solid amine and molecular sieve carbon dioxide scrubber systems. The summation of the partial pressures is consistently low because of the incorrect summing resistor in the water channel, as predicted by the last data point taken during the five-day test run. This effect from the water channel is further substantiated by comparing the correlation between the water vapor output and the error in the summation of the partial pressures. Note that whenever

the water vapor level goes up the summation of the partial pressures goes down and visa versa. This is exactly what was expected from a detailed analysis that was made of the interchannel effects of an incorrectly established summing resistor.

TABLE 7

Results of Calibration Verification During the Ninety-Day Test

		Error, Percent			
DATE	TIME	O_2	N_2	CO_2	pp
6-13	1315	+1.1	+0.1	-1.5	+0.4
6-18	1902	+0.7	-0.4	0.0	0.0
7-8	1135	+0.9	-0.6	+0.8	0.0
7-13	1346	+1.3	-0.5	+0.6	0.0
9-9	0250	+2.1	-0.3	+2.7	+0.1

During the course of the ninety-day test it was found that the carbon dioxide output of the mass spectrometer was not in agreement with the infrared analyzer. Consequently, on 21 August 1970 a portion of the gas utilized to make the initial calibration of the mass spectrometer was sent to the laboratory that made the original mixture analysis. The results are shown in Table 8.

TABLE 8

Comparison of Calibration Gas Analyses

	Mixture 7130P	
Component	1/30/70	8/21/70
Nitrogen	66.166	66.336%
Oxygen	31.271	31.632%
Carbon Dioxide	2.544	2.012%

APPENDIX F

Note that the calibration for carbon dioxide changed by more than twenty (20) percent. If the later calibration figures are utilized the agreement with the infrared analyzer is very close. There is no reason to suspect that the calibration gas changed during this period, and therefore, it must be concluded that the original calibration was in error.

At the conclusion of the ninety-day test the Atmospheric Sensor was shut down and returned to Perkin-Elmer Aerospace Division, where it is now being operated on laboratory ambient atmosphere for a period of 180 days.

CONCLUSIONS

The Atmospheric Sensor was shown to be a reliable and accurate instrument for monitoring nitrogen, oxygen, carbon dioxide, and water vapor during the course of the Ninety-Day Manned SSS Test. It demonstrated its capability not only for monitoring these constituents, but to provide outputs that could be utilized by an atmospheric control system for regulation of the primary atmospheric constituents of a closed environment. The closed loop operating mode controlled the sensitivity of the mass spectrometer so that it could operate for a period of 132 days without calibration. The accuracy of the outputs was affected by the initial calibration, which was found to be in error because of a faulty calibration technique in the case of water vapor, and an inaccurate calibration gas mixture in the instance of carbon dioxide. These procedural matters have been rectified and should allow the Atmospheric Sensor to perform to its full capability in future applications.

The Ninety-Day Manned SSS Test was intended to prove out equipment for application to future space stations. Therefore, assessing the feasibility of reducing the size, weight and power of the Atmospheric Analyzer to levels that are compatible with a flight program is important. A contract, under the direction of NASA Manned Spacecraft Center, is currently in progress for the development of a flight qualified Mass Spectrometer Atmospheric Sensor System (M.A.S.S.) as well as a modified version to be used as a respiratory gas analyzer as part of the M-171 Metabolic Analyzer, which will be used in Skylab in 1972. A photograph of the instrument is shown in Figure 29.

These units are fully self-contained, requiring only a sample inlet and bypass line, a small diameter vacuum line to outer space for initial roughing of the mass spectrometer, system power, and command functions for the ion pump mass spectrometer electronics, open loop/closed loop control, and selection of one of the dual ion source filaments. The system is fully

protected against operation at excessive pressures and provides status indicator outputs on all important functions that can change during operation. The inputs and outputs are fully isolated and protected and the instrument has sample inlet heaters and ion source temperature control for improved performance.

The design is fully compatible with Apollo and Skylab environments including a 38 lbf/in2 abs over-pressure requirement. The atmospheric monitoring version of this instrument measures the partial pressures of hydrogen, water vapor, nitrogen, oxygen, carbon dioxide, and hydrocarbons in the mass range 50 to 120 u (amu). The final configuration of this sytem weighs 21 pounds, requires 19 watts of power during normal operation and has a cylindrical enclosure with a diameter of 7.2 inches and a length of 12.5 inches. The first design verification test unit of the M.A.S.S. is scheduled for delivery to NASA/MSC in November 1970.

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APPENDIX G

TWO GAS SENSOR SYSTEM EXTENDED 180-DAY TEST REPORT

APPENDIX G

TWO GAS SENSOR SYSTEM EXTENDED 180-DAY TEST REPORT

By J.H. Stuart
Perkin-Elmer Corporation
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Pomona, California

Upon return of the instrument to Perkin-Elmer Aerospace Division (ASD), following the ninety-day test at McDonnell-Dougals it was set up and operated in the standby mode while a close visual inspection was made to determine the physical condition of the instrument.

The visual inspection found the general appearance of the instrument to be excellent with the exception of the Ion Pump Power Supply low voltage assembly circuit board and a power resistor suspended from the Temperature Control circuit board. Localized heat discoloration was discovered on the ion pump circuit board in the vicinity of two selectable, fixed base drive resistors and two switching transistors (2N3716). Laboratory tests, conducted prior to delivery of the instrument to McDonnell-Douglas, did not indicate any heat dissipation problems with the transistors or drive resistors. The transistors are properly heat sinked for normal operation and the drive resistors are mounted directly to the circuit board.

An engineering analysis was conducted to determine the probable cause of the high temperatures. From this analysis it was determined that the Ion Pump Control switch, on the front panel of the instrument, had inadvertently been left in one of the Filament Inhibit positions for an excessive length of time. There are specific warnings against operating in this mode for periods exceeding five (5) minutes in the Operation Manual. However, immediately prior to and after the five-day test the instrument was accidentally operated in an inhibit filament mode for several hours.

It was recommended that, since the specification ratings of these power devices had not been exceeded and only the circuit board was damaged, the extended life test be continued. It was also recommended that in the future any systems requiring this ion pump low voltage assembly circuit card use a modified circuit card that provides additional heat sinking of these power devices.

A calibration verification of the system was conducted, with the following results.

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GAS	SYSTEM OUTPUT (Torr)	CALCULATED OUTPUT* (Torr)	% DEVIATION
N_2	482.0	479.0 (65.154%)	+0.6
O_2	247.7	238.3 (32.376%)	+3.9
CO_2	19.3	18.0 (2.448%)	+7.2
H_2O	1.44	-- --	--
	Σ pp = 750.44	Amb Press = 735.9	

This verification was at local atmospheric pressure, sampling internal calibration gas. The calibration was also verified with the instrument sampling ambient air as follows:

GAS	SYSTEM OUTPUT (Torr)	CALCULATED OUTPUT (Torr)	% DEVIATION
N_2	577.50	573.0 (78.03%)	+0.8
O_2	156.50	154.0 (20.99%)	+1.6
CO_2	0.48	0.2 (0.03%)	N/A
H_2O	7.12	Approx 7.0 (55% RH @ 77°F)	--
	Σ pp = 741.60	Amb Press = 734.4 (Includes 1% Argon, 7.2 torr)	

The above results, when compared with the calibration verification data of Table 2 from the ninety-day test did not compare favorably, which was further evidence that the system was not calibrated properly versus total pressure variations.

*Based on West Coast Technical Laboratories calibration on Cylinder No. DL27742 (1-30-70).

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Attempts were made to recalibrate the water (H_2O) channel by the method described in the Statement of Work*** without success. It was decided to recalibrate using ambient air, along with a relative humidity indicator, and three new gas mixtures acquired from Precision Gas Products Co. as follows:

Mixture No.	Cylinder No.	% N_2	% O_2	% CO_2	% A
1	131510	68.74	29.4	1.86	< 200 ppm
2	131495	65.76	31.7	2.54	< 200 ppm
3	131413	63.12	33.7	3.18	< 200 ppm

These sample gasses were also used to reset the oxygen (O_2) and carbon dioxide (CO_2) summing and scaling resistors. The results, as follows, are quite satisfactory.

GAS	SYSTEM OUTPUT (Torr)	CALCULATED OUTPUT (Torr)	% DEVIATION
N_2	572.7	566.7 (78.03%)	+ 1.0
O_2	153.1	152.4 (20.99%)	+0.5
CO_2	0.39	0.22 (0.03%)	N/A
H_2O	7.96	8.12 (33% RH @ 78°F)	-1.9
	Σ pp = 734.15	Amb Press = 734.2 (includes 1% Argon	-0.01

***Item c, Statement of Work, the water vapor channel will be recalibrated using a water/nitrogen mixture of known relative humidity and the scaling and summation resistors will be reset.

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MIXTURE No. 2 (131495)

GAS	SYSTEM OUTPUT (Torr)	CALCULATED OUTPUT (Torr)	% DEVIATION
N_2	482.5	482.7	-0.04
O_2	232.2	232.7	-0.3
CO_2	18.66	18.64	+0.1
H_2O	2.04	N/A	N/A
	Σ pp = 735.4	Amb Press = 736.0	

The system was then set up to sample ambient laboratory air for the 180-day life test and the test commenced. Data was taken on a daily basis and a calibration verification was conducted once weekly using the three sample gas mixtures. Figures 30 through 33 are plots of the daily data, and Figures 34 through 36 are plots of the weekly calibration verification.

Since the commencement of the 180-day test on 11 November 1970, there have been a few incidences which have interrupted the continuity of the 180-day test.

The first occurred on day 31 of the test when in making a comparative check of meter voltages a test lead was accidently shorted across the ion pump circuitry resulting in the loss of filament emission in the analyzer.

Evaluation of the instrument electronics indicated the following failures:

a. Filament Transformer: The insulation between the primary and static shield had been punctured rendering the transformer useless.

b. Series Pass Transistor (2N3720): The shorted filament transformer presented a zero ohm load to this transistor resulting in failure by overheating. The failure mode was an emitter-collector short.

c. Switching Regulator Clamp Transistor (1N3712): Apparently this diode failed from overstress in the reverse direction.

d. Multivibrator Transistor (2N2432): A transistor in the multivibrator for the electrode bias supply failed with a collector-emitter short.

Since the above items all ran from the same twenty (20) volt, direct current (dc) power line, it was assumed that the test error involved only these circuits. The discrepant items were replaced and data was taken for comparison with previous runs. A discrepancy of plus three percent (+3%) in the summation of the partial pressures, compared to the total pressure was observed, so further analysis was made and the difficulty appeared to be a shifting zero point in the pressure transducer. The problem was finally traced to a faulty scaling resistor in the pressure transducer summing circuit. This resistor was replaced and the instrument was operating normally again. This was day 41 of the 180-day test.

The second was the loss of the ion pump current meter scaling resistor. The resistor changed from the designated value of 69.8 ohms to 2.1 k ohms, showing visible physical damage. It is believed that the random ion pump current pulses overstressed an RN55 resistor. It was replaced with a 68 ohm, one watt carbon resistor and no problems have occurred since.

The third was a readjustment of the inlet leak valve on day 63 of the 180-day test. This was done to bring the anode current back to its nominal value of ten (10) microamperes. The anode current drift was due to a drift in the inlet leak valve conductance. At this time, the reason for the conductance change can only be speculated since the conductance change is a physical change and a visual inspection of the valve seal, valve leak actuator mechanism, or heater is required to determine the true cause. The most likely reason, though, is contamination build up at the leak seat.

The most serious problem is the ion pump current pulsing. The pulses occur on a random basis and range from barely noticeable on the 100 microampere pump meter scale to such a large magnitude that they actuate the mass spectrometer filament protection circuit at over 900 microamperes. This problem, though, has not interfered with overall system operation, provided that data is not taken during or immediately after these pulses. Again, though this problem cannot be fully investigated without disassembly of the ion pump, and since the system performance is not degraded, it will not be investigated within the scope of this contract.

The last and least significant was the loss of calibration mixture No. 3. It was lost due to an accidental venting of the bottle. This occurred about day 148 of the 180-day test and since the calibration of the system had been good to this point, it did not warrant the replacement of the third calibration gas. The balance of the calibration data from day 141 is, therefore, for only two calibration gases, as shown in Figure 30 (Sheet 2 of

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CONCLUSIONS AND SUMMARY

A review of the data in Figure 30 shows that the summation of the partial pressures, as measured by the Two Gas Atmospheric Sensor, agrees with the local ambient pressure to within plus or minus one percent ($\pm$1%) constantly for over 180 days of the test. The data shown in Figures 34 through 36, shows the individual channel calibration points at the weekly intervals. The data points are easily within an error band of plus or minus one percent ($\pm$1%).

The Two Gas Atmosphere Sensor has again been shown to be capable of monitoring to within plus or minus two percent ($\pm$2%) the major atmospheric components for an extended period of time, with very little or no maintenance. The only true maintenance point which occurred during the extended period was the readjustment of the inlet leak valve and this could have been left alone with no detrimental effect on overall system operation.

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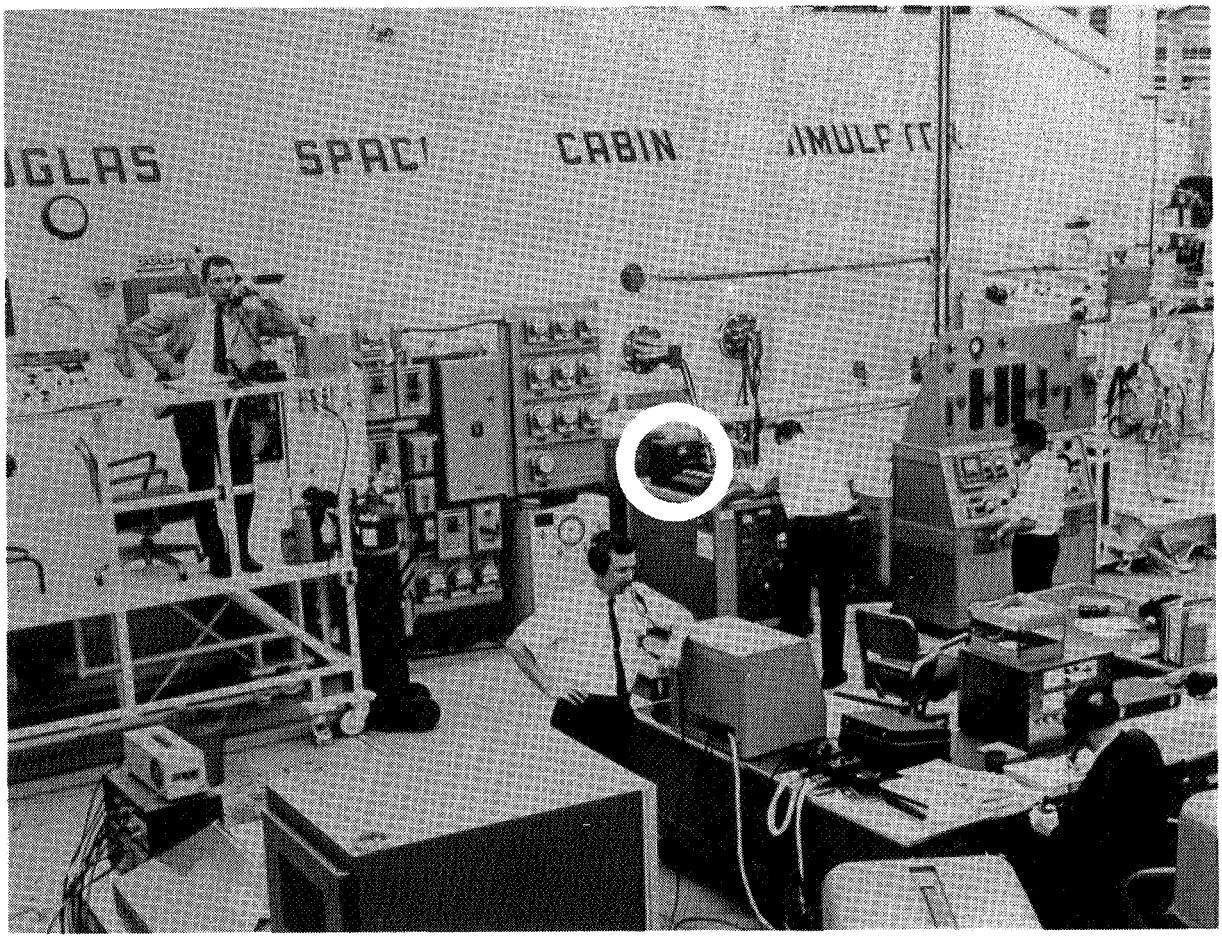


FIGURE 1.- Space Cabin Simulator (60-Day Test)

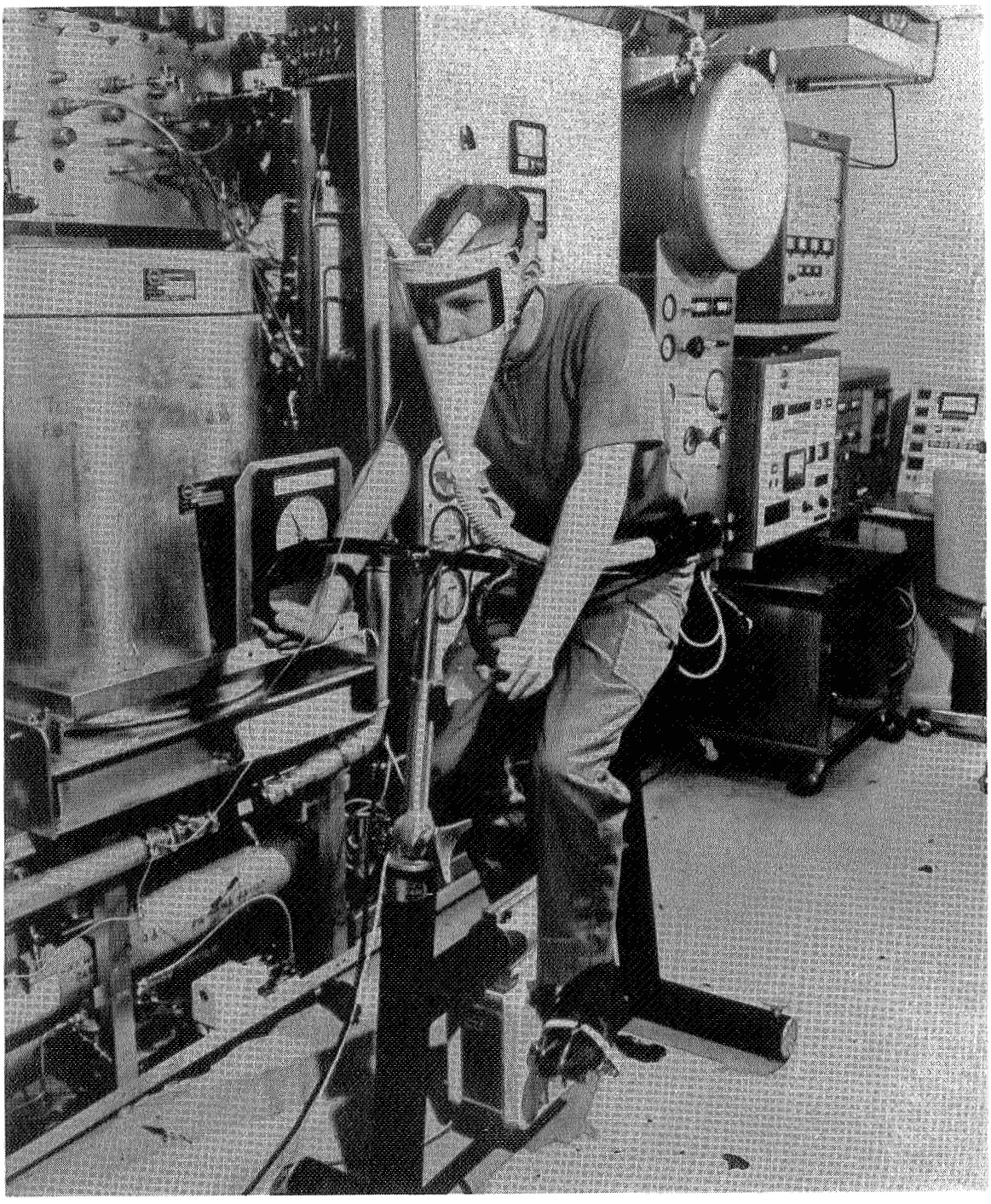


FIGURE 2.- Installation of Two Gas Sensor
For 90-Day Test (Sheet 1 of 2)

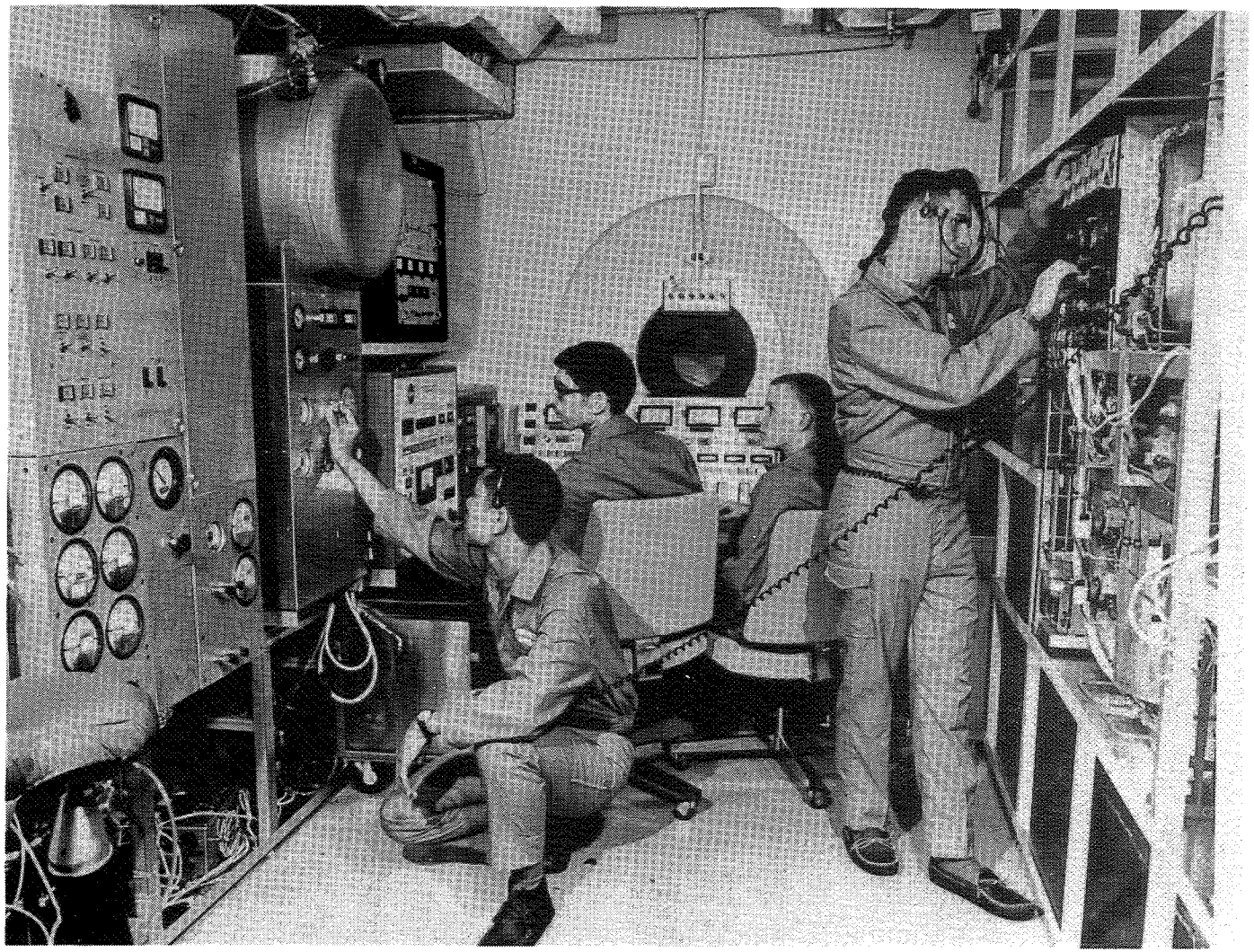


FIGURE 2.- Installation of Two Gas Sensor
For 90-Day Test (Sheet 2 of 2)

