REGENERATIVE CARBON DIOXIDE ADSORPTION SYSTEM USING CHARCOAL

PETER WILDERMUTH

FOREWORD

This study was done by The Bendix Corporation, Instruments & Life Support Division, 2734 Hickory Grove Road, Davenport, Iowa 52808, under Contract Number AF33(615)2443, in support of Project No. 6373, "Equipment for Life Support in Aerospace", and Task No. 637302, "Respiratory Support Equipment". This program was conducted under the sponsorship of the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The contract monitor was Mr. Clemens M. Meyer of the Biotechnology Branch, Biomedical Laboratory. The project leader for the Instruments & Life Support Division was Peter Wildermuth, Staff Scientist was Dr. George H. Bancroft, Senior Engineer was Dr. Blase J. Sollami who provided technical consultation and the Chief Engineer Paul Gardner provided administrative supervision. The report summarizes work begun 1 April 1965 and concluded 30 September 1966.

This technical report has been reviewed and is approved.

Wayne H. Mc Candless
Technical Director
Biomedical Laboratory
Aerospace Medical Research Laboratories

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ABSTRACT

A system was designed and built for testing activated charcoal as a regenerative carbon dioxide adsorbent in an atmosphere involving oxygen pressures of 240-275 mm Hg. Barnebey Cheney KB-1 charcoal was used, and the system gas flow rate was 160-340 liters/minute. The gas stream was composed of oxygen, humidified to 50%. Carbon dioxide was added to simulate the production rate of two men. Because of the subatmospheric operation, the system was a closed loop design and any carbon dioxide not adsorbed on the first pass through the charcoal continued to circulate through the system. The charcoal was subjected to an ambient room temperature of approximately 27C, and the gas stream controlled at 26.7 ± 2.7C during the adsorption testing. Regeneration of the charcoal was by vacuum. The testing program demonstrated that charcoal will continue to adsorb carbon dioxide at a significant rate after repeated cycling with no apparent change or degradation. The presence of water vapor in the gas stream tends to reduce the capacity of the charcoal for adsorbing carbon dioxide. However, it is readily removed from the charcoal by vacuum and exhibits no cumulative effect on the carbon dioxide adsorptive capacity of the charcoal.

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SECTION I

INTRODUCTION

Since the durations and crew sizes of future space missions are to be increased, this will necessarily place a greater demand on the air-purifying systems presently in use. To meet this demand, development of a system using regenerable adsorbents for removal of CO_2 which will meet the stringent weight and volume requirements is considered necessary.

Several possible regenerative systems for the control of carbon dioxide in a manned-space vehicle have been studied. These studies were conducted by the University of Iowa Chemical Engineering Department and Dr. K. Kammermeyer under the direction and sponsorship of The Bendix Corporation. The adsorbents investigated included molecular sieves, silver oxide, activated charcoal, and a silver oxide - activated charcoal mixture. At the conclusion of that investigation, activated charcoal was determined to be an adsorbent that bore further study.

Sixteen varieties of activated charcoals were screened during this testing period and six showed superior adsorption capacity from a dry 100% carbon dioxide gas stream. Some preliminary work had been done with Barneby Cheney KB-1 activiated charcoal before the screening program had been completed. When none of the other charcoals screened offered any significant advantages over it, we decided to continue the preliminary testing program with KB-1. Throughout the testing program, KB-1 charcoal held up extremely well and showed no degradation upon repeated cycling. Therefore, we decided to use it in the laboratory-type regenerative carbon dioxide removal system.

TEST SYSTEM

TEST LOOP

A schematic of the test apparatus is shown in figure 1. The oxygen is supplied from a 50-cubic inch pressure cylinder with an attached pressure regulator and pressure gauge that rests on a laboratory balance. From the cylinder the oxygen passes through a modified Model 29240 Bendix oxygen demand regulator that serves as the primary system pressure control. The demand regulator allows oxygen to flow into the canister until a pressure of approximately 247 mm Hg is reached and then automatically stops the flow of oxygen into the system.

The carbon dioxide is supplied from a similar 50-cubic inch pressure bottle-balance arrangement and fed through a flowmeter to maintain a relatively uniform flow rate during adsorption. Some variations occured in the flow rate and the actual addition rate ran closer to 1.5 g/min than the desired 1.67 g/min. This caused little concern since the true weight of added gas was determined by the balance.

The blower used to circulate the gas through the test loop is a sliding vane type unit, specially designed to be leak tight. The output of the blower can be varied from approximately 160 to 340 liters/min by a variable speed pully and V-belt arrangement.

The flow through the system is measured by a National Instruments Vol-O-Flo S/N2592 flow element and is read out on a water manometer. This gives a stated flow-rate accuracy of ± 0.5%.

The humidity control system, shown in figure 2, used for regulating the humidity in the test loop consists of a device that sprays water into the gas stream at 10C with saturation resulting at this temperature. The temperature of the gas stream is then raised to 27C by a thermostatically controlled electric heater, giving a resultant 50% relative humidity at this higher temperature. The humidity is measured by a Minneapolis Honeywell SSP-128801 humidity sensor which fed into a Minneapolis Honeywell SSP136F011 converter and is read out on a Hewlett Packard voltmeter, Model 412A Vacuum Tube DCVTVM.

The pressure of the canister and test loop during adsorption is measured using mercury barometers.

A partial evacuation pump, Air Shield G-4 Diaphragm pump, is used to investigage the possibility of saving part of the system oxygen by returning it to the test loop before complete desorption.

The carbon dioxide content of the circulating gas stream is monitored by a Greenbriar thermal conductivity analyzer, Model No. T/CO4, with read-out by a Leeds and Northrup Speedomax H recorder calibrated to give the carbon dioxide content of the gas stream versus time.
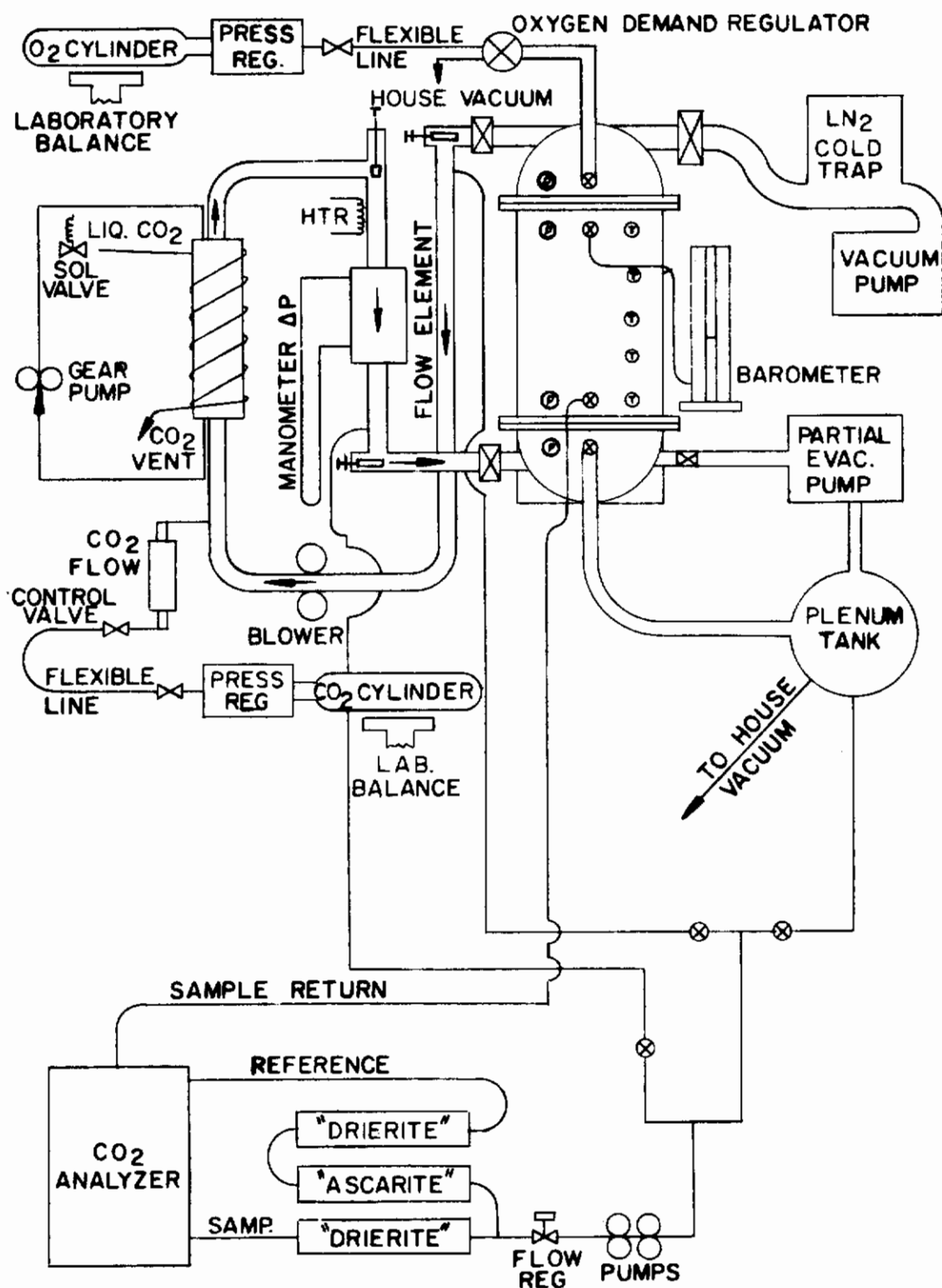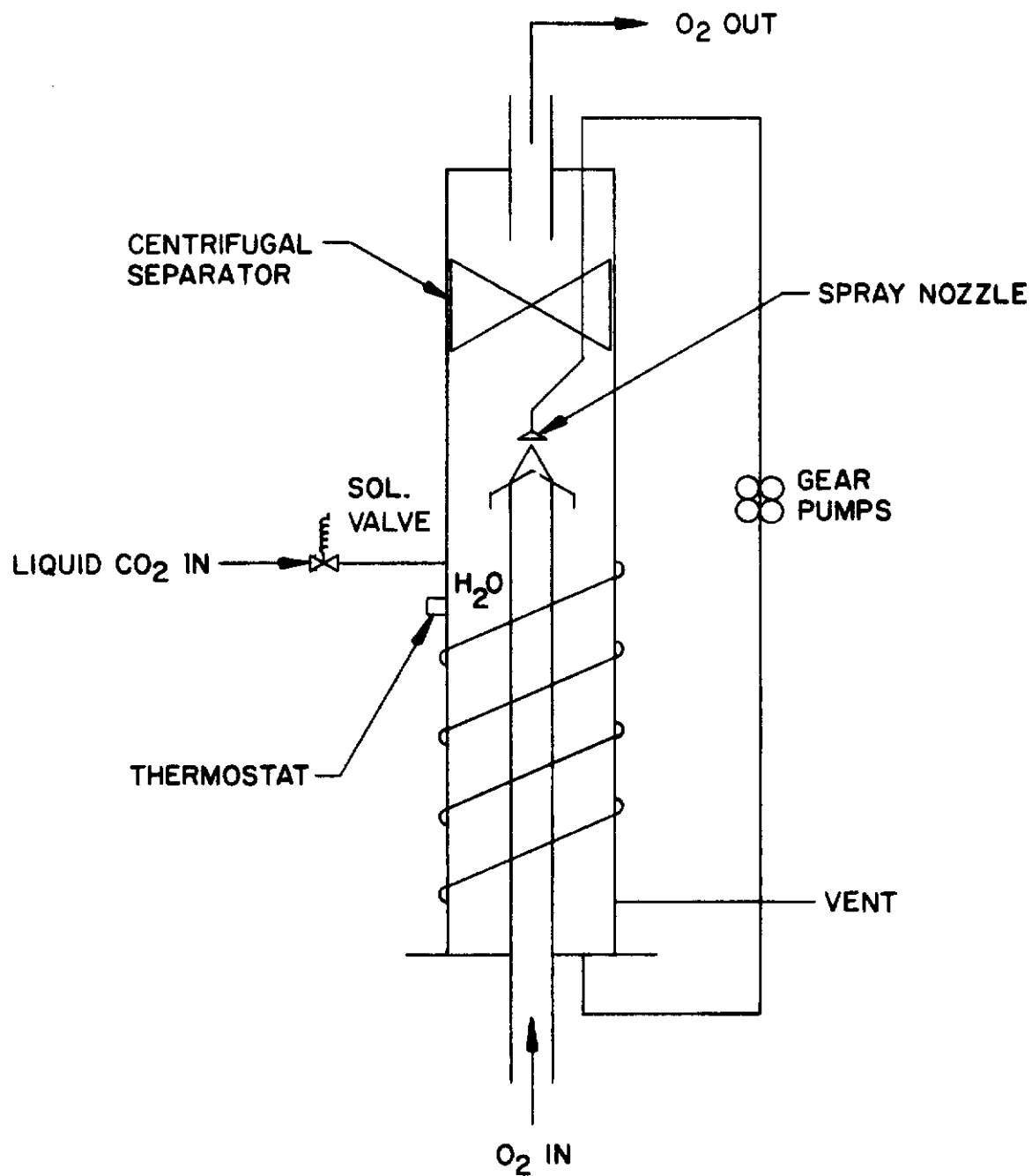
FIGURE 1. CARBON DIOXIDE ADSORPTION - TEST LOOP

O$_2$ OUT

CENTRIFUGAL
SEPARATOR

SPRAY NOZZLE

SOL.
VALVE

GEAR
PUMPS

LIQUID CO$_2$ IN

H$_2$O

THERMOSTAT

VENT

O$_2$ IN

FIGURE 2. HUMIDIFIER SYSTEM

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Since the thermal conductivity analyzer requires a pressure slightly above atmospheric for operation, and the gas stream during adsorption is controlled at approximately 1/3 atmosphere, the gas must be brought to a higher pressure for analysis. Air Shield diaphragm pumps are used because they have no rotating seals and are not susceptible to leakage. Contamination is also eliminated because there are no sliding or rubbing parts. Since diaphragm pumps have limited pressure capacities, the pumps are staged to move the gas from 250 mm Hg absolute to above atmospheric pressure, and this is accomplished by using two pumps in series.

As can be seen in figure 1, the gas sample passes through a column of Drierite to remove any moisture, since the thermal conductivity analyzer is susceptible to water vapor. After passing through the drying column, the sample is divided, one half goes directly into the analyzer (sample side) and the other half through Ascarite, a carbon dioxide scrubber, and then another drying column on the reference side. This is done so that the samples going into the analyzer have exactly the same gas makeup, except that carbon dioxide is absent from the reference stream.
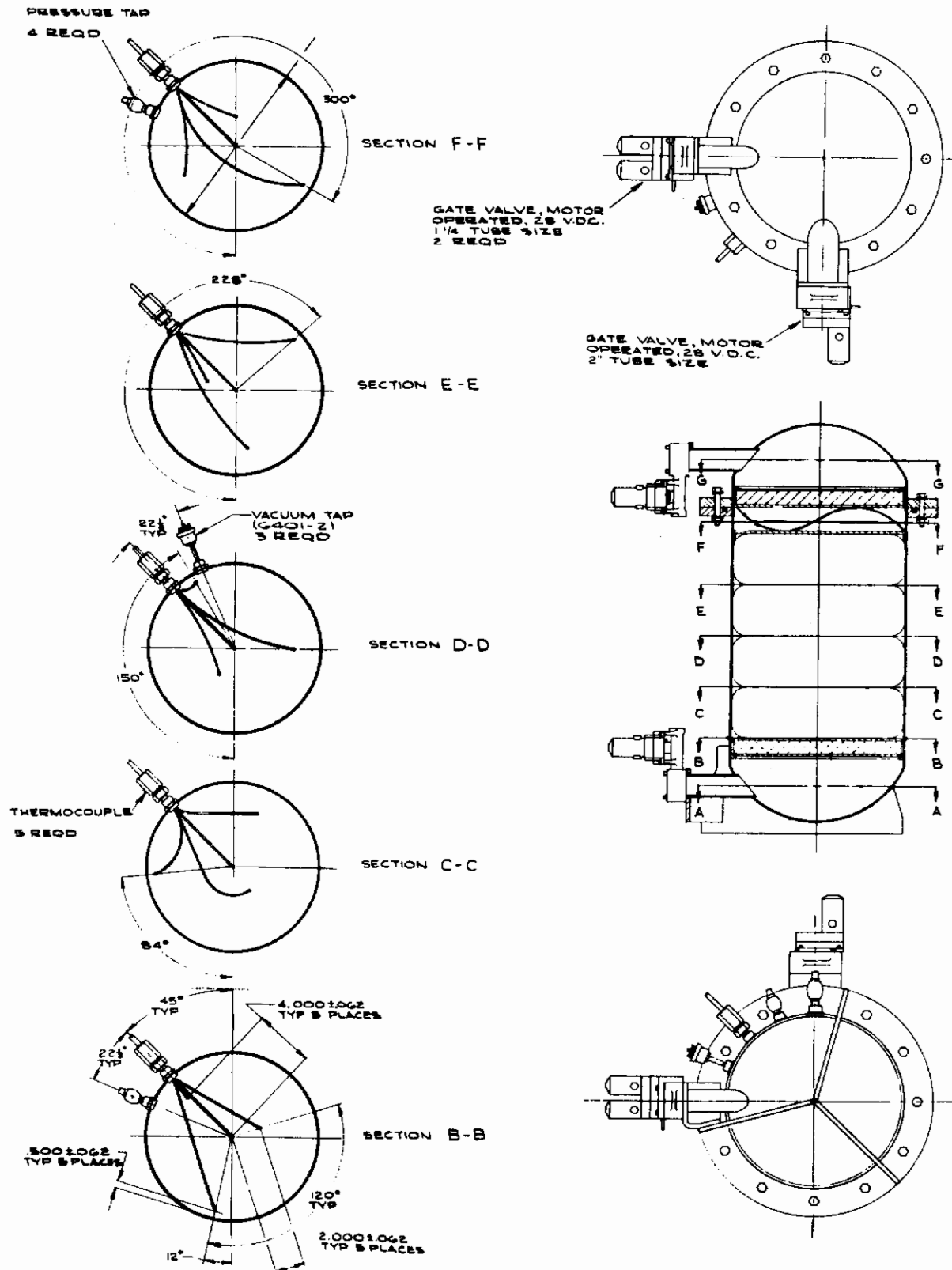
CHARCOAL CANISTER

The general overall design of the canister is shown in figure 3. It contains approximately 14.5 kg of Barnebey Cheney KB-1 activated charcoal. The charcoal is divided between four fiberglass bags containing approximately 3.63 kg each. The charcoal bed is 34.3 cm long and 29.6 cm in diameter. At each end of the charcoal bed is a polyurethane foam filter held in place by stainless steel screens. The body of the canister is made of stainless steel and is constructed from three basic sections: a cylindrical section and two dome end sections. One of the dome ends is welded directly to the cylindrical section, .forming the lower portion of the canister. The outer or top end is attached by means of a flange joint, sealed with an O-Ring and held in place by 12 equally spaced 3/8-inch bolts.

