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PERFORMANCE TESTS OF AN ORGANIC AMINE CARBON DIOXIDE REMOVAL SYSTEM

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ABSTRACT

An experimental evaluation was conducted on a regenerable two-bed carbon dioxide removal system which utilized an organic amine sorbent. This sorber formulation absorbs CO_2 in the presence of H_2O vapor and thus does not require pre-drying the gas stream.

The primary objective of the test program was to relate the system performance of CO_2 removal rate, power, and water carry-over with CO_2 during regeneration to the operating parameters of air-flow rate through the bed, absorption-regeneration time, and bed cooling and heating rates. All other operation conditions were held constant. The Box-Wilson composite design was used in the experiment design, and to generate quadratic equations relating system performance to the operating conditions.

SUMMARY

An experimental evaluation was conducted on the regenerable two-bed carbon dioxide removal system originally designed, fabricated and delivered to NASA, Langley Research Center on NAS1-2915. The system was returned to GARD for testing in July 1968. The solid absorbent is an organic amine formulation which absorbs CO_2 in the presence of H_2O vapor and this does not require pre-drying the gas stream.

The primary objective of the test program was to relate system performance, i.e., CO_2 removal rate, power required and water carried over with CO_2 during regeneration to various operating conditions. The operating conditions varied in testing were air-flow rate through the bed, absorption-regeneration time, and bed cooling and heating rates. All other operation parameters were held constant. The Box-Wilson composite design was used to design the experiment and to generate quadratic equations relating system performance to the operating conditions.

The equations developed can be used to determine the optimum CO_2 removal capacity within the range of test conditions and based on total system weight penalty, when appropriate power, heating, and cooling penalties are specified. In addition the effect of specific mechanical design characteristics (heat transfer effects) were observed. The developed equations and the observed mechanical characteristics can be utilized to design an advanced system using this amine absorbent or to compare the present system to other CO_2 removal systems.

Other objectives achieved during this program were to perform a continuous duration test of at least 48 hours, to determine the effect of operating the system under off-design conditions; and to determine the effect of total operating time on the ability of the sorbent to maintain CO_2 absorption capacity.

FOREWORD

This report summarizes the work accomplished under Contract NAS1-8360 for testing of the GAT-O-SORB carbon dioxide removal system. This work was initiated on 24 July 1968 and completed on 29 May 1969. The program was performed by the General American Research Division of the General American Transportation Corporation, 7449 Natchez Avenue, Niles, Illinois 60648. The work was monitored by Mr. Rex Martin, National Aeronautics and Space Administration, Langley Research Center, Langley Station, Hampton, Virginia 23365.

The work reported herein was performed by personnel within the atmospheric Control Sections of GARD's Chemical and Life-Support Systems Group, under the direction of Mr. J. D. Zeff, and supervision of Mr. G. A. Remus; Mr. A. J. Glueckert served as project engineer and Mr. J. E. Kane as technician. Dr. F. Ozkan, statistician, assisted in the data analysis and computer programming.

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SECTION 1

INTRODUCTION

The removal of metabolic carbon dioxide is a necessary part of environmental control. To accomplish CO_2 removal in a weightless state and to avoid complicated phase separation techniques it is desirable that the sorbent be in the form of a solid. A regenerable absorbent which utilizes an amine was developed to meet this need by the Research Division of the General American Transportation Corporation.

The absorbent was originally developed for CO_2 removal by GARD in 1962. After feasibility of the absorbent for CO_2 removal in an environmental control system was demonstrated, GARD designed and fabricated a 2 man capacity prototype CO_2 removal system. A photograph of the system is shown in figure 1.

In this cyclic two-bed system, one bed absorbs CO_2 from a flowing airstream while the other is being regenerated simultaneously by heating under moderate vacuum. Heat is transferred into and out of each bed by a liquid circulated through in-bed heat exchangers.

After the system was delivered to and tested by NASA it was returned to GARD for further testing. Under the present program, the effect of operating conditions on CO_2 removal capacity, water carry over, and power were determined and polynomial expressions relating the performance characteristics to the operating parameters were developed.

To obtain the best CO_2 removal system for a given application, all candidate systems must be evaluated on a comparable basis. Usually this is done on a weight basis which includes basic system weight, weight of spares

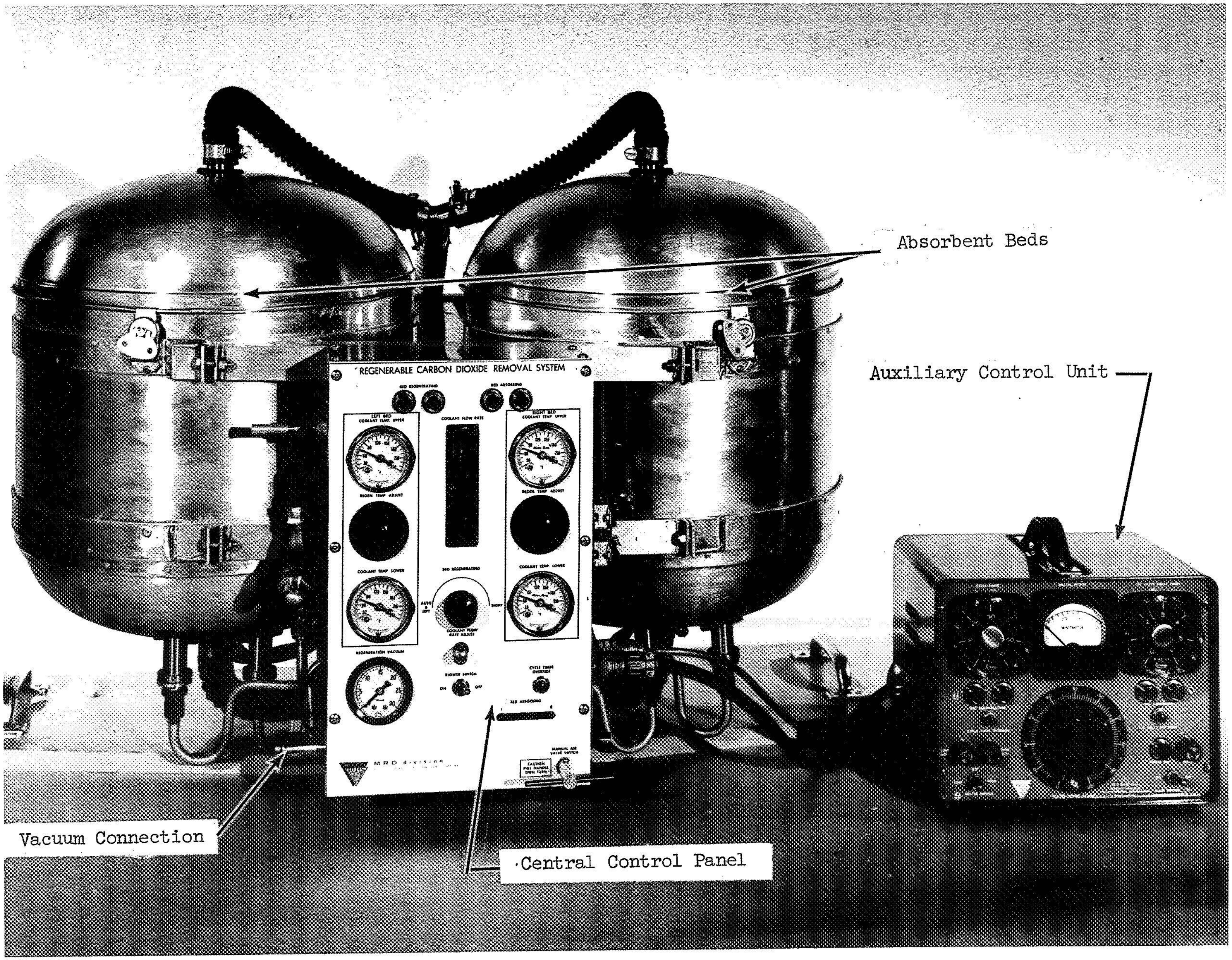

Fig. 1 THE GAT-O-SORB CARBON DIOXIDE REMOVAL SYSTEM

necessary to provide a chosen degree of reliability, and equivalent weight penalties for power, heat absorption, or heat rejection.

In order to obtain input information for evaluating the GAT-O-SORB system so that it can be compared to other systems , empirical polynomial expressions were developed which relate response characteristics to operating conditions. The polynomials do not furnish optimum operating conditions because no penalties are assigned for spares, power, water carryover, heat absorption, or heat rejection. If penalties were assigned, the polynomials would lead toward optimum operating conditions within the range that tests were conducted. Also the polynomials furnish design inputs which can be used for an advanced model of the GAT-O-SORB system.

SECTION 2

BACKGROUND

The amine process for carbon dioxide removal has several important advantages over other types of regenerable CO_2 removal processes. These advantages are 1) the ability to absorb CO_2 or other acid gases from a gas mixture without prior dehumidification of the gas stream, and 2) the ease of regeneration of the GAT-O-SORB absorbent when compared to other sorbents of the same absorption capacity.

2.1 Chemistry of Absorption and Regeneration

In the absorbing system carbon dioxide combines with the amine in the presence of water. An airstream with a 45°F dewpoint contains sufficient moisture for the reaction to proceed. In normal operation both water and carbon dioxide are removed from the gas stream during absorption.

During regeneration the carbonated absorbent separates into rejuvenated absorbent, carbon dioxide, and water vapor. The temperature and pressure of regeneration affect the relative amounts of CO_2 and H_2O desorbed. Since it may be desirable to minimize water carry-over the amount of water desorbed was measured as a system performance characteristic.