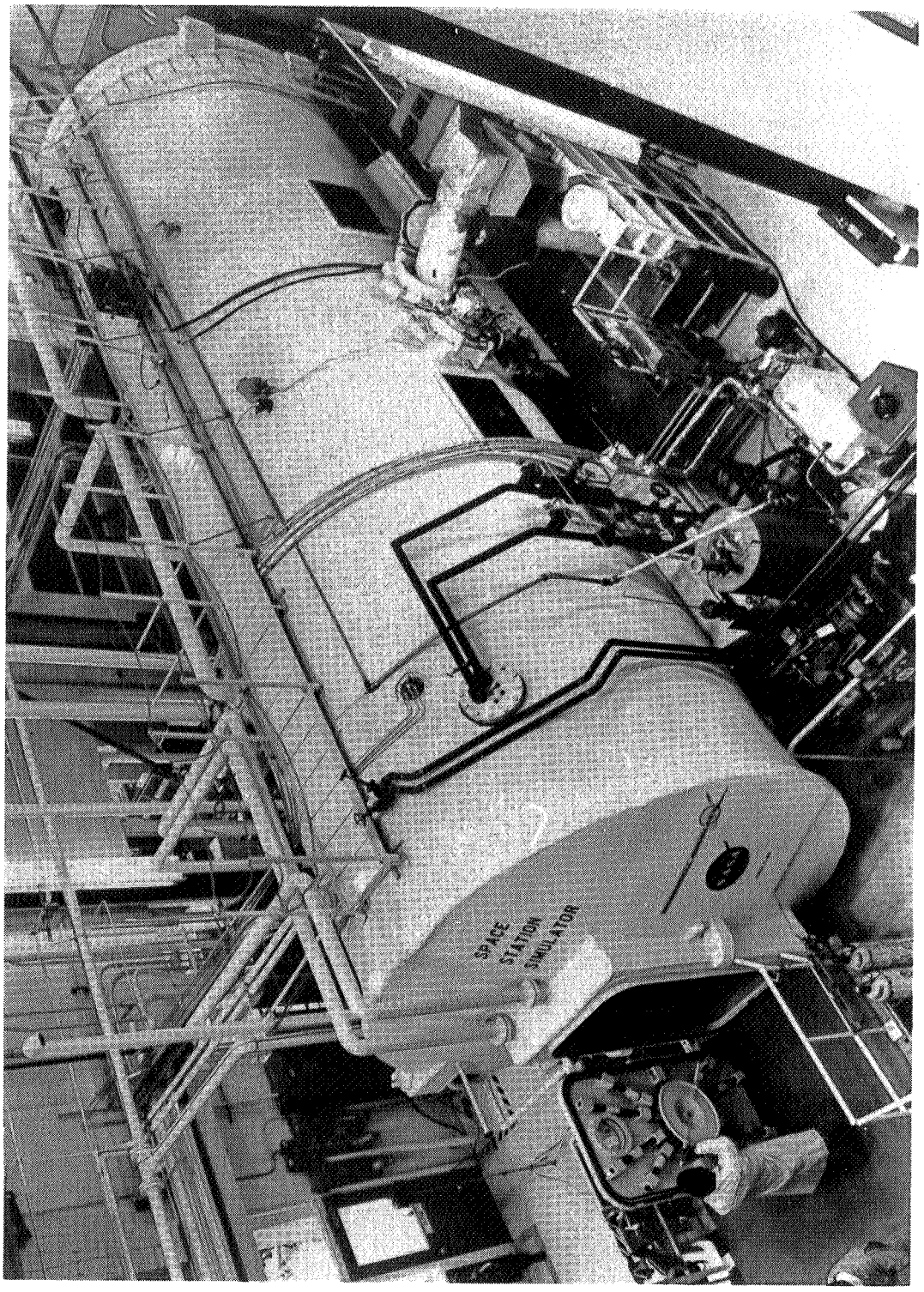


FIGURE 3.- Space Station Simulator (90-Day Test)