Located in the upper dome of the canister are the outlet port to the circulation loop, the vacuum port for desorption, a pressure tap for measuring the pressure drop through the canister and mounting the oxygen demand regulator, and a tap for measuring pressure during the evacuation period. The port for the gas inlet, the partial evacuation port, the differential pressure tap, and another tap for measuring pressure during evacuation are located in the lower dome.

VALVES

The inlet, outlet and vacuum ports are each fitted with a General Controls, Inc. electrically operated gate valve. The valves on the inlet and outlet air stream are identical and have ports 2.74 mm in diameter. The valve on the partial evacuation port is a manually operated quick opening HoKe globe valve, having a port size of 0.56 mm in diameter. These valves were leak checked and the largest leak found was in the vacuum valve which had a leak rate of less than 2.9×10^{-7} cc of helium per second.

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FIGURE 3. CARBON DIOXIDE ADSORPTION CANISTER

VACUUM GAUGES

As shown in figure 3, the three vacuum gauges are located in the plenum chambers at either end of the canister and at the center of the charcoal bed to determine the pressures in the canister during desorption. They also indicate the time lag in evacuation pressure from one end of the bed to the other during the desorption cycle. The gauges are NRC thermocouple type 521 with a type 721 NRC readout, having a pressure range of 1 to 2500 microns.

TEMPERATURE GRADIENT WITHIN THE CANISTER

Twenty thermocouples placed in the charcoal bed at the points indicated in figure 3 enter the canister through five Conax fittings. Each fitting contains eight wires (four thermocouples). Leak tightness around the thermo-couple wires is insured by the lava sealant through which the wires pass. The thermocouple wires used are iron versus constantan and are readout with a Minneapolis Honeywell Model No. 156 x 11 PS-W13 vertical scale precision indicator.

PRESSURE DROP THROUGH THE CANISTER

Four taps are included in the canister for measuring pressure drop during testing. These taps are fitted with quick-opening stainless steel globe-type valves. By using the ports in various combinations, pressure drop through the entire canister, through the charcoal only, or through either of the filters can be measured. Pressure drop is measured using a standard water manometer.

FILTERS

A polyurethane foam filter 2.54 cm thick, with a density of 20 kg/m^3 is located at either end of the charcoal bed. These filters are included to trap any dust which might come from the charcoal during the adsorption-disorption cycling. The filters and charcoal are both supported by wire mesh reinforced screens.

These supports are held in place by means of a wave washer in the upper end of the canister. The screens are supported by rings welded into each dome end of the canister, which prevent compression of the polyurethane foam from the weight of the charcoal and the compression of the spring.

VACUUM SYSTEM

Evacuation of the canister is accomplished by combining a Welch Duo Seal Model 1397B vacuum pump, with a pumping capacity of 425 liters/minute and an ultimate vacuum of 0.1 microns Hg, and a National Research Corpora-tion Model 0314 liquid nitrogen cold trap, modified with the addition of a liquid nitrogen reservoir and a drain valve for removal of water condensed during desorption.

The test system is shown in figures 4 and 5.

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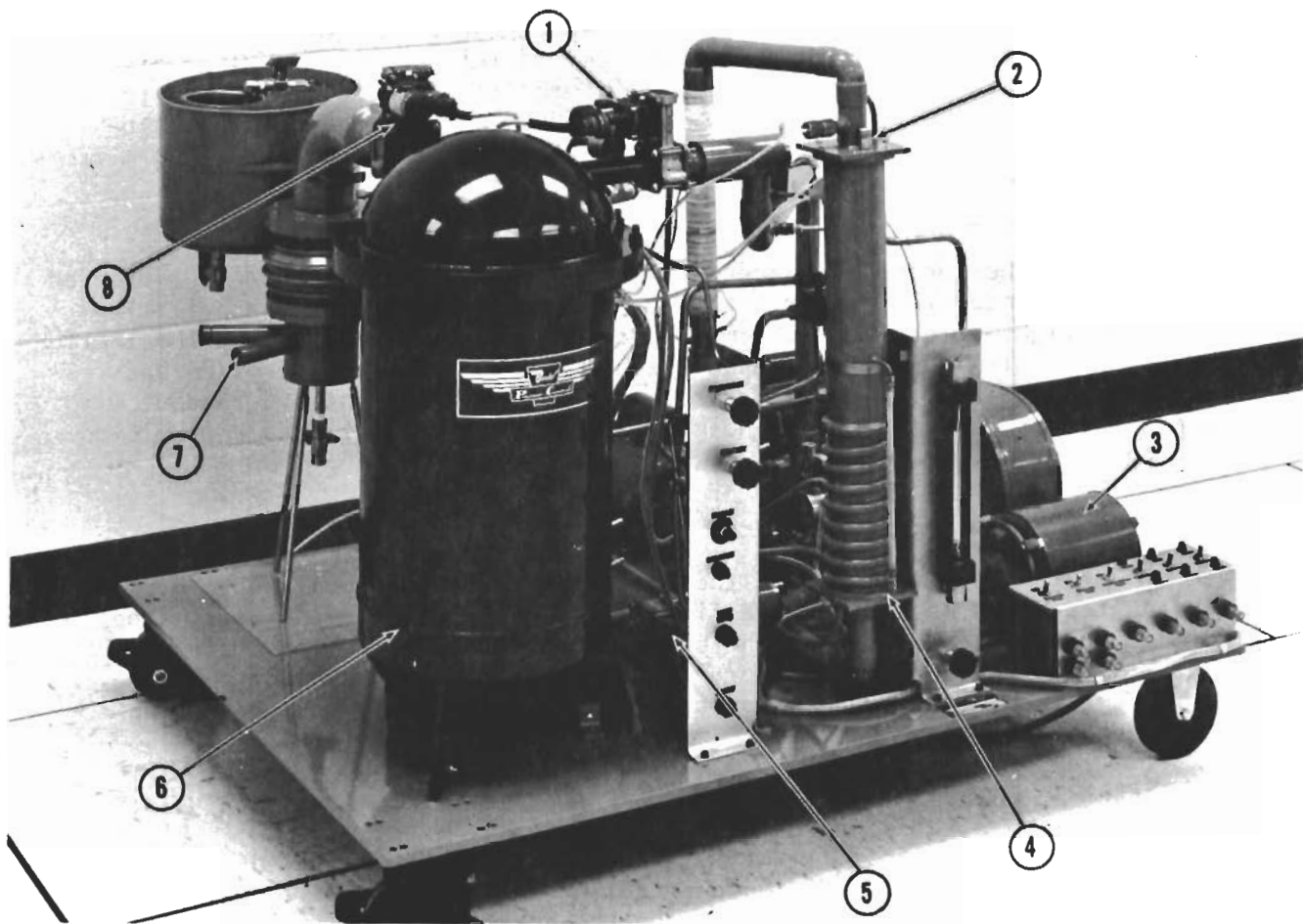
1 OUTLET VALVE
2 HUMIDITY CONTROL FILL CAP
3 GEAR PUMP
4 HUMIDITY CONTROL
5 INLET VALVE
6 CANISTER
7 VACUUM OUTLET
8 VACUUM VALVE

FIGURE 4. TEST SYSTEM - FRONT VIEW

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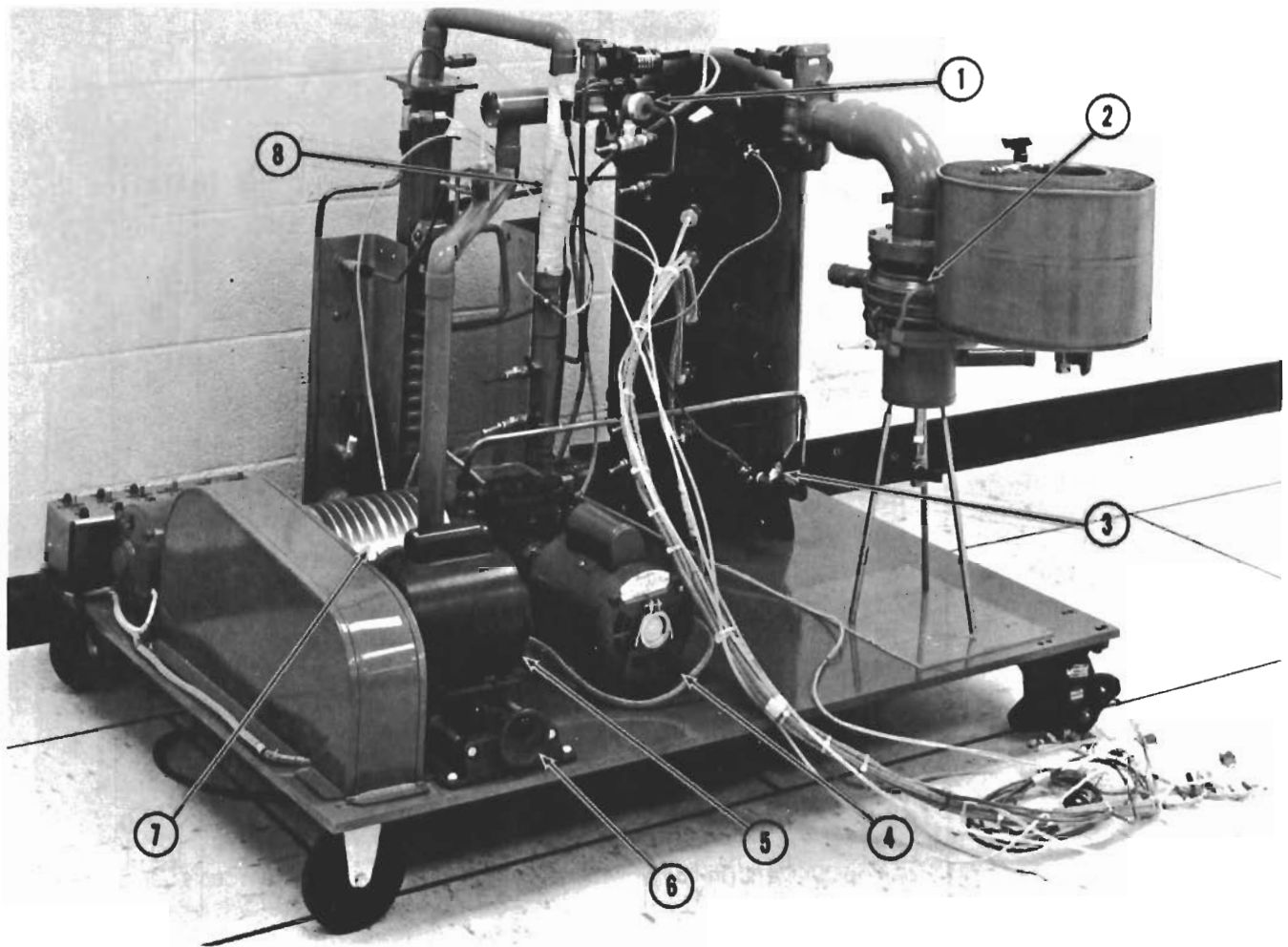
1 OXYGEN REGULATOR
2 LIQUID NITROGEN COLD TRAP
3 PARTIAL EVACUATION VALVE
4 PARTIAL EVACUATION PUMP
5 BLOWER MOTOR
6 BLOWER SPEED ADJUSTMENT
7 BLOWER
8 TEMPERATURE CONTROL

FIGURE 5. TEST SYSTEM - BACK VIEW

SECTION III

SYSTEM OPERATION

The system was designed to operate in an atmosphere within the following environmental limits.

 (1) Carbon dioxide level, 3-8 mm Hg
 (2) Water vapor - 50% relative humidity
 (3) Oxygen level, 240-250 mm Hg
 (4) Total pressure, 240-275 mm Hg
 (5) Carbon dioxide production rate, 100 grams/hour
 (6) Temperature, 26.7 ± 2.7C

The testing program was oriented toward collecting data primarily in the following areas:

 (1) Carbon dioxide capacity and operating level
 (2) Flow rate for two-man capacity
 (3) Duration of cycle times for adsorption and desorption cycles
 (4) Operating temperature ranges
 (5) Power requirements
 (6) Heat output
 (7) Pressure drop across the system
 (8) Air losses of the system

In the adsorption cycle the gas stream flows through the canister of charcoal from bottom to top. Carbon dioxide is adsorbed in the process and the gas stream exits through the outlet valve. At the end of the adsorption cycle, the inlet and outlet valves are closed and the canister is ready for desorption. At this point the partial evacuation pump can be employed to reduce the gas losses from the system. If the partial evacuation pump is used, the pressure in the canister is reduced and the removed gas is pumped back into the circulation loop. The vacuum valve is then opened and the charcoal is stripped of its carbon dioxide, adsorbed water, and any remaining oxygen. If the partial evacuation pump is not used, this step is omitted and the vacuum valve is opened immediately after the inlet and outlet valve are closed.

The system was operated as a closed test loop and was leak checked with a helium mass spectrometer before adsorption testing to prevent atmospheric gases from leaking into the system during operation. The only gas loss during adsorption was the negligible amount consumed by the analyzer during testing. More than 100 adsorption runs were performed during the testing phase, and the carbon dioxide content of the gas stream was monitored continuously during adsorption by the thermal conductivity analyzer.

The analyzer was calibrated and the accuracy determined to be ± 0.5%, traceable to the National Bureau of Standards.

As a check on the calibration of the overall system, the analyzer was attached to the test loop and the inlet sample gas monitored during an adsorption test run.