2.2 Prototype Model

The prototype model which was built under contract NAS1-2915 and used for this program was shown in Figure 1; the flow schematic is shown in Figure 2. The system contains 2 beds which alternate between absorption and regeneration modes. Each canister contains 15 pounds of GAT-O-SORB and the total weight of the system is 93 pounds. The system is contained within an envelope 19 inches x 24 inches x 33 inches. An additional control module is furnished so

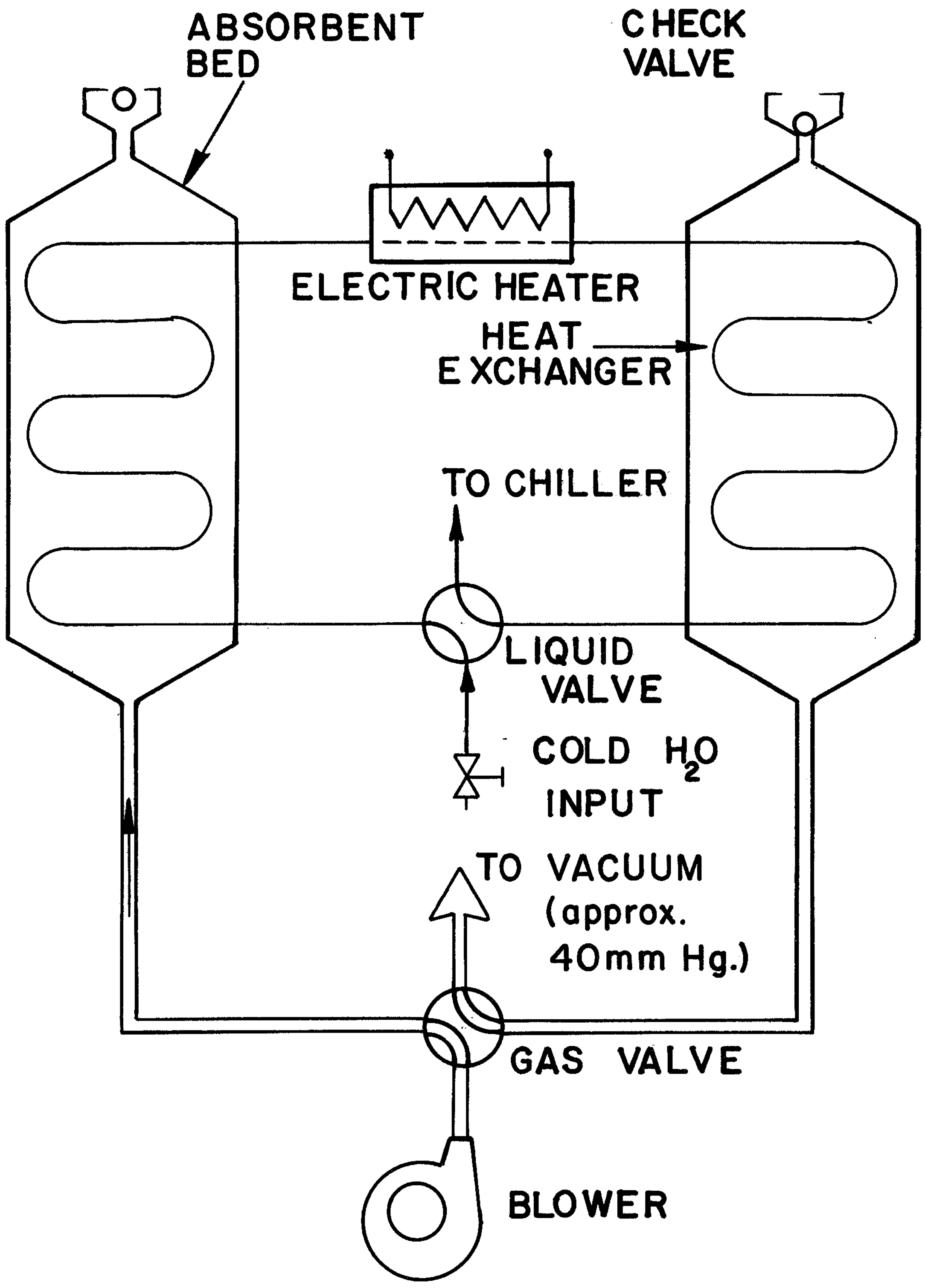

Figure 2. SCHEMATIC DIAGRAM OF THE GAT-O-SORB SYSTEM

that the system can be tested in an environmental chamber, and parameters such as cycle time or bed precool time can be changed without entering the chamber.

As shown in Figure 2, system operation is dependent upon three flow loops: the main air-stream absorption loop, the vacuum regeneration loop, and the heat transfer liquid loop.

In the air loop the system blower circulates chamber air through a four way air/vacuum control valve and into the absorbing bed. In the absorbent bed carbon dioxide and water are removed from the air stream; CO_2-free air is returned to the chamber.

In the vacuum loop, a vacuum pump is connected to the four-way air/vacuum control valve. This valve connects the pump to the inlet of the bed in the regeneration mode. A check valve at the outlet of each bed isolates the bed during regeneration. The pump evacuates the bed and discharges the desorbed CO_2 and H_2O for collection or disposal.

In the heat transfer liquid loop, 50°F water passes through a four-way liquid valve into a heat exchanger within the absorbing bed during the absorption mode. The water cools this bed down from its regeneration temperature to the 60-80°F range required for efficient absorption. After exiting the absorbing bed the water, which has picked up heat, is further heated to 180°F with an electric heater. The 180°F water passes through the heat exchanger in the regenerating bed and heats the sorbent. The water then leaves the regenerating bed at a lower temperature and exits the system through the four-way liquid valve. The water is then cooled to 50°F and returned to the absorbing bed to complete the loop. In actual testing, discharged water was discarded, and fresh tap water was used continuously.

The four-way air/vacuum valve and the four-way liquid valve are synchronized so that the liquid is directed to the proper bed at the proper time. To provide a period for precooling the bed going into the absorption mode, the cooled heat-transfer liquid is directed into the bed heat-exchanger before the air stream is allowed to enter the bed. This interval is designated as "precool time".

2.3 Original Test Program

After the GAT-O-SORB unit was fabricated in 1964, the canisters were filled with absorbent and a series of tests were run 1) to verify that the system was operational, and 2) to obtain an approximation of the average CO_2 removal rate, water loss, and power requirements. The system was delivered to NASA LRC for further testing, then the system was returned to GARD in August 1968.

The original test program was run in the laboratory under ambient conditions. Carbon dioxide was fed to the inlet of the system blower at a rate which maintained the inlet CO_2 concentration at 1.0 percent. Inlet humidity varied according to ambient conditions.

The system was operated through 91 cycles during twenty-two different runs as shown in table 2. The parameters which were varied included CO_2 concentration, coolant water flow rate, coolant water temperature, inlet air temperature, cycle time, and bed pre-cool time. The maximum average CO_2 removal rate, 0.41 lb per hour occurred when the CO_2 concentration was 1.0%, water flow 4 gph, water temperature 85°F, air temperature 79°F, cycle time 30 minutes and zero bed pre-cool time. During all tests the air flow rate was 14 cfm.

Table I.. TEST RESULTS IN ORIGINAL PROGRAM (1964)

Run No.	Feed Comp. % CO_2	Water Flow Rate gph	Water Temp. °F	Air Temp. °F	Air Relative Humidity %	Time Cycle Minute	Precool Time Minute	CO_2 Removal cfh	CO_2 Removal lb/hr	Water Loss Ratio $\frac{lb\ H_2O}{lb\ CO_2}$	Average Continuous Power w/o Heater Watts	Makeup Heater Power Per Man $\frac{Watts}{Man\ Capacity}$	Total $\frac{Watts}{Man}$
1	1	3	75-80	90	40	30	2	1.93	0.235	0.315	288	---	
2A	1	3	75-80	80	38-43		2	2.69	0.330	0.281		---	
2B	1	3	80	80	39		4	2.45	0.294	-----		---	
3	1	5	75-85	75-77	44-52		2	2.71	0.325	0.50		---	
4A	1	2.75	75-85	78	50-63		0	2.45	0.294	-----		154	252
4B	1	0.85	85	--	--			0.975	0.117	-----		160	306
4C	1	1.95	85	78	42			1.97	0.236	-----		125	248
4D	1	4.05	85	79	43			3.45	0.417	-----		163	232
5	1	2.0	65	81-82	41-42			1.64	0.200	0.150		175	319
6	1	0.8-1.0	66-72	79-80	48-51	20		0.42	0.052	0.115		340	916
7	1	4.0	68-75	82-85	43	40		3.10	0.381	0.453		185	282
8	0.5	4.0	60-70	77-80	35-41	20		1.25	0.153	0.520		445	633
9	0.5	1.0	68-78	78-83	35-50	20		0.45	0.051	0.20		467	1042
10	0.5	2.0	61-69	85-87	33-35	30		1.25	0.153	0.28		262	450
11	0.5	1.0	71-78	78	41	40		0.04	0.005	Very High		Very High	---
12	2.0	2.0	59-84	77	40-43	30		3.10	0.382	0.10		118	194
13A	1	2.0	56-63	77	40-42	30		2.08	0.256	0.218		165	278
13B	1	2.0	56-63	77	40-42	30	2	2.28	0.280			144	247
14	1	2.0	80-87	77	42	30	0	NO TEST RESULTS - MECHANICAL DIFFICULTY					
15A	1	2.0	70	90	Approx. 50	30		2.89	0.356	-----		114	195
15B	1	2.0	90	90	Approx. 50	30		2.03	0.250	-----		154	269
15C	1	2.0	114	90	Approx. 50	30		1.62	0.200	-----		175	319
15D	1	2.0	80	90	Approx. 50	30		2.33	0.287	-----		115	215

TOTAL NUMBER OF CYCLES RUN ⟶ 91

For most tests run at an inlet CO_2 concentration of 1.0 percent (p_{CO_2} = 7.6 mm Hg) the CO_2 removal rate ranged from 0.2 to 0.3 lb per hour. When the inlet CO_2 concentration was decreased to 0.5 percent (p_{CO_2} = 3.8 mm Hg) the CO_2 removal rate decreased to a maximum of 0.15 lb per hour.

SECTION 3

SYSTEM TESTING

Under the present program the GAT-O-SORB Carbon Dioxide Removal System was tested to determine the relationship between system performance characteristics and varied operating conditions.

3.1 Performance Characteristics

The system performance characteristics that were measured were:

1. Average CO_2 removal rate, lb CO_2/hr
2. Water carry-over during regeneration, lb H_2O/lb CO_2
3. System power, kwhr/lb CO_2

The average CO_2 removal rate was determined by dividing the weight of CO_2 absorbed during a cycle by the length of the absorption period, i.e., cycle time. The weight of CO_2 absorbed was derived from the automatic CO_2 feed system which continuously maintained the CO_2 partial pressure at a fixed level of 7.6 mm Hg (Test Plan 1) or 3.8 mm Hg (Test Plan 2).