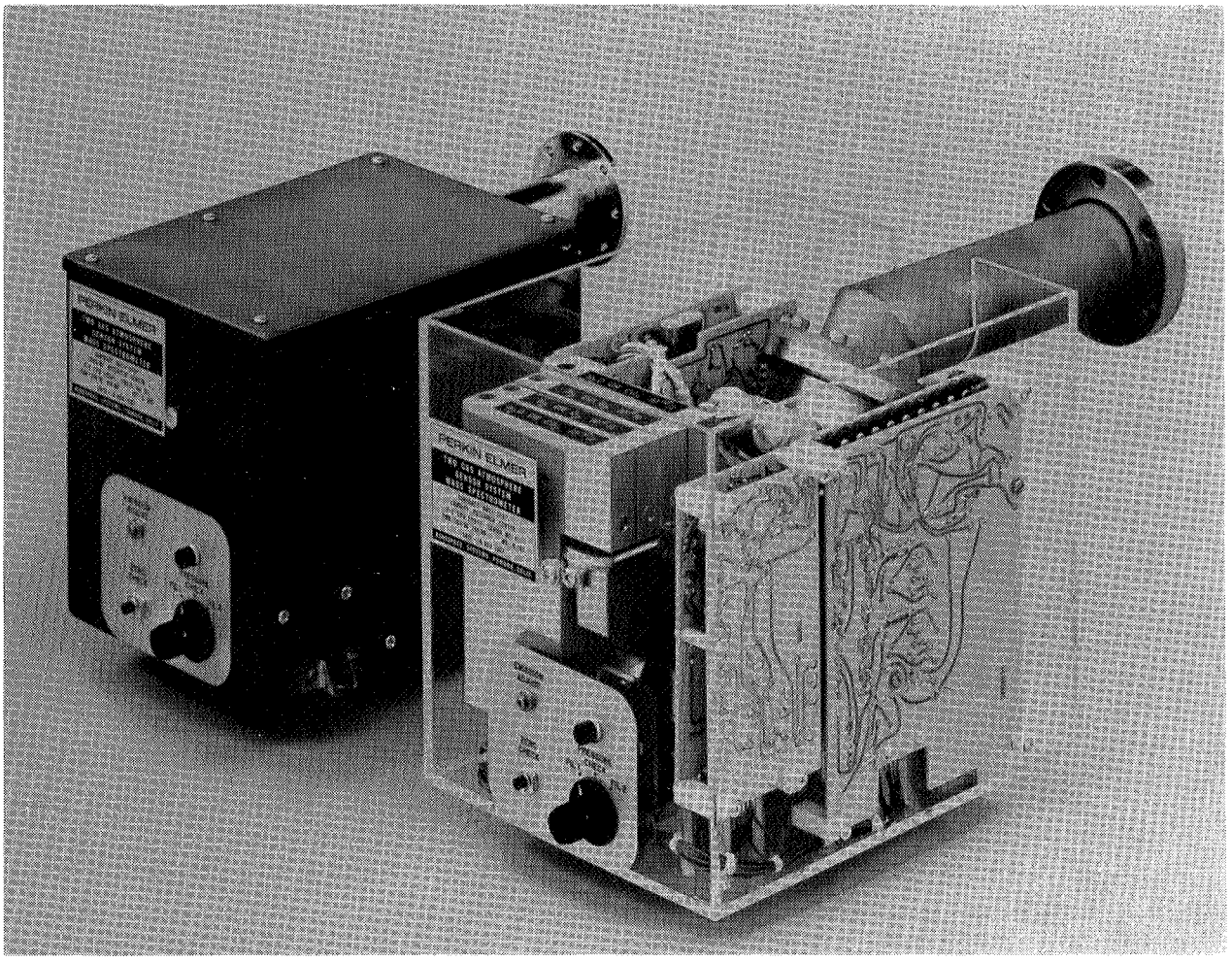


FIGURE 4.- Two Gas Atmosphere Sensor System

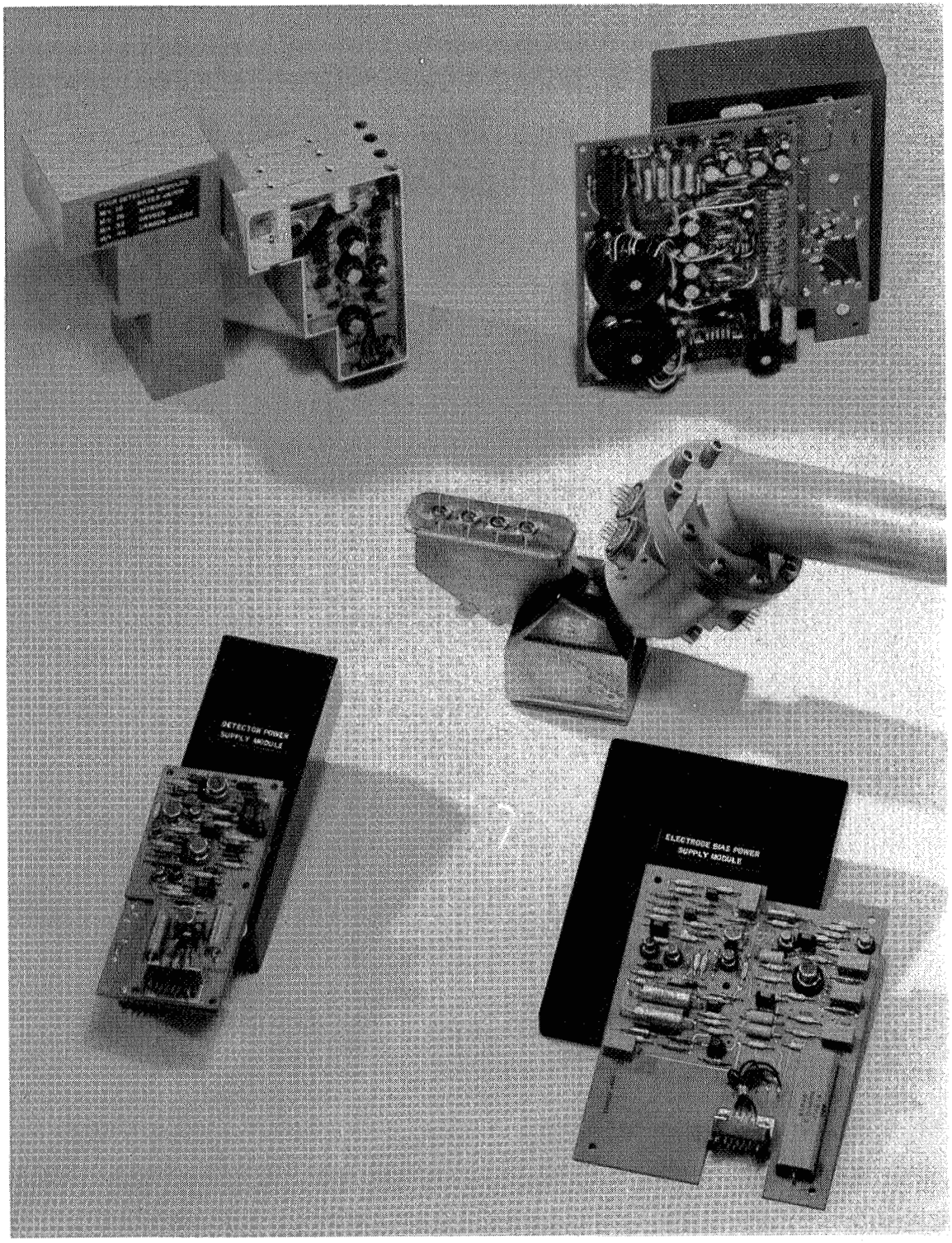


FIGURE 5. Two Gas Sensor Ion Source and Electronics

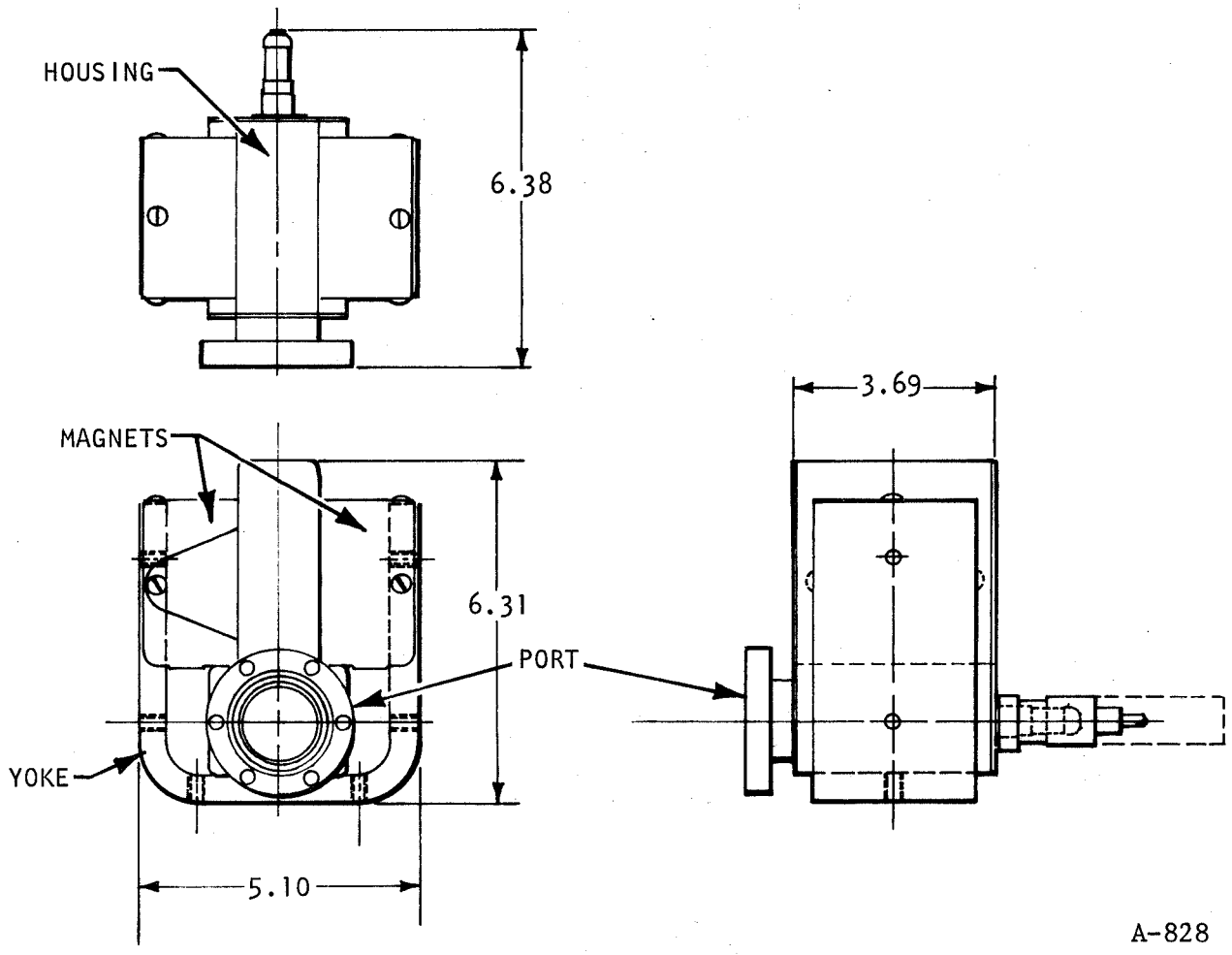


FIGURE 6.- Ultek 8/11 Liters per Second D-I Ion Pump

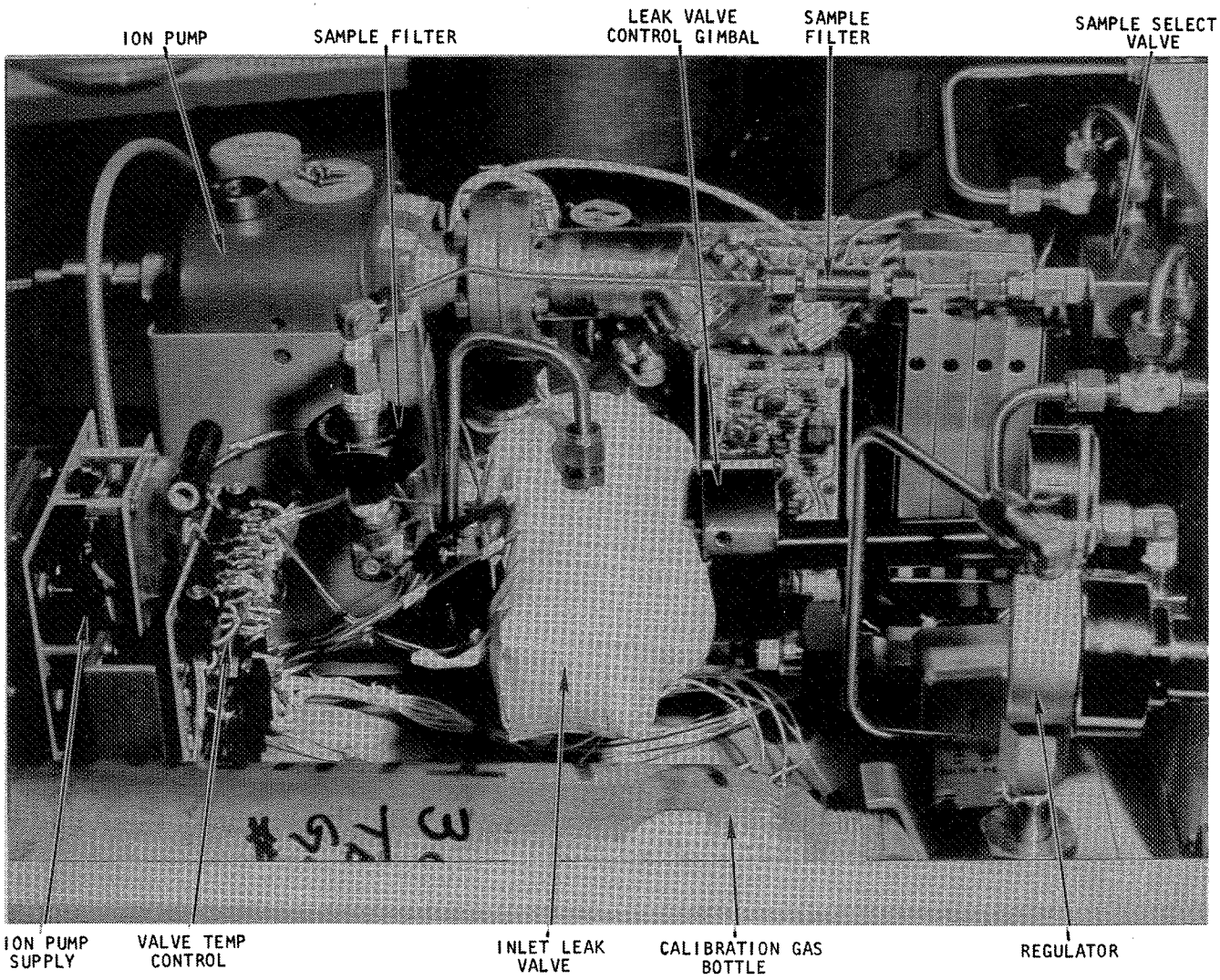


FIGURE 7.- Ultek D-I Ion Pump Installation

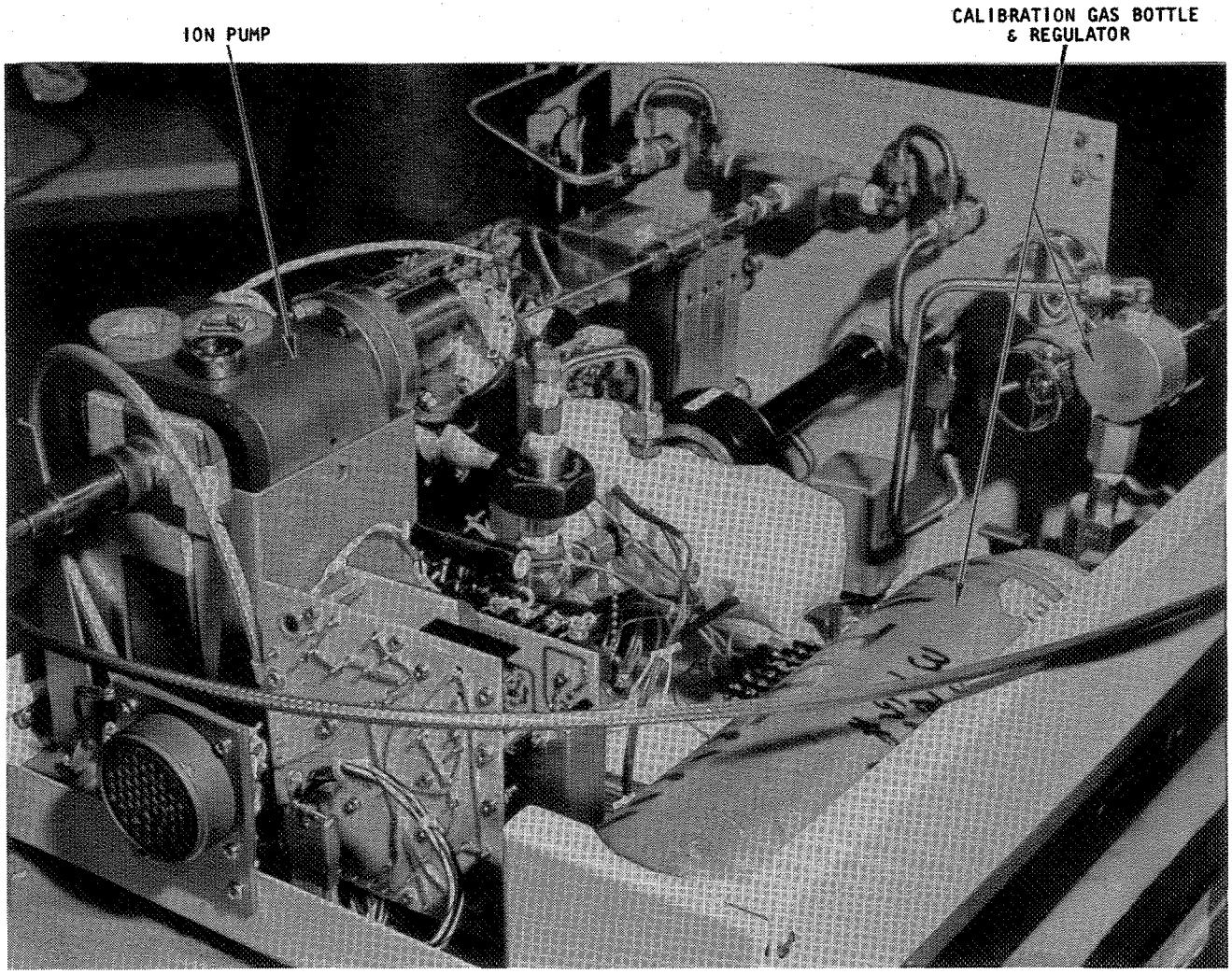


FIGURE 8.- Inlet System Installation

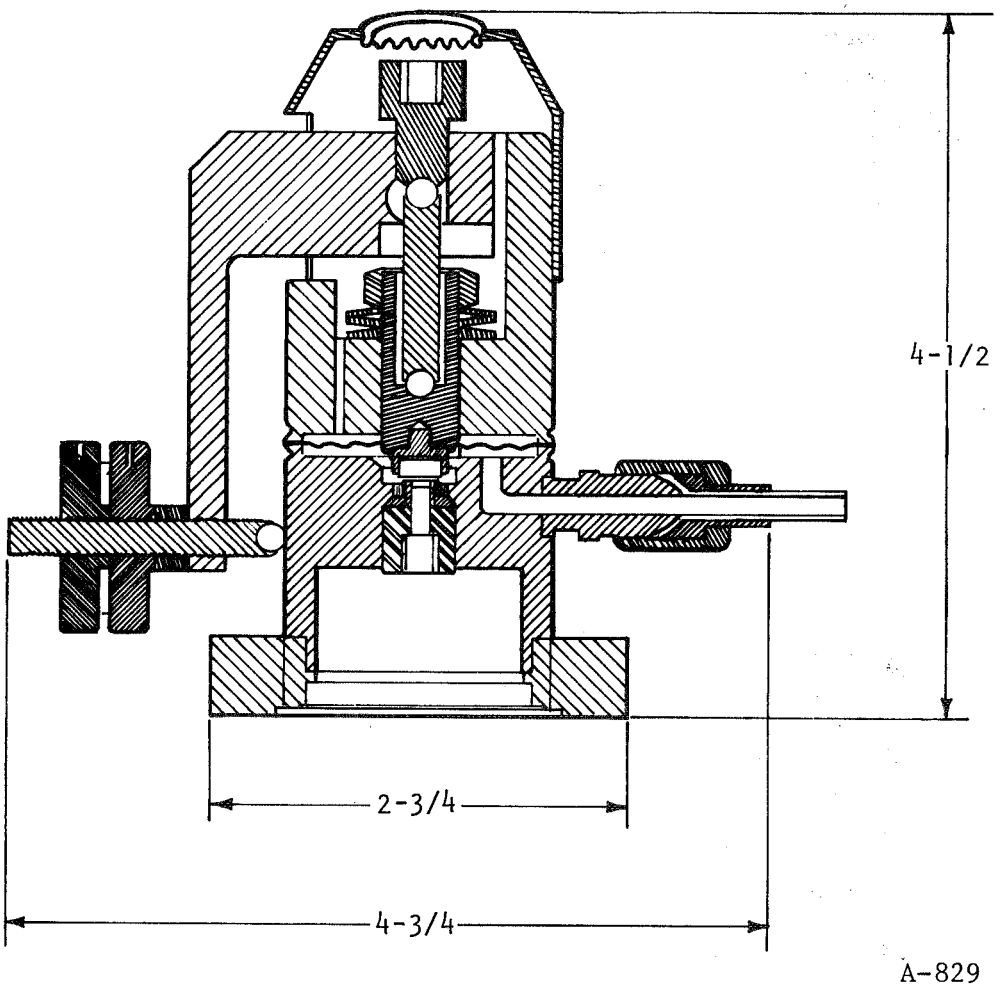


FIGURE 9.- Variable Leak Valve Section Drawing

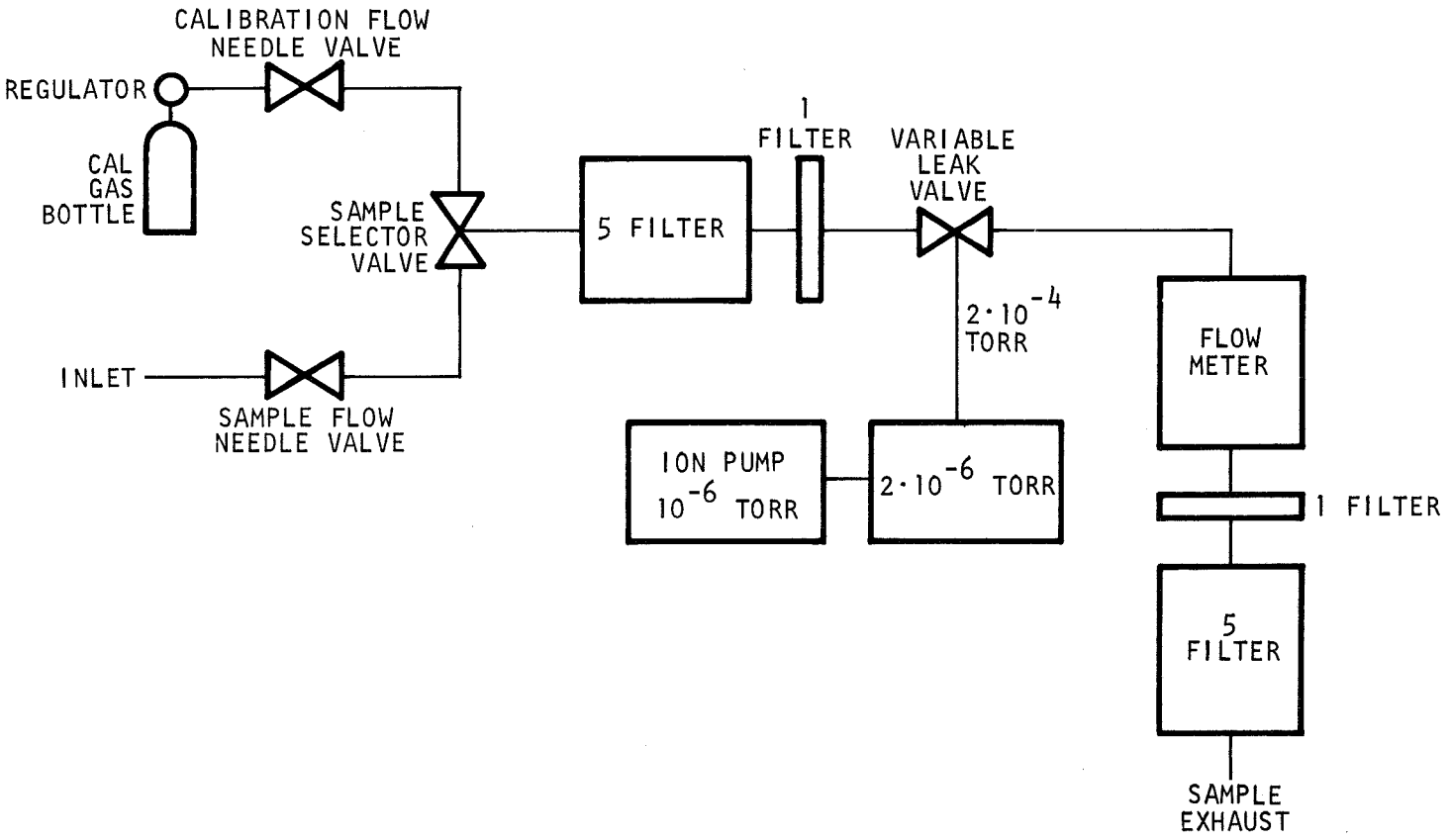


FIGURE 10.- Inlet and Vacuum System Schematic

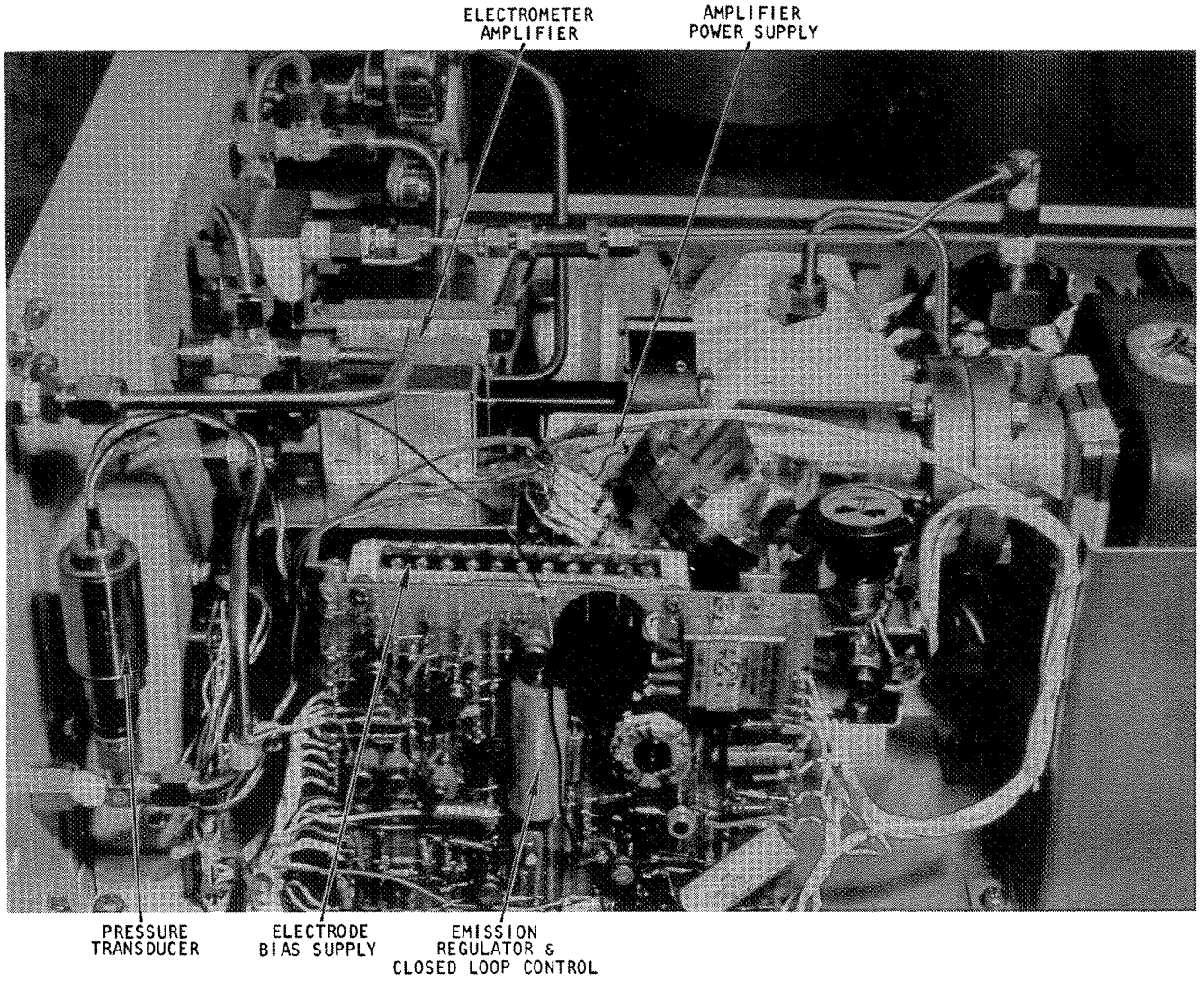


FIGURE 11.- Two Gas Sensor Electronics Subsystem (Sheet 1 of 3)

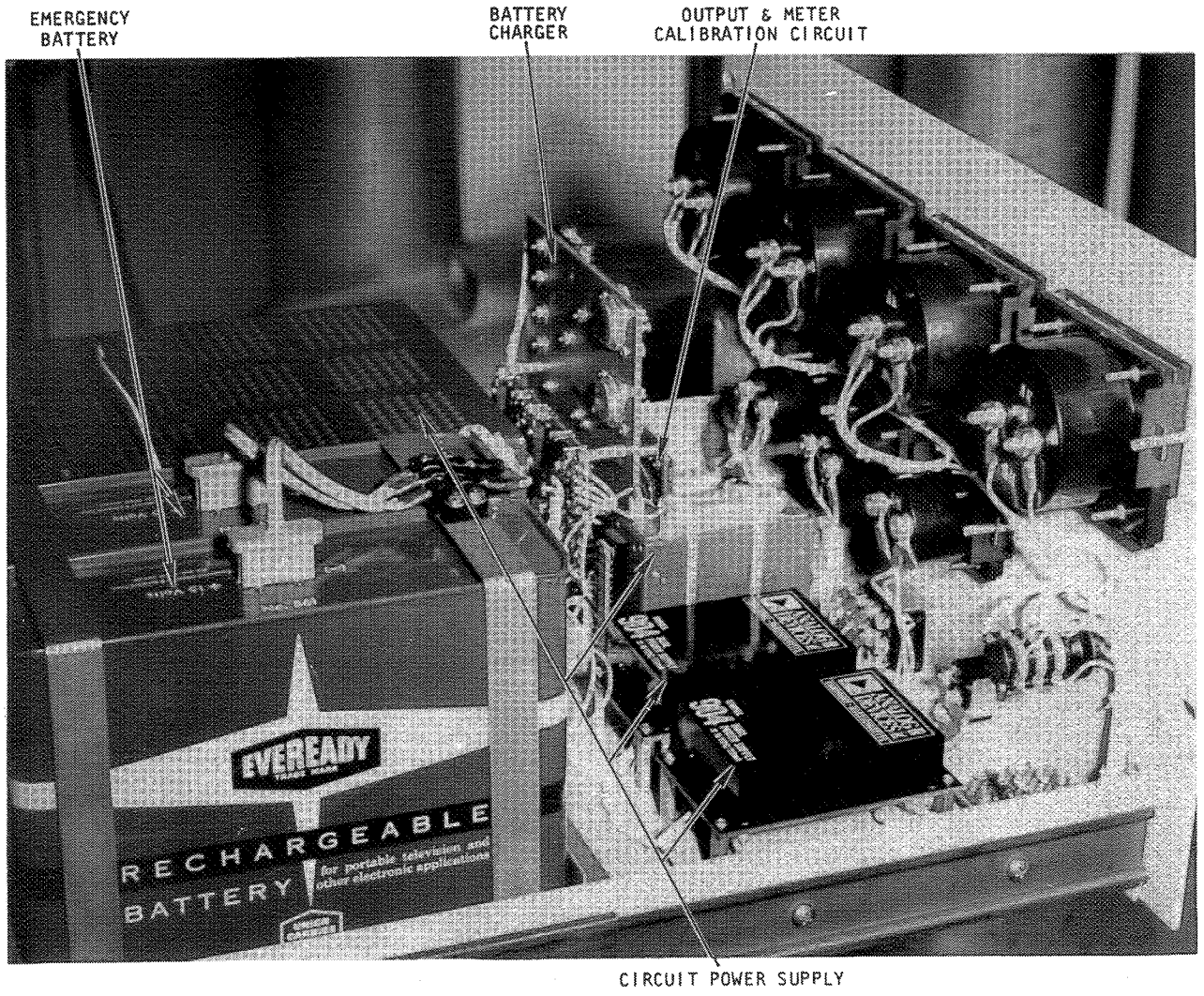


FIGURE 11.- Two Gas Sensor Electronics Subsystem (Sheet 2 of 3)

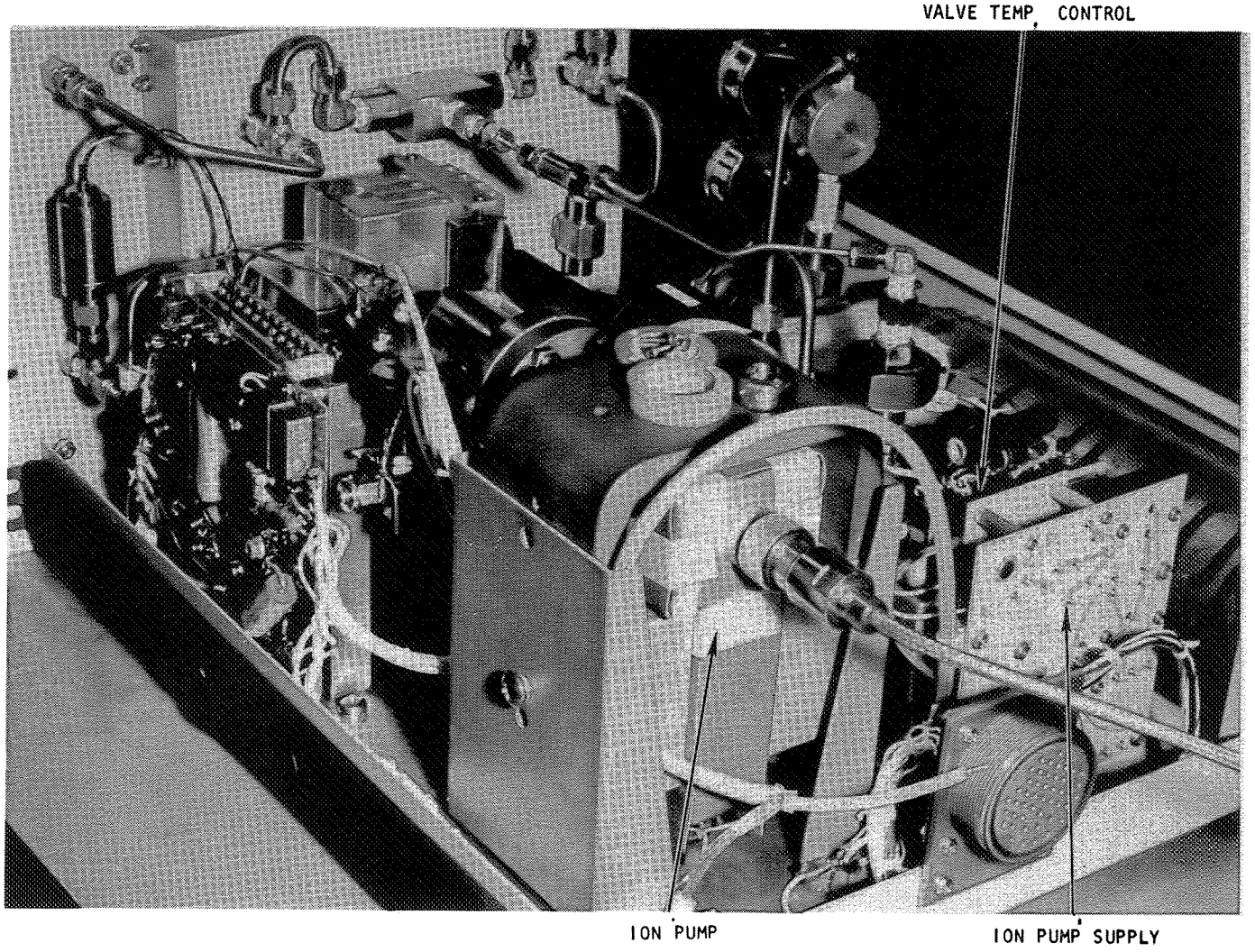


FIGURE 11.- Two Gas Sensor Electronics Subsystem (Sheet 3 of 3)

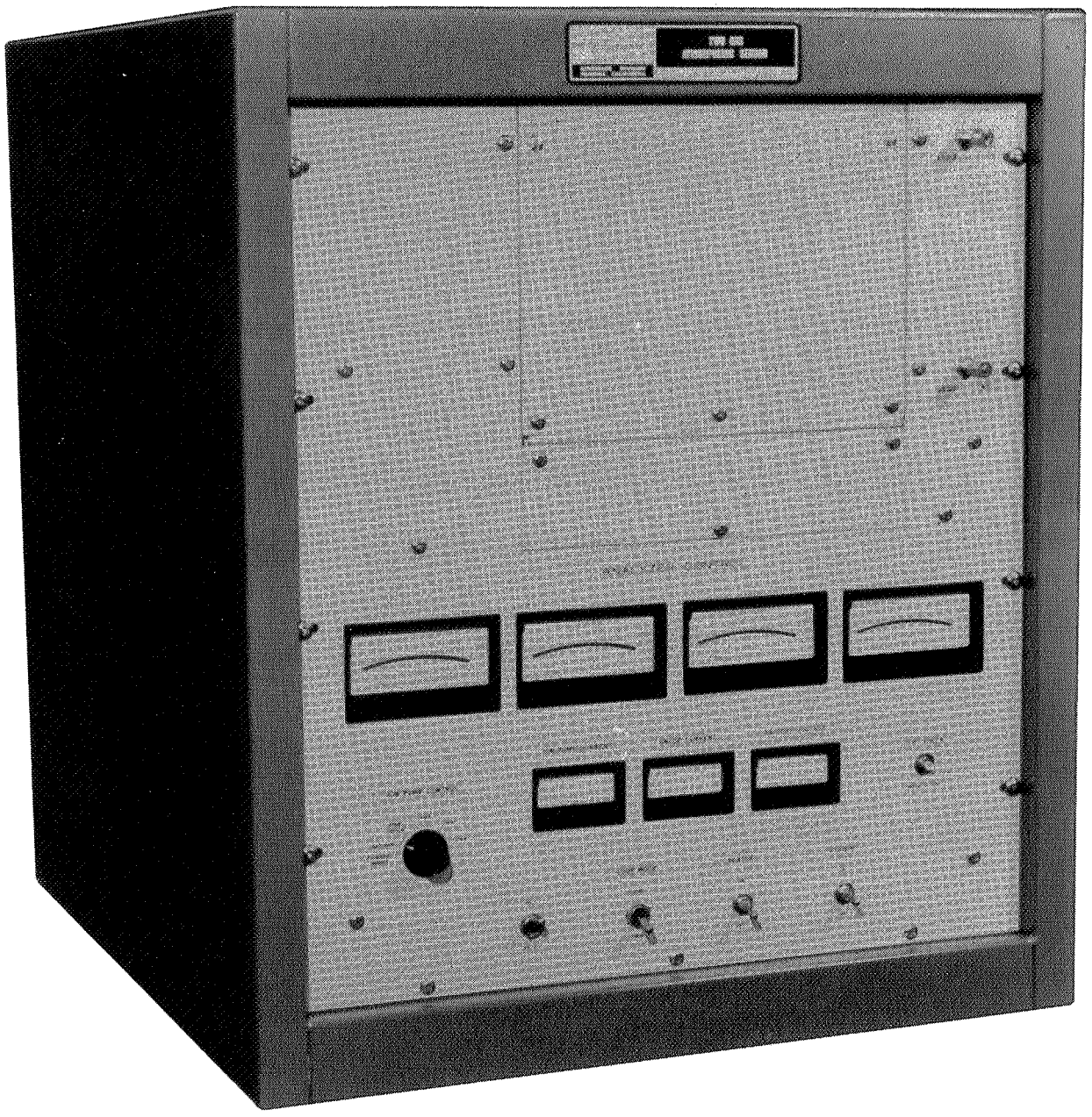


FIGURE 12.- Two Gas Atmospheric Sensor Enclosure

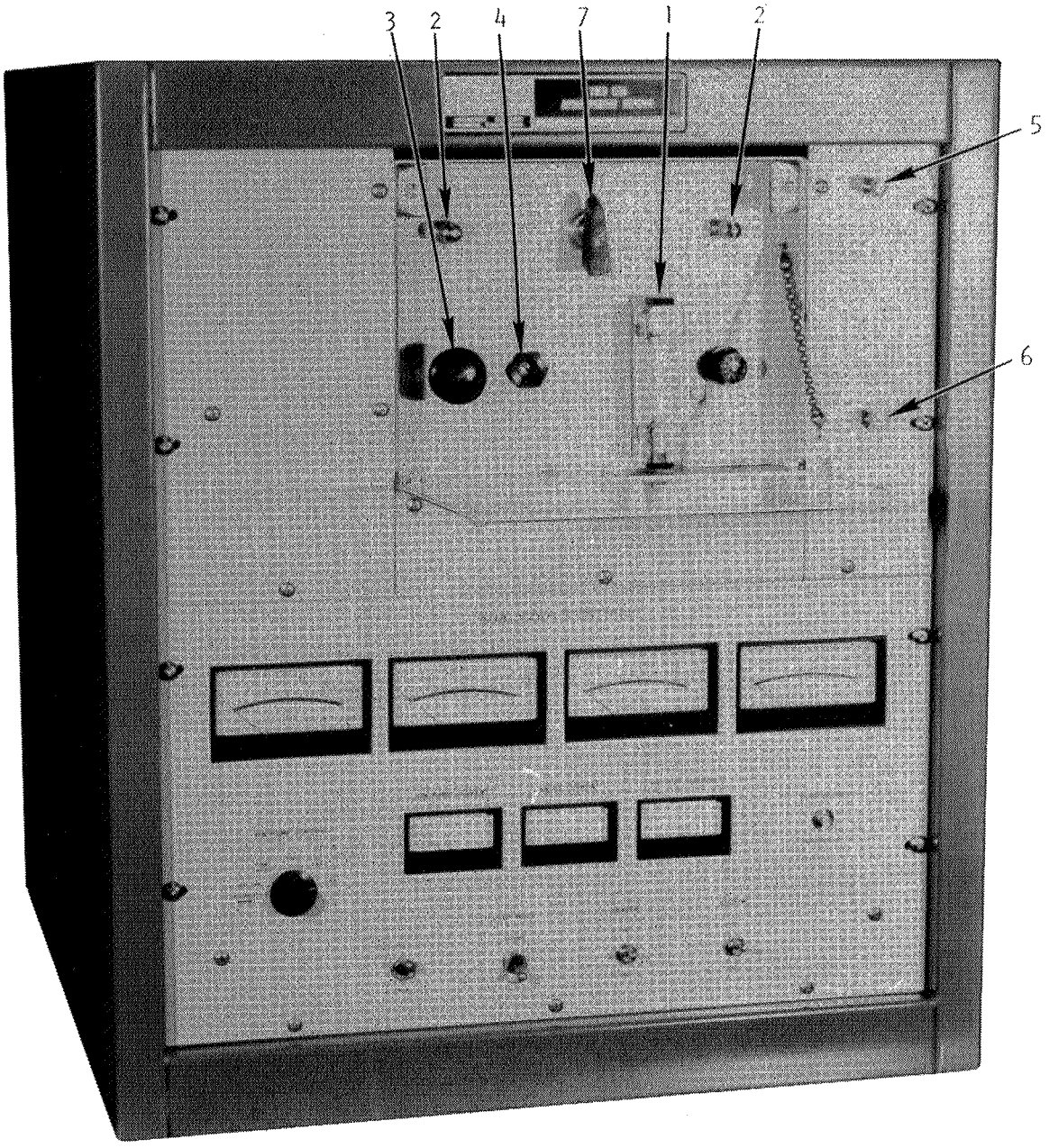


FIGURE 13.- Two Gas Atmospheric Sensor Enclosure
(Recessed Panel Open)