Figure 6 shows an example of the curve obtained. The curve remains at a constant 1.1% carbon dioxide from 8 minutes to 13 minutes, indicating that steady-state adsorption has been achieved between the time that the lag of the analyzer (to be discussed later) has been overcome and the time when carbon dioxide appears in the effluent. By comparing this portion of the curve with the calculated average carbon dioxide percentage of the gas stream, based on the weight of carbon dioxide removed during adsorption and the flow rate through the system, a maximum deviation of 0.5% was found for all of the adsorption runs checked, with most deviating less than 0.2%. The run shown in figure 6 had a calculated carbon dioxide percentage of 1.2% while the analyzer showed 1.1%. This indicates that the carbon dioxide weight and system flow rate measurements agreed closely with the calibration of the analyzer.
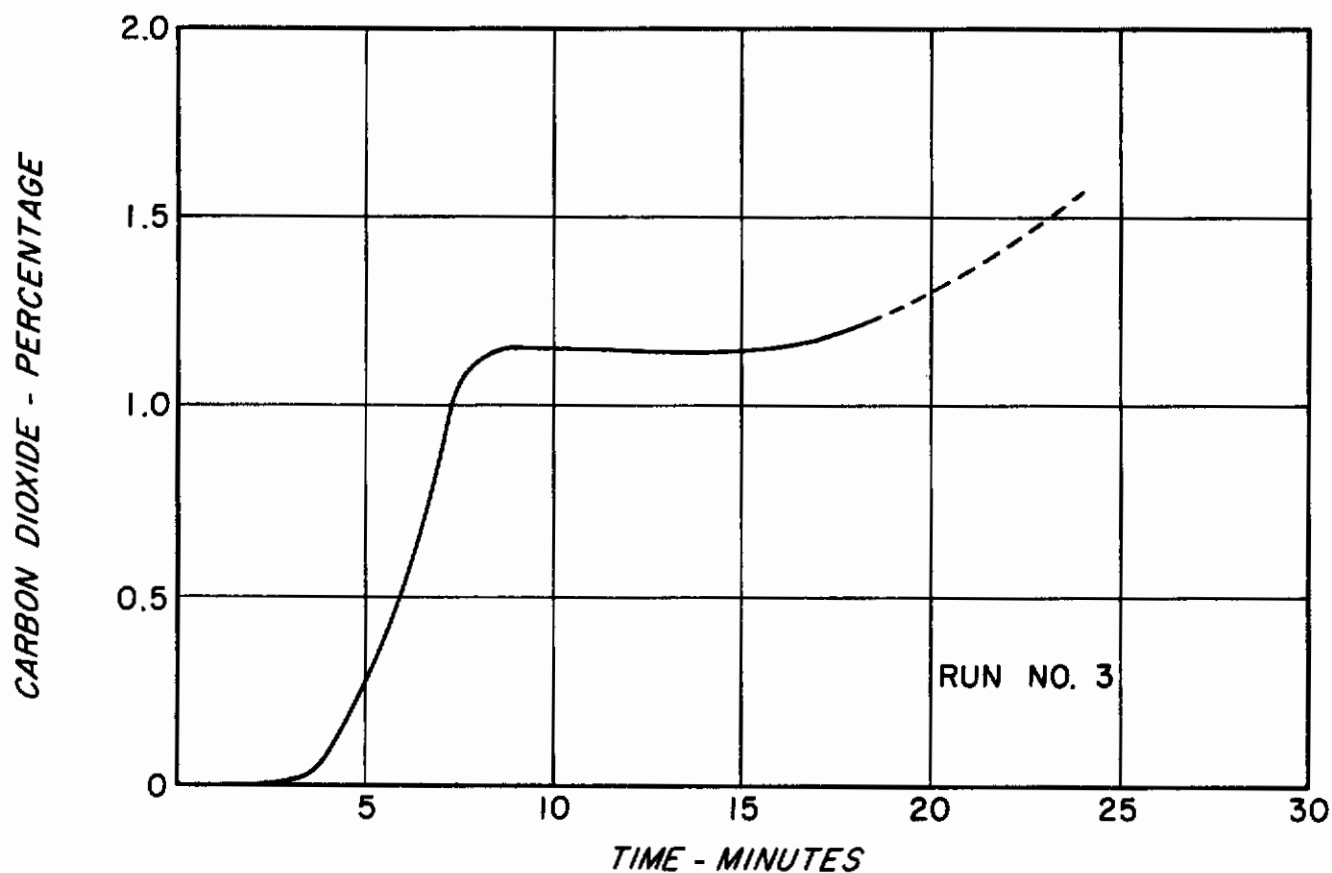
FIGURE 6. CARBON DIOXIDE CONCENTRATION OF THE INLET GAS

The need to pressurize the gas stream for analysis mentioned in Section II led to time delay problems in the gas stream analysis for two reasons:

1. The need for the two pumps and the necessary plumbing to connect them to the loop greatly increases the length of the sample line, which increases the time required for the sample to go from the test loop to the analyzer.

2. As the gas sample passes through the pumps, a great deal of mixing of the gas front occurs, making it impossible to determine sudden changes in the gas composition and as a result, it appears as a gradual change.

The method used to overcome the effect of this time lag was to feed carbon dioxide into the system for a period of time (usually from 5 to 40 minutes) and then to allow the blower to circulate the gas stream throughout the charcoal until the carbon dioxide percentage of the gas stream reached equilibrium. While this does not overcome the analyzer time lag, it gives a true indication of the carbon dioxide adsorbed by the charcoal at that particular carbon dioxide partial pressure. The one fault with this system is that it does not give the percentage of carbon dioxide in the gas stream at a specific time during adsorption and only estimates could be made.

SECTION IV

TEST PROGRAM

All test results reported are for Barnebey Cheney KB-1 charcoal operating in a leak-tight closed test loop at a total pressure of 250-275 mm Hg (oxygen partial pressure of 240-250 mm Hg, carbon dioxide partial pressure of 3-8 mm Hg) and an adsorption temperature of 26.7 ± 2.7C. Tests were performed on both a dry gas stream and a gas stream having a 50% relative humidity and are so specified. Gas flow rates given are at system operating conditions unless otherwise specified.

PRESSURE DROP

Pressure drop tests were carried out on the various portions of the canister before adsorption testing. The same tests were repeated at the end of the testing program. The results of these tests are shown in figures 7-10. Flow rates are given in liters/minute (LPM). The solid line in the graphs represents the pressure drop versus flow rate curve for the various portions of the canister before cycling, and the dotted line represents the pressure drop at the completion of the testing program. The pressure drop through both the charcoal and filters is quite low. The pressure drop tests were run before and after the adsorption testing program to determine if repeated cycling caused any dusting of the charcoal, with resultant increased pressure drop through the filters. Very little change was noted. There appears to be a slight increase in the pressure drop through the top filter. This is where most of the dust which might have been given off would be collected, since the flow was from bottom to top. The increase is so slight as to be within the limits of experimental error, and the increase was sufficiently small that if it is caused by dusting it would not be harmful to the operation of the system. The actual amount of dust that may have been collected by the filter could be determined by removing the filter and physically examining it. This was not done since the canister was leak tight and further testing was planned with it.

HEAT OUTPUT AND OPERATING TEMPERATURE

All tests were performed with the gas stream at 26.7 ± 2.7C during adsorption. No attempt was made to control the temperature of the charcoal. Since the primary purpose of this investigation was to determine the ability of activated charcoal to withstand repeated carbon dioxide adsorption at room temperature, and subsequent vacuum desorption cycling without the aid of supplemental heating, the charcoal was subjected only to ambient room temperature. Even though the temperature of the gas stream was held constant during adsorption, there were significant temperature changes noted in the charcoal.

Typical temperature profiles for the charcoal bed during adsorption and desorption respectively are given in tables I and II (Appendix) for both a dry gas stream and a gas stream having 50% relative humidity. There
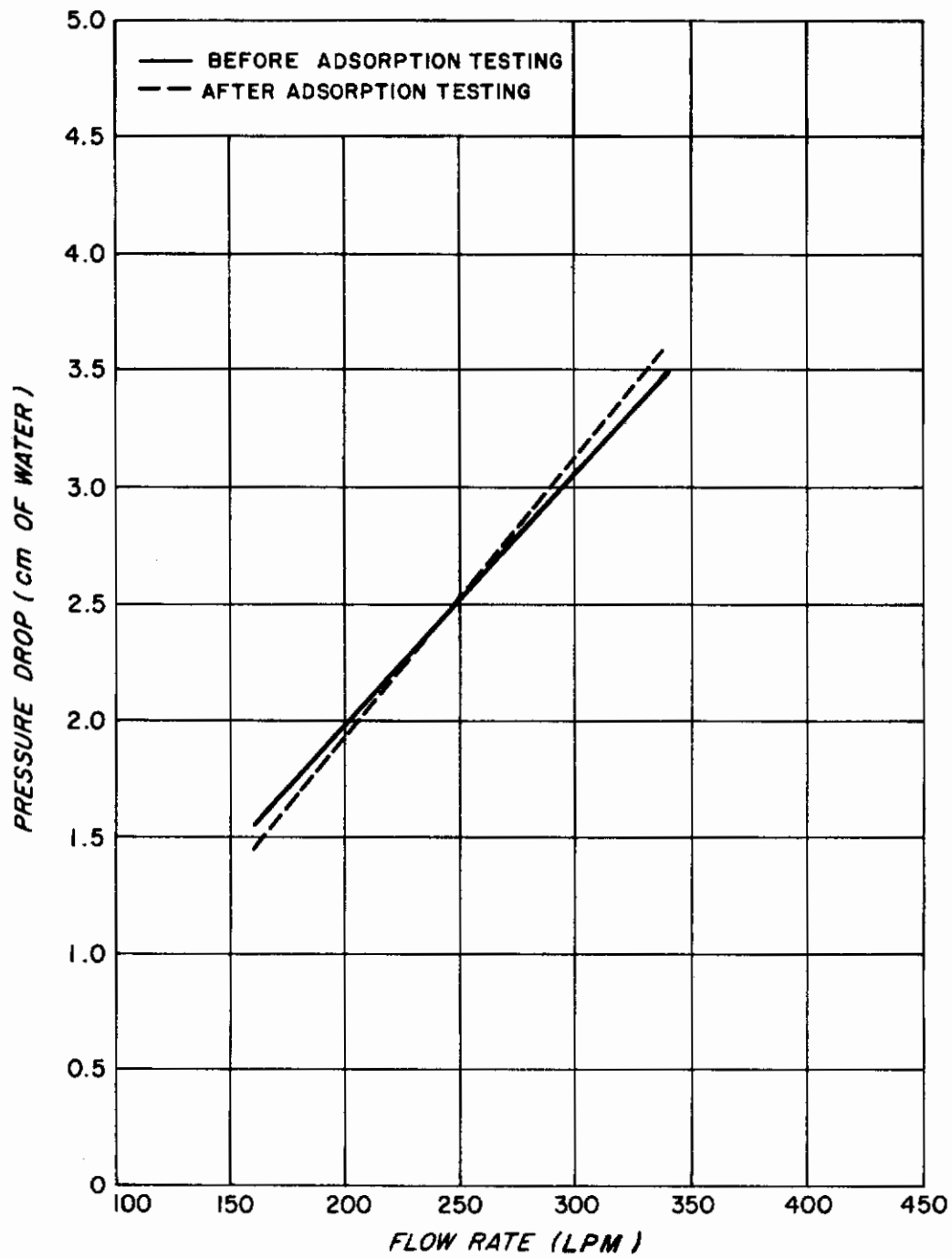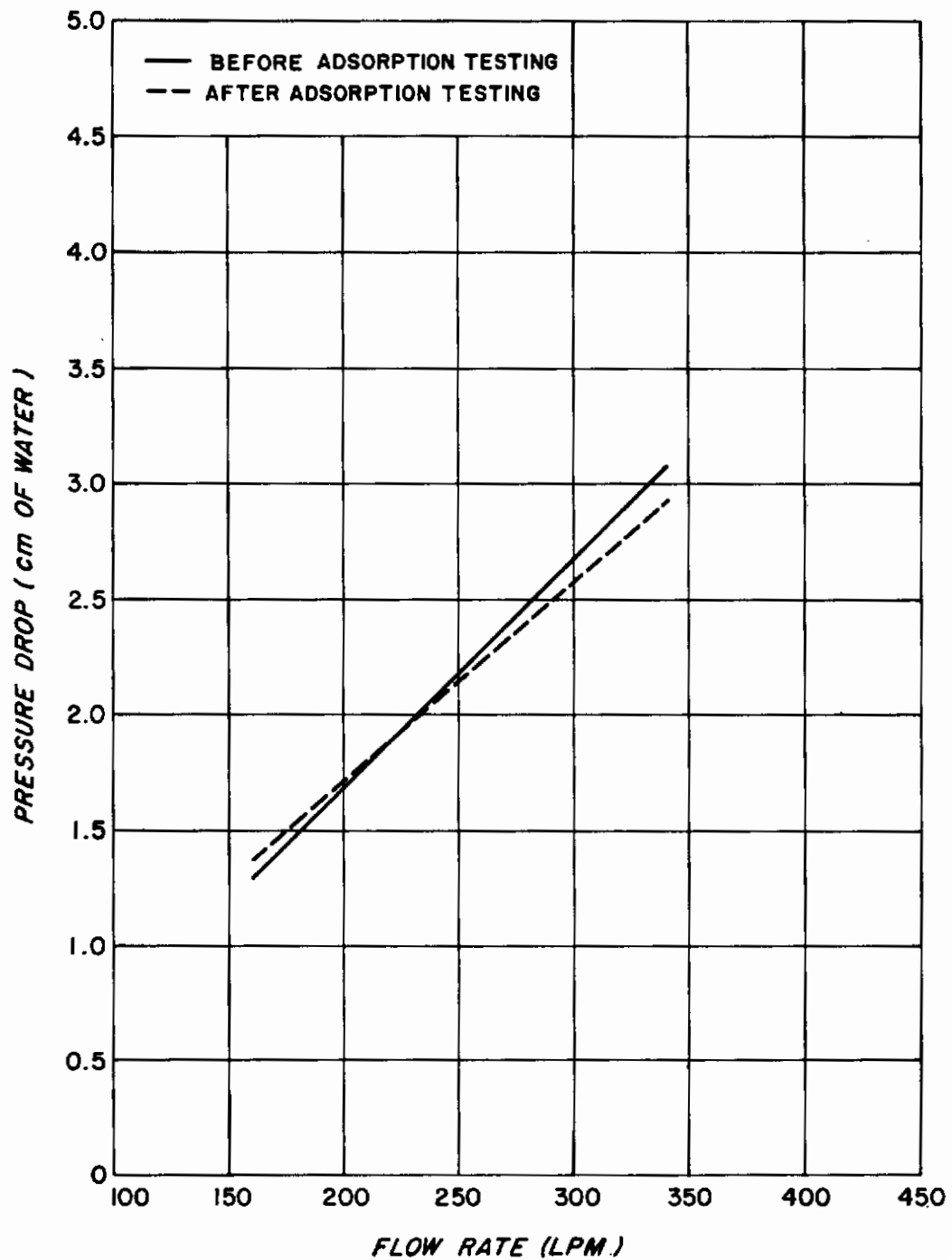
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FIGURE 7. PRESSURE DROP THROUGH THE CANISTER
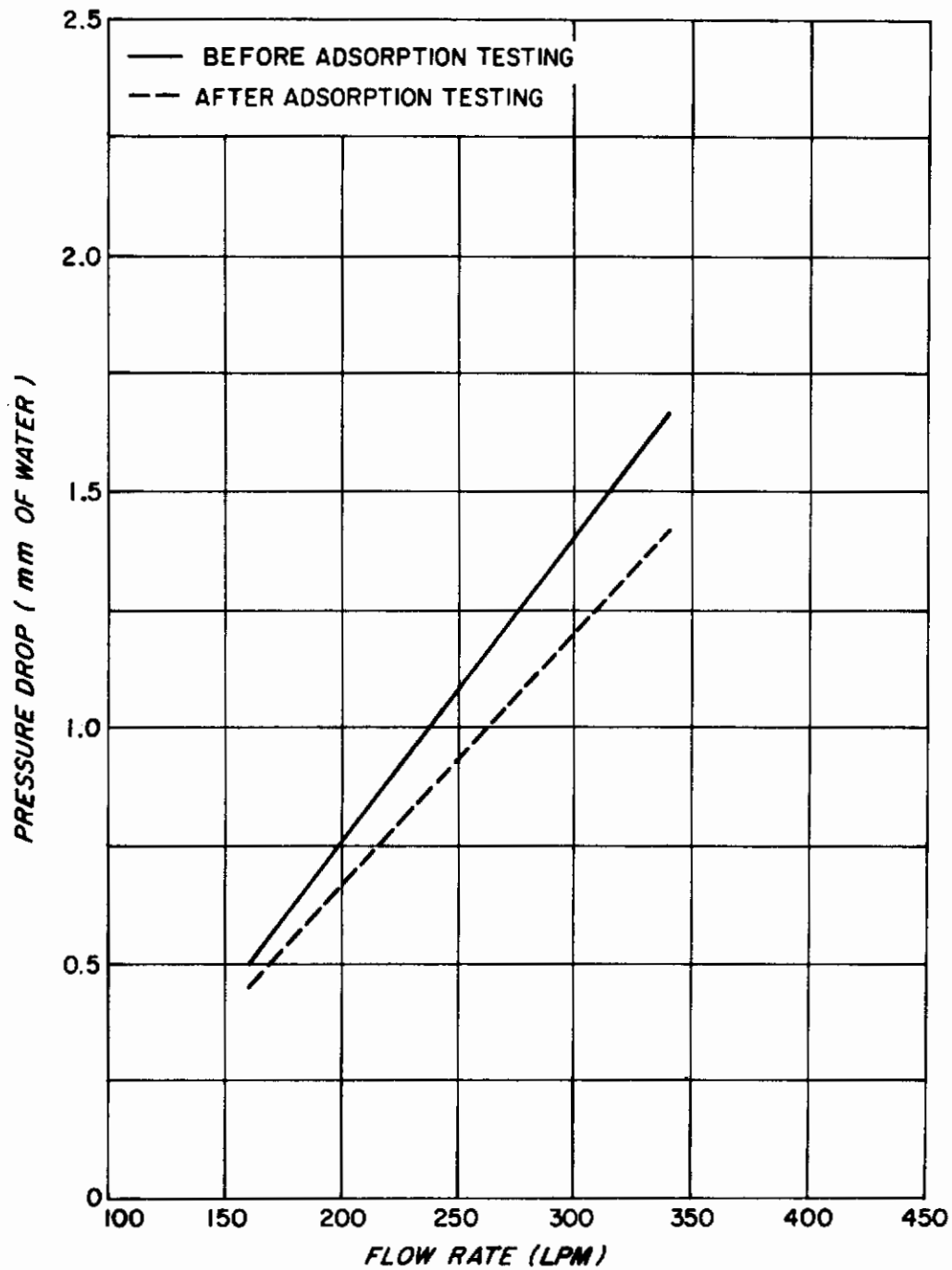
14