Water carry-over was determined by weight analysis of the total desorbed CO_2 and water vapor mixture for the complete series of cycles in a test run.

Power was measured directly, indicating the integrated input for the electric heater, air blower, and controls, for the complete series of cycles in a test run.

3.2 Test Plan

To determine system performance characteristics, the operating conditions were varied according to values established by the Box Wilson composite design. A detailed description of system instrumentation used in measurements and performance observation is shown in appendix B.

3.2.1 Selection of Operating Conditions

The primary operation parameters specified in the contract are cycle time, precool time, coolant flow rate and air flow rate.

Because the Box Wilson Central Composite design was the test plan selected, five levels of each parameter were tested to furnish 2 factorial points, 2 star points, and a center point. Previous experience and system design, i.e., fan size, heater size, and coolant pump capacity delineated the testing range of the parameters. The levels selected for each parameter were:

Cycle time;	10, 20, 30, 40, 50 minutes
Precool time;	0, 1.5, 3.0, 4.5, 6.0 minutes
Coolant flow;	1, 2, 3, 4, 5 gph
Air flow;	6, 8, 10, 12, 14 cfm

Cycle time was the length of time for absorption or for regeneration. The time of absorption was concurrent with and equal to the time of regeneration.

Precool time was the time elapsed between the start of cooling of the absorbing bed and the starting of air flow through the absorbing bed. The purpose of this delay was to precool the bed being transferred from the regeneration mode to the absorption mode before air was blown through the bed.

The heat transfer liquid rate is the volumetric liquid rate through the in-bed heat exchangers in the absorbing and regenerating beds.

Air flow rate is the volumetric flow of air through the absorbing bed.

The Box Wilson design determines which combination of parameters are tested. These are shown in appendix C.

Fixed operating conditions during testing were:

1.	Chamber pressure	360 mm Hg
2.	p_{CO_2}	7.6 mm Hg, in Test Plan 1
		3.8 mm Hg, in Test Plan 2
3.	Inlet air temperature to blower	50°F (bed inlet temperature averaged 25°F higher due to blower heat-up)
4.	Inlet air dew point	45°F
5.	Heat transfer coolant liquid temperature	50°F
6.	Regeneration liquid temperature	180°F
7.	Vacuum for regeneration	40 mm Hg absolute pressure

3.2.2 Measurement of Performance Characteristics

The following methods were used to determine the variation of CO_2 removal rate, ratio of H_2O/CO_2, and ratio of Power/CO_2.

3.2.2.1 CO_2 Removal Rate

The carbon dioxide removal rate was determined by measuring the volume of pure CO_2 which needed to be added to the chamber in order to maintain the bulk chamber concentration at a constant preselected level.

The concentration of CO_2 within the chamber was measured and the output of the CO_2 sensor was used to control the CO_2 feed as the CO_2 concentration fell below the predetermined set-point. Thus the volume of CO_2 added to the chamber and the length of time of the test run were used to calculate the average CO_2 removal rate for the test. Corrections were made for CO_2 lost from the chamber through the trim pump which periodically corrects chamber pressure variation resulting from air in-leakage.

3.2.2.2 Water Loss/CO_2 Ratio

The ratio of H_2O/CO_2 removed during regeneration was determined by weighing the amount of water trapped out of the regeneration vacuum loop during the length of time for a test. Thus the total amount of water collected during a test divided by the total amount of CO_2 removed during the same test gives an average ratio of H_2O/CO_2 for a particular test.

3.2.2.3 Power/CO_2 Ratio

The total energy used by the GAT-O-SORB system for the duration of a test was measured with a watt-hour meter. This included power to operate the blower and controls plus electric power to heat the fluid entering the regenerating bed. This energy divided by the total amount of CO_2 removed during the test produced a number equal to average energy/weight of CO_2 or average power/CO_2 removal rate.

An ammeter was used to measure the required current for operation of the GAT-O-SORB system. The current indicated the instantaneous power level and was used to verify proper functioning of the system components. The ammeter was also used to indicate when the liquid loop electric heaters were on or off.

3.2.3 Test Cycle

A test run consists of two parts. The first part of a run is known as "pre-run" during which the system comes to thermal equilibrium. The normal prerun lasts for three or four cycles. The second part of the run is the data run during which the system performance characteristics are measured as a function of operating conditions.

SECTION 4

PROGRAM TASKS AND TEST RESULTS

The testing program included several auxiliary tasks in addition to the major task of system performance testing. The program tasks in chronological order were:

1) checking all mechanical and electrical system components to verify proper function for continuous and sustained operation.
2) comparing the CO_2 absorption capacity of original absorbent with fresh absorbent to ascertain stability, retention of chemical properties, and other unexpected effects of long duration storage.
3) designing the experiment by using the Box Wilson central composite design technique.
4) conducting the performance testing of the total CO_2 absorption system.
5) conducting a duration test, consisting of continuous operation for 48 to 96 hours, to demonstrate absorbent stability and system reliability.
6) conducting off-design tests to show specific effects on system performance.

4.1 System Checkout for Component Function

Two changes were made in the system during the preliminary checkout. The electric water switch valve with manual override was replaced with a 4-way solenoid valve; the ports in the original valve were small and clogged easily. The new valve with 9/64" orifices eliminated clogging and lowered the pressure drop in the coolant loop.

An 850-watt heater was installed in the liquid loop to replace the 550-watt unit originally supplied. This provided the additional heating capacity required for circulating the heat-exchanger liquid at required higher rates.

4.2 Comparison of Old and New Absorbent

After the GAT-O-SORB system was returned to GARD, all of the original absorbent was removed from the canisters. Undersize material was removed by screening. A sample of the original absorbent from each bed was tested in a 1 inch glass tube absorbing column to determine CO_2 removal capacity. The average dynamic capacity of the sorbent for 3 regeneration-absorption cycles for each sample was 1.4 percent by weight. This capacity was the same as determined in the original tests. The conditions of these tests were:

CYCLE: 30 minutes absorption - 30 minute regeneration

FEED GAS: 1% CO_2 in air

AIR FLOW RATE: 4 SCFH

REGENERATION: 180°F at 40 mm Hg absolute pressure

After completing testing in the small scale bed, the right absorbent system canister was filled with 15-3/4 pounds of 10/20 mesh original absorbent, and the left canister with 15-3/4 pounds of 10/20 mesh fresh absorbent. This allowed continuous comparison of the old and new absorbent throughout the test program while operating under identical test conditions. No significant difference was detected between the performance of the two beds throughout all of the tests.

After comparing the old and new absorbent materials an additional shake-down test at one-atmosphere was run under conditions which were similar to the tests performed in 1964.

The test conditions and results summarized in table 2 show that the CO_2 removal rate was similar, although not identical, to test 13-B of the original test program. The difference in removal rate can be attributed to the fact that, in the original test program, the temperature of the heating fluid going to the bed in the regeneration mode was approximately 5 to 10°F warmer than in the shakedown test. An 850-watt liquid heater was used in original tests while a 550-watt heater was used in the shakedown test. A new 850-watt heater was installed and used in all subsequent tests. The effect of higher inlet air humidity in the shakedown test was assumed neglible because off-design tests (table 5) show the effect of inlet air dew point is small.

The two CO_2-removal rates being nearly equal is highly significant, indicating that the absorbent did not deteriorate either during the original test program or while being stored for four years.

4.3 Composite Design Test Plan

The Box Wilson Central Composite design was used to design the experiment and to develop a quadratic polynomial equation for CO_2-removal rate, water loss, and power in terms of the cycle time, precool time, heat-transfer liquid flow rate, and air flow. The experiment design is based on a two-level-factorial design with star points and center points. A series of tests based on the factorial design were run first to verify that the tests were performed in the correct range. The two-level-factorial design yielded only linear relationships. To obtain a quadratic effect, testing at three levels was required. For a complete three-level-factorial design plan a total of 81 tests would be required. The Central Composite design has the advantage of significantly reducing the number of tests while not significantly reducing the precision of the regression coefficients determined for the quadratic polynomial.

TABLE 2

COMPARISON OF ORIGINAL TEST PERFORMANCE AND PRESENT TEST PERFORMANCE

Test Parameters	Test 13-B (July 1964)	Shakedown Test 10-2-68
Chamber Pressure	1 atm	1 atm
Chamber p_{CO_2}	7.6 mm	7.6 mm
Cycle Time	30 min	30 min
Air Valve Delay	2 min	2 min
Coolant Flow	2 gph	2 gph
Heating Fluid Temp	185-190°F	180°F
Inlet Air Temp	77°F	75-85°F
Inlet air Relative Humidity	40-42%	70-75%
Air Flow	14 cfm	14 cfm
Results		
CO_2 Removal Rate	0.28 lb/hr	0.24 lb/hr

4.4 Performance Test Results

The test design produced coefficients for all first order and second order terms in the polynomial expression. The second order terms are composed of square terms and two level interaction terms. Higher level interactions were assumed to be insignificant and were neglected. Each coefficient was tested by a statistical method to determine if the term was significant or negligible. The results of the "t" test used are shown in appendix C.

4.4.1 Performance Equations

As shown by the high "F" value in appendix A, the results of the experiments run at a p_{CO_2} level of 3.8 mm Hg indicated a high degree of correlation. Therefore, the "t" test was used to select all coefficients which had a 95% or greater confidence level. The resulting simplified performance equations were:

$$Y_1 = -.644 + 0.0139\,A + 0.167\,C + 0.050\,D - 0.000096\,A^2 - 0.0170\,C^2 - 0.0025\,D^2 - 0.00176\,AC \quad (1)$$

$$Y_2 = 0.187 + 0.888\,C - 0.066\,D - 0.148\,C^2 \quad (2)$$

$$Y_3 = 238 - 5.58\,A - 41.0\,B - 12.3\,D + 0.0671\,A^2 + 4.1\,BD \quad (3)$$

where:

Y_1 = CO_2 removal rate, $\frac{lbCO_2}{hr}$

Y_2 = Water carry over, $\frac{lbH_2O}{lbCO_2}$

Y_3 = Power, $\frac{kwhr}{lbCO_2}$

A = Cycle time, minutes

B = Air valve delay, minutes

C = Water flow, gal/hr

D = Air flow, cfm

Simplified equations are not presented for the experiments run at a p_{CO_2} level of 7.6 mm Hg because the results for this set did not have high correlation. The confidence level decreased to 70%

before significant terms appeared in the polynomial expressions.