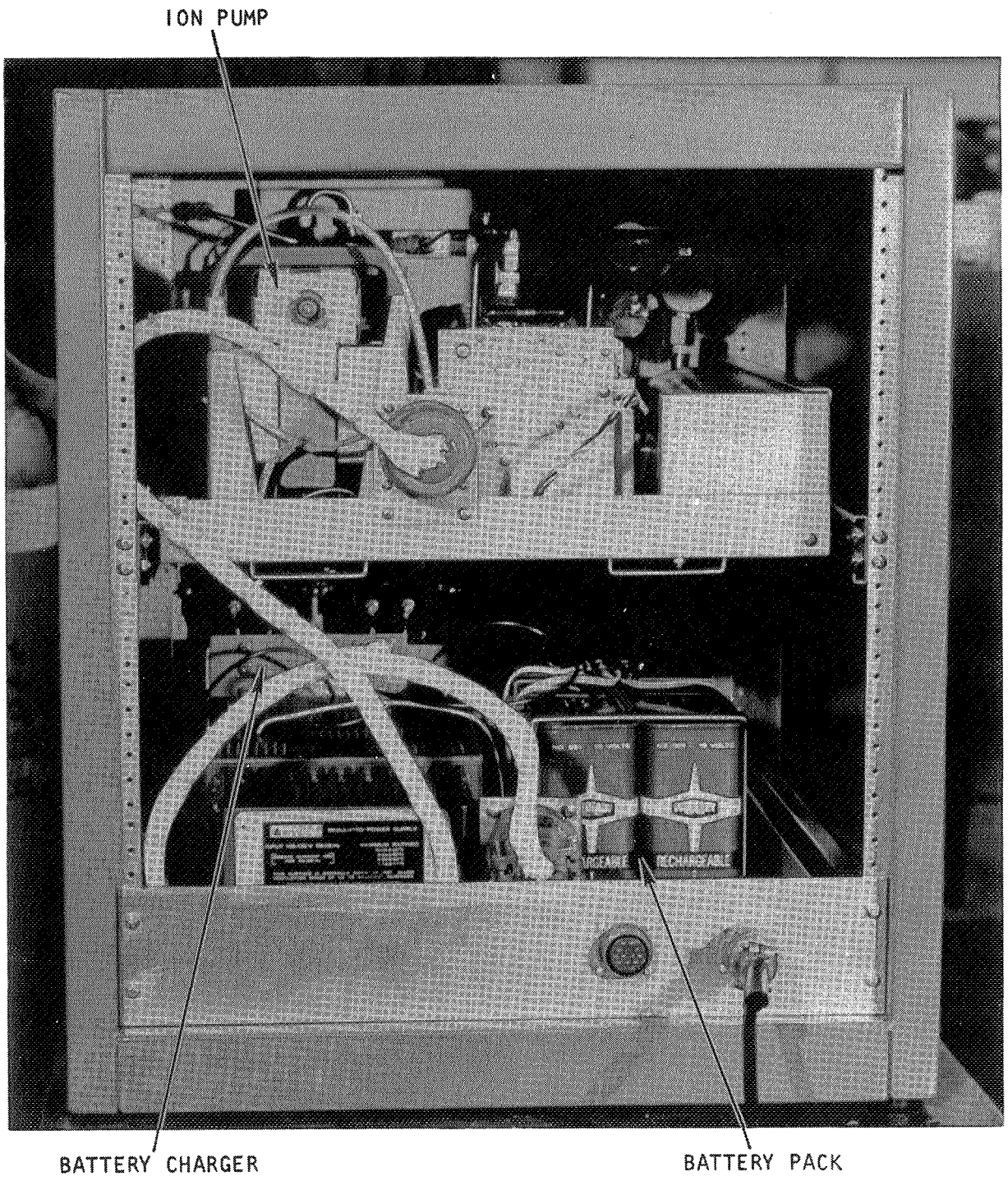


FIGURE 14.- Two Gas Atmospheric Sensor Battery Pack Installation

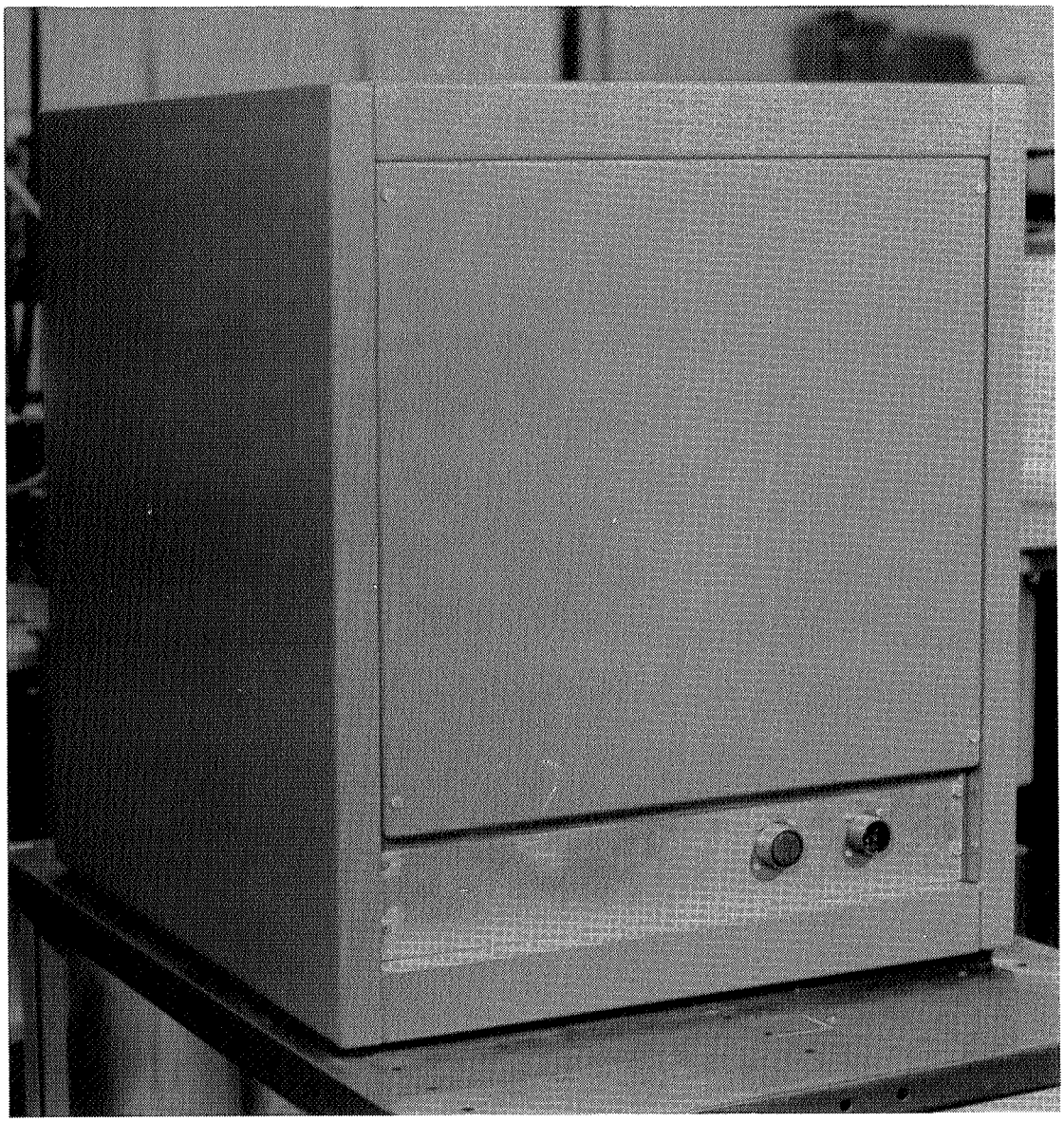
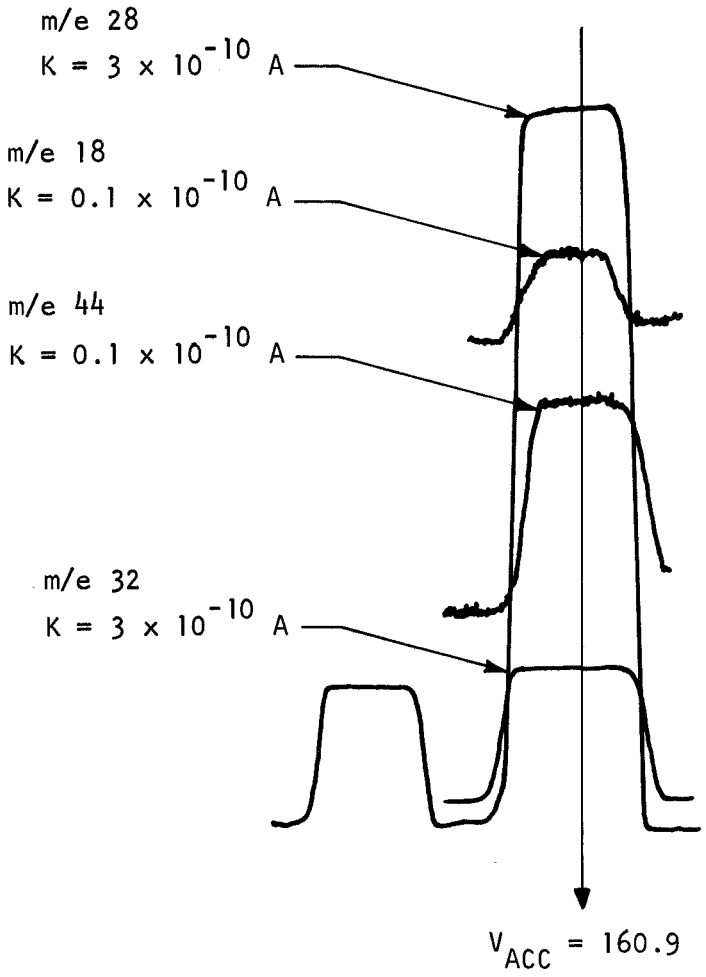


FIGURE 15.- Two Gas Atmospheric Sensor Connector Panel



AIR SAMPLE I_p = 16 μA (≅ 1.1 x 10^{-7} T)

WITH MAGNET ON REFERENCE LINE

A-687A

FIGURE 16.- Peak Alignment Check After Bakeout

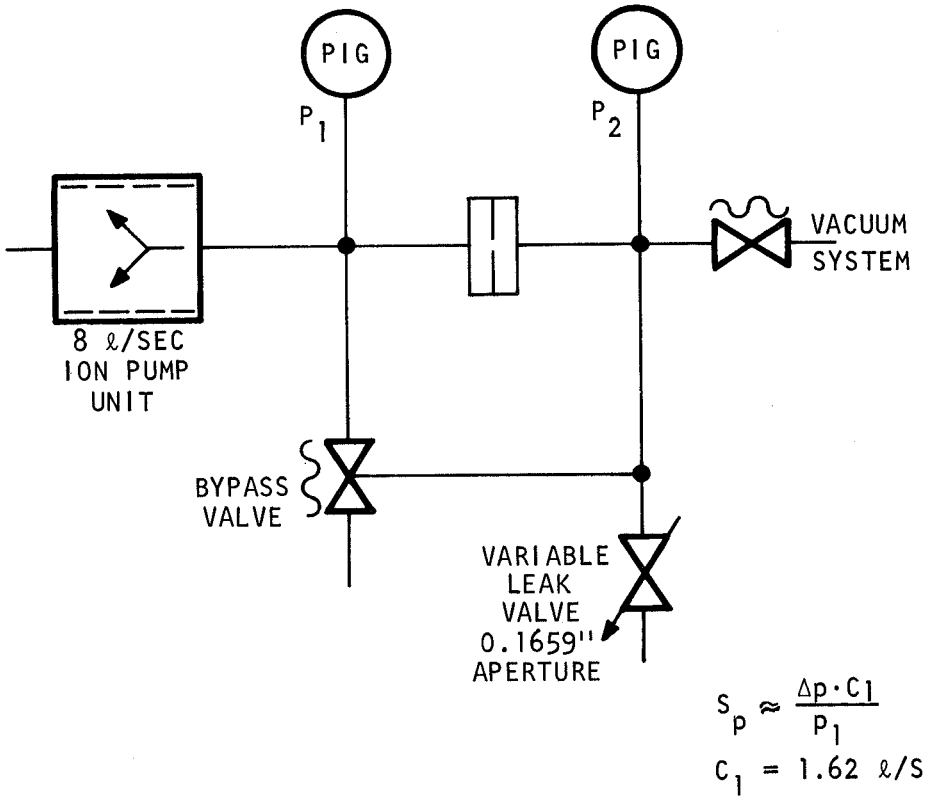


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FIGURE 17.- Test Setup Schematic

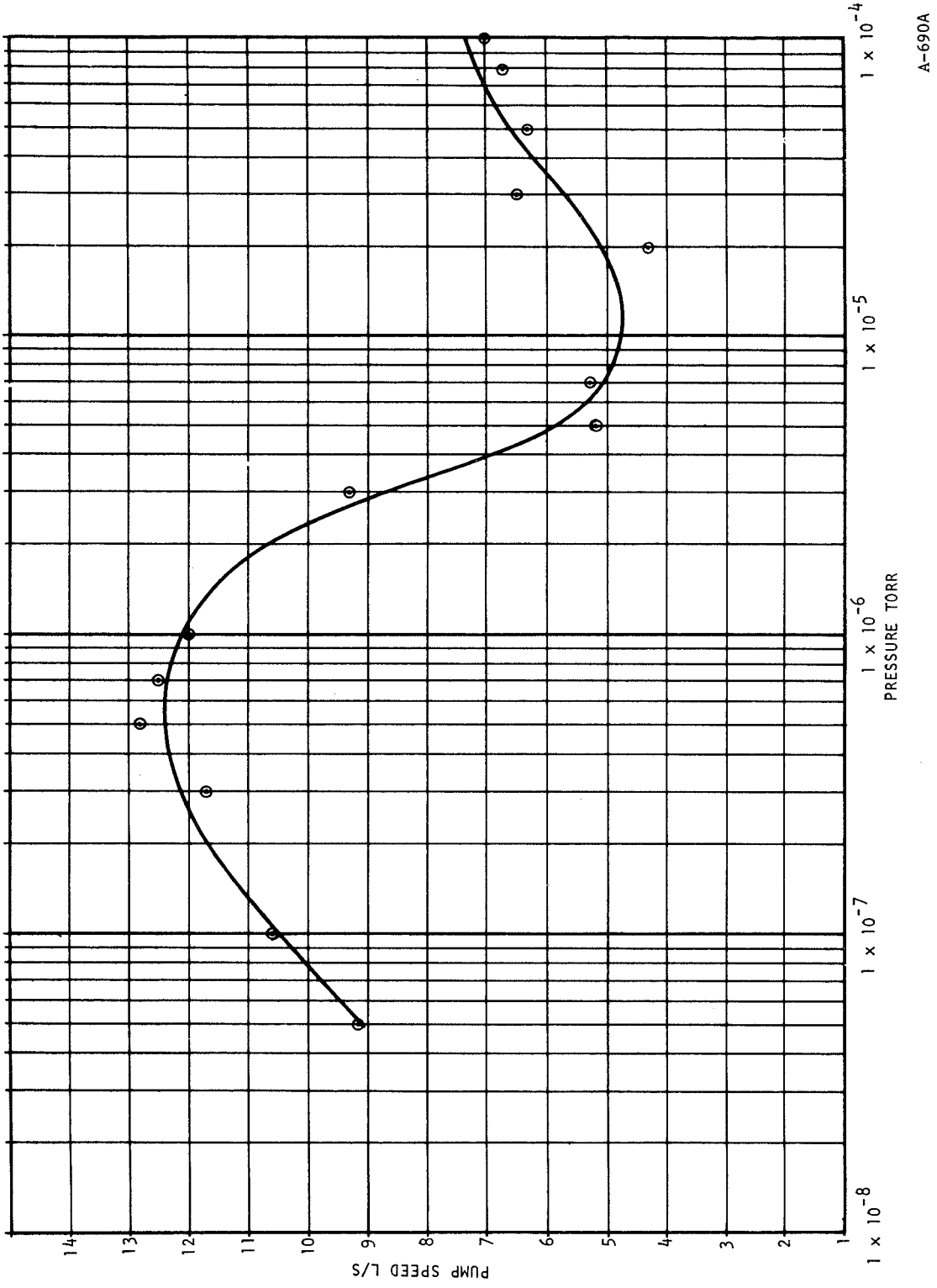

FIGURE 18.- Pumping Speed Test Results

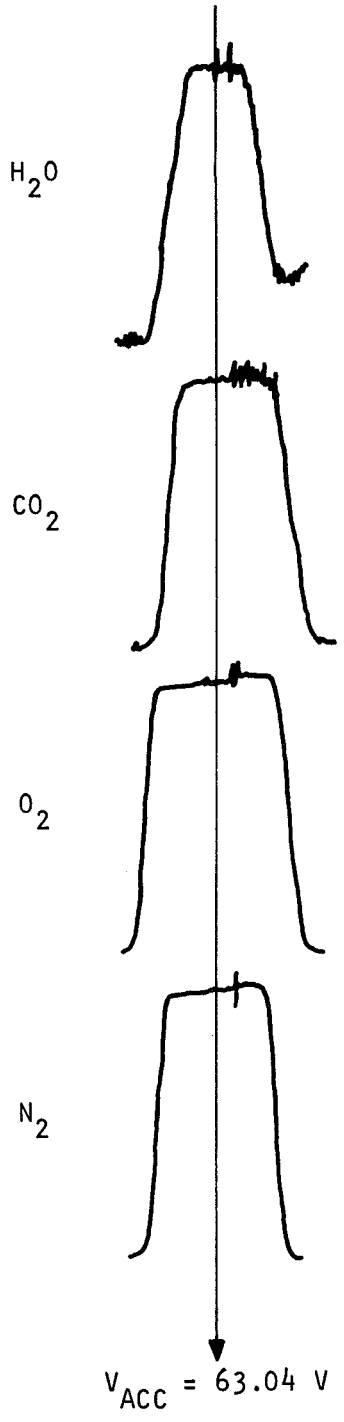

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FIGURE 19.- Final Alignment Check With Full Electronics

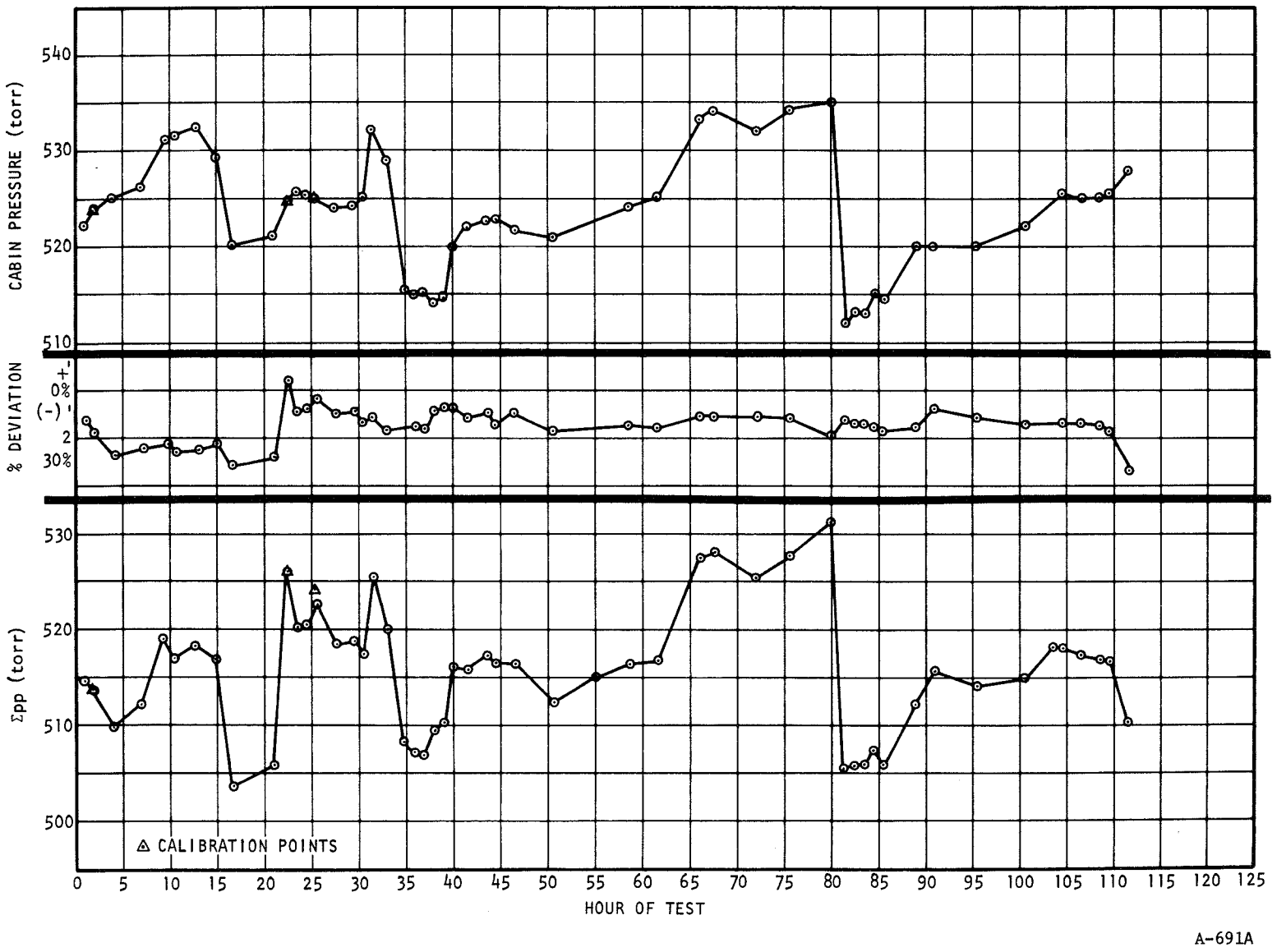

FIGURE 20.- System Performance Curves for 5-Day Mission (Sheet 1 of 3)

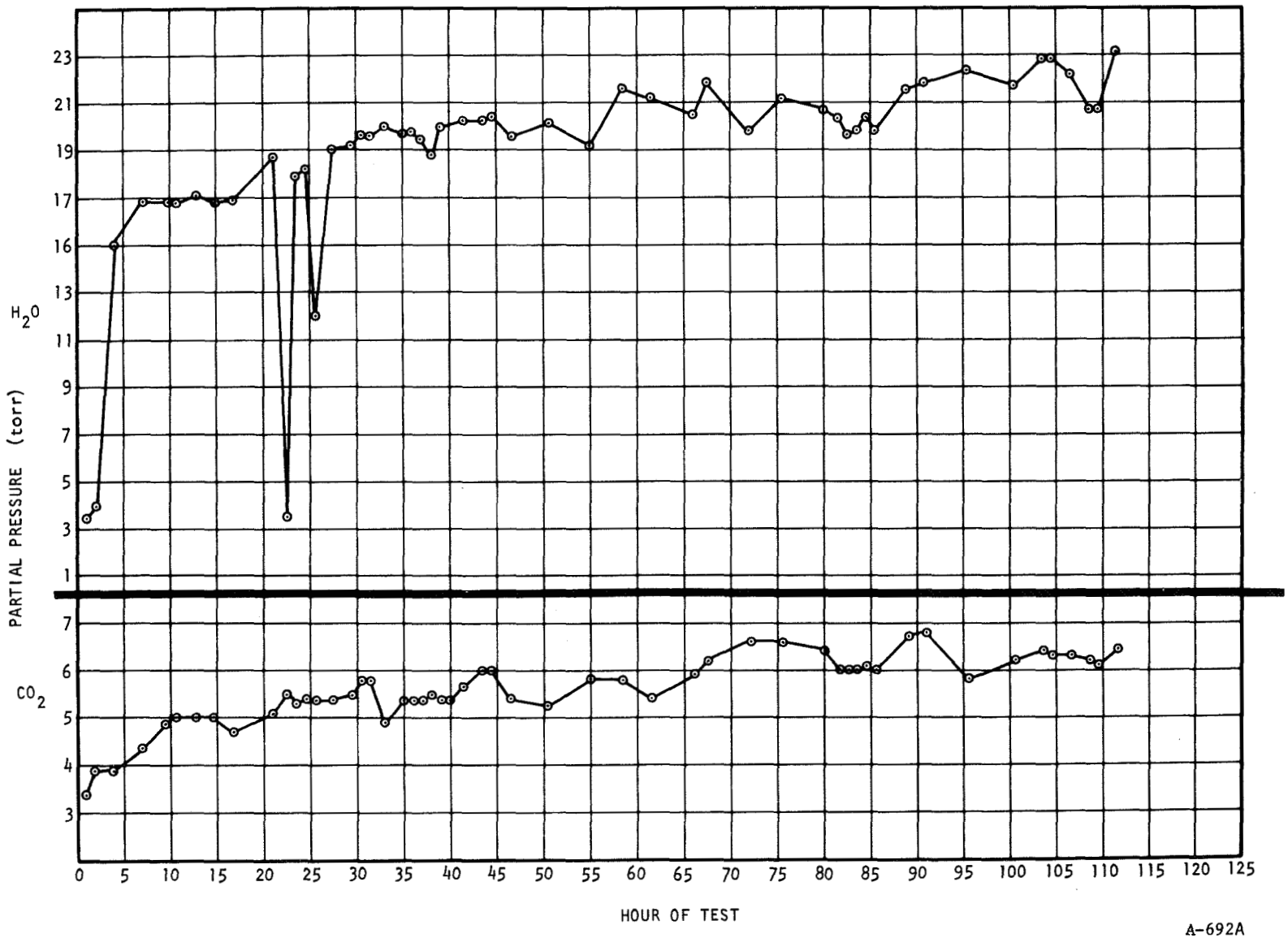

FIGURE 20.- System Performance Curves for 5-Day Mission (Sheet 2 of 3)