FIGURE 8. PRESSURE DROP THROUGH THE CHARCOAL

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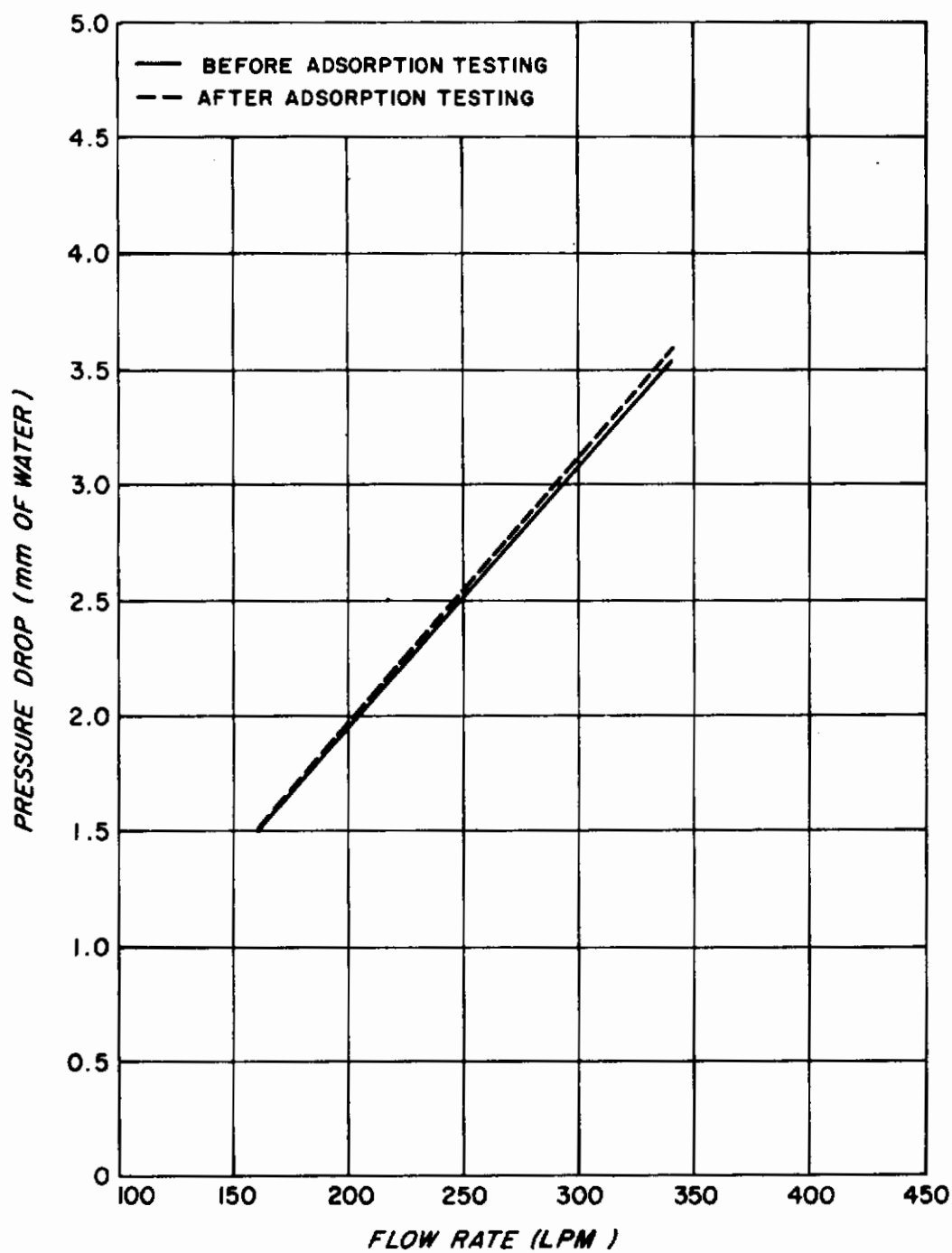FIGURE 9. PRESSURE DROP THROUGH THE TOP FILTER

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FIGURE 10. PRESSURE DROP THROUGH THE BOTTOM FILTER

is a warming of the bed during adsorption and a cooling during the desorption period. The temperature changes were much greater for the humidified gas stream than for the dry gas, resulting from the adsorption and desorption of water by the charcoal.

Table III (Appendix) shows a typical temperature profile of the charcoal bed before and after pressurizing with oxygen at the start of the adsorption cycle. There is a noticeable temperature incresse when the canister is pressurized with oxygen to 240-250 mm Hg. This is an indication that some oxygen is being adsorbed by the charcoal. If none were adsorbed, the expected temperature change would be a lower temperature, owing to the gas expansion as the oxygen is being fed from a high pressure cylinder into the evacuated canister. The actual quantities of oxygen adsorbed will be discussed further under "Air Losses of the System."

AIR LOSSES OF THE SYSTEM

When the charcoal is desorbed by vacuum, the air losses of the systems are the adsorbed oxygen and water vapor plus the nonadsorbed water vapor and oxygen in the void space.

The oxygen losses of the system were determined from the amount of oxygen required to initially pressurize the canister to 240-250 mm Hg following the desorption portion of the cycle. The average amount of oxygen required over the entire testing program was 76 grams to pressurize the whole system. Of this quantity, approximately 2 grams were required to pressurize the test loop and 74 grams to pressuize the canister alone. If none of the oxygen were removed by the partial evacuation pump before total evacuation of the canister, 74 grams of oxygen would be lost per cycle. The amount of oxygen required for pressurization represents a significant amount of adsorbed oxygen.

The volume of the canister is 42 liters; therefore, from the ideal gas law (PV=nRT) the canister should require approximately 17.5 grams of oxygen at operating temperature and pressure, if there were no charcoal and filters present. The charcoal occupies 24.6 liters and the filters 3.7 liters, or a combined volume of 28.3 liters. The charcoal has a void volume of 73% and, assuming approximately the same void volume for the filter, there would be 7.6 liters physically occupied by the charcoal and filters. The canister would therefore have a total void volume of 34.2 liters and should have a capacity of 14 grams of oxygen at 245 mm Hg and 27C. Thus, an average of approximately 60 grams of oxygen is adsorbed per cycle.

To determine the quantity of oxygen adsorbed by this means, a plenum simulating the canister was attached to the test loop and the weight of oxygen required to pressurize it was compared with the calculated quantity that should be required based on the ideal gas law. This gave a good check wherein a difference of less than one gram was noted. A similar check was not made on the canister because of the difficulty in removing and reinserting the 20 thermocouples spaced through the charcoal.

To determine if the amount of oxygen adsorbed was directly proportional to pressure, a series of tests was performed to determine the quantity of oxygen required to pressurize to various pressure levels. The amount of oxygen required to pressurize to a number of different levels between 21 mm Hg and 358 mm Hg was determined in two different manners. First, the canister was evacuated to less than 500 microns, pressurized stepwise to 21, 34, 54, 87, 141, 226 and 258 mm Hg with the amount of oxygen required for each step, and then weighed and recorded. Following this, a 20-minute adsorption run was performed; the canister was evacuated to 226 mm Hg, brought back to 258 mm Hg with oxygen, evacuated to 141 mm Hg with oxygen etc. through 21 mm Hg with the oxygen weighed and recorded each time. The second method was applied to determine if the adsorbed water and carbon dioxide had any effect on the quantities of oxygen adsorbed by the charcoal. Virtually no difference was noted in the results found by the two methods. The tests were repeated several times and the average results are shown in figure 11. Also shown in this figure is the theoretical amount of oxygen required if the canister was empty, and also the amount required assuming a void volume of 34 liters, as discussed.

The water losses from the system were determined by measuring the water removed from the liquid nitrogen cold trap, following desorption of the charcoal. The humidifier system created a constant 50% relative humidity in the gas stream flowing into the charcoal, and was monitored by a humidity sensor. The higher the flow rate, the higher the quantity of water adsorbed. Thus, the maximum water loss occurred at the maximum flow rate of the blower.
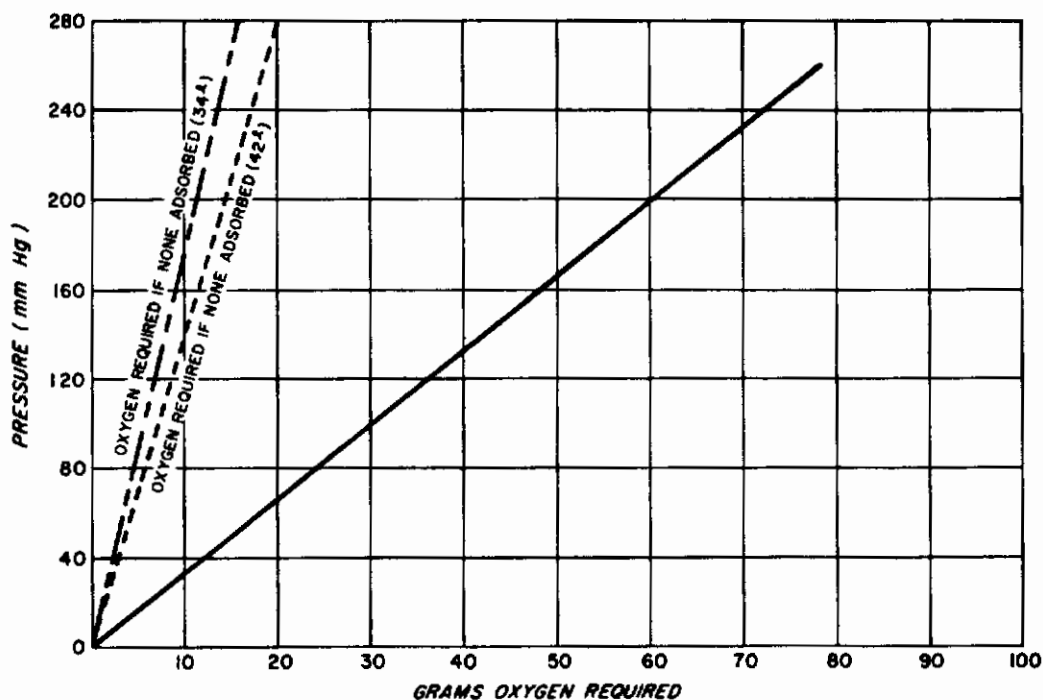

FIGURE 11. OXYGEN REQUIRED TO PRESSURIZE THE CANISTER

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Operating at the maximum flow rate of 340 liters per minute, the average amount of water removed was 1.9 grams per minute of adsorption time. There was considerable variation in the amount of water removed from the cold trap from run to run, with fluctuations of 1.7 - 2.2 grams per minute of adsorption time. The variation was caused by failure to desorb all the water on one run which subsequently became part of a succeeding run.

A humidity sensor that had a range of 35-70% relative humidity was located at the outlet of the canister. Even after adsorption periods of 35 minutes the humidity did not reach the 35% mark, and therefore the sensor proved to be of no value in measuring the water loss from the system.

CARBON DIOXIDE CAPACITY

The majority of the testing program was devoted to determining the carbon dioxide capacity of the charcoal. More than 100 adsorption-desorption cycles were run to determine its capacity to adsorb from both a dry gas stream and a gas stream having 50% relative humidity.

The first adsorption tests were conducted with a dry gas stream, as were several of the last ones. This was done in order that comparisons could be made to determine if the charcoal retained uniform adsorptive capacity while adsorbing carbon dioxide from both a wet and dry gas stream. Figure 12 shows the results of two typical adsorption tests in which the carbon dioxide concentration was monitored on the effluent stream. These two tests were carried out under nearly identical conditions at a total gas stream flow rate of 340 liters/min with the only significant difference being a carbon dioxide flow rate of 1.4 g/min for run number 18 and 1.5 g/min for number 74. This higher addition rate resulted in a slightly higher percentage of unadsorbed carbon dioxide in the gas stream. Figure 13 shows the effect of varying the adsorption time with a dry gas feed of 340 liters/min. All four adsorption runs were carried out under nearly comparable conditions, except for the addition times which varied from 5 to 35 minutes. As can be seen, each increase of adsorption time of 10 minutes shows an increase of approximately 0.8% in the final carbon dioxide content of the effluent gas stream, indicating that the carbon dioxide adsorptive capacity of the charcoal is directly proportional to the partial pressure of the carbon dioxide.

Figure 14 shows a composite curve of the results of all the adsorption tests with a dry gas stream at the various flow rates. This curve results from plotting the final carbon dioxide percentage of the effluent gas stream against the time period for which carbon dioxide was added to the system at a relatively constant rate. Here, again, the 9.8% increase in carbon dioxide percentage can be seen for each 10 minute increase in addition time.

Figure 15 represents test data obtained in comparing the weight of carbon dioxide added versus addition time for the same tests presented in figure 14. This second plot eliminates the effect of variations in the carbon dioxide flow rate, which is not taken into account when the plot is made in terms of addition time.
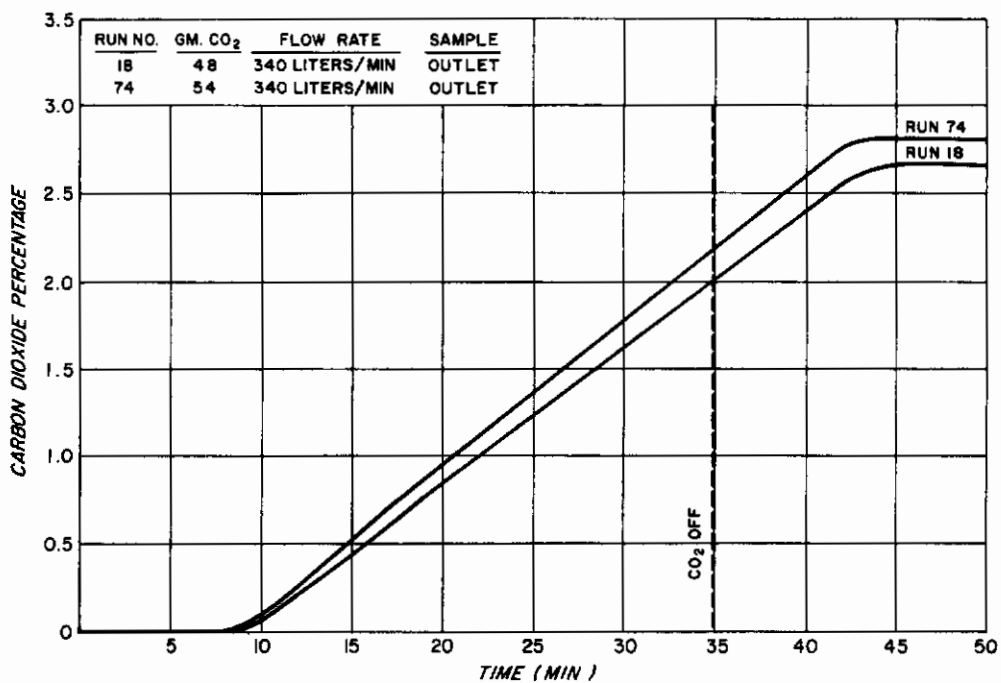
FIGURE 12. CARBON DIOXIDE ADSORPTION FROM A DRY GAS STREAM
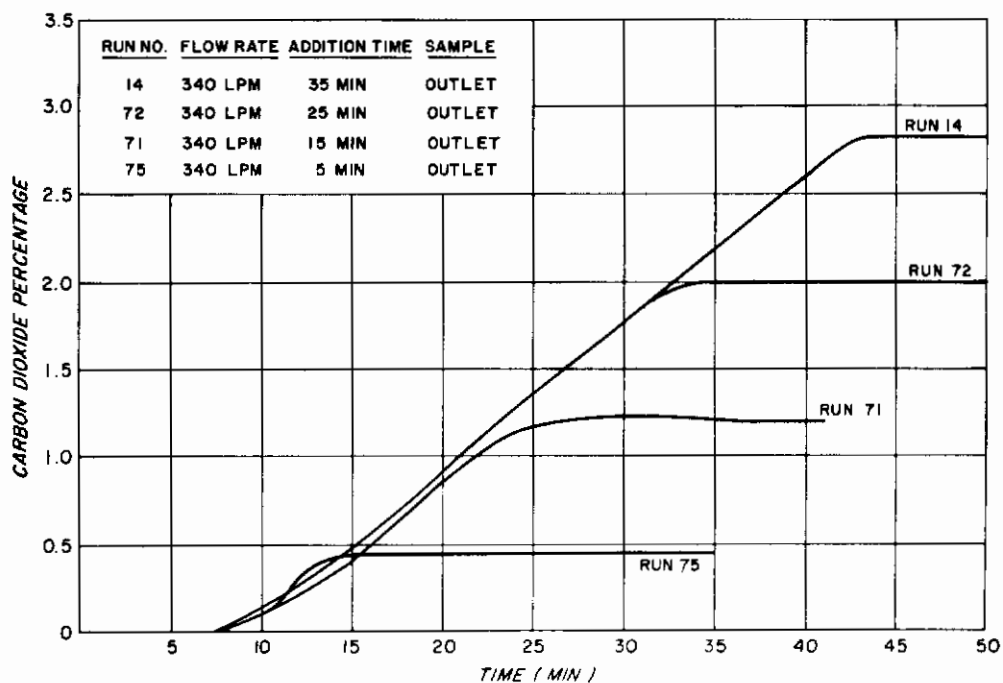
FIGURE 13. CARBON DIOXIDE ADSORPTION FROM A DRY GAS STREAM
WITH VARIED ADDITION TIMES
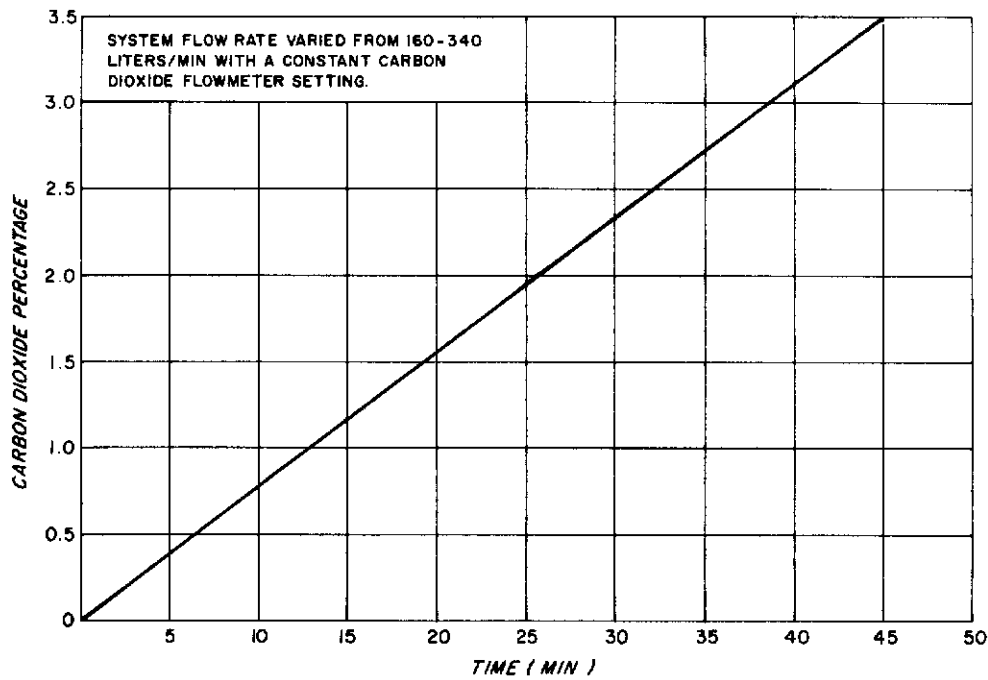
FIGURE 14. COMPOSITE FOR DRY GAS FEED (TIME)