The primary objective of this program was to determine the effect of operating condition on performance characteristics. This could not be accomplished from a purely theoretical approach because all of the necessary chemical and physical properties of the absorbent were not known. Properties such as equilibrium CO_2 and H_2O partial pressures in the vapor phase, diffusion rates at the absorbent surface, and effective film transfer coefficients, must be known in order to solve the mass transfer and heat transfer equations associated with predicting CO_2 absorption and desorption rates. In spite of this lack of information certain effects can be estimated based on knowledge of how the system operates.

4.4.2 Effect of Operating Conditions on CO_2 Removal Rate

The operating conditions affected the average CO_2 removal rate in the manner described.

4.4.2.1 Cycle Time

Equation 1 shows that air increase in time will produce an increase in CO_2 removal rate until a maximum point is reached. Then any additional increase in cycle time will decrease CO_2 removal rate. The equation shows that the optimum cycle time shifts and is dependent upon the interaction between cycle time and coolant flow.

4.4.2.2 Precool Time

Precool Time had no significant effect on CO_2 Removal Rate.

4.4.2.3 Liquid Flow Rate

Likewise equation 1 shows that an increase coolant flow rate will increase CO_2 removal rate until a maximum CO_2 removal rate is obtained. Then any additional increase in coolant flow will decrease CO_2 removal rate. The point of optimum CO_2 removal as a function of liquid flow shifts because of the interaction between liquid flow rate and cycle time.

4.4.2.4 Air Flow

An increase in air flow should increase the CO_2 removal rate because an increase in air flow increases the average partial pressure of CO_2 in the air stream within the absorbing bed. Thus the average gradient of CO_2 in the gas phase and that held on the solid absorbent is increased. This increase in the gradient between the two phases should increase the rate of CO_2 transferred from the air stream to the sorbent. Also, if the airstream cools the absorbent as the sorbent changes from the regeneration to absorption modes, an increase in air flow should increase bed cooling and therefore increase CO_2 removal rate because the absorbent has increased capacity for CO_2 as bed temperature decreases.

This behavior was verified by the experimental results as air flow increased from 6 to 10 cfm. Unexpectedly an increase in air flow beyond 10 cfm produced a decrease in CO_2 removal rate. This was caused by the air stream heating the bed. It was observed that the exit temperature from the air blower into the absorbing bed ran about 20°F higher than the inlet air temperature of 50°F when the air flow was 6 to 8 cfm. When air flow was increased to the maximum of 14 cfm, the increase in temperature was about 15°F. This temperature rise was due to heat conduction from the blower motor and frictional effects within the blower. Thus a significantly greater amount of heat is added to the absorbing bed at high air flow.

The CO_2 absorption capacity consequently decreased as air flow increased. Thus air flow is useful in cooling an absorbing bed from 180° to 75°F, but opposes the effect of the 50°F liquid coolant in cooling the bed between 75° to 50°F.

4.4.3 Effect of Operating Conditions on the Ratio Water Carry Over/CO_2 Removed

An increase in cycle time, coolant flow and air flow should increase water carry over rate. Equation 2 indicates that cycle time affects the water absorption and desorption in the same manner as CO_2 absorption and desorption because there is no term for cycle time in the equation for the H_2O/CO_2 ratio.

The presence of terms in equation 2 for liquid flow and air flow show that these operating conditions affect the water carry over rate differently from the CO_2 removal rate. In other words, the H_2O/CO_2 ratio would equate to a constant number if the operating conditions affected water carry over and CO_2 removal in the same way.

4.4.4 The effect of Operating Conditions on the Ratio of Power/CO_2

An increase in air flow should increase the amount of heat removed from the absorbing bed; and this will increase the amount of heat required for subsequent regeneration of the bed. Thus an increase in air flow causes an increase in thermal power required.

However increased air flow also raises the CO_2 removal rate, therefore the behavior of the power/CO_2 ratio cannot be reliably estimated.

In contrast liquid flow can either increase or decrease the thermal power required; an increase in thermal power occurs when an increase in liquid flow causes more heat to be lost from regenerating bed than is transferred out of the absorbing bed; less power is required when the reverse occurs.

An increase in liquid flow generally will raise the CO_2 removal rate. Again the behavior of the Power/CO_2 ratio with respect to liquid flow cannot be reliably predicted.

4.4.5 Maximum and Minimum Operating Conditions

Experimental test conditions which produced maximum CO_2 removal rate, minimum ratio of water/CO_2 and minimum ratio of power/CO_2 for both test plan 1 and test plan 2 are summarized in table 3. Graphs of performance characteristics as a function of operating conditions are shown in figures 3, 4, 5, and 6. These plots are derived from the equations 1, 2 and aid in visualizing where maxima or minima occurs.

4.5 Duration Test

The objective of the duration test was to run the GAT-O-SORB system continuously for a minimum of 48 hours. The actual test lasted for 73 hours and was terminated when the system air blower failed.

The blower was designed for one atmosphere operation and overheated during one-half atmosphere operation. At one-half atmosphere the blower-motor cooling fan does not dissipate all of the heat which the motor produces.

All other components performed satisfactorily. The conditions for the duration test were:

Pressure 1/2 atm	air flow 10 cfm
Cycle time 30 min	p_{CO_2} 7.6 mm Hg

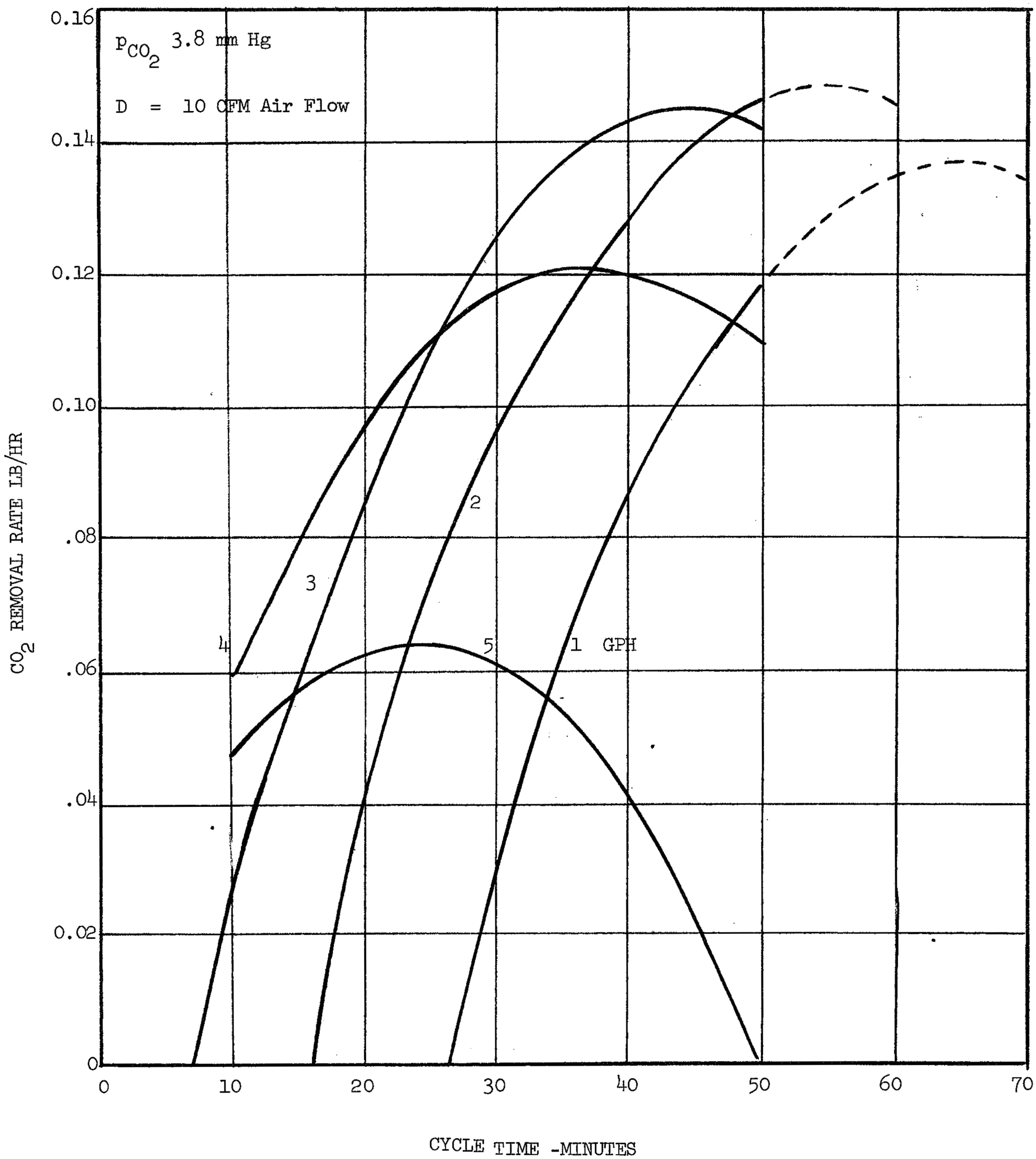

Figure 3. The Effect of Cycle Time and Coolant Flow on CO_2 Removal Rate

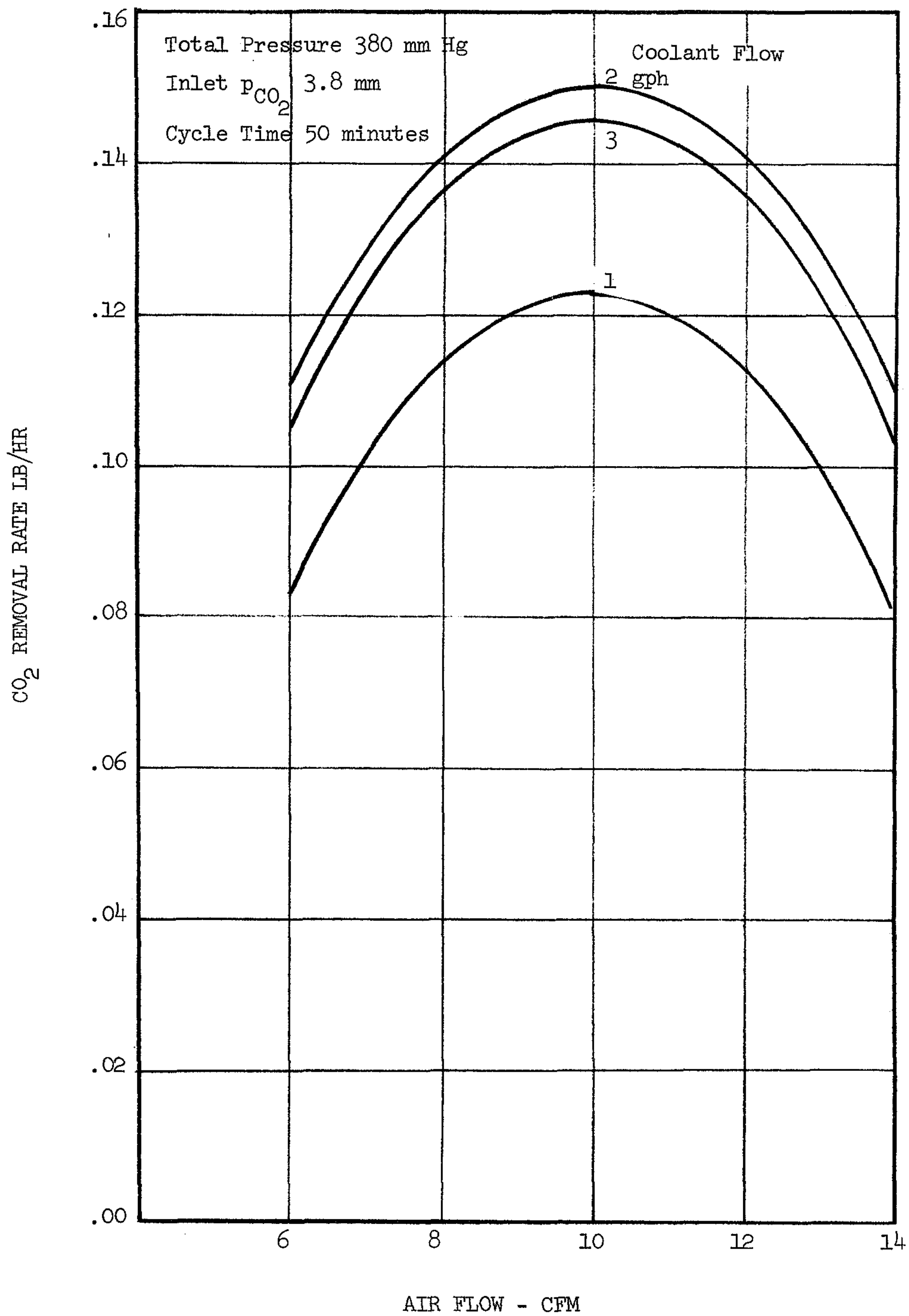

Figure 4. The Effect of Air Flow and Coolant Flow on CO_2 Removal Rate

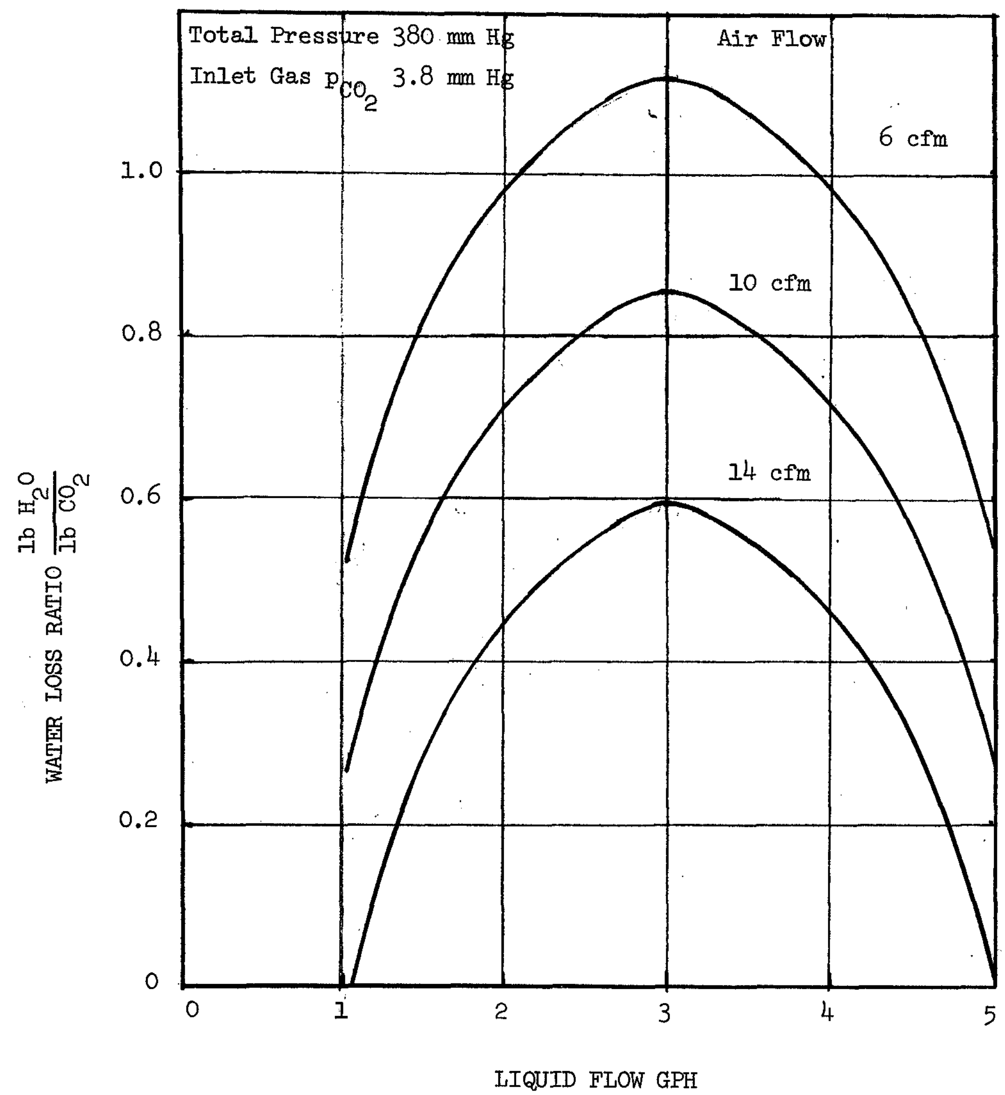

Figure 5. The Effect of Coolant Flow and Air Flow on Water Carryover

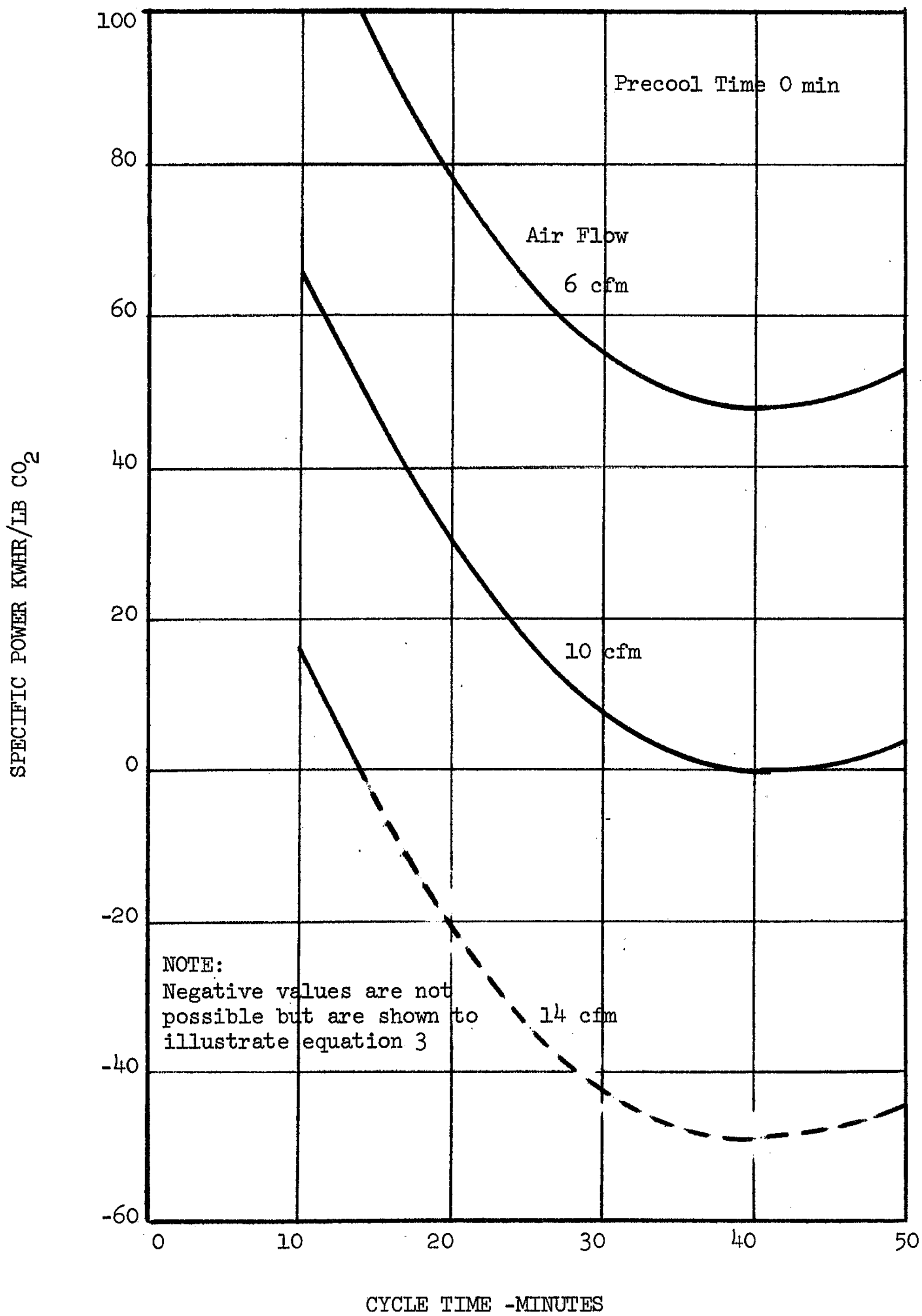

Figure 6. The Effect of Cycle Time and Air Flow an Power

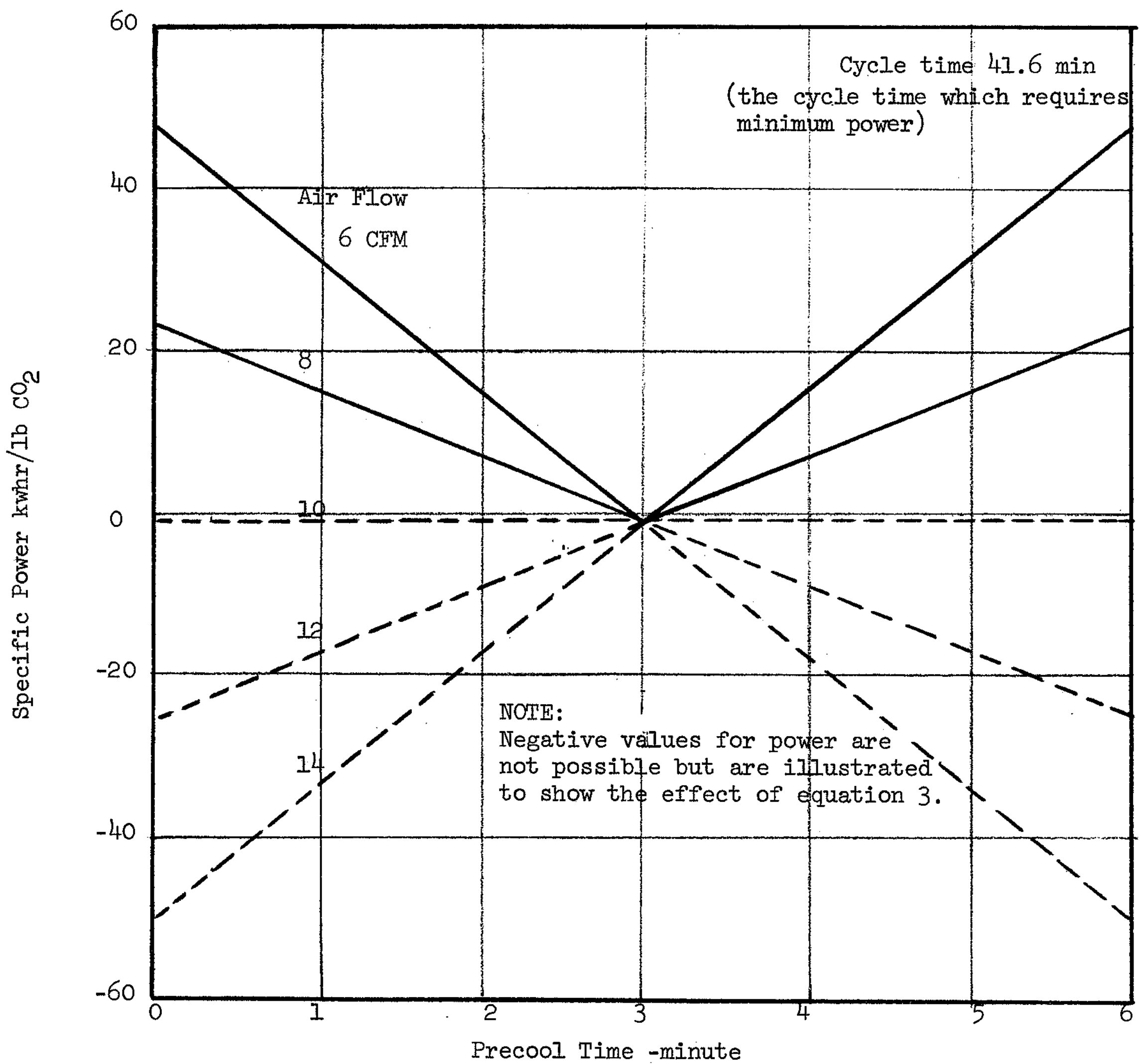

Figure 7. The effect of air flow and precooling on power

TABLE 3

System Performance Characteristics

	Performance			Varied Operating Conditions*			
	lb CO_2/hr.	lb H_2O/lb CO_2	KWH/lb CO_2	Cycle Time Min	Precool Time Min	Liquid Flow gph	Air Flow cfm
A. Test Plan 1, p_{CO_2} = 7.6 mm Hg							
1. Maximum CO_2 Removal Rate	0.33	0.48	2.9	20	1.5	4	8
2. CO_2 Capacity at min. lb H_2O/lb CO_2	0.20	.24	4.5	30	3.0	3	10
3. CO_2 Capacity at min. power/lb CO_2	0.30	0.32	2.0	20	1.5	2	8
B. Test Plan 2, p_{CO_2} = 3.8 mm Hg							
1. Maximum CO_2 Removal Rate	0.15	1.00	5.5	30	3.0	3	10
2. CO_2 Capacity at min. lb H_2O/lb CO_2	0.078	0.22	14.0	30	3.0	5	10
3. CO_2 Capacity at min. power/lb CO_2	0.142	0.81	5.3	30	6.0	3	10

* Varied Operating Conditions are as indicated;
the fixed operating conditions were: Inlet air temp 50°F
inlet air dew point 45°F
coolant temp 50°F
Regeneration press 40 mm Hg
regeneration liq. temp 180°F
Chamber pressure 380 mm Hg

Air valve delay 3.0 min | Inlet air dew point 40°F

The average responses for the overall duration test were:

CO_2 removal rate	0.12 $lbCO_2/hr$
Water carry-over	0.70 $lbH_2O/lbCO_2$
Power	6.5 $kwhr/lbCO_2$

The duration test did prove that other than the blower motor failure, the system was capable of continuous operation and was able to maintain its CO_2 removal rate throughout the test.

4.6 Off-Design Tests

Off-design tests were run to determine how well the system performed when certain design parameters were varied. These parameters include total pressure, CO_2 partial pressure, regeneration vacuum, regeneration temperature, inlet air temperature and humidity.

The tests were run under conditions similar to the center-point tests of the central composite design except for the off-design parameter being tested.

The off-design tests revealed that the CO_2-removal capacity of the system is not seriously affected by off-design conditions except for the heat-transfer fluid temperature. This agrres with the original work in which the minimum temperature for regeneration was found to be about 140°F.

4.7 Total Run Time

During the performance of this contract in which the GAT-O-SORB system was tested at GARD with original absorbent in the right canister and fresh absorbent in the left canister, 593 hours of running time were accumulated on the system. This includes 55.5 hours of prerun shakedown tests at one atmosphere and 537.5 hours of actual testing at one-half atmosphere.

TABLE 4

OFF-DESIGN TEST RESULTS