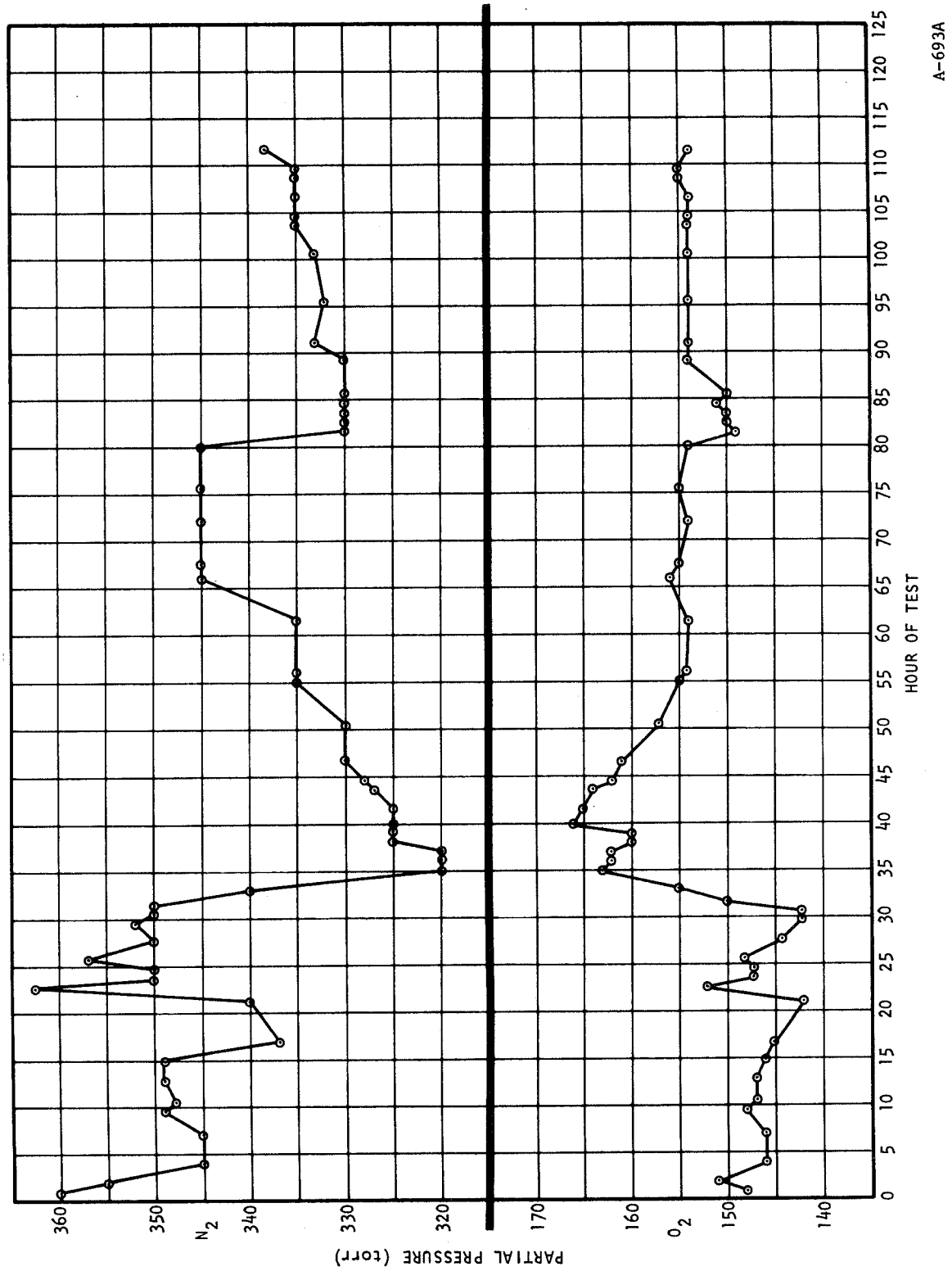

FIGURE 20.- System Performance Curves for 5-Day Mission (Sheet 3 of 3)

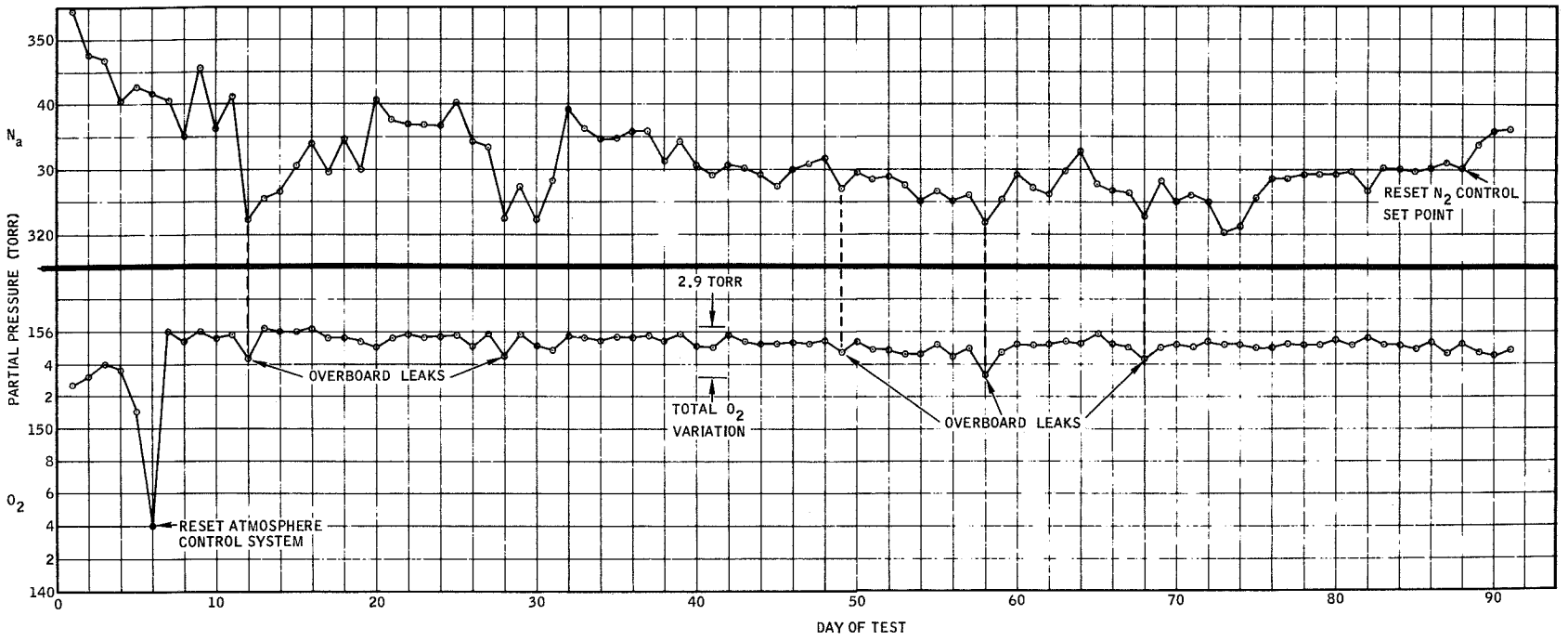

FIGURE 21.- Atmospheric Sensor System Outputs for 90-Day Run (Sheet 1 of 3)

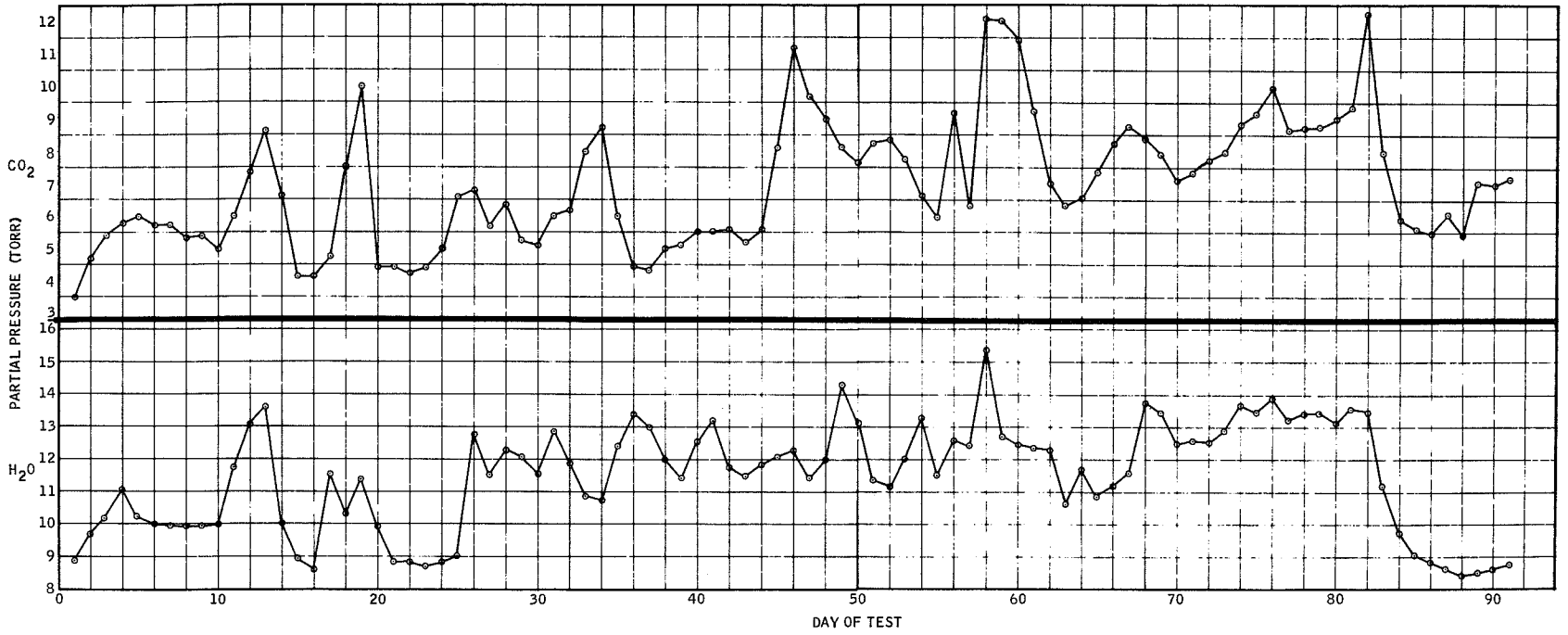

FIGURE 21.- Atmospheric Sensor System Outputs for 90-Day Run (Sheet 2 of 3)

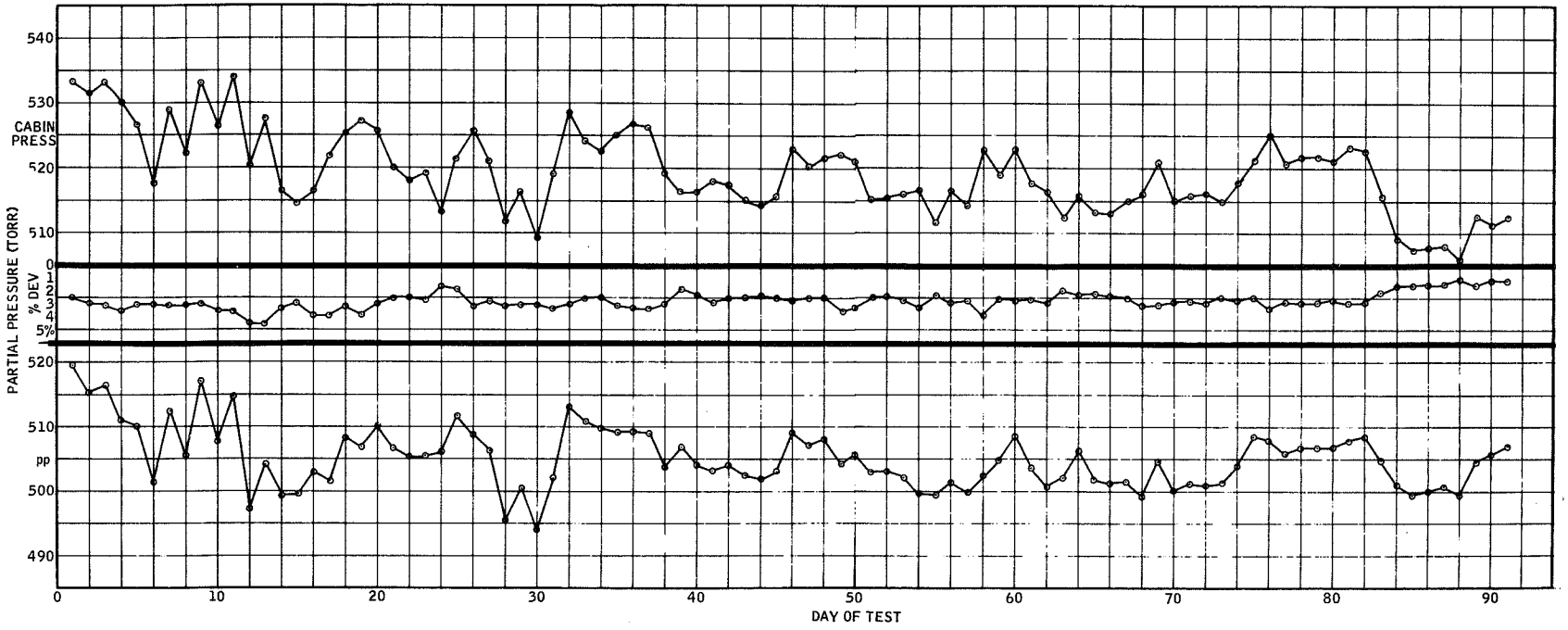

FIGURE 21.- Atmospheric Sensor System Outputs for 90-Day Run (Sheet 3 of 3)