Chart text: SYSTEM FLOW RATE VARIED FROM 160-340 LITERS/MIN WITH A CONSTANT CARBON DIOXIDE FLOWMETER SETTING.

Y-axis: CARBON DIOXIDE PERCENTAGE
X-axis: TIME (MIN)
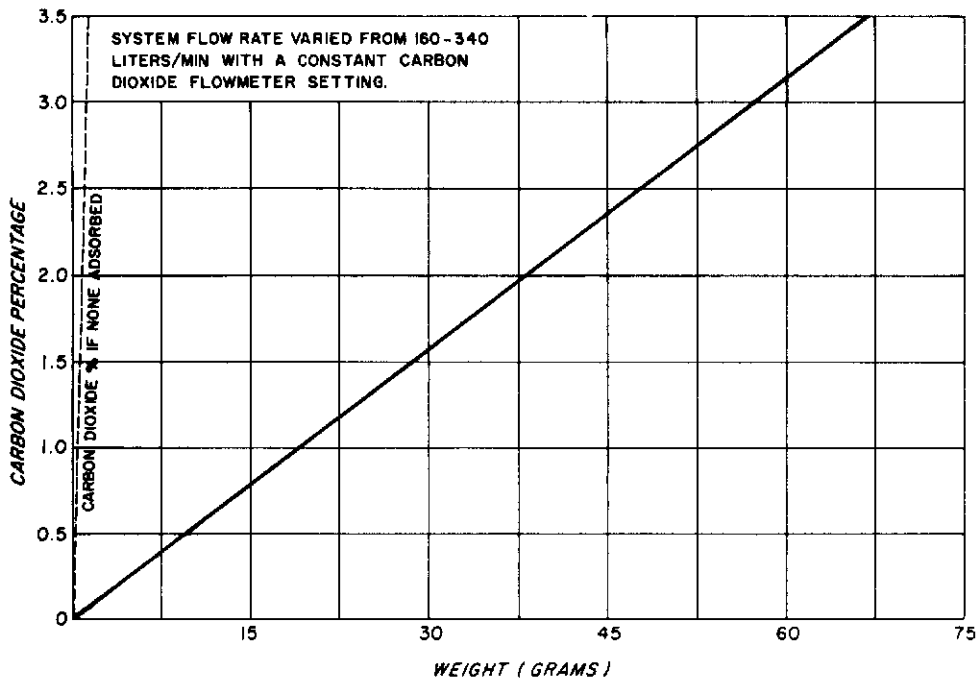
FIGURE 15. COMPOSITE FOR DRY GAS FEED (WEIGHT)

Chart text: SYSTEM FLOW RATE VARIED FROM 160-340 LITERS/MIN WITH A CONSTANT CARBON DIOXIDE FLOWMETER SETTING.

Y-axis: CARBON DIOXIDE PERCENTAGE
(vertical label: CARBON DIOXIDE % IF NONE ADSORBED)
X-axis: WEIGHT (GRAMS)

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The composite curves of both figures 14 and 15 take the form of a straight line. Since some of these points represent early adsorption runs, and some later tests, it is evident that there is no change in the adsorptive capacity of the charcoal after repeated cycling. This also indicates that the adsorption capacity of the charcoal is directly proportional to the carbon dioxide partial pressure of the dry gas stream from which it is adsorbing, at least over the pressure range investigated.

Figure 15 also shows the carbon dioxide increase of the system with respect to the weight of the carbon dioxide added, if none is being adsorbed by the charcoal. This line is based on the 34 liters free volume of the canister, discussed under "Air Losses from the System." The difference between these two lines gives the total grams of carbon dioxide adsorbed.

This testing program showed that the activated charcoal can be repeatedly recycled and will continue to adsorb carbon dioxide from a dry gas stream at a uniform rate with no apparent degradation. A quantity of 14.5 kg of KB-1 charcoal will adsorb approximately 58 grams of carbon dioxide before reaching the maximum design limit of 3.2% carbon dioxide at 250 mm Hg total pressure. At a flow rate of 100 grams per hour, this could allow an adsorption time slightly over 34 minutes. The tests also showed that cycling the charcoal with a gas stream having a 50% relative humidity does not affect its ability to adsorb carbon dioxide from a dry gas stream.

HUMIDIFIED GAS FEED

A large number of adsorption tests were carried out using a gas feed having a relative humidity of 50%. The actual amount of water to which the charcoal was exposed varied directly with the flow. Since the gas stream was held at a constant 50% relative humidity, the more gas that passes through the charcoal the more water vapor that comes in contact with the charcoal.

Figures 16 and 17 show the effect of a humidified gas stream on the adsorptive capacity of activated charcoal. Figure 16 shows two typical 10 minute adsorption runs carried out under nearly identical conditions except Run No. 15 was a dry gas stream and Run No. 23 was a humidified stream. As can be seen, the water vapor has a definite degrading effect on the adsorptive capacity of the charcoal. The slope of the humidified stream curve is greater, indicating a slower adsorption rate of carbon dioxide and the final percentage of carbon dioxide in the gas stream is greater, indicating lower capacity. Another significant difference is the small peak or hump which appears in the adsorption curve of Run No. 23 in the time period from approximately 18 to 23 minutes. This is characteristic of the analysis of the humidified gas stream. This peak appears to be caused by carbon dioxide that is not adsorbed initially by the bed. Figure 17 shows basically the same thing but for an adsorption period of 20 minutes. Run No. 68 is a dry gas stream analysis and Run No. 52 shows the same peak as noted in No. 23. Here again, the curve for the humidified stream has a greater slope and the final effluent carbon dioxide percentage is higher than for the dry gas stream.
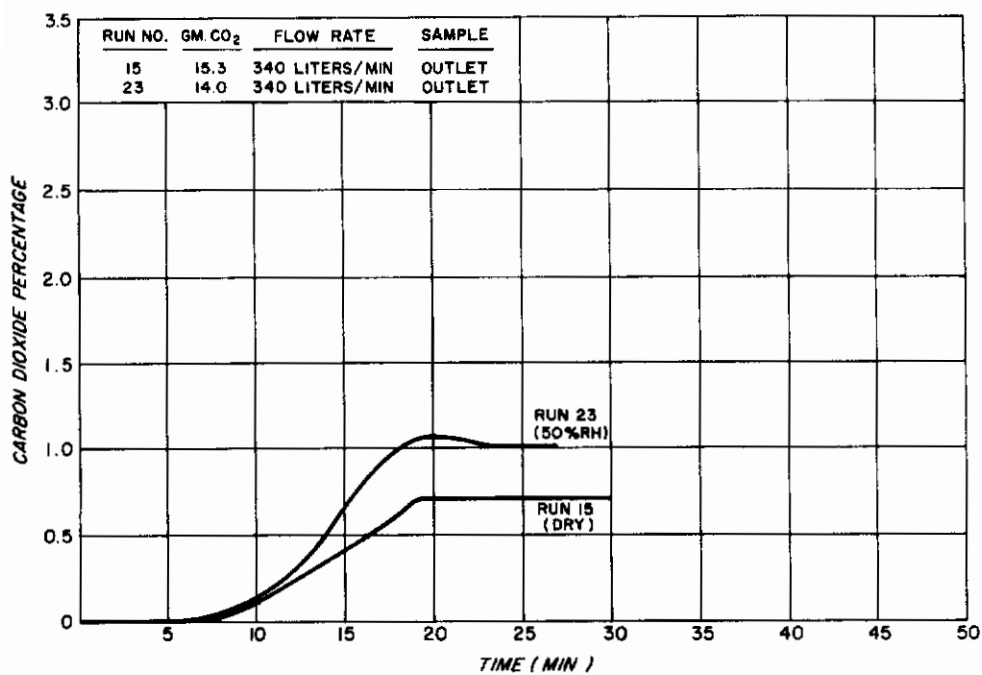
23

FIGURE 16. COMPARISON FOR HUMIDIFIED AND DRY GAS ADSORPTION (10 MIN)
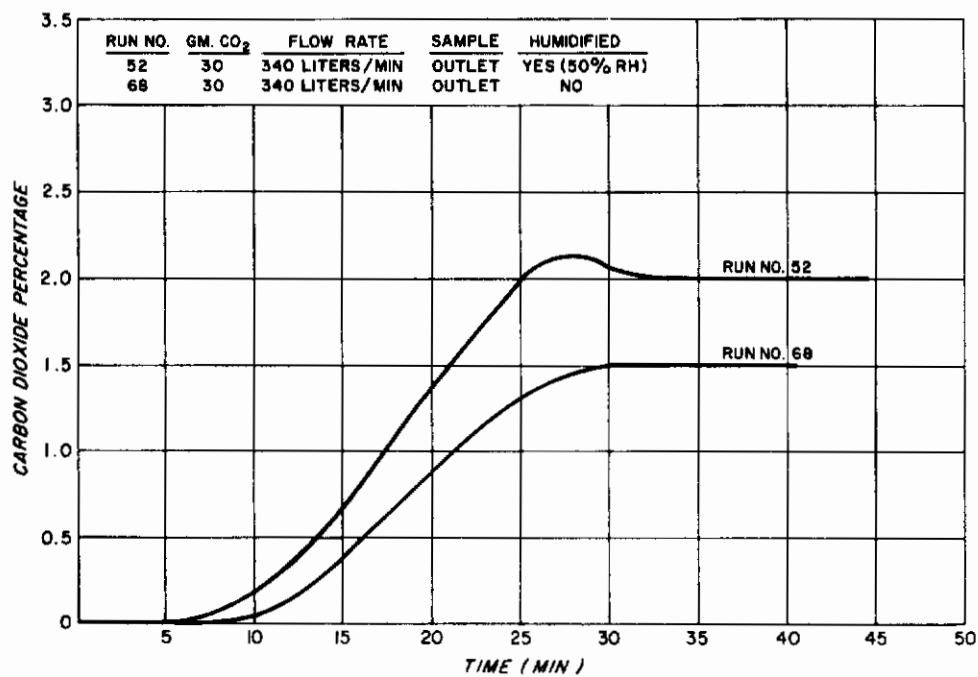

FIGURE 17. COMPARISON OF HUMIDIFIED AND DRY GAS ADSORPTION (20 MIN)

Figure 18 shows the effect of varying the adsorption time when adsorbing from a humidified gas stream. All of the tests were carried out under nearly identical conditions except for the length of the carbon dixoide addition time. A comparison of these curves with those of figure 13 shows that the humidified adsorption runs do not have the same degree of adsorption uniformity as the dry gas stream tests. The dry gas stream showed an increase of approximately 0.8% for each 10 minutes of addition time, but this was not the case when the gas stream had water vapor present. The first 10-minute addition resulted in a carbon dioxide percentage of 0.95%, the next 10-minute addition time resulted in an increase of 1.3%. Both of these increases are typical of results normally found and fall close to the composite curve figure 19. The 30-minute addition time shown in Run No. 86 resulted only in an increase of 0.95% carbon dioxide over that found for the 20-minute run, No. 66. This does not agree with the composite results shown in figure 19. It is typical however of the variation found in the humidified analysis, but not found in the dry gas analysis. Results shown in figure 19 indicate that for a 30-minute adsorption period the final carbon dioxide percentage should be greater than 3.5% (the highest percentage that could be read on the analyzer as it was calibrated). Other adsorption attempts of 30 minutes produced results of over 3.5% which were higher than could be read on the analyzer. Therefore, while Run No. 86 is not a typical run, it is indicative of the variations found in some of the humidified tests.

Figure 19 represents the composite results of all humidified test results in terms of the carbon dioxide percentage of the effluent gas stream versus addition time, while figure 14 is for the dry gas stream.

Figure 20 shows the same information, however, it is plotted in terms of grams of carbon dioxide added versus carbon dioxide percentage of the effluent gas stream.

A comparison of the carbon dioxide adsorbed from a dry gas stream and from a gas stream having a relative humidity of 50% is shown in figure 21. The charcoal adsorbed slightly more carbon dioxide from the dry stream than from the humidified one. In terms of weight of carbon dioxide adsorbed, this is an insignificant quantity. However, in terms of carbon dioxide percentage increase of the effluent gas stream it is significant. For example, with an input of 34 grams of carbon dioxide (two man output for 20 minutes) the difference is approximately 0.13 grams more adsorbed from the dry gas stream than from the humidified stream. Percentage-wise, there is a difference of 0.5%, since the carbon dioxide percentage in the effluent gas stream was 1.8% for the dry stream and 2.3% for the humidified gas stream. The difference becomes greater as the carbon dioxide input increases, i.e., the longer the adsorption time. In view of the data accumulated, adsorption cycles are anticipated to be 20 minutes in duration. For this period of time the humidity appears to have a minimal effect on the actual quantity of carbon dixoide adsorbed.