Cond. Changd	Test No.	CO_2 Rate $\frac{lb\ CO_2}{hr}$	Water Loss $\frac{lbH_2O}{lbCO_2}$	Power $\frac{kwhr}{lbCO_2}$	Total Press mm Hg	CO_2 mm Hg	Regen Press mm Hg	Coolant Temp °F	Regen Temp °F	Inlet Gas Temp °F	Inlet Gas Dew Point °F
	*	0.17	0.69	5.1	380	7.6	40	50	180	45°	40°
Total Press	39	0.20	0.59	4.9	760	15.2	40	50	180	45°	40°
Regen Press	40	0.14	0.77	5.8	380	7.6	80	50	180	45°	40°
Regen Temp	41	0.09	0.68	7.4	380	7.6	40	50	150	45°	40°
CO_2 mm Hg	43	0.17	1.33	4.8	380	15.2	40	50	180	45°	40°
Regen Press	44	0.13	0.64	6.0	380	7.6	20	50	180	45°	40°
Inlet Dew Pt.	45	0.16	0.25	4.5	380	7.6	40	80	180	80°	70°

*The standard consists of the average of the 7 center point tests.

For all tests
- cycle time = 30 min
- air valve delay 3 min
- coolant flow 3 gph
- air flow 10 cfm

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based on the data obtained from the experiments performed during this contract, and the recommendations are based on the conclusions and on design and absorbent modifications which would improve efficiency.

5.1 Conclusions

1. The CO_2 removal rate is directly dependent on air flow, coolant flow, and regeneration heat rate up to values of 8 cfm, 4 gph, and then decreases with further increase in these parameters. At higher air flow rates the blower heat conduction to the bed increased and raised the temperature of the absorbing bed, causing decreased capacity. As the coolant flow rate increased the coolant was heated slightly as it passed through a metal switch valve common with the hot liquid loop, and thus the bed cooling was decreased resulting in decreased capacity. Finally, at higher heating liquid flow rates, the liquid heater could not maintain the fluid at the desired 180°F level and the lower regenerating bed temperature caused a decrease in capacity.

However, under more ideal equipment conditions the average CO_2 removal rate should have increased with increased air flow, increased absorbing bed cooling, and increased regenerating bed heating rates.

The CO_2 removal rate would be expected to increase with a decrease in cycle time because more fresh absorbent is brought on stream per unit time. The CO_2 capacity was lower than expected at short cycle times, probably because the finite time required for the absorbent to be cooled before it can begin absorbing CO_2 takes up a greater portion of the cycle time. Thus the CO_2 removal rate was restricted by (1) the heating effect of the air blower, (2) the heat transfer through the liquid switch valve, (3) the limited heating capacity of the liquid heater, and (4) the capacity of the in-bed heat exchangers.

Operating with these mechanical restrictions the highest CO_2 removal rate achieved was 0.15 lb/hr when the p_{CO_2} was 3.8 mm, and 0.33 lb/hr when p_{CO_2} was 7.6 mm. This corresponds to a 1.5 and 3.3 man capacity system respectively. For tests at a p_{CO_2} of 3.8 mm Hg and at low liquid flow, 1 to 3 gph, an increase in cycle time produced a proportional increase in CO_2 removal rate. At high liquid flow, 4 or 5 gph, an increase in cycle time initially caused a proportional increase in CO_2 removal, then a maximum, and finally a decrease with further increase in cycle time.