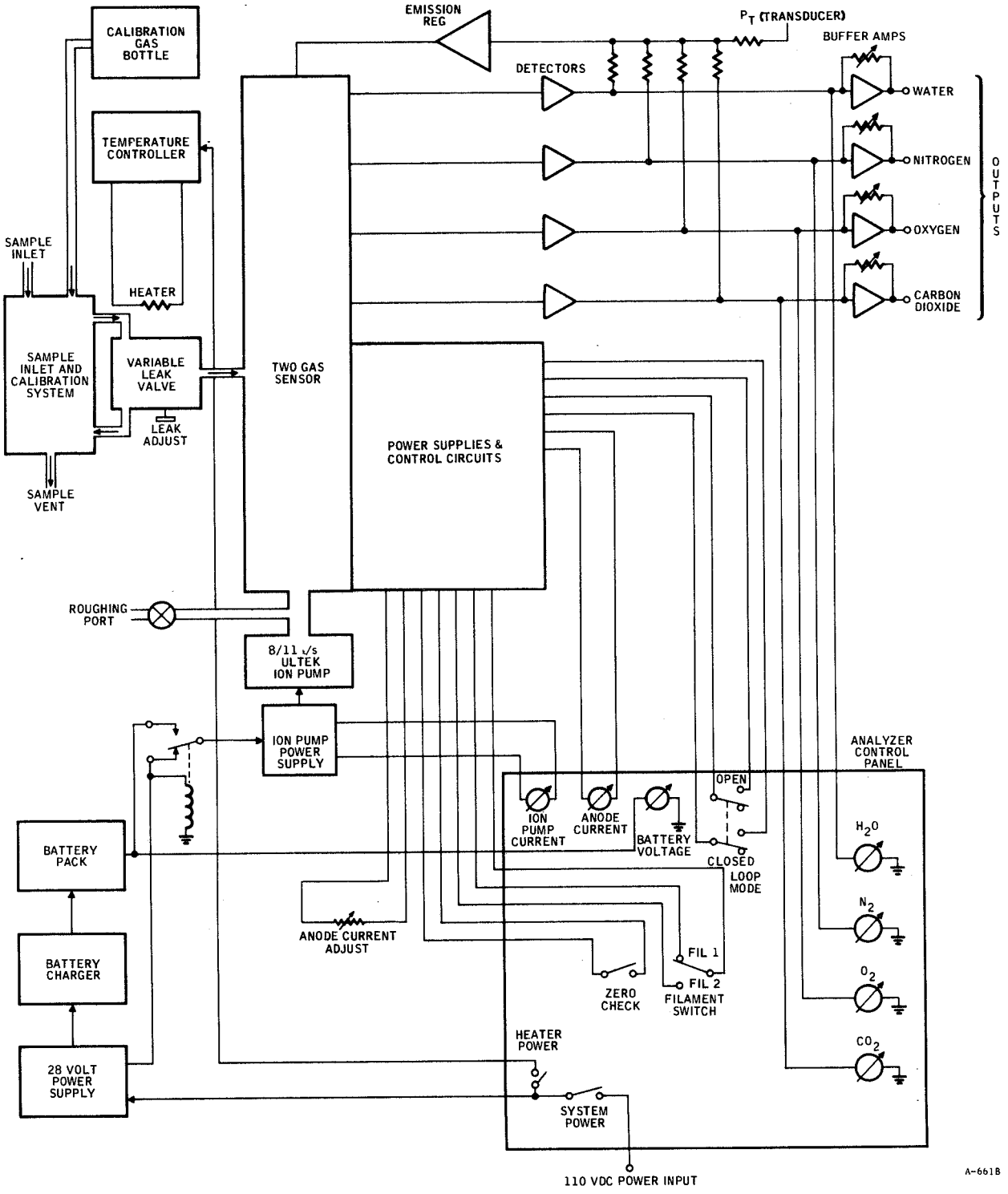

FIGURE 22.- Two Gas Atmospheric Sensor Block Diagram

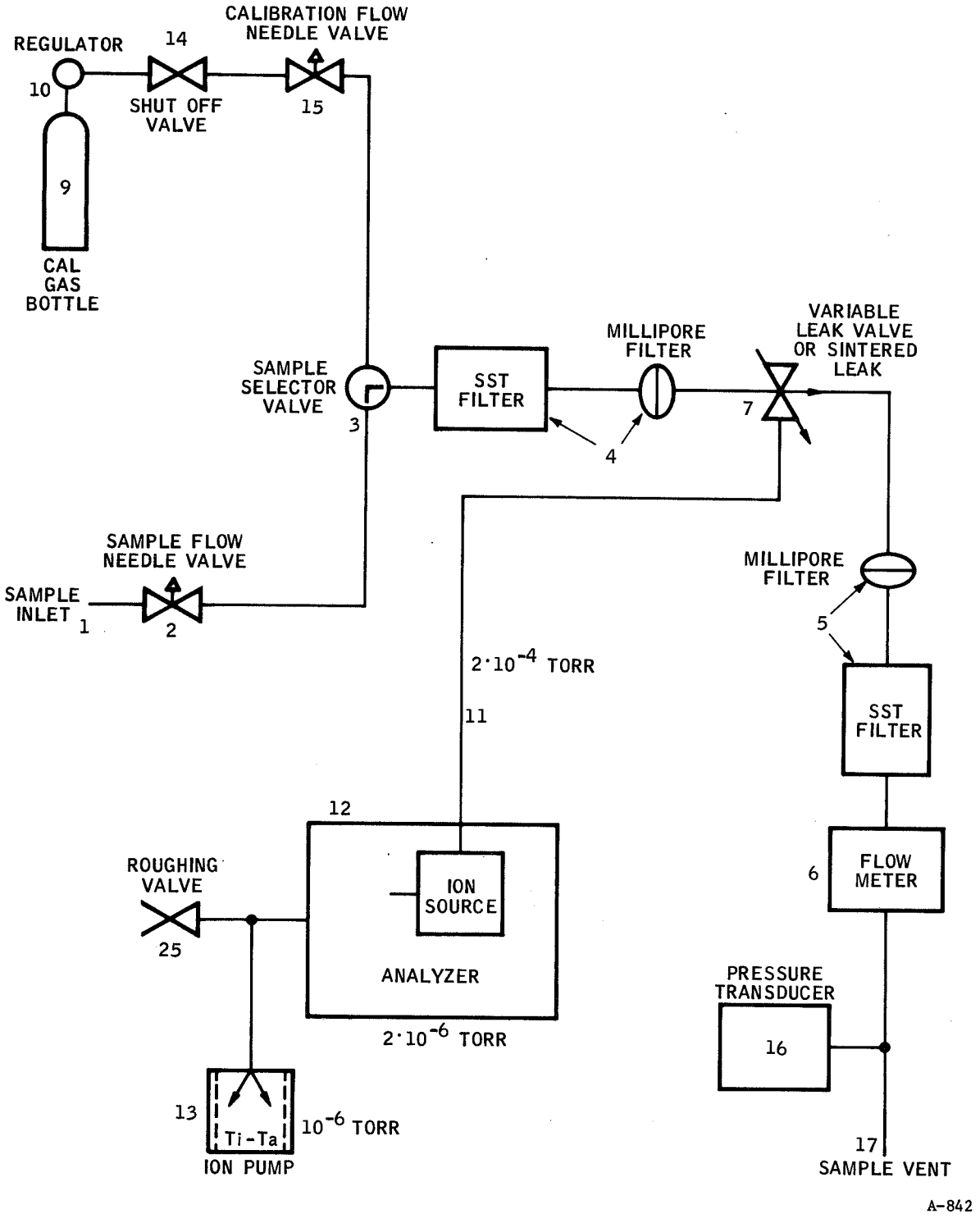

FIGURE 23.- Sample and Calibration Inlet System
Schematic Flow Diagram

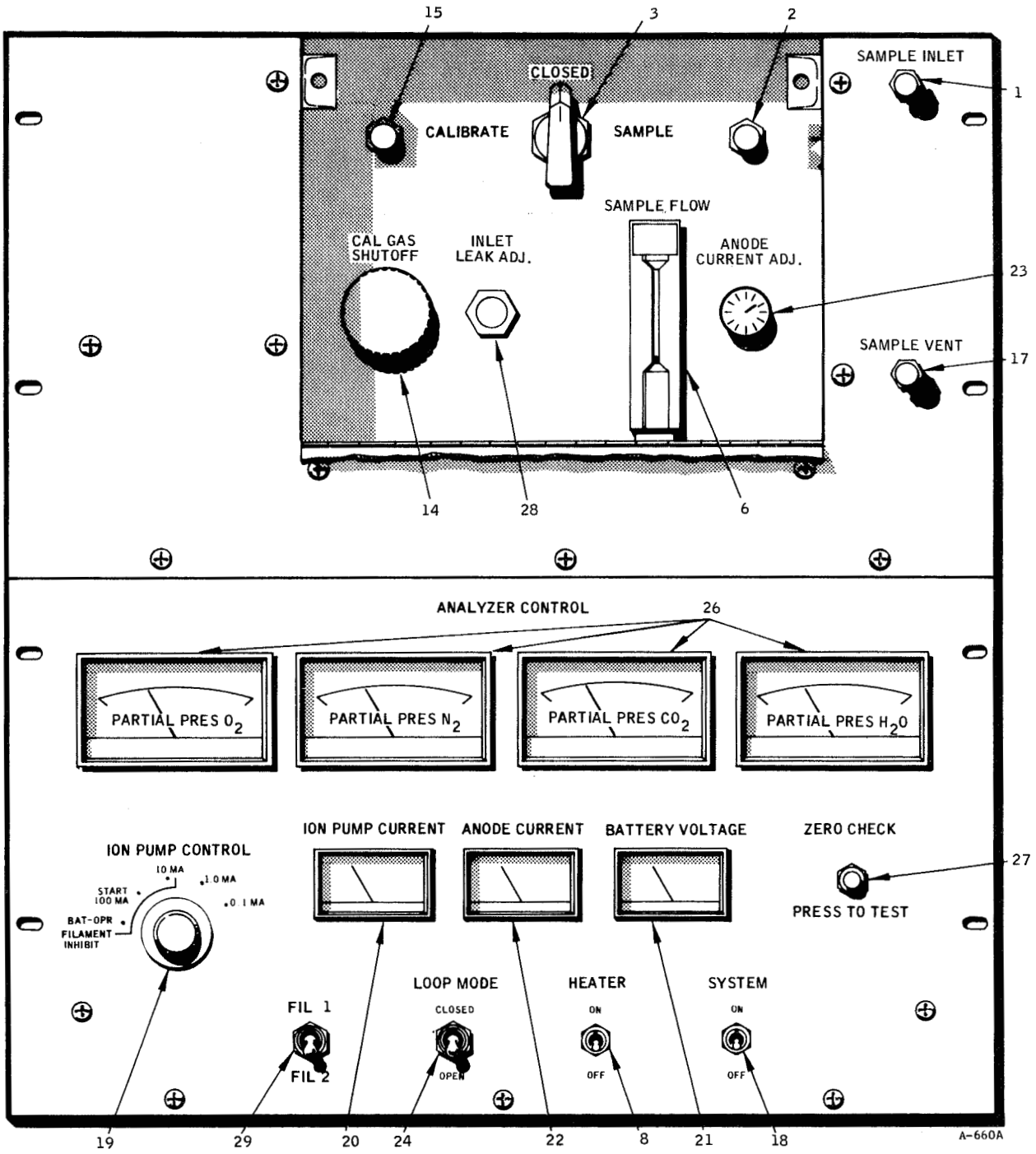

FIGURE 24.- Front Panel

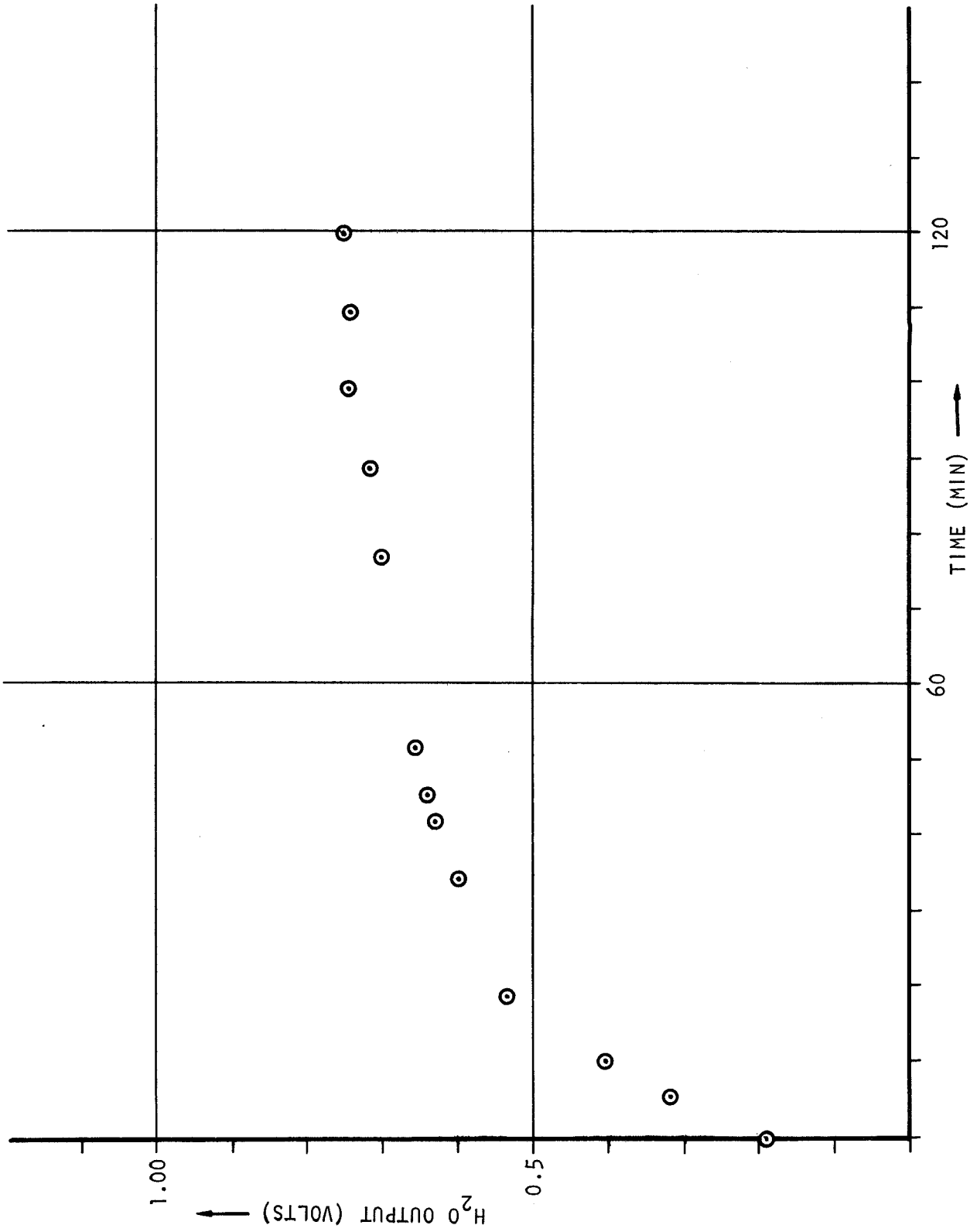

FIGURE 25.- Water Output Curve

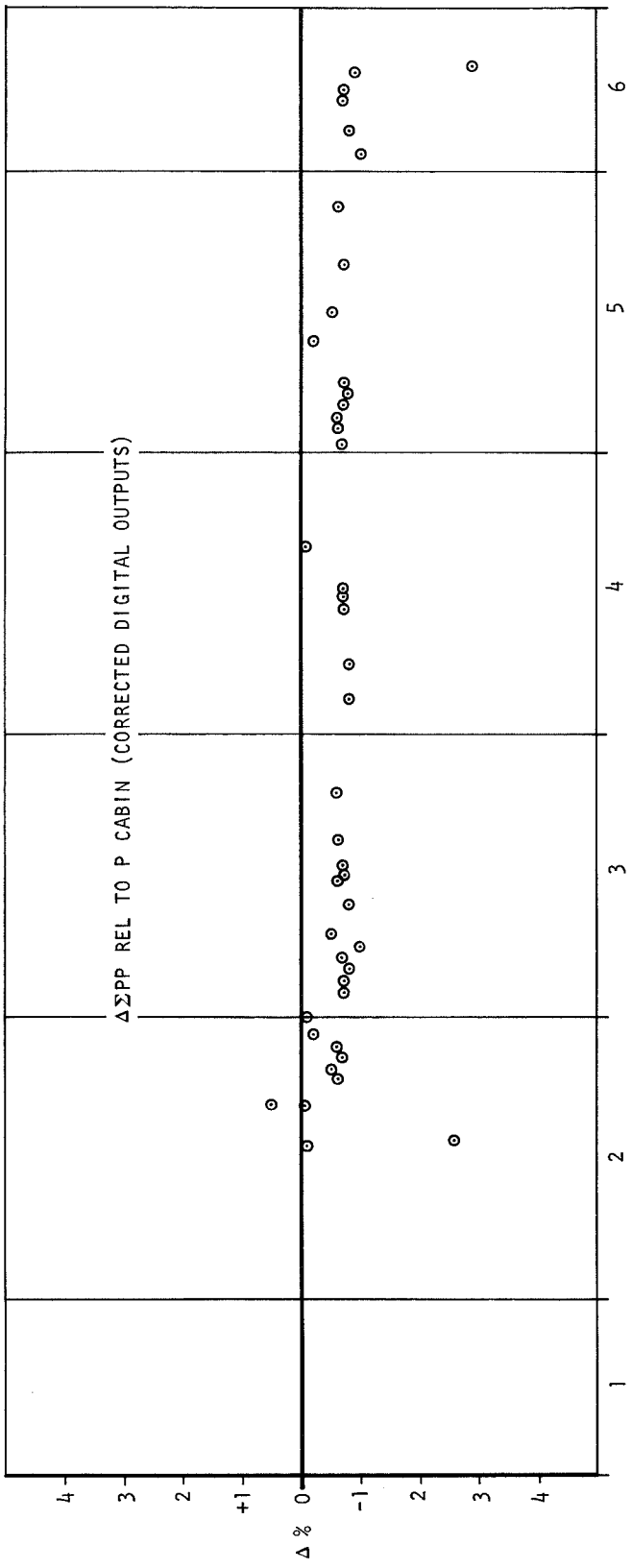

FIGURE 26.- Output Data for Cabin Atmosphere Run

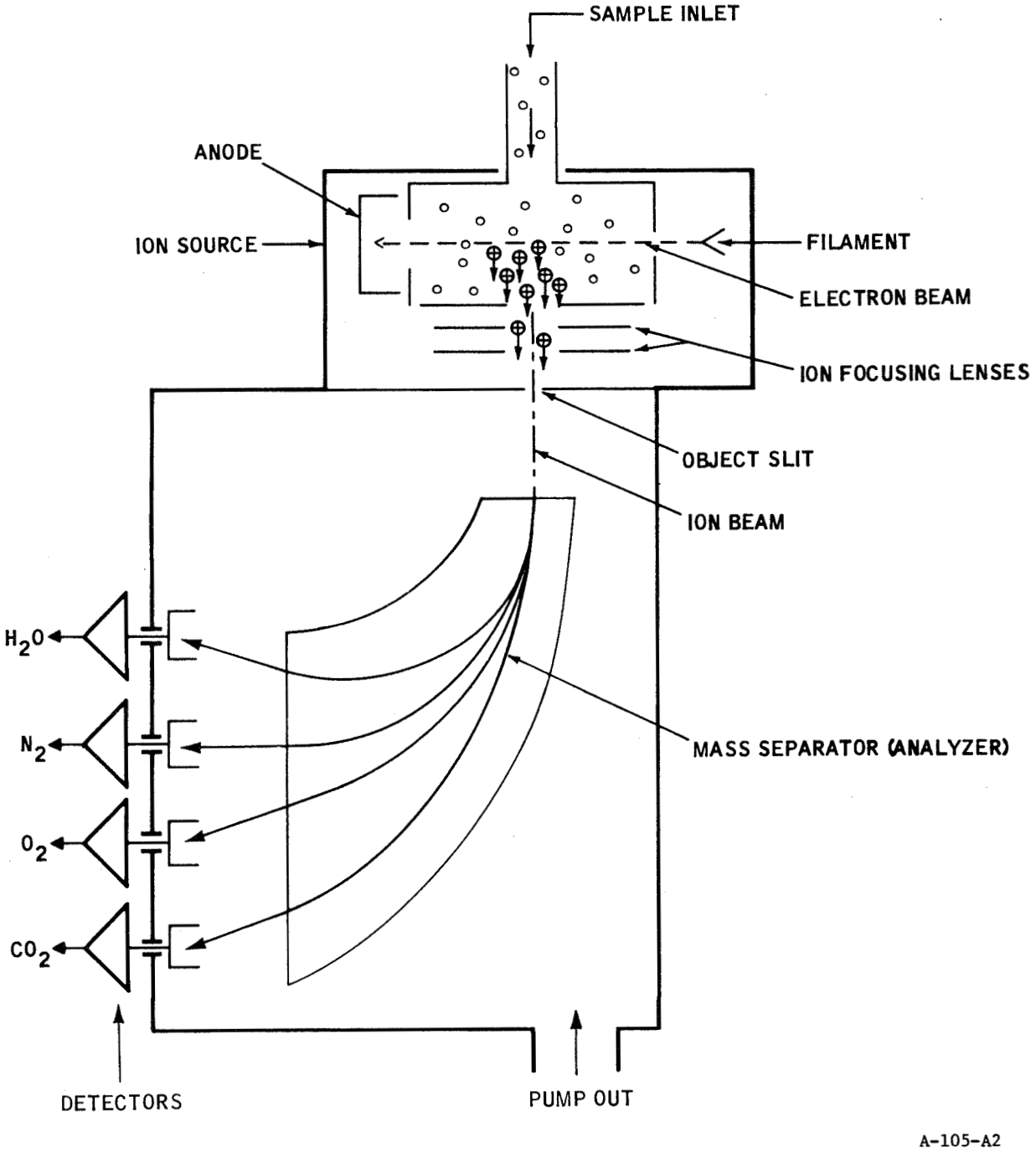

FIGURE 27.- Principles of Mass Spectrometer Operation

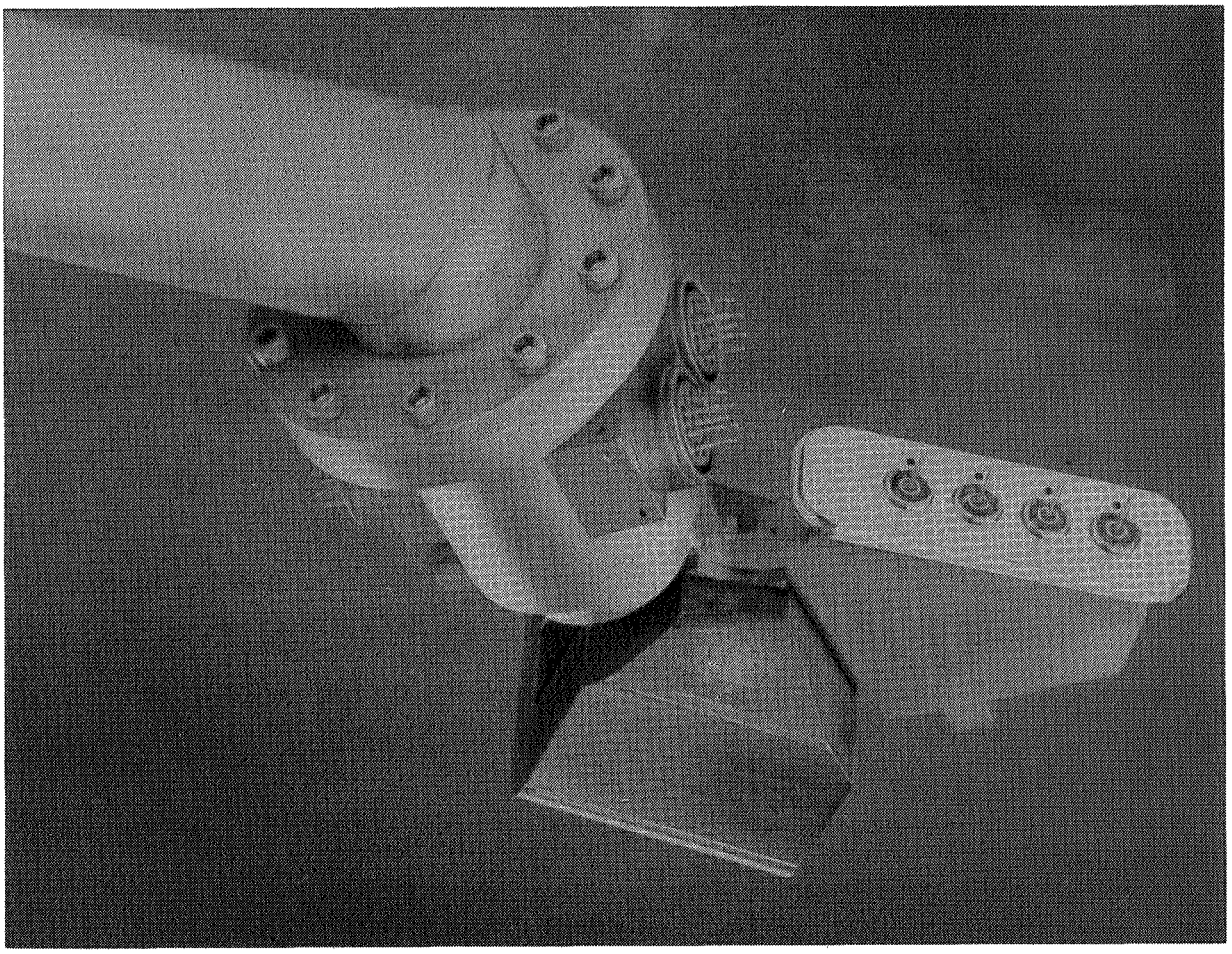

FIGURE 28.- Two Gas Atmosphere Analyzer Assembly

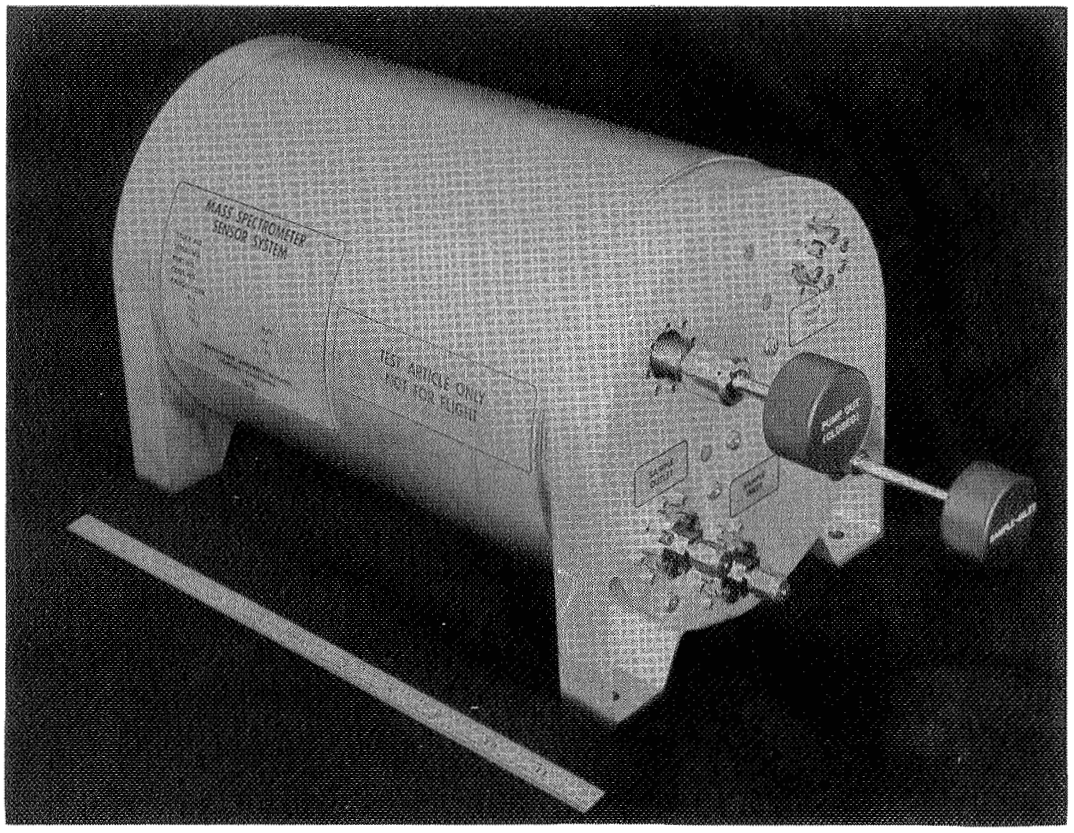

FIGURE 29.- Flight Qualified Mass Spectrometer Atmospheric Sensor System for Atmospheric and Respiratory Monitoring

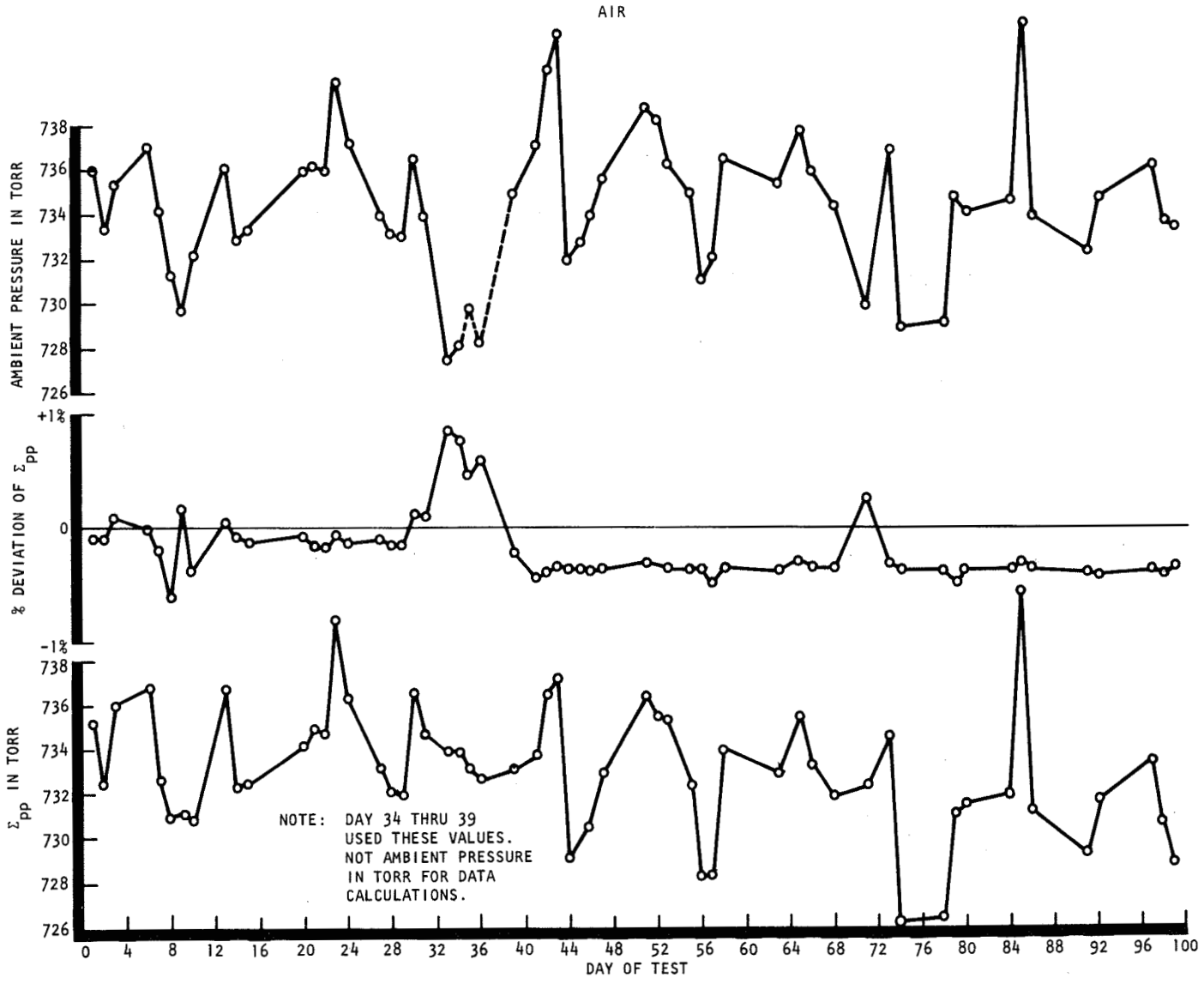

FIGURE 30. System Performance on Daily Basis (Air) (Sheet 1 of 2)