REDUCTION OF AIR LOSSES FROM THE SYSTEM

A diaphragm pump was included in the test loop so that some of the

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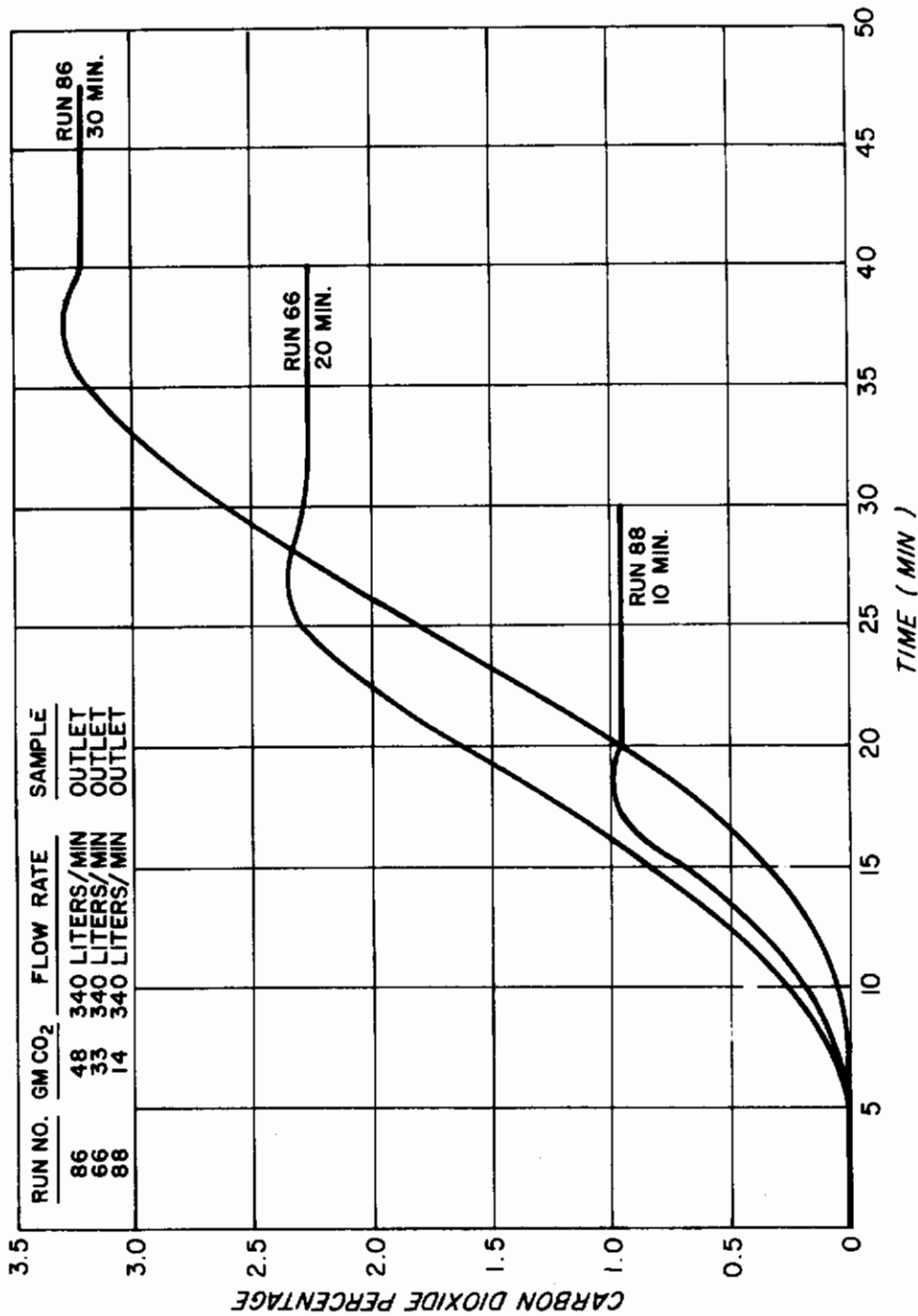
FIGURE 18. CARBON DIOXIDE ADSORPTION FROM A HUMIDIFIED GAS STREAM WITH VARIED ADDITION TIMES

RUN NO.	GM CO₂	FLOW RATE	SAMPLE
86	48	340 LITERS/MIN	OUTLET
66	33	340 LITERS/MIN	OUTLET
88	14	340 LITERS/MIN	OUTLET

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FIGURE 19. COMPOSITE FOR DRY GAS FEED HAVING 50% RELATIVE HUMIDITY (TIME)

FIGURE 20. COMPOSITE FOR GAS FEED HAVING 50% RELATIVE HUMIDITY (WEIGHT)
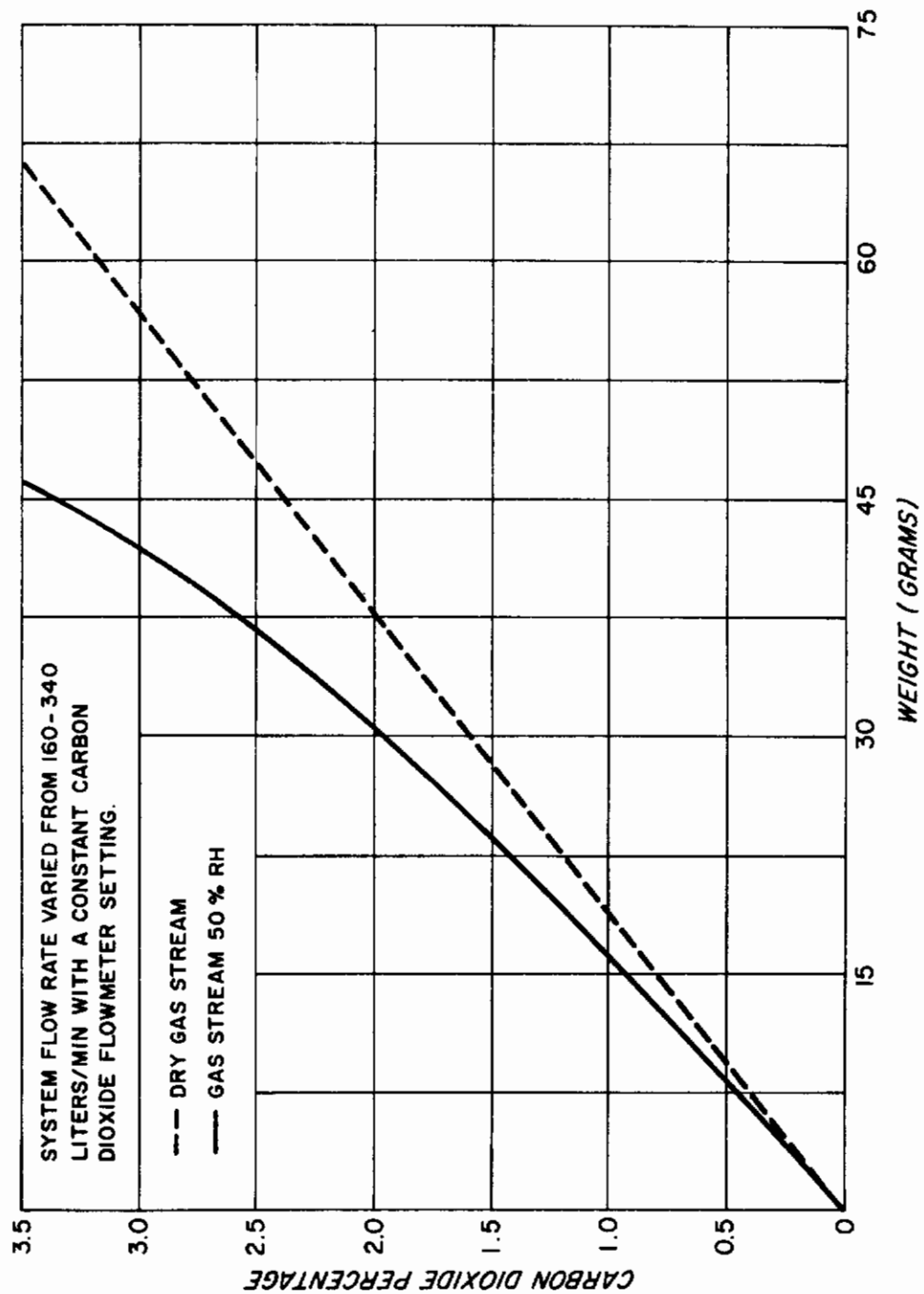
FIGURE 21. COMPARISON OF CARBON DIOXIDE ADSORPTION FROM A DRY AND A HUMIDIFIED GAS STREAM

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gases could be pumped from the canister into the test loop before complete evacuation. This was done to determine the possibility of using this method to reduce some of the air losses from the system. To prevent excessive pressurization in the test loop, a plenum tank was added to the system for these tests. The method used for analysis was to pump some of the gas from the canister into the plenum, record the pressure in the canister before and after the gas removal, and then analyze the gas in the plenum for carbon dioxide content using the thermal conductivity analyzer. By using the data obtained in this manner, and the data given in figure 11 (Oxygen Required to Pressurize) the weight of carbon dioxide desorbed at various pressures can be determined. Figure 22 shows a typical desorption curve obtained in this manner. A comparison of this curve with figure 11 shows that at 60 mm Hg, 1.6 grams of carbon dioxide have been removed from the charcoal (15 grams were added during the adsorption period). Figure 11 shows that at this same pressure 18 grams of oxygen would remain on the charcoal. Since 76 grams were originally required for pressurization, this means that 58 grams of oxygen are desorbed by this method.

The lowest pressure obtainable with the diaphragm pump was approximately 60 mm Hg. Further testing needs to be carried out at even lower pressures, since this method appears to hold a great deal of promise for reducing oxygen losses of the system.
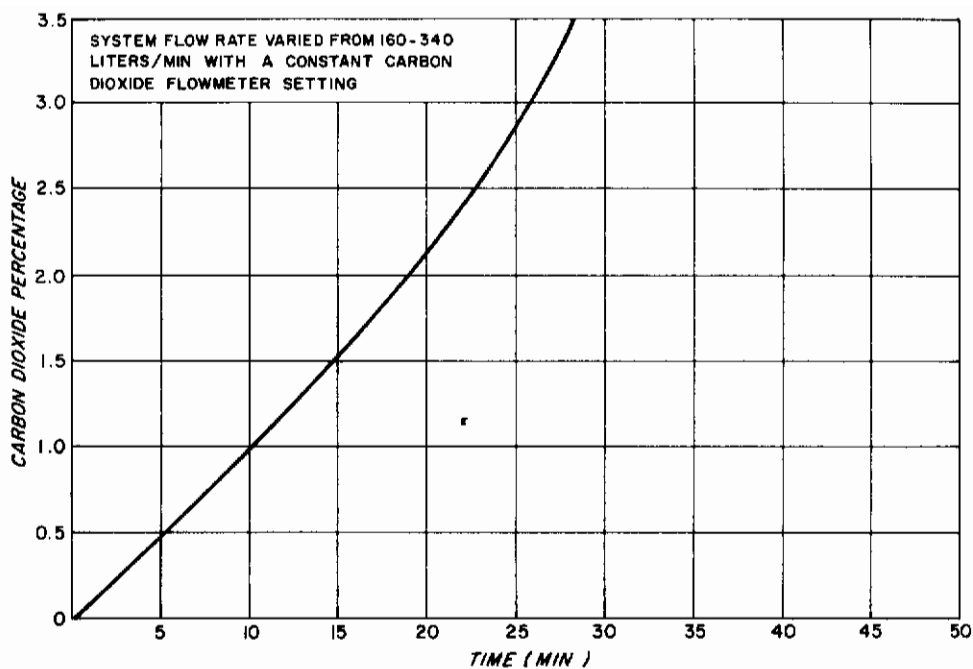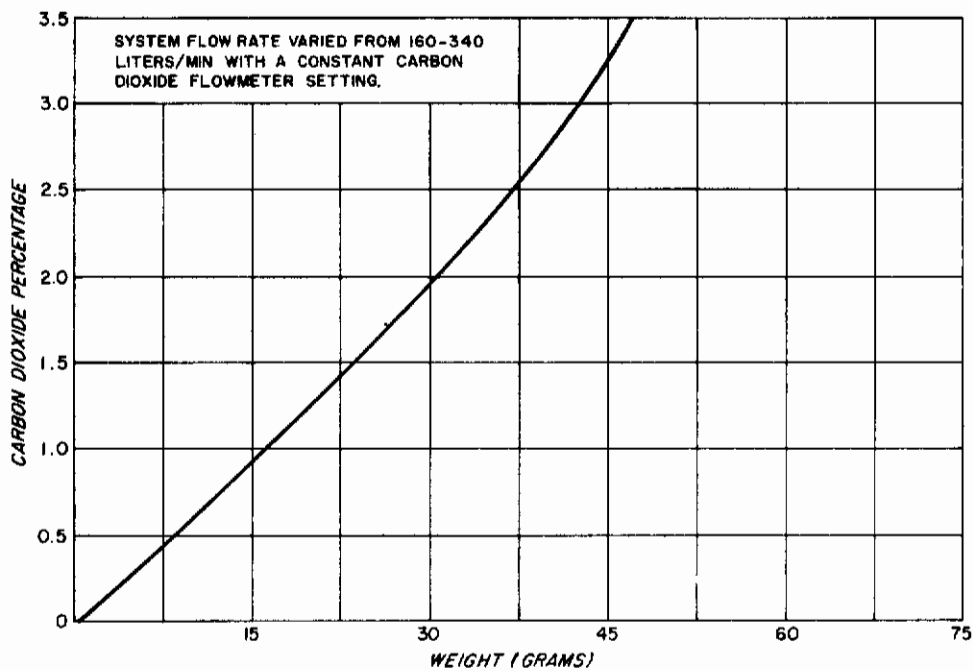
No attempt was made to determine if any of the water vapor was removed during this "Partial Evacuation Testing."

DURATION OF CYCLE TIME

The duration of the adsorption cycle time can be determined directly from figures 14 and 19 for dry and humidified gas streams, respectively. In a dry gas stream 60 grams of carbon dioxide must be added before the design limit of 3.2% in the effluent gas stream is reached. However, in a humidified stream only 47 grams are required to reach this limit. Consequently, for a humidified gas stream with a carbon dioxide input of 1.67 g/min, (two men), operating with a oxygen partial pressure of 247 mm Hg, the maximum adsorption time would be 26 1/2 minutes and for a dry stream it would be 36 minutes. Cycle times for other carbon dioxide feed rates and maximum percentages can also be taken directly from these two graphs.

Figure 23 shows the minimum pumpdown time obtainable for the charcoal with the vacuum system used. This curve was for desorption following adsorption of carbon dioxide for a 30-minute period from a dry gas stream. Considerably longer desorption times were required when the charcoal had been exposed to a humidified gas stream and they were directly proportional to the length of the adsorption cycle.

As previously discussed, the activated charcoal adsorbs water vapor more readily than carbon dioxide and thus the quantity of adsorbed vapor increases as the adsorption time increases. Since the evacuation system

15 GRAMS OF CARBON DIOXIDE WAS ADDED DURING THE 10 MINUTE ADSORPTION PERIOD PRIOR TO THIS DESORPTION TEST. THE GAS STREAM HAD A RELATIVE HUMIDITY OF 50 %.

DESORP-
TION RUN
NO. C

GRAMS CARBON DIOXIDE DESORBED
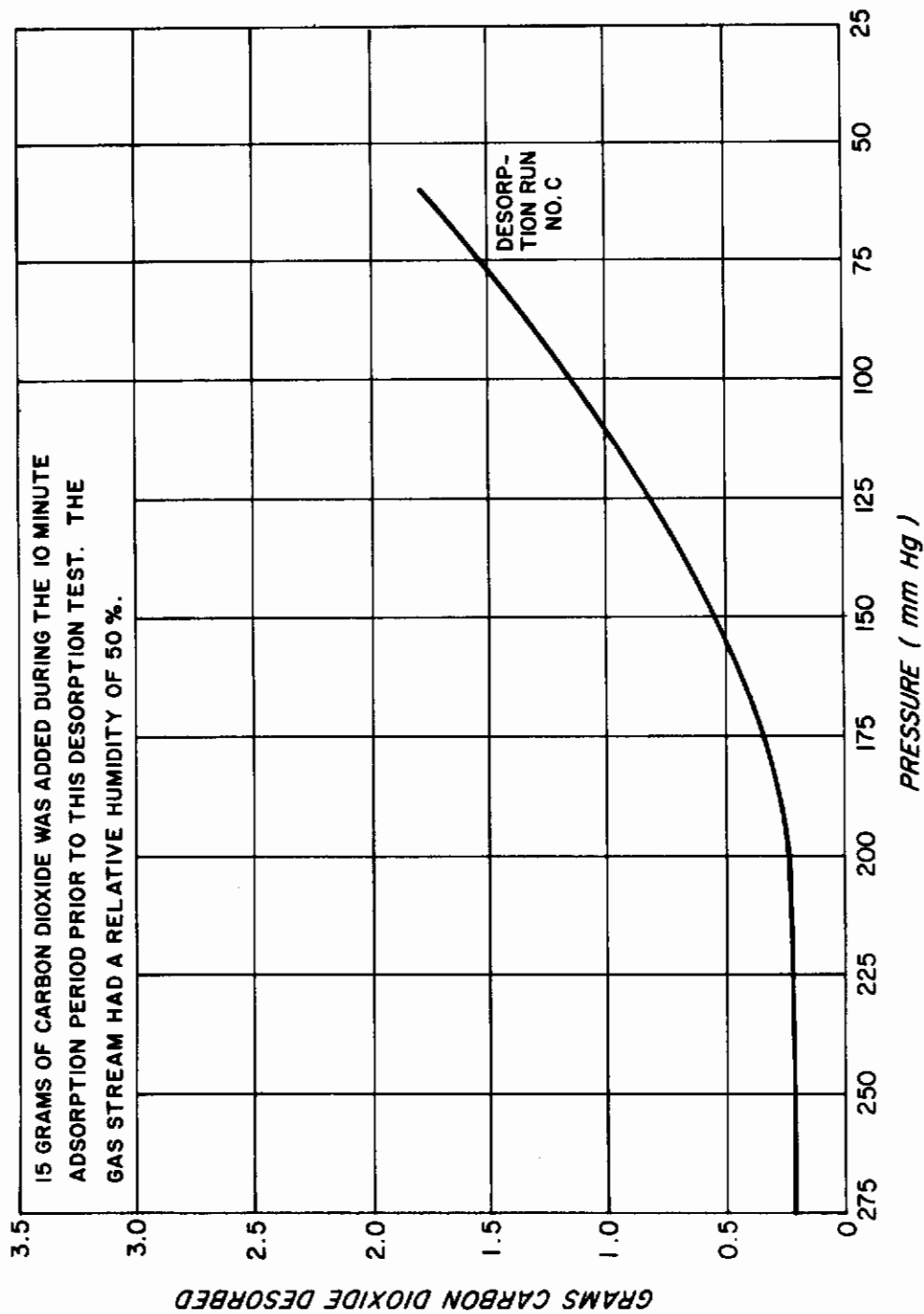
PRESSURE (mm Hg)
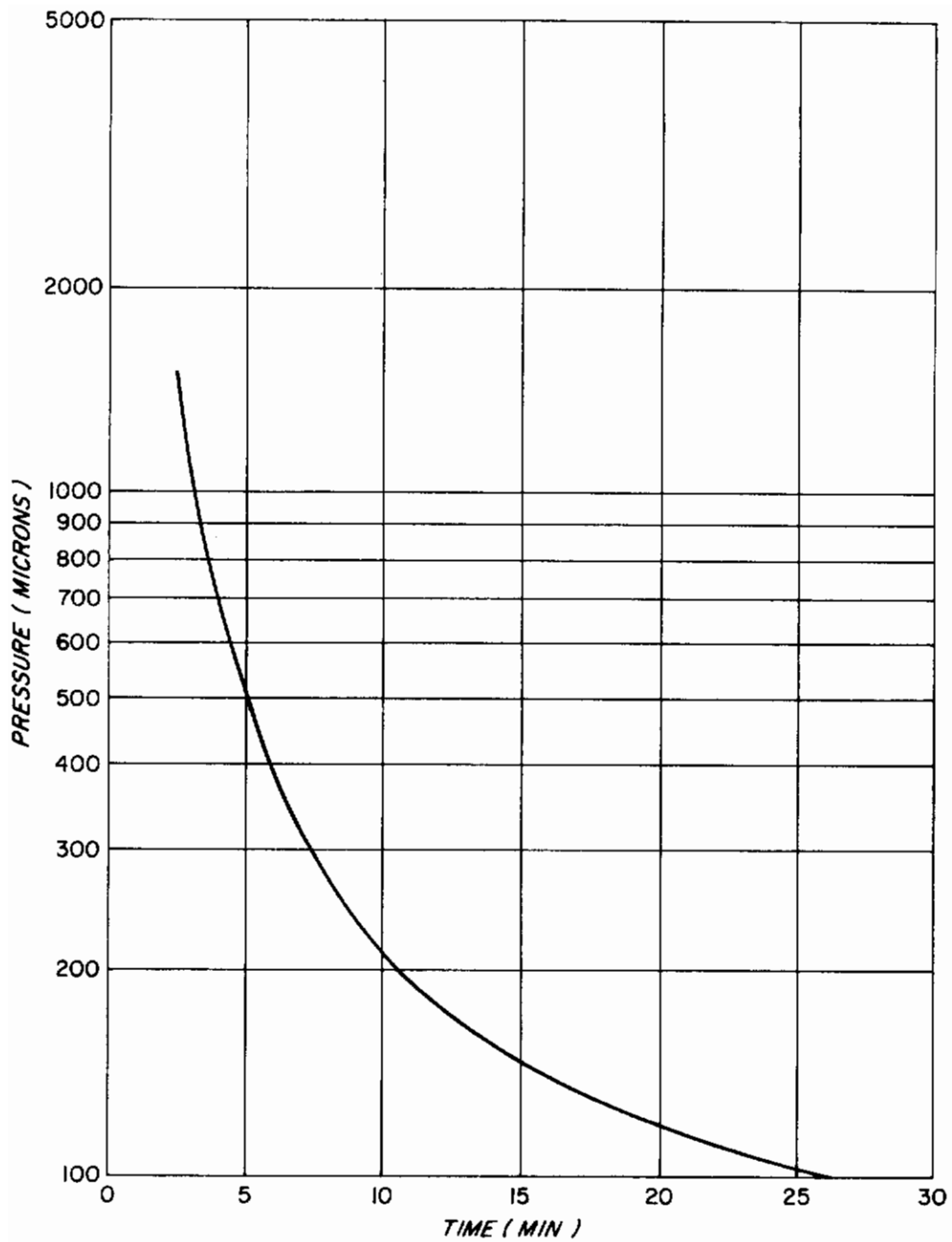
FIGURE 22. DESORPTION ANALYSIS