2. Power for controls, valves, and the blower was essentially constant. Power for the liquid heater was primarily a function of CO_2 removal rate and heat loss. Power should increase with increased air flow, increased absorbing bed cooling, increased regenerating bed heating, and decreased cycle time. These operating parameters produced the same general effect on power as on CO_2 removal rate. If both power and CO_2 removal rate are influenced in the same manner and degree by the operating parameters, the equation for the ratio of power/CO_2 would equate to a constant. The equation did not equate to a constant indicating that power and CO_2 removal rate are influenced to a difference degree by each operating parameter. Since neither rate can be predicted with accuracy it is not possible to theoretically predict the effect of operating parameters on the ratio of these rates.

If the thermal power for heating the regenerating bed can be provided from waste heat at 180°F, the electrical power for operation of the system, i.e., blower and controls,would be reduced and influenced only by air flow rate. At inlet CO_2 partial pressures of 3.8 and 7.6 mm Hg, the minimum ratios of power to CO_2 were 5.3 and 2.0 $\frac{\text{kwhr}}{\text{lb } CO_2}$ respectively. These minina occured approximately at the maximum CO_2 removal rates. If 180°F waste heat is available for heating the regenerating bed, the ratios would be reduced to 2.0 and 0.96 $\frac{\text{kwhr}}{\text{lb } CO_2}$ or 200 and 96 watts per man, respectively.

3. The water carryover, i.e.,water removed from the air stream during CO_2 absorption and released with CO_2 during regeneration, should be influenced by the operating parameters in a manner similar to the way the operating parameters influence CO_2 absorption and desorption. If water carryover is affected in the same manner and degree as CO_2 removal, the equation for the ratio of H_2O/CO_2 would equate to a constant. The equation for this ratio did not equate to a constant, indicating the water carryover and CO_2 removal are not influenced in an identical manner and degree. At inlet CO_2 partial pressures of 3.8 and 7.6 mm Hg, the minimum ratios for water carryover/CO_2 were 0.22 and 0.24 lb H_2O/lb CO_2. The minima occured at random and at apparently unrelated levels of CO_2 removal rate.

The only conditions which affected the water loss ratio were liquid flow and air flow. An increase in air flow produced a proportional decrease in water loss for the entire test range. Liquid flow at 3 gal/hr produced a maximum H_2O/CO_2 ratio. The minimum water loss ratio occured when the liquid flow was either 1 or 5 gal/hr. Cycle time and precool time did not influence the water loss ratio.

4. A 73 hour duration test showed the ability of the system to function reliably under continuous unattended operation.

The system was operated for 593 hours without a decrease in CO_2 removal capacity. Thus the absorbent was shown to be suitable for long term continuous use.

5. The system can be operated under most off-design conditions without significantly changing the overall capacity for CO_2 removal. The most significant change was regeneration temperature, where a decrease from 180°F to 150°F, lowered the CO_2 capacity by 50%.

6. The absorbent appears to have long shelf live because no difference was detected between the absorbent formulated in 1964 and fresh absorbent made in 1968.

5.2 Recommendations

The performance of the GAT-O-SORB system could be improved by various changes in the system and absorbent materials.

1. The following design changes should be made on the present system to increase the CO_2 removal rate.

a. The present 850 watt liquid heater should be replaced with a larger capacity heater to prevent the fluid entering the regenerating bed from falling below 180° F at high liquid flow rates. This would increase peak power but not necessarily the ratio of power / lb. of CO_2 because the CO_2 removal rate would increase.

b. The present 4-way liquid switch valve should be replaced with two 3-way switch valves to prevent heat transfer through the valve from the warm fluid leaving the regenerating bed to the cool fluid entering the absorbing bed.

c. An alternate to using an electric heater in the system would be to provide separate hot and cold fluid loops for regeneration and absorption. This would be equivalent to operating with liquid available from the waste heat loop, and coolant from the coolant system loop.

It is anticipated that the above changes would significantly increase the CO_2 removal rate, while the power penalty per pound of CO_2, or per man, would be held the same, or possibly decrease.

2. The design of the in-bed heat exchanger should be improved to increase CO_2 removal rate. These improvements would consist of:

a. Depositing the absorbent directly on the fins of the in-bed heat exchanger, or

b. Providing more actual heat-transfer surface area in the bed by changing of the heat exchanger configuration.

3. The capacity of the absorbent might be increased by altering the composition of the granules. Possible alterations would include:

a. Making formulations containing carriers possessing higher surface areas and

b. Altering the ratio of absorbent ingredients.

4. Investigate the possibility of using a low power rapid-cycling process of "heatless desorption" for this absorbent.

5. Investigate lower pressure and correspondingly lower temperatures for regeneration to decrease total heat input.

6. Determine the composition of the effluent of the absorbing bed, and of the regenerating bed to verify that no undesirable trace contaminants leave or are generated by the system, and that high purity CO_2 is recovered.

7. The polynomial expressions developed from the Box-Wilson composite design yield good results for the present system; however the expressions are only applicable within the range of parameter values tested and only for the present system. General theoretical equations based on mass and heat transfer should be developed because these equations would be applicable for a broader range of parameters for any system which uses the GAT-O-SORB absorbent. In order to develop these equations, physical and chemical properties of the absorbent, heat of reaction, and mass transfer coefficients should be determined.

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3. Bowker A., Lieberman G., "Engineering Statistics" Prentice Hall, Inc. 1959.

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APPENDIX A

COMPUTER COMPUTATIONS

The tables in this appendix show the computed regression coefficient by a least squares fit, the standard error, the t value for the coefficients plus a multiple correlation coefficient, a standard error, and F values for the overall test design. Also furnished are tables of measured and computed responces. Table A-1 shows the correspondence between variable number and the terms in the polynomial equations.

Table A-1 Correspondence
Between Variable Number and Variables

Variable No.	Term
1	X_1
2	X_2
3	X_3
4	X_4
5	Y_1
6	Y_2
7	Y_3
8	X_2^2
9	X_3^2
10	X_4^2
11	X_1X_2
12	X_1X_3
13	X_1X_4
14	X_2X_3
15	X_2X_4
16	X_3X_4
17	X_1^2

Table A-2

Results for CO_2 Removal Rate
at p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 1

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.85280	0.56004	0.03474	0.00693	5.01205
2	0.00000	0.85280	0.20548	0.01274	0.00693	1.83895
3	0.00000	0.85280	0.25114	0.01168	0.00490	2.38395
4	0.00000	0.85280	0.21354	0.01449	0.00693	2.09136
8	0.69565	1.14553	0.09515	-0.00069	0.00373	-0.18706
9	0.69565	1.14553	-0.42875	-0.01707	0.00373	-4.57146
10	0.69565	1.14553	-0.20479	-0.01007	0.00373	-2.69721
11	0.00000	0.60302	0.08167	-0.00912	0.00980	-0.93063
12	0.00000	0.60302	-0.26780	-0.01762	0.00693	-2.54208
13	0.00000	0.60302	0.09686	-0.00637	0.00980	-0.65016
14	0.00000	0.60302	0.03608	0.00237	0.00693	0.34255
15	0.00000	0.60302	0.26400	-0.01737	0.00980	-1.77202
16	0.00000	0.60302	-0.03988	-0.00262	0.00693	-0.37860
17	0.69565	1.14553	-0.19279	-0.00969	0.00373	-2.59681
DEPENDENT						
5	0.09173	0.03968				

INTERCEPT	0.11785
MULTIPLE CORRELATION	0.95457
STD. ERROR OF ESTIMATE	0.01961

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	0.03157	0.00225	5.86452
DEVIATION FROM REGRESSION	8	0.00307	0.00038	
TOTAL	22	0.03465		

Table A-3

Comparison of Responses

for CO_2 Removal Rate at p_{CO_2} equal to 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 1

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	0.10000	0.10324	-0.00324
2	0.09500	0.09824	-0.00324
3	0.07700	0.08024	-0.00324
4	0.08300	0.08624	-0.00324
5	0.11600	0.11562	0.00037
6	0.03000	0.02962	0.00037
7	0.09200	0.09162	0.00037
8	0.03800	0.03762	0.00037
9	0.10800	0.10656	0.00143
10	0.05000	0.04856	0.00143
11	0.07800	0.07293	0.00506
12	0.02400	0.02618	-0.00218
13	0.14200	0.14056	0.00143
14	0.09100	0.08956	0.00143
15	0.15000	0.14856	0.00143
16	0.01100	0.00956	0.00143
17	0.15500	0.11785	0.03714
18	0.10800	0.11785	-0.00985
19	0.13800	0.11785	0.02014
20	0.11900	0.11785	0.00114
21	0.09200	0.11785	-0.02585
22	0.09700	0.11785	-0.02085
23	0.11600	0.11785	-0.00185

Table A-4

Results for Water Loss at

p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 2

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.85280	0.05486	-0.08999	0.09328	-0.96480
2	0.00000	0.85280	-0.18583	0.00249	0.09328	0.02680
3	0.00000	0.85280	-0.24600	-0.08687	0.06596	-1.31707
4	0.00000	0.85280	-0.37343	-0.14249	0.09328	-1.52761
8	0.69565	1.14553	-0.09492	-0.04180	0.05024	-0.83200
9	0.69565	1.14553	-0.56397	-0.15305	0.05024	-3.04594
10	0.69565	1.14553	0.02102	-0.01430	0.05024	-0.28473
11	0.00000	0.60302	-0.24278	0.02124	0.13192	0.16108
12	0.00000	0.60302	0.01752	0.00874	0.09328	0.09380
13	0.00000	0.60302	-0.26781	-0.13624	0.13192	-1.03281
14	0.00000	0.60302	0.00250	0.00124	0.09328	0.01340
15	0.00000	0.60302	0.25779	0.21874	0.13192	1.65818
16	0.00000	0.60302	0.02753	0.01374	0.09328	0.14740
17	0.69565	1.14553	0.13169	0.01194	0.05024	0.23765

DEPENDENT

6	0.75565	0.30116

INTERCEPT 0.89285

MULTIPLE CORRELATION 0.84905

STD. ERROR OF ESTIMATE 0.26384

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	1.43845	0.10274	1.47596
DEVIATION FROM REGRESSION	8	0.55690	0.06961	
TOTAL	22	1.99536		

Table A-5

Comparison of Responses for

Water carryover at p_{CO_2} equal to 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 2