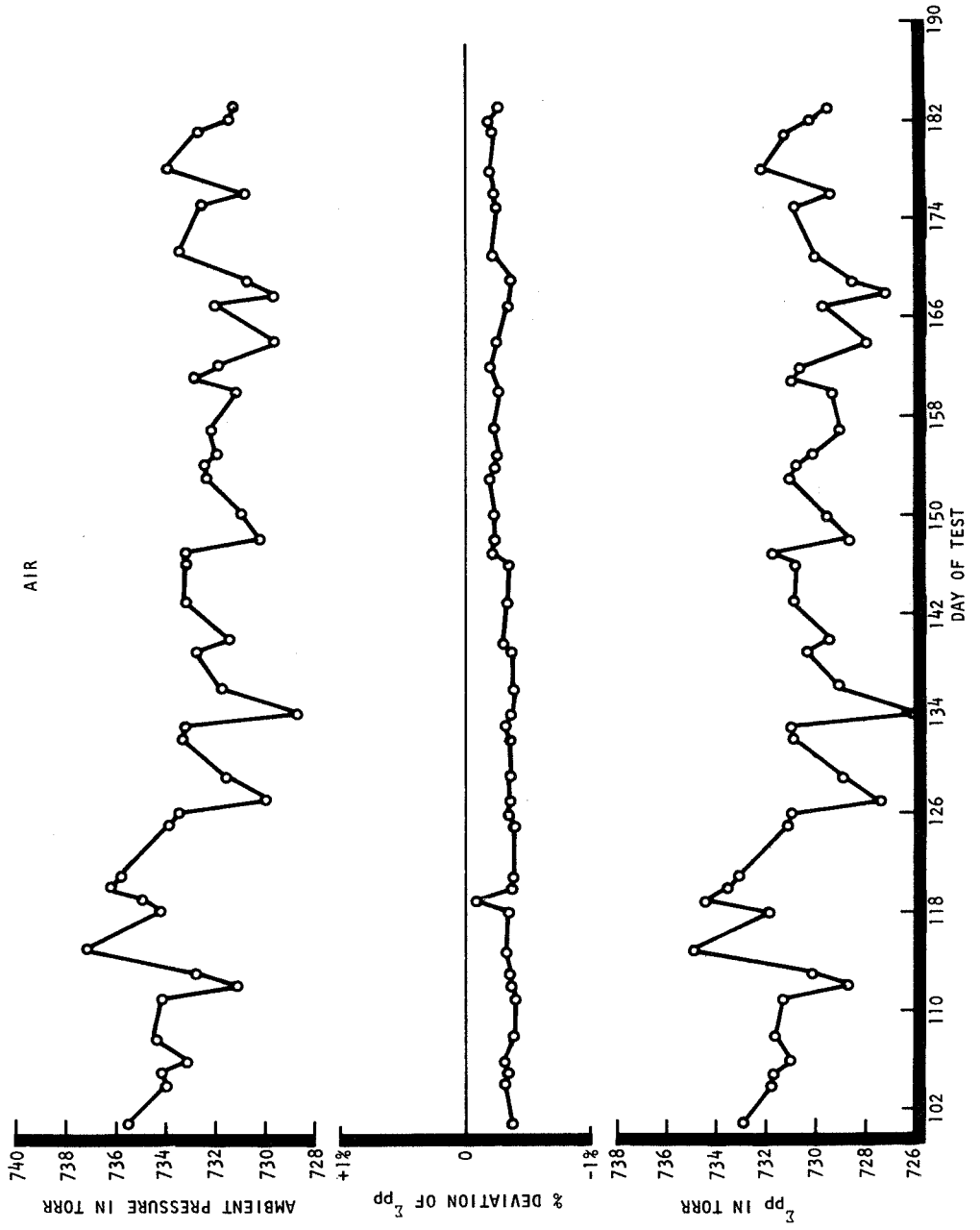

FIGURE 30. System Performance on Daily Basis (Air (Sheet 2 of 2)

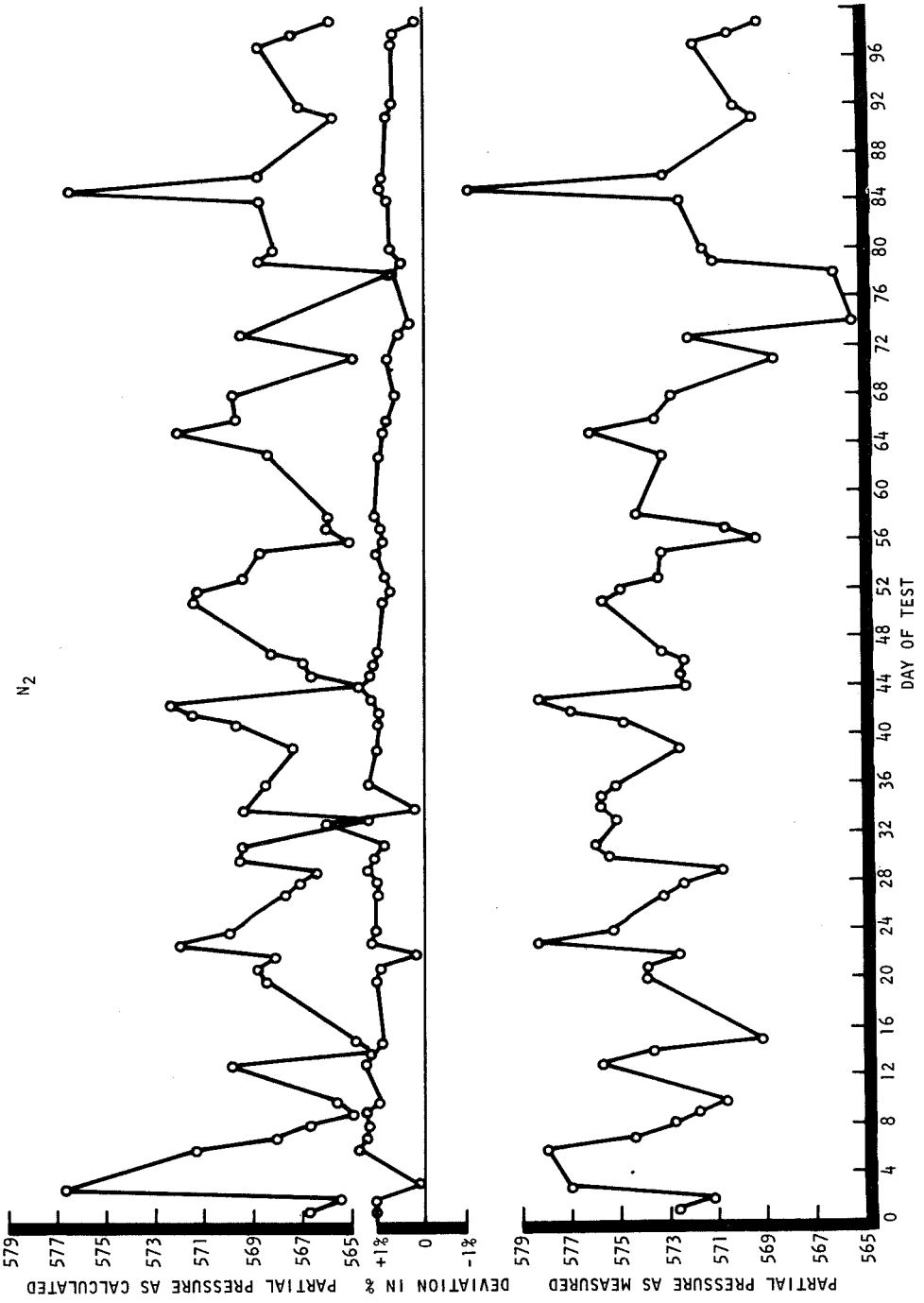

FIGURE 31. System Performance on Daily Basis (N_2) (Sheet 1 of 2)

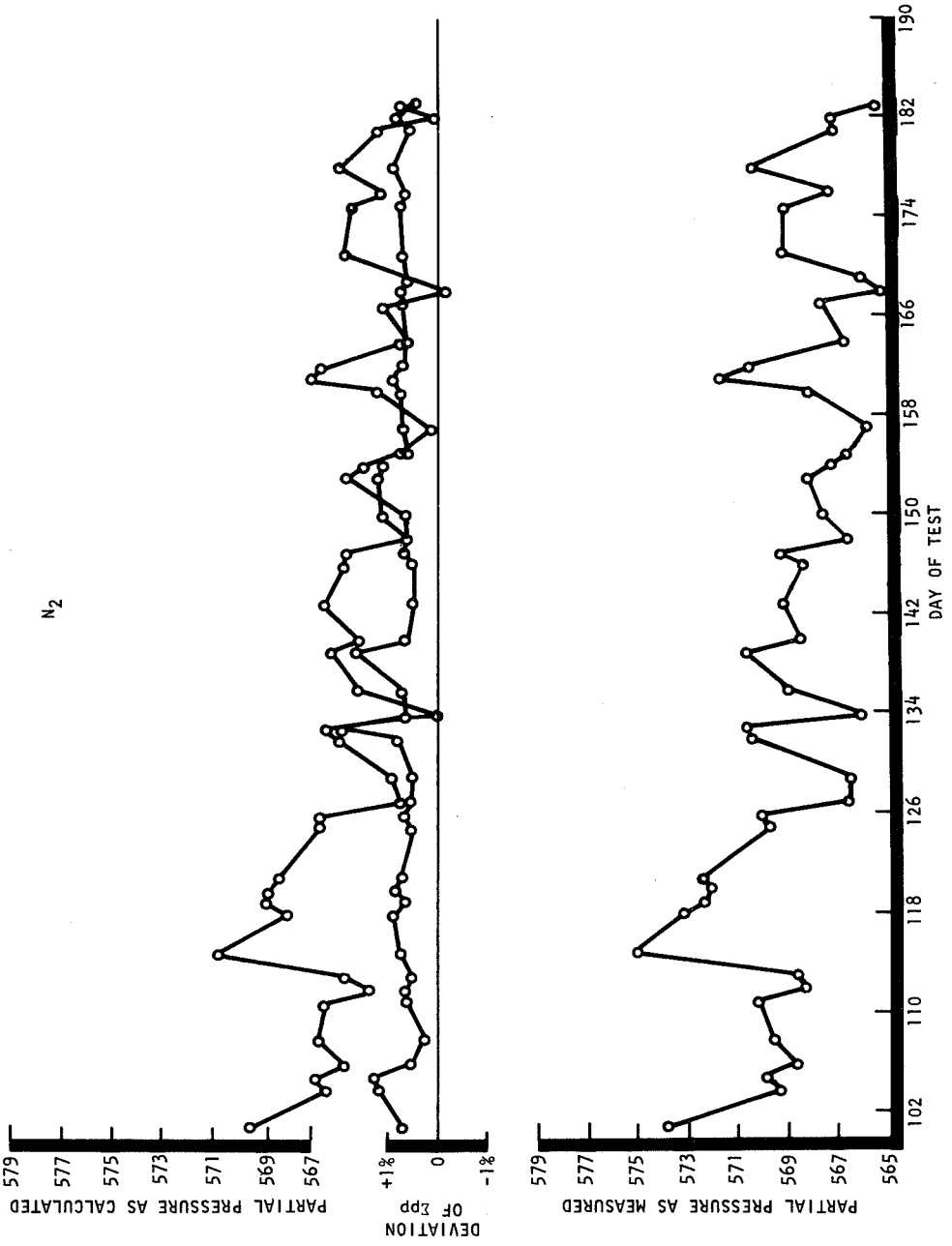

FIGURE 31. System Performance on Daily Basis (N_2) (Sheet 2 of 2)

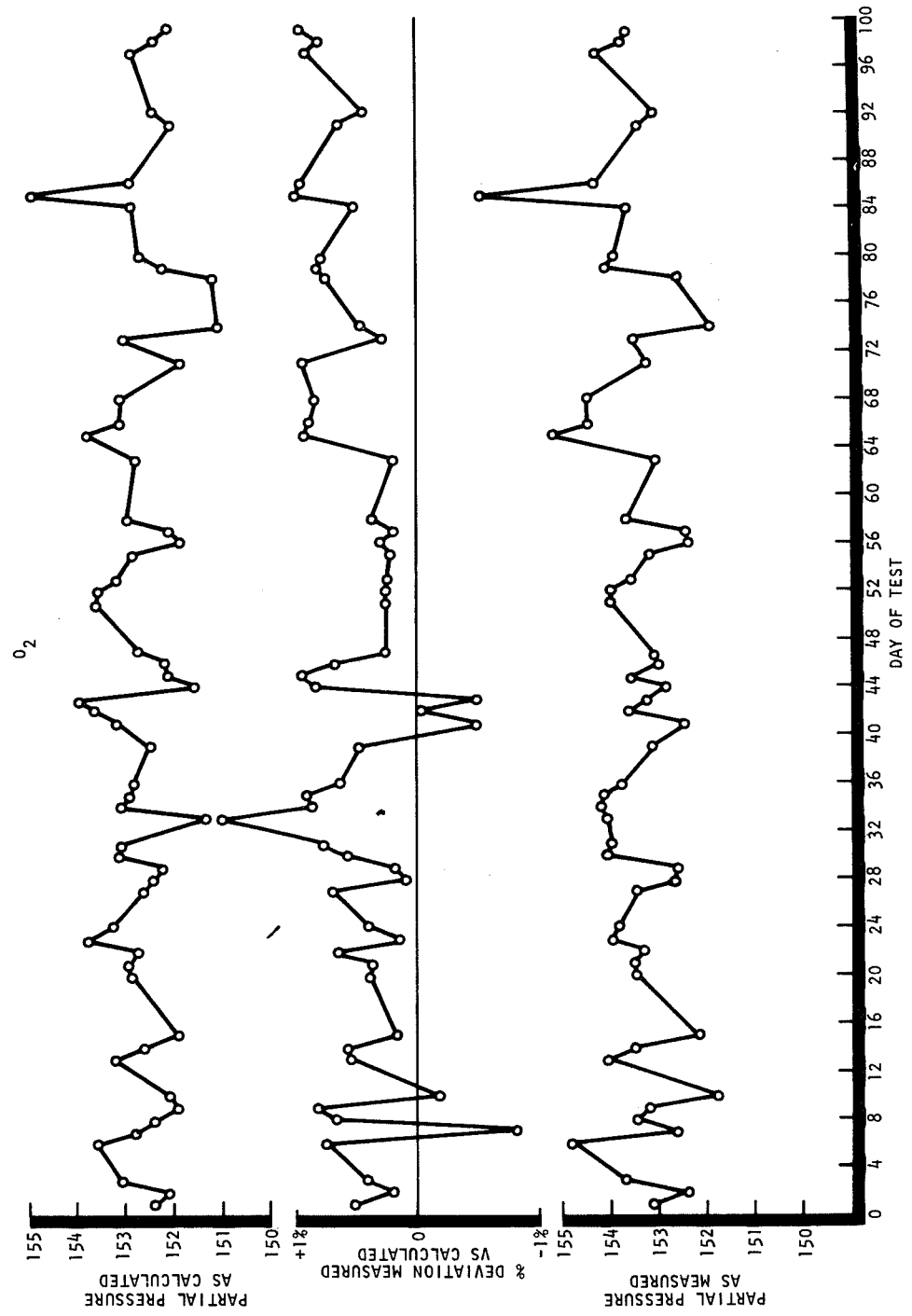

FIGURE 32. System Performance on Daily Basis (O_2) (Sheet 1 of 2)

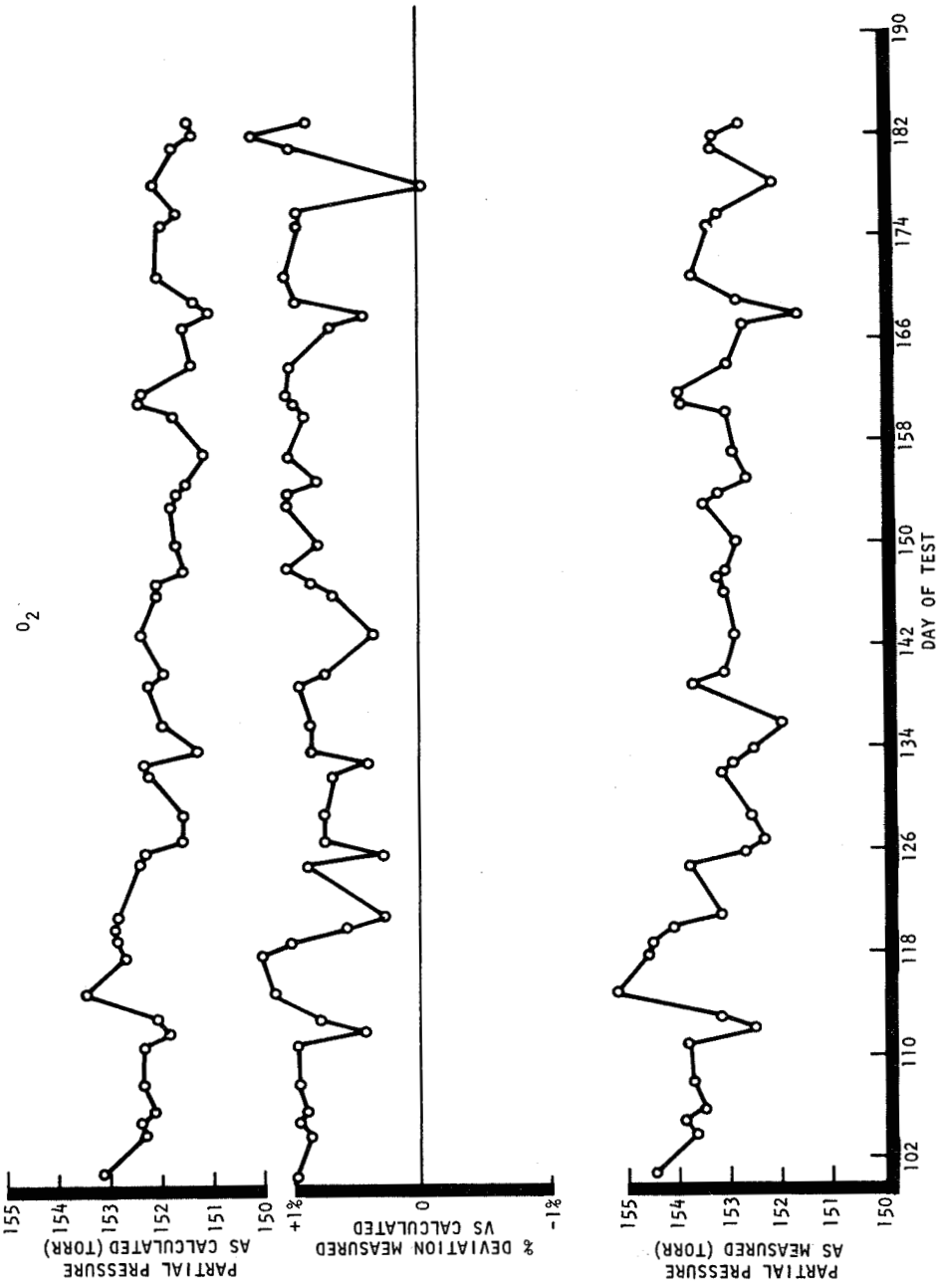

FIGURE 32. System Performance on Daily Basis (O_2) (Sheet 2 of 2)

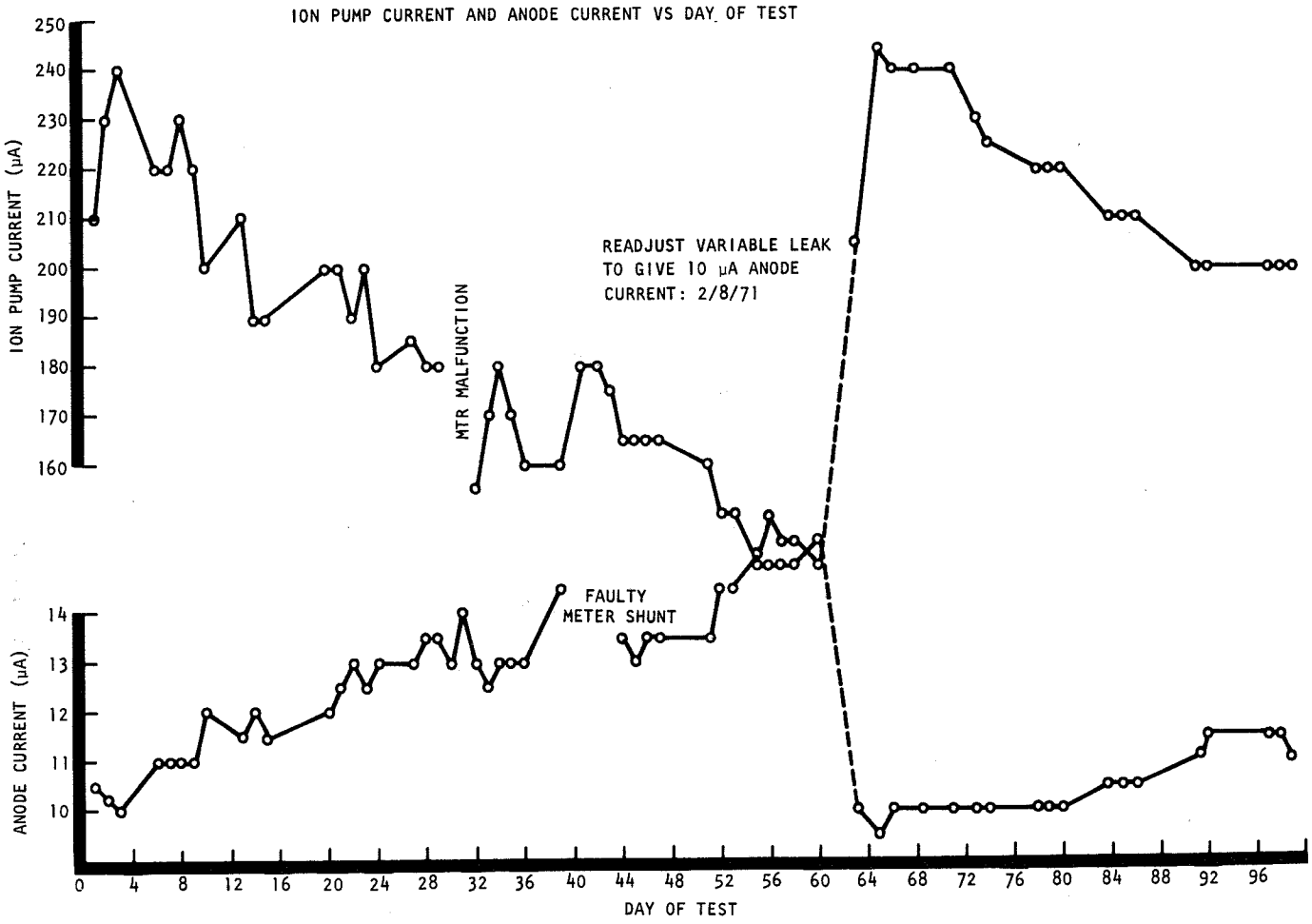

FIGURE 33. System Performance on Daily Basis (Ion Pump Current and Anode Current vs Day of Test) (Sheet 1 of 2)

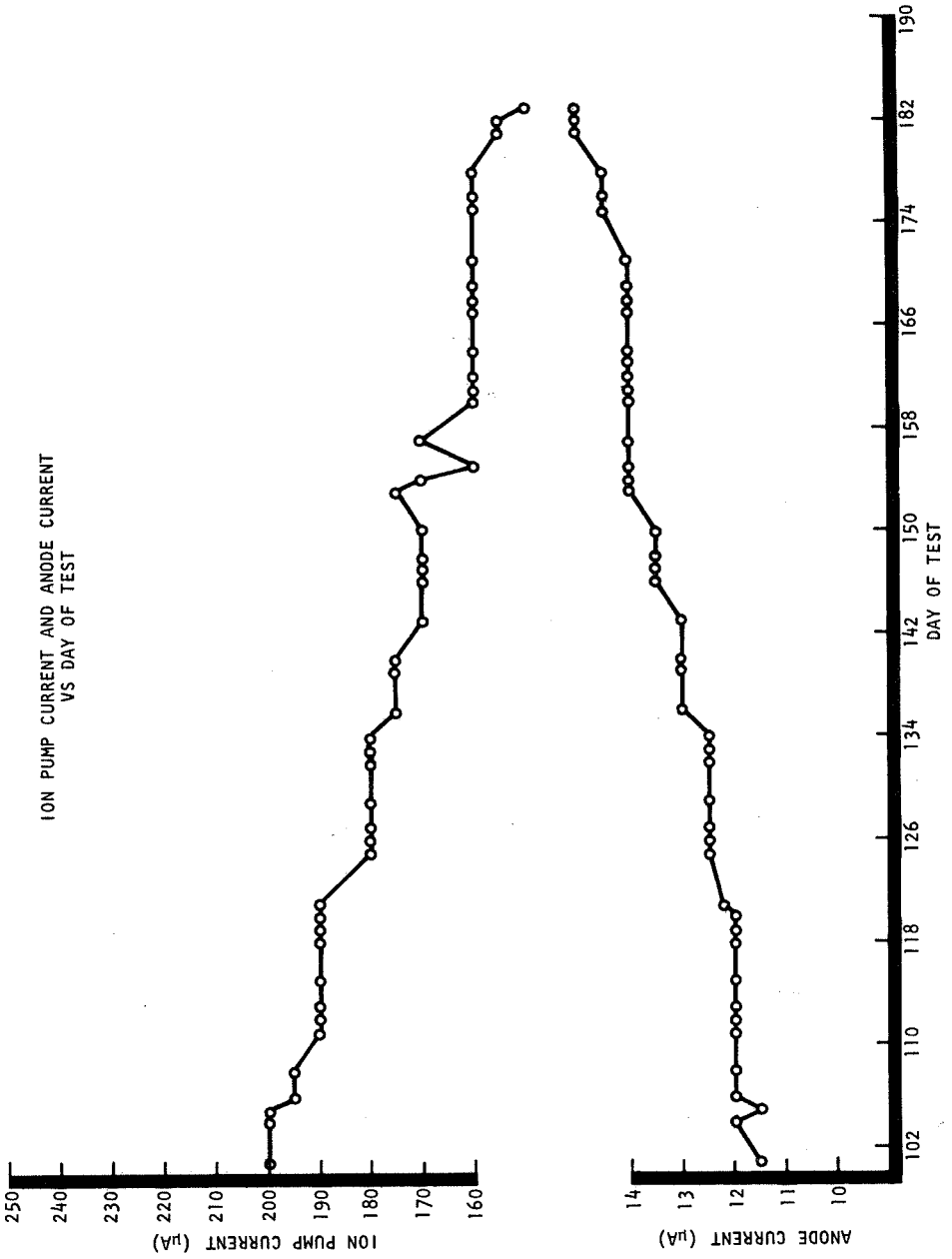

FIGURE 33. System Performance on Daily Basis (Ion Pump Current and Anode Current vs Day of Test) (Sheet 2 of 2)