FIGURE 23. MINIMUM DESORPTION TIME

of the test loop has a fixed pumping speed, the addition of adsorbed water vapor on the charcoal also increases the quantity of gases to be desorbed.

To determine the minimum desorption time necessary, a series of tests was performed whereby the adsorption time was held constant and the desorption time was reduced. The adsorption cycle was of 20 minute duration, using a 50% humidity gas stream flowing at 340 liters/min, and a carbon dioxide addition rate of about 1.67 g/min. After each desorption cycle, the test loop was evacuated and the system was then pressurized to operating pressure. At this time the carbon dioxide concentration of the entire system was determined.

The carbon dioxide concentration in the system after repressurization for the various desorption periods is shown in figure 24. Also included in the figure is the lowest pressure achieved in the canister at the uppermost vacuum gauge which corresponds to the time of desorption.

From these tests, it was determined that an evacuation period approximately equal in time to the adsorption period is necessary for adequate desorption when using a humidified circulating gas stream. With space vacuum this time period may be further reduced. However, this is not essential since the design concept was a two canister system with equal length cycles and was achieved with the vacuum system used. If the pumping time can be improved by using space vacuum, there would be a weight savings, and one canister should be adequate because only 1 or 2 minutes desorption time would be required.

The pressure differential was considerably different from top to bottom, especially during the evacuation periods following adsorption from a humidified gas stream. Therefore, more than one vacuum port may be necessary to reduce the desorption time of the canister significantly. Pressures during the evacuation period varied from 400 microns at the top to 2000 microns at the bottom of the canister. With space vacuum, it may prove beneficial to include vacuum ports at each end of the bed to speed up the evacuation time.

FLOW RATE

The recirculating flow rate of the system could be varied from 160 to 340 liters/min. by adjusting the speed of the blower. One characteristic of the thermoconductivity analysis system is that the peak carbon dioxide effluent concentration is a function of the recirculating gas flow rate. For example, at the lower flow rate of 160 liters/min, for both the dry and humidified gas streams, the peak carbon dioxide concentration was reached at approximately 12 minutes after completion of the carbon dioxide addition to the system. At the higher flow rate of 280 liters/min this peak was reached in approximately 8 minutes. When the flow rate was between 160 and 280 liters/min this peak was reached at times proportionate to the variation in flow rate between these values.

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FIGURE 24. H₂O DESORPTION

ADSORPTION TIME WAS 20 MIN FROM A HUMIDIFIED GAS STREAM.
* ALL PRESSURES ARE FOR THE TOP PRESSURE GAUGE AND WERE RECORDED JUST PRIOR TO CLOSING THE VACUUM VALVE.

DESORPTION TIME (MIN)

CARBON DIOXIDE PERCENTAGE FOLLOWING PRESSURIZATION
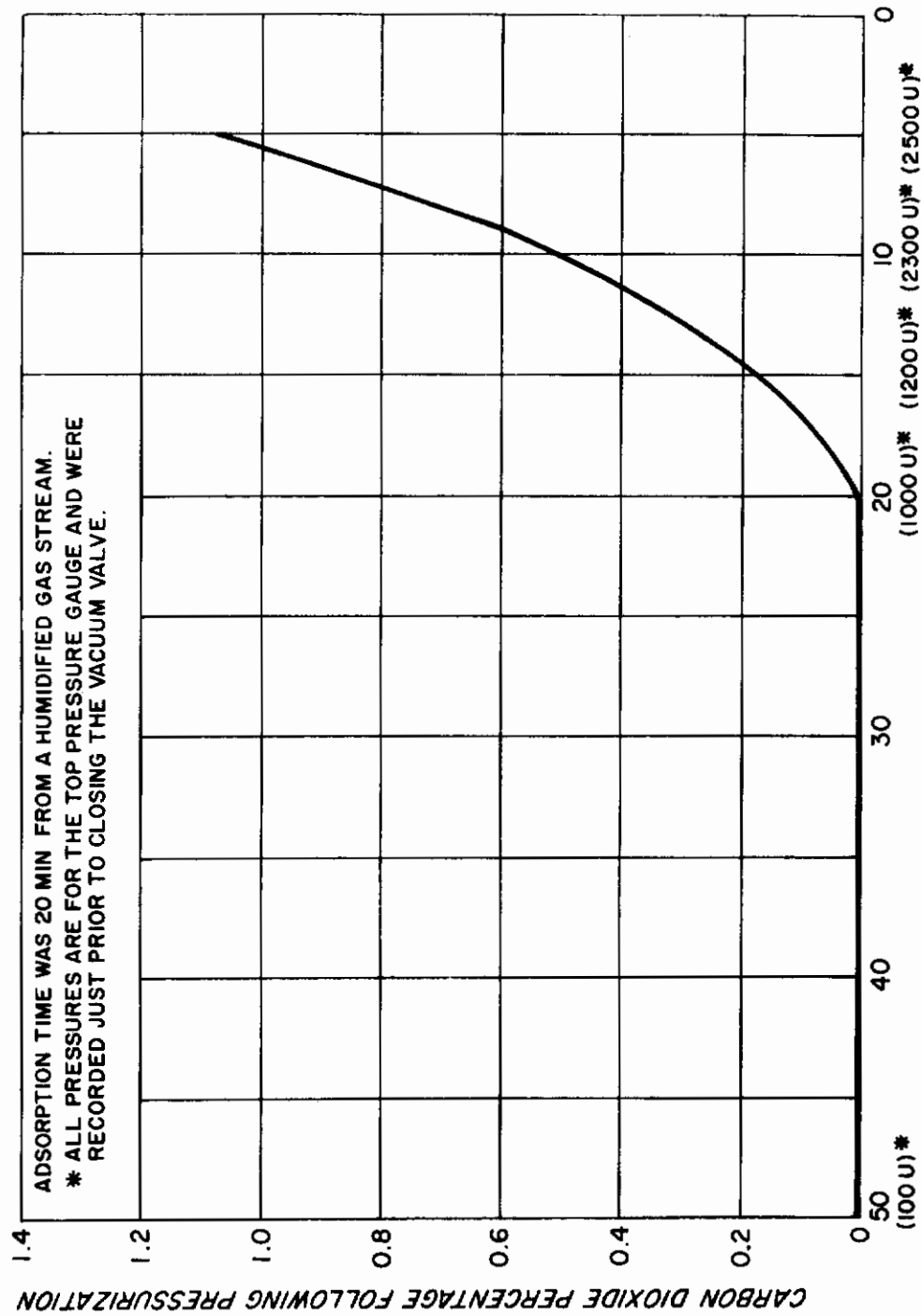
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The foregoing time delays in the peak or equilibrium carbon dioxide concentration of the effluent gas streams are shown graphically in figure 25. The data presented in this figure are for 20 minute adsorption runs.

When an analysis of the inlet gas stream was made, the phenomenon of the carbon dioxide effluent concentration being a function of the recirculating gas stream was noted but there were some differences. The peak concentration was not affected by flow rate. Figure 25 shows that the final or equilibrium concentration had the same time correlation as in the outlet tests.

Figure 25 shows carbon dioxide concentrations with comparable inlet and outlet gas streams for recirculating flow rates of 160 and 340 liters/min. Runs 43 and 92 show the carbon dioxide content of the inlet and outlet gas stream for the flow rate of 160 liters/min, while the carbon dioxide content for the 340 liters/min flow rate is shown by runs 68 and 95.

As expected, the equilibrium concentration for a given quantity of carbon dioxide is achieved much more rapidly at the higher flow rate in a closed system. At the system operating pressure of 245 mm Hg, the equilibrium concentration is slightly greater for the lower flow rate than for the higher flow rate for the outlet gas stream.

Figure 25 also shows that with a fixed quantity of carbon dioxide a peak of 2.18% was reached at the 160 liters/min flow rate as opposed to 1.70% for the 340 liters/min flow rate. This is because a constant amount of carbon dioxide was flowing into the system in both cases, but at the lower flow rate it was mixed with a smaller amount of the circulating gas stream, which in turn resulted in a higher carbon dioxide concentration.

As the flow rate increases, the rate of unadsorbed carbon dioxide build-up increases in the outlet gas stream. During approximately the first 10 minutes of each dry gas-stream cycle, the outlet concentration was independent of the flow rate. This was true for all flow rates regardless of the inlet carbon dioxide concentration for the range shown in figure 25. Beyond this time period however, the carbon dioxide percentage of the outlet stream increases more rapidly at the higher flow rate and the equilibrium concentration is approached sooner.

The area between the respective curves for a given flow rate is directly proportional to the quantity of carbon dioxide adsorbed by the activated charcoal. Furthermore, the ratio of areas for the two flow rates shown in figure 25 is equal to the inverse ratio of the flow rates. It can be shown that the ratio of the flow rate to the area increases as the flow rate increases. For the 20 minute adsorption period, there is a decrease in the quantity of carbon dioxide adsorbed as the flow rate increases. This is better illustrated in figure 26.

When the data are presented as in figure 25, the rate of carbon dioxide adsorption is easily determined. Figure 26 shows the rate of carbon dioxide adsorption as a function of time for the recirculating flow rates of 160 and 340 liters/min as presented in figure 25. Figure 26 also shows that the rate

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FIGURE 25. INLET AND OUTLET COMPARISON

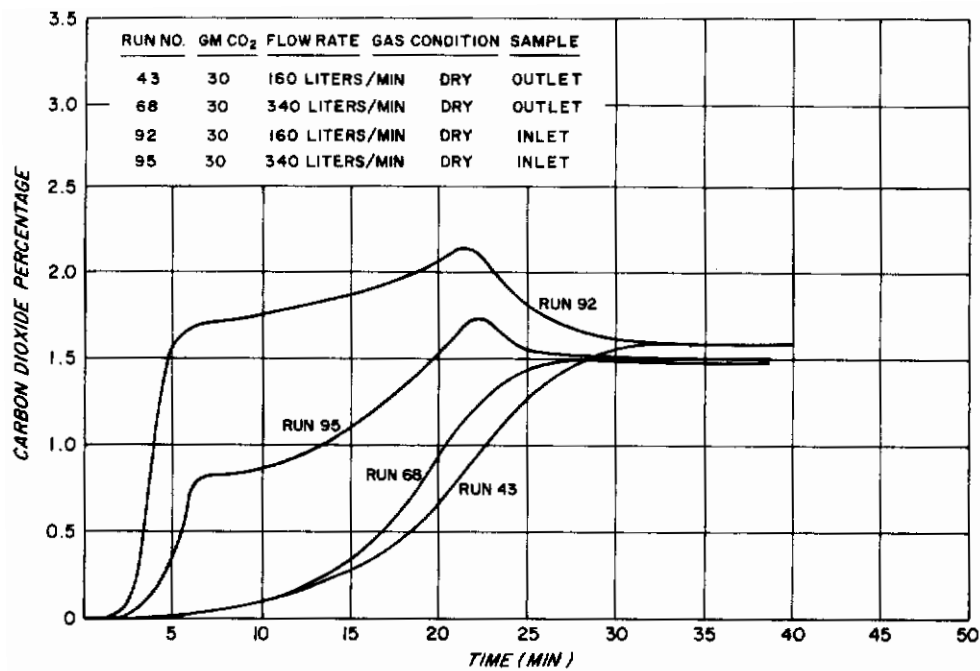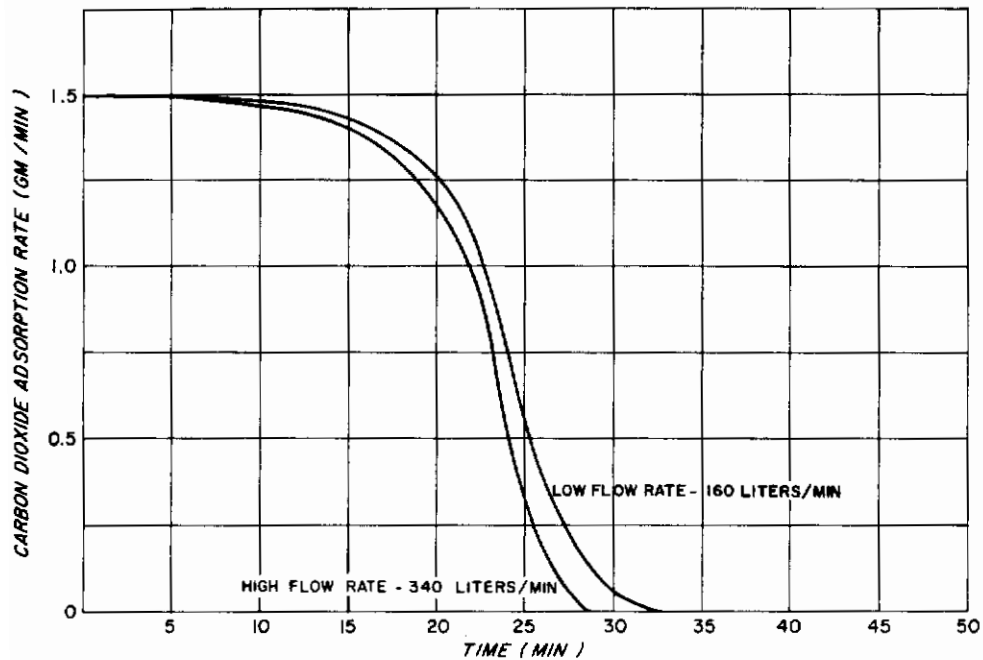| RUN NO.	GM CO₂	FLOW RATE	GAS CONDITION	SAMPLE
43	30	160 LITERS/MIN	DRY	OUTLET
68	30	340 LITERS/MIN	DRY	OUTLET
92	30	160 LITERS/MIN	DRY	INLET
95	30	340 LITERS/MIN	DRY	INLET

FIGURE 26. AFFECT OF SYSTEM FLOW RATE

of carbon dioxide adsorption decreases slowly for the first 15 minutes of the adsorption cycle, and then decreases more rapidly as equilibrium is approached. These two curves have essentially the same shape and characteristics. The initial carbon dioxide concentrations for the flow rates shown in figure 26 were 0.76% at 340 liters/min and 1.83% at 160 liters/min. Therefore, it is apparent that the rate of carbon dioxide adsorption is independent of the carbon dioxide concentration within these values.