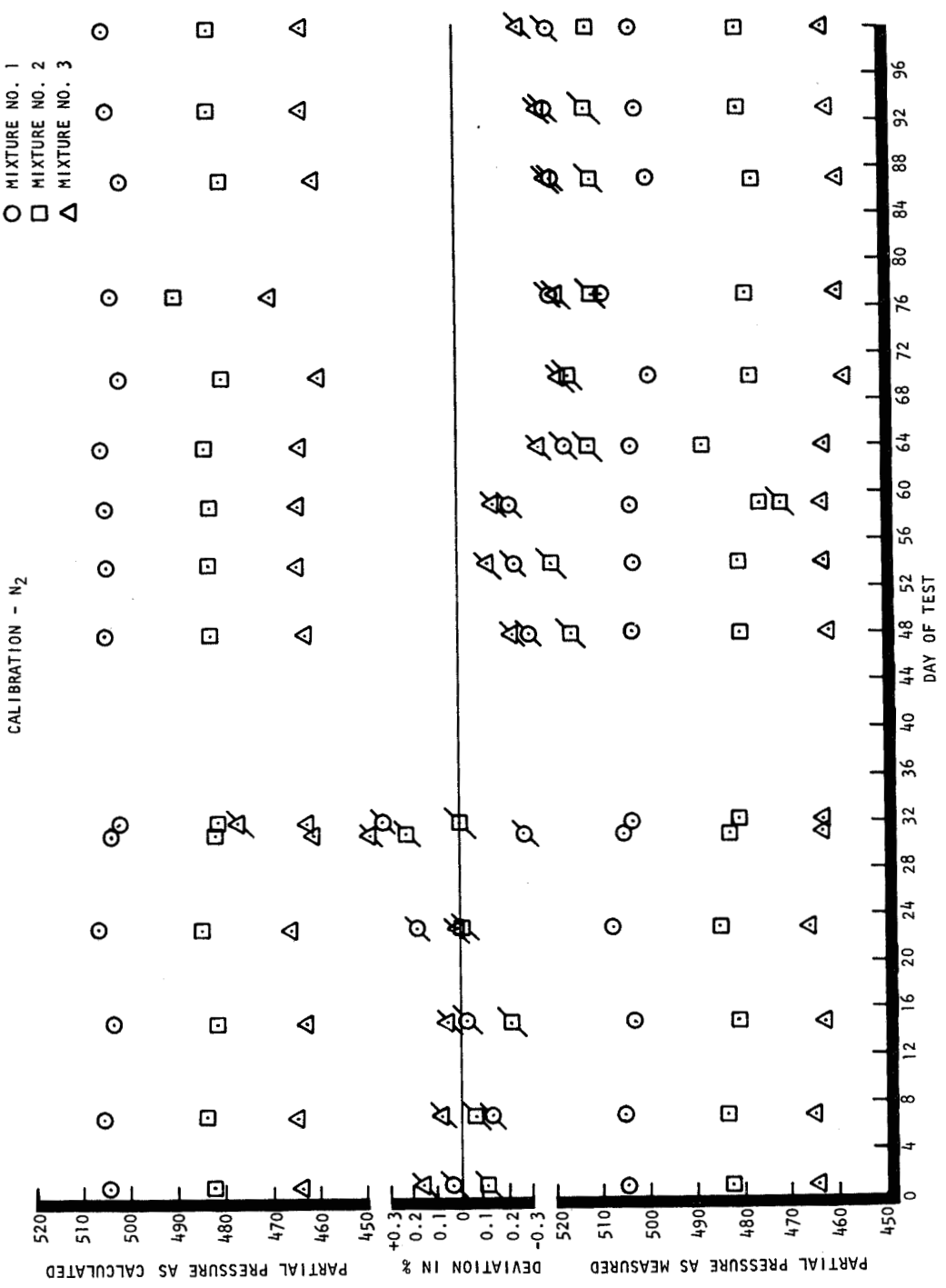

FIGURE 34. System Calibration on Weekly Basis (N_2) (Sheet 1 of 2)

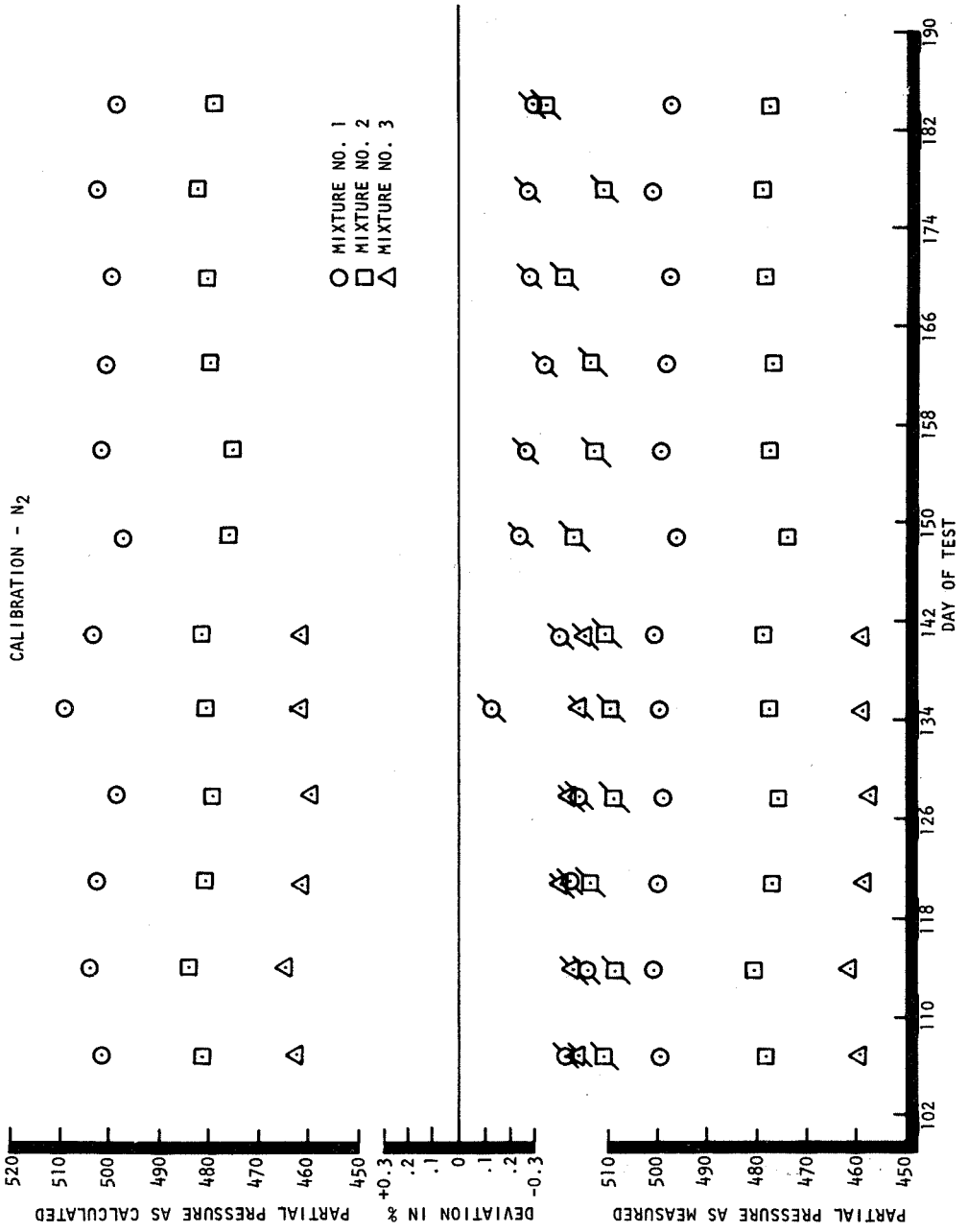

FIGURE 34. System Calibration on Weekly Basis (N_2) (Sheet 2 of 2)

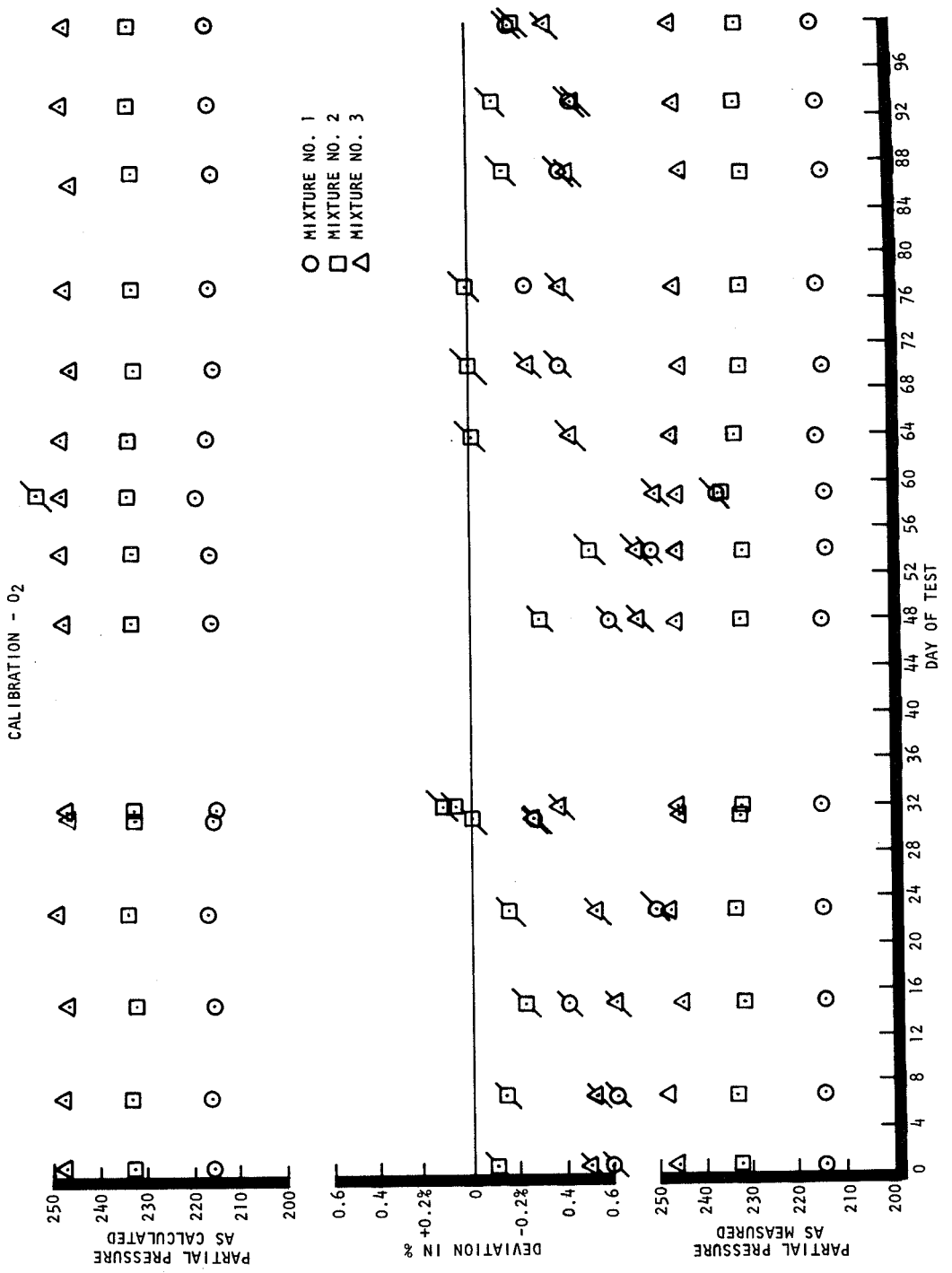

FIGURE 35. System Calibration on Weekly Basis (O_2) (Sheet 2 of 2)

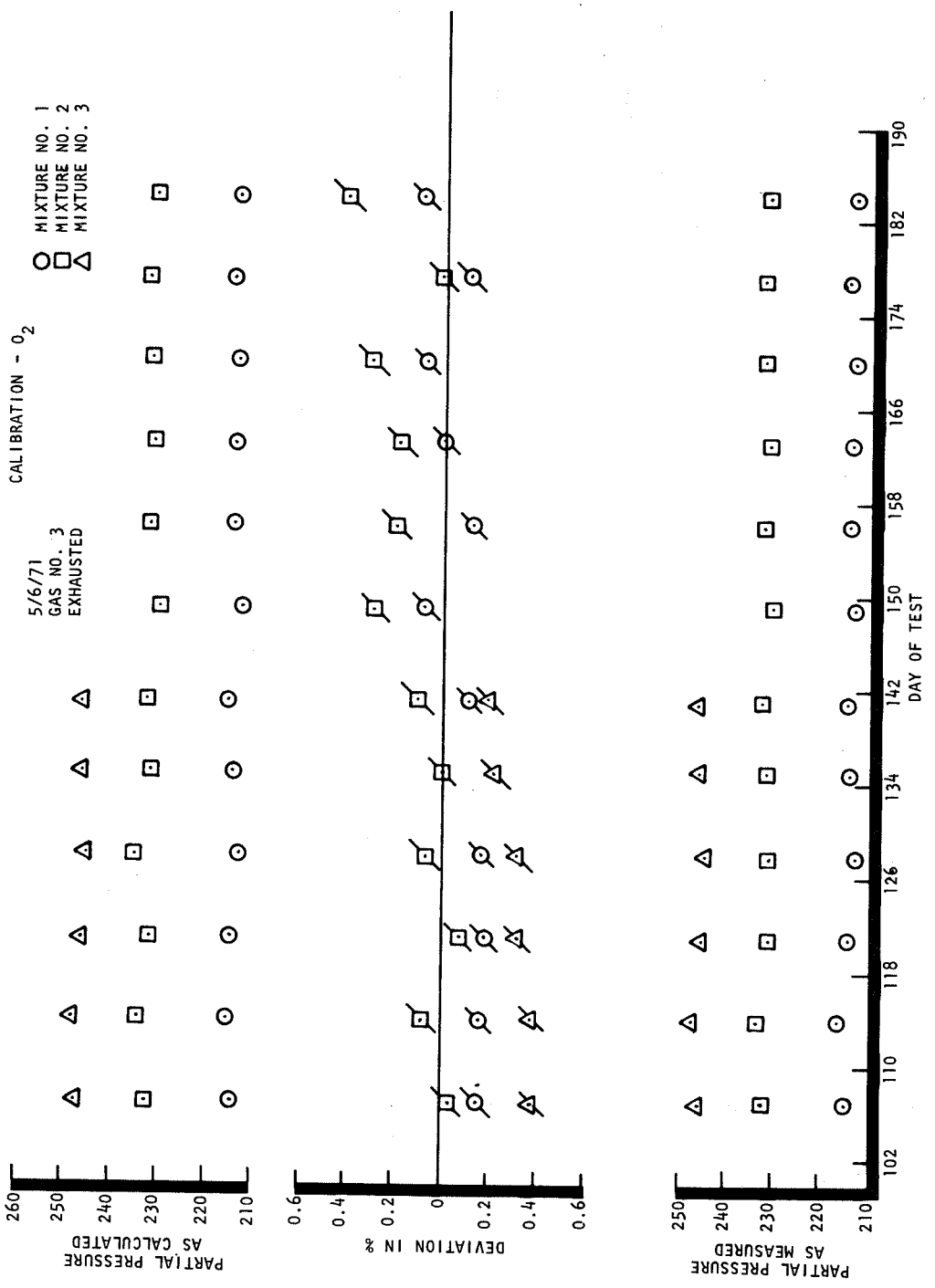

FIGURE 35. System Calibration on Weekly Basis (O_2) (Sheet 1 of 2)

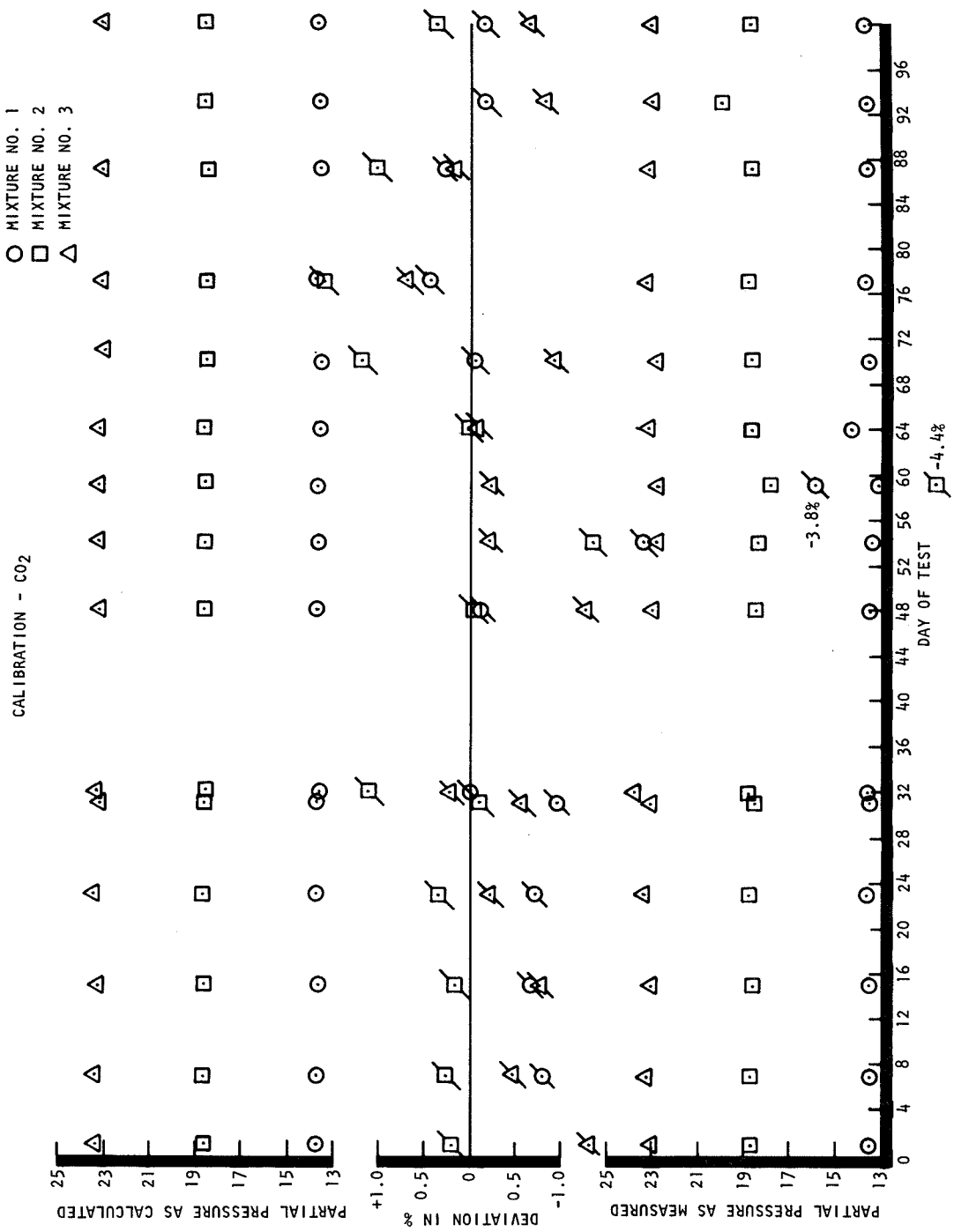

FIGURE 36. System Calibration on Weekly Basis (CO_2) (Sheet 1 of 2)

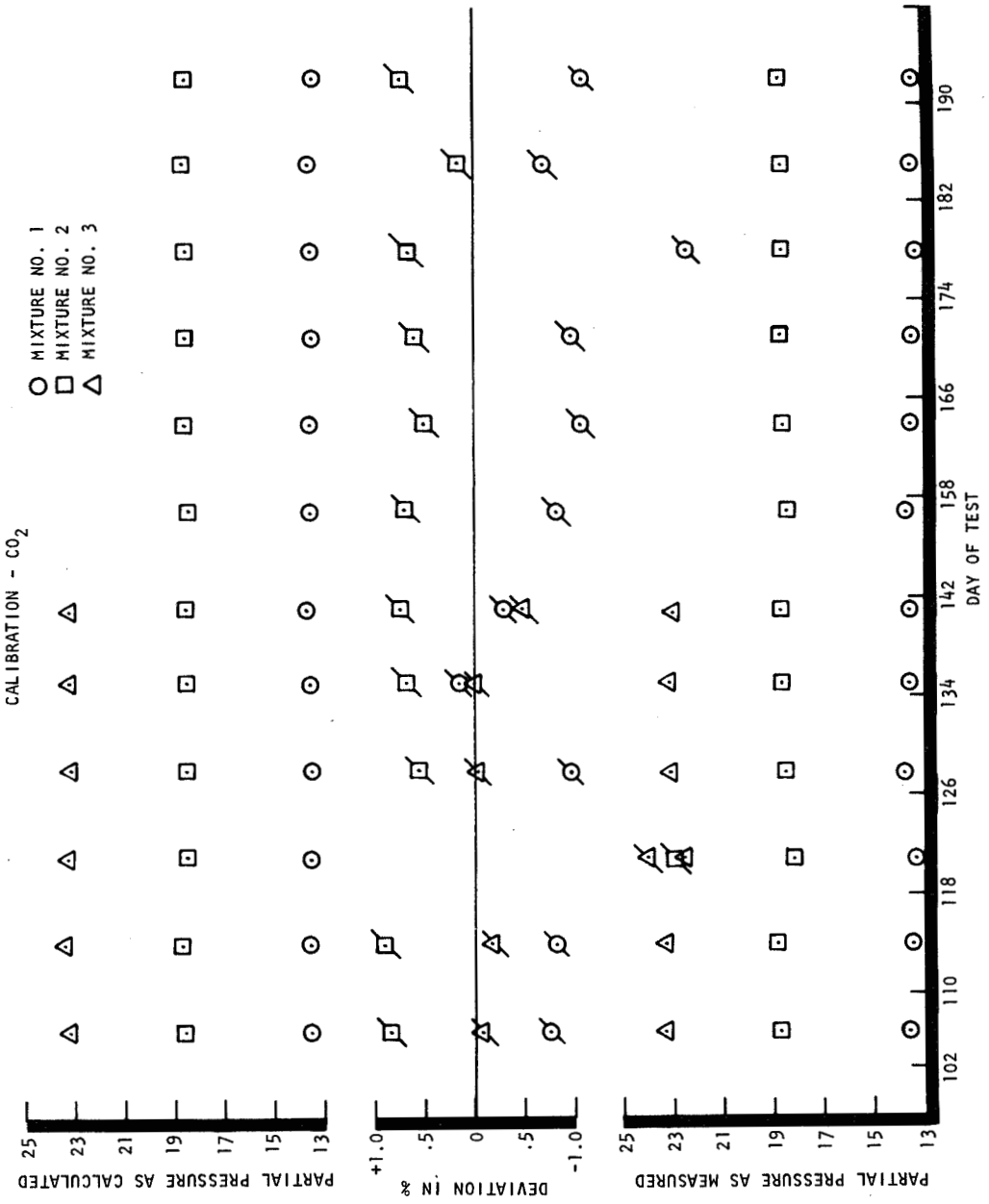

FIGURE 36. System Calibration on Weekly Basis (CO_2) (Sheet 2 of 2)