Initially, the rate of adsorption for both the high and low flow rates is similar. In comparing figure 25 and 26 it can be seen that practically all the carbon dioxide added was adsorbed in the closed test system which had a void volume of 34 liters. Figure 26 shows that in the beginning the rate of adsorption is equivalent to the rate of carbon dioxide addition. It is only after a 10 minute period that the lower flow rate shows an increased rate of carbon dioxide adsorption. Hence, the effect of the flow rate on the rate of carbon dioxide adsorption by activated charcoal is only applicable when the adsorber has adsorbed approximately 75% of its capacity. At that point, the rate of carbon dioxide adsorption decreases as the flow rate increases.

POWER REQUIREMENTS

In general, the equipment used in the test loop consisted of off-the-shelf items. The electrical characteristics of the equipment used in the test loop are presented in Table IV.

TABLE IV

EQUIPMENT POWER CONSUMPTION

ITEM	VOLTS	CURRENT (AMPS)	POWER (WATTS)
Solenoid Valves			
Inlet	26.5 DC	2.5	76
Outlet	26.5 DC	2.5	76
Evacuation	26.5 AC	2.5	76
Recirculation Blower			
160 liters/min	110 AC	4.3	473
340 liters/min	110 AC	7.1	781
Partial Evacuation Pump	110 AC	7.1	781

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The blower is the only one of these items that would operate continuously if the system was subjected to actual flight operation. The power requirements for the blower could be significantly improved since the prime design consideration for this test blower was leak tightness and a variable flow rate. Power consumption was not considered in designing the test model, and it is therefore conceivable that a savings up to 20 percent could be realized.

The valves operate only during the cycle changes, for periods slightly less than one second each. In a 2-canister system there would be six valve cycles per system cycle (three valves opened and three valves closed). For a system operating on 20-minute cycles, this would mean 18 valve cycles or less than 18 seconds valve operation time for each hour of operation.

The total power consumed by the partial evacuation pump is determined by the amount of oxygen that can be removed using the partial evacuation pump. The pump used for test purposes was an off-the-shelf item since its only purpose was to investigate the feasibility of this method of reducing gas losses. Considerable improvements in power consumption, weight, and pumping times would be necessary for an aerospace system, and would necessitate a major design program.

Figure 27 shows the typical evacuation time of the canister following adsorption from a humidified gas stream, using the partial evacuation pump. The rate of pressure reduction in the canister is dependent on the capacity of the partial evacuation pump. Figure 27 shows that the rate of pressure reduction in the canister diminishes quite rapidly as the evacuation pump approaches its ultimate pressure differential. The rate of pressure change beyond 10 minutes is very low, and any gain in further evacuation would require excessive power.

Considering that there is only partial evacuation up to a pressure of 75 mm Hg the quantity of oxygen which can be recovered is easily determined. Figure 11 shows the quantity of oxygen adsorbed by the activated charcoal and required to fill the voids. The residual oxygen remaining in the system is 23 grams. With the system operating at 245 mm Hg an average of 74 grams of oxygen is required to completely fill the system and it permits as much as 69% of the oxygen to be returned to the system. This overall savings, however, is slightly offset by the fact that at the 75 mm Hg pressure considered, approximately one gram of carbon dioxide is returned to the system. This is determined by referring to figure 22 in conjunction with figures 11 and 27.
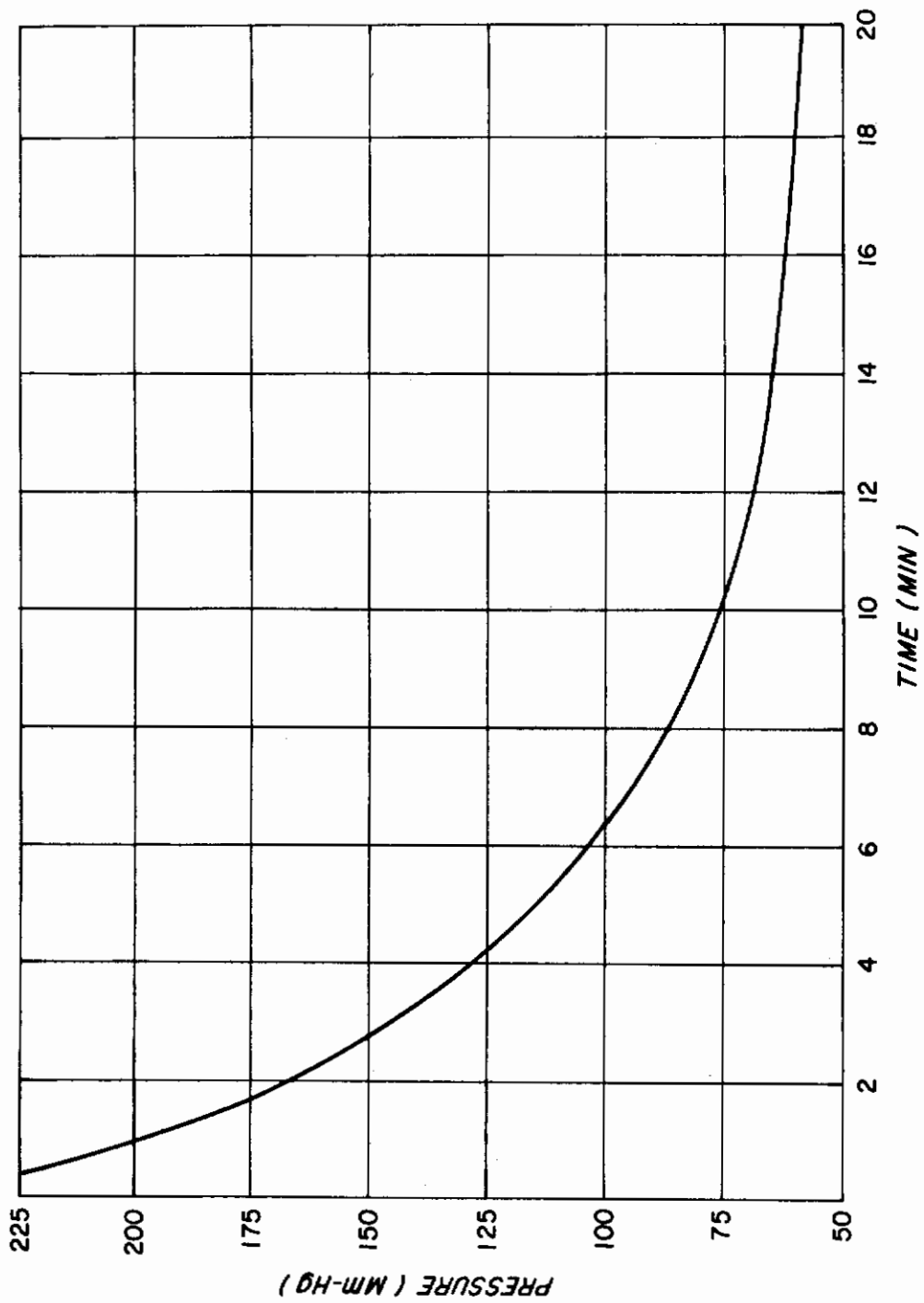
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FIGURE 27. PARTIAL EVACUATION PUMP - DESORPTION TIME

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SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Based on the test results, the following conclusions are believed to be justified for a closed regenerative carbon dioxide system using activated charcoal.

1. Activated charcoal as a regenerative adsorbent for carbon dioxide removal is feasible.

2. Oxygen losses from the system were greater than had been anticipated but the use of the partial evacuation pump was shown to be a worthwhile method for reducing these losses. A development program would be necessary, however, to design a pump that is satisfactory from a standpoint of weight, pumping speed, and power consumption.

3. The actual quantities of the carbon dioxide adsorbed exceeded expectations.

4. Some heat is evolved during the adsorption process, and it is likewise adsorbed during the desorption process; therefore, this should present no load to the environmental temperature control system.

5. Water vapor in the gas stream reduces the amount of carbon dioxide adsorbed by the charcoal, but the water is removed by the application of vacuum. The water vapor has no cumulative adverse effect on the ability of charcoal to adsorb carbon dioxide,

6. A system flow rate of 340 liters per minute was apparently adequate for adsorption of the carbon dioxide at a rate of 100 g/hour. An analysis system with no delay time would be beneficial for pinpointing the minimum flow rate that would give the required adsorption rate.

7. A weight optimized two man system can be developed which will weigh 23 kg or less. The weights of the components are:

Canister	3.6 kg
Charcoal	14.5 kg
Valves	2.3 kg
Blower	1.0 kg
Misc. Plumbing	1.6 kg

    The partial evacuation pump is not included because the one used for testing would not be efficient in an actual aerospace system.

8. Pressure drop through the charcoal bed is low and shows no significant change after repeated cycling.

9. Tests with human subjects would be the next logical step since this would present an opportunity to observe the ability of the charcoal to adsorb trace gas impurities in addition to carbon dioxide.

10. More accurate quantitative results can be obtained by using an open
system in which the carbon dioxide concentration of the inlet gas stream
is maintained constant throughout the test period. However, a closed
system, with a large plenum chamber in the circulating system could
accomplish essentially the same results. It would be necessary however
for the volume of the chamber to be of sufficient size so that the small
quantity of carbon dioxide added to the system would not appreciably
affect the concentration of the recirculating gas stream.

APPENDIX I
TEMPERATURE OF CHARCOAL DURING ADSORPTION (°C)

THERMOCOUPLE LOCATION	AT START OF CO_2 FLOW		AFTER 5 MIN.		AFTER 10 MIN.		AFTER 20 MIN	
	A	B	A	B	A	B	A	B
1. Center, top of upper bag.	29	24	29	26	29	27	29	30
2. Two inches from center, top of upper bag of charcoal.	29	24	29	26	29	27	29	30
3. Four inches from center, top of upper bag of charcoal.	29	24	29	26	29	27	29	30
4. Five inches from center, top of upper bag of charcoal.	29	24	29	26	29	27	29	30
5. Center, between top and second bag of charcoal.	28	24	29	26	29	27	29	30
6. Two inches from center, between top and second bag of charcoal.	28	24	28	26	29	30	29	42
7. Four inches from center, between top and second bag of charcoal.	29	24	29	26	29	30	29	43
8. Five inches from center, between top and second bag of charcoal.	29	24	29	26	29	30	31	43
9. Center, between second and third bag of charcoal.	29	24	29	29	29	36	31	43
10. Two inches from center, between second and third bag of charcoal.	28	24	28	29	28	36	29	43
11. Four inches from center, between second and third bag of charcoal.	28	24	28	29	28	36	29	43
12. Five inches from center, between second and third bag of charcoal.	29	24	29	29	29	36	31	43
13. Center, between third and bottom bag of charcoal.	28	24	29	32	29	42	31	43
14. Two inches from center, between third and bottom bag of charcoal.	28	24	29	32	29	42	31	43
15. Four inches from center, between third and bottom bag of charcoal.	29	24	29	32	29	42	31	43
16. Five inches from center, between third and bottom bag of charcoal.	29	24	30	32	29	42	31	43
17. Center, beneath the bottom bag of charcoal.	29	24	30	32	29	32	31	32
18. Two inches from center, beneath the bottom bag of charcoal.	29	24	30	32	29	32	31	32
19. Four inches from center, beneath the bottom bag of charcoal.	29	24	29	32	29	32	31	32
20. Five inches from center, beneath the bottom bag of charcoal.	29	24	29	32	29	32	21	32

A. DRY GAS
B. 50% RELATIVE HUMIDITY

APPENDIX II
TEMPERATURE OF CHARCOAL DURING DESORPTION (°C)

THERMOCOUPLE LOCATION	AT START OF DESORPTION A	B	AFTER 5 MIN. A	B	AFTER 10 MIN. A	B	AFTER 20 MIN. A	B
1. Center, top of upper bag.	22	44	19	38	17	36	17	36
2. Two inches from center, top of upper bag of charcoal.	22	44	19	38	17	36	17	36
3. Four inches from center, top of upper bag of charcoal.	22	44	19	38	17	36	17	36
4. Five inches from center, top of upper bag of charcaol.	22	44	19	38	17	36	17	36
5. Center between top and second bag of charcoal	22	44	19	38	17	36	18	36
6. Two inches from center, between top and second bag of charcoal.	22	44	19	38	17	36	18	36
7. Four inches from center, between top and second bag of charcoal.	22	42	19	38	17	36	18	36
8. Five inches from center, beteen top and second bag of charcoal.	22	42	19	38	17	36	18	32
9. Center, between second and third bag of charcoal.	22	42	19	38	19	36	18	32
10. Two inches from center, between second and third bag of charcoal.	22	42	19	38	19	36	18	32
11. Four inches from center, between second and third bag of charcoal.	22	42	19	38	19	36	18	32
12. Five inches from center, between second and third bag of charcoal.	27	42	19	36	19	36	18	32
13. Center, between third and bottom bag of charcoal.	27	42	20	36	19	36	18	32
14. Two inches from center, between third and bottom bag of charcoal.	27	42	20	36	19	36	18	32
15. Four inches from center, between third and bottom bag of charcoal.	27	42	20	36	19	32	18	28
16. Five inches from center, between third and bottom bag of charcoal.	27	42	20	36	19	32	18	28
17. Center, beneath the bottom bag of charcoal.	27	32	21	36	21	18	20	13
18. Two inches from center, beneath the bottom bag of charcoal.	27	32	21	36	21	18	20	13
19. Four inches from center, beneath the bottom bag of charcoal.	27	32	21	36	21	18	21	13
20. Five inches from center, beneath the bottom bag of charcoal.	27	32	21	36	21	18	21	13

A. DRY GAS
B. 50% RELATIVE HUMIDITY

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APPENDIX III

TEMPERATURE OF CHARCOAL BEFORE AND AFTER PRESSURIZING

THERMOCOUPLE LOCATION	BEFORE PRESSURIZING	AFTER PRESSURIZING
1. Center, top of upper bag.	24	27
2. Two inches from center, top of upper bag of charcoal.	24	27
3. Four inches from center, top of upper bag of charcoal.	24	27
4. Five inches from center, top of upper bag of charcoal.	25	27
5. Center, between top and second bag of charcoal.	25	27
6. Two inches from center, between top and second bag of charcoal.	24	27
7. Four inches from center, between top and second bag of charcoal.	24	27
8. Five inches from center, between top and second bag of charcoal.	24	27
9. Center between second and third bag of charcoal.	24	27
10. Two inches from center, between second and third bag of charcoal.	24	27
11. Four inches from center, between second and third bag of charcoal.	24	27
12. Five inches from center, between second and third bag of charcoal.	25	28
13. Center, between third and bottom bag of charcoal.	24	27
14. Two inches from center, between third and bottom bag of charcoal.	24	27
15. Four inches from center, between third and bottom bag of charcoal.	24	27
16. Five inches from center, between third and bottom bag of charcoal.	24	27
17. Center, beneath the bottom bag of charcoal.	24	27
18. Two inches from center, beneath the bottom bag of charcoal.	24	27
19. Four inches from center, beneath the bottom bag of charcoal.	24	27
20. Five inches from center, beneath the bottom bag of charcoal.	25	27

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Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

A system eas designed and built for testing activated charcoal as a regenerative carbon dioxide adsorbent in an atmosphere involving oxygen pressures of 240-275 mm Hg. Barnebey Cheney KB-1 charcoal was used, and the system gas flow rate was 160-340 liters/minute. The gas stream was composed of oxygen, humidified to 50%. Carbon dioxide was added to simulate the production rate of two men. Because of the sub-atmospheric operation, the system was a closed loop design and any carbon dioxide not adsorbed on the first pass through the charcoal continued to circulate through the system. The charcoal was subjected to an ambient room temperature of approximately 27C, and the gas stream controlled at 26.7 ± 2.7C during the adsorption testing. Regeneration of the charcoal was by vacuum. The testing program demonstrated that charcoal will continue to adsorb carbon dioxide at a significant rate after repeated cycling with no apparent change or degradation. The presence of water vapor in the gas stream tends to reduce the capacity of the charcoal for adsorbing carbon dioxide. However, it is readily removed from the charcoal by vacuum and exhibits no cumulative effect on the carbon dioxide adsorptive capacity of the charcoal.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Charcoal						
Activated Carbon						
Carbon Dioxide						
Carbon Dioxide Control/Removal						
Life Support						
Gaseous Adsorption/Desorption						
Atmosphere Regeneration						
Sorption Processes						
Solid Assorbents						
Regenerative Processes						