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	0.41000	0.50624	-0.09624
2	0.35000	0.44624	-0.09624
3	0.89000	0.98624	-0.09624
4	0.40000	0.49624	-0.09624
5	0.57000	0.63249	-0.06249
6	0.60000	0.66249	-0.06249
7	1.11000	1.17249	-0.06249
8	0.60000	0.66249	-0.06249
9	0.63000	0.55062	0.07937
10	1.20000	1.12062	0.07937
11	0.22000	0.10687	0.11312
12	0.50000	0.45437	0.04562
13	0.81000	0.73062	0.07937
14	0.80000	0.72062	0.07937
15	0.84000	0.76062	0.07937
16	1.20000	1.12062	0.07937
17	1.00000	0.89285	0.10714
18	1.00000	0.89285	0.10714
19	1.09000	0.89285	0.19714
20	1.00000	0.89285	0.10714
21	0.38000	0.89285	-0.51285
22	1.13000	0.89285	0.23714
23	0.65000	0.89285	-0.24285

Table A-6

Results for Power at

p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 3

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.85280	-0.61218	-15.52499	1.39753	-11.10880
2	0.00000	0.85280	0.01391	-0.87499	1.39753	-0.62610
3	0.00000	0.85280	-0.05728	-0.87499	0.98820	-0.88543
4	0.00000	0.85280	-0.14076	-1.42499	1.39753	-1.01964
8	0.69565	1.14553	--0.15036	-0.81428	0.75283	-1.08163
9	0.69565	1.14553	0.05192	1.26071	0.75282	1.67463
10	0.69565	1.14553	-0.05043	0.21071	0.75283	0.27989
11	0.00000	0.60302	-0.13310	-1.44999	1.97641	-0.73364
12	0.00000	0.60302	0.12731	2.74999	1.39753	1.96774
13	0.00000	0.60302	0.06018	2.17499	1.97641	1.10047
14	0.00000	0.60302	-0.10301	-2.22499	1.39753	-1.59208
15	0.00000	0.60302	-0.14699	12.34999	1.97641	6.24867
16	0.00000	0.60302	0.05324	1.15000	1.39753	0.82287
17	0.69565	1.14553	0.59052	6.78571	0.75282	9.01360

DEPENDENT

7	12.83477	13.02506

INTERCEPT	7.65713
MULTIPLE CORRELATION	0.98311
STD. ERROR OF ESTIMATE	3.95283

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	3607.35010	257.66784	16.49080
DEVIATION FROM REGRESSION	8	124.99952	15.62494	
TOTAL	22	3732.34961		

Table A-7

Comparison of Responses

for Power at p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 3

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
~~1~~	~~8.30000~~	~~11.14999~~	~~-2.84999~~
2	12.60000	15.44998	-2.84998
~~3~~	~~13.60000~~	~~16.44998~~	~~-2.84998~~
4	11.00000	13.84998	-2.84997
~~5~~	~~7.10000~~	~~9.54999~~	~~-2.44999~~
6	27.00000	29.44997	-2.44996
7	8.10000	10.54999	-2.44999
~~8~~	~~11.90000~~	~~14.34997~~	~~-2.44997~~
9	8.30000	5.64999	2.65000
~~10~~	~~14.00000~~	~~11.34999~~	~~2.65001~~
11	14.00000	10.94998	3.05001
~~12~~	~~16.70000~~	~~14.44998~~	~~2.25001~~
13	5.30000	2.64999	2.65000
~~14~~	~~8.80000~~	~~6.14999~~	~~2.65000~~
15	6.40000	3.74999	2.65000
~~16~~	~~68.50001~~	~~65.84997~~	~~2.65004~~
17	5.50000	7.65713	-2.15713
~~18~~	~~8.30000~~	~~7.65713~~	~~0.64286~~
19	6.50000	7.65713	-1.15713
~~20~~	~~6.70000~~	~~7.65713~~	~~-0.95713~~
21	8.70000	7.65713	1.04286
~~22~~	~~9.30000~~	~~7.65713~~	~~1.64286~~
23	8.60000	7.65713	0.94286

Table A-8

Results for CO_2 Removal Rate
at p_{CO_2} equal 7.6 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 1

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.89442	-0.23118	-0.01583	0.01350	-1.17198
2	0.00000	0.89442	-0.12775	-0.00874	0.01350	-0.64767
3	0.00000	0.89442	0.22874	0.01566	0.01350	1.15964
4	0.00000	0.89442	-0.20076	-0.01374	0.01350	-1.01777
8	0.77419	0.99027	0.13545	0.00842	0.01237	0.68076
9	0.77419	0.99027	-0.17884	-0.00944	0.01237	-0.76348
10	0.77419	0.99027	0.17941	0.01092	0.01237	0.88275
11	0.00000	0.73029	0.17137	0.01437	0.01654	0.86878
12	0.00000	0.73029	-0.14156	-0.01187	0.01654	-0.71768
13	0.00000	0.73029	0.20117	0.01687	0.01654	1.01987
14	0.00000	0.73029	0.00745	0.00062	0.01654	0.03777
15	0.00000	0.73029	0.02235	0.00187	0.01654	0.11331
16	0.00000	0.73029	0.21607	0.01812	0.01654	1.09542
17	0.77419	0.99027	-0.02938	-0.00094	0.01237	-0.07670
DEPENDENT						
5	0.17264	0.06125				

INTERCEPT 0.16571

MULTIPLE CORRELATION 0.61435

STD. ERROR OF ESTIMATE 0.06618

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	0.04249	0.00303	0.69286
DEVIATION FROM REGRESSION	16	0.07008	0.00438	
TOTAL	30	0.11257		

Table A-9

Comparison of Responses for

CO_2 Removal Rate at p_{CO_2} equal 7.6 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 1

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	0.30000	0.23733	0.06266
2	0.19000	0.16691	0.02308
3	0.26000	0.18608	0.07391
4	0.21000	0.17316	0.03683
5	0.33000	0.25491	0.07508
6	0.17000	0.13699	0.03300
7	0.22000	0.20616	0.01383
8	0.14000	0.14574	-0.00574
9	0.20000	0.13608	0.06391
10	0.16000	0.13316	0.02683
11	0.10000	0.09233	0.00766
12	0.13000	0.14691	-0.01691
13	0.23000	0.22616	0.00383
14	0.16000	0.17574	-0.01574
15	0.22000	0.18491	0.03508
16	0.17000	0.19199	-0.02199
17	0.07500	0.19358	-0.11858
18	0.15000	0.13024	0.01975
19	0.13000	0.21691	-0.08691
20	0.17000	0.18191	-0.01191
21	0.00700	0.09658	-0.08958
22	0.15000	0.15924	-0.00924
23	0.13000	0.23691	-0.10691
24	0.19000	0.18191	0.00808
25	0.20000	0.16571	0.03428
26	0.17000	0.16571	0.00428
27	0.18000	0.16571	0.01428
28	0.17000	0.16571	0.00428
29	0.13000	0.16571	-0.03571
30	0.16000	0.16571	-0.00571
31	0.15000	0.16571	-0.01571

Table A-10

Results for Water Loss at

p_{CO_2} equal 7.6 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 2

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.89442	0.33393	0.07291	0.04258	1.71227
2	0.00000	0.89442	-0.07442	-0.01624	0.04258	-0.38159
3	0.00000	0.89442	-0.09731	-0.02124	0.04258	-0.49900
4	0.00000	0.89442	-0.05533	-0.01208	0.04258	-0.28374
8	0.77419	0.99027	-0.01851	-0.01581	0.03901	-0.40546
9	0.77419	0.99027	-0.32874	-0.07206	0.03901	-1.84729
10	0.77419	0.99027	0.01595	-0.00956	0.03901	-0.24526
11	0.00000	0.73029	-0.02570	-0.00687	0.05215	-0.13181
12	0.00000	0.73029	0.07244	0.01937	0.05215	0.37148
13	0.00000	0.73029	-0.09114	-0.02437	0.05215	-0.46735
14	0.00000	0.73029	-0.17060	-0.04562	0.05215	-0.87478
15	0.00000	0.73029	0.15191	0.04062	0.05215	0.77892
16	0.00000	0.73029	-0.05842	-0.01562	0.05215	-0.29958
17	0.77419	0.99027	-0.24601	-0.05706	0.03901	-1.46280

DEPENDENT

6	0.57322	0.19530

INTERCEPT	0.69285
MULTIPLE CORRELATION	0.62564
STD. ERROR OF ESTIMATE	0.20862

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	0.44790	0.03199	0.73509
DEVIATION FROM REGRESSION	16	0.69636	0.04352	
TOTAL	30	1.14427		

Table A-11

Comparison of Responses for

Water Loss at p_{CO_2} equal 7.6 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 2

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	0.32000	0.48249	-0.16249
2	0.61000	0.65208	-0.04208
3	0.50000	0.47374	0.02625
4	0.70000	0.61583	0.08416
5	0.48000	0.52374	-0.04374
6	0.96000	0.77083	0.18916
7	0.43000	0.33249	0.09750
8	0.26000	0.55208	-0.29208
9	0.67000	0.45708	0.21291
10	0.41000	0.52916	-0.11916
11	0.40000	0.61083	-0.21083
12	0.62000	0.65541	-0.03541
13	0.33000	0.43583	-0.10583
14	0.48000	0.58541	-0.10541
15	0.37000	0.40708	-0.03708
16	0.67000	0.52916	0.14083
17	0.38000	0.31874	0.06125
18	0.65000	0.61041	0.03958
19	0.70000	0.66208	0.03791
20	0.66000	0.59708	0.06291
21	0.52000	0.44708	0.07291
22	0.39000	0.36208	0.02791
23	0.70000	0.67874	0.02125
24	0.71000	0.63041	0.07958
25	0.24000	0.69285	-0.45285
26	0.61000	0.69285	-0.08285
27	0.85000	0.69285	0.15714
28	0.65000	0.69285	-0.04285
29	0.90000	0.69285	0.20714
30	0.96000	0.69285	0.26714
31	0.64000	0.69285	-0.05285

MULTIPLE REGRESSION.....CO2CON

Table A-12

Results for Power at

p_{CO_2} equal 7.6 mm Hg

SELECTION..... 3

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.89442	0.02265	0.24166	1.79145	0.13489
2	0.00000	0.89442	0.03749	0.39999	1.79145	0.22328
3	0.00000	0.89442	-0.37654	-4.01666	1.79145	-2.24212
4	0.00000	0.89442	0.03437	0.36666	1.79145	0.20467
8	0.77419	0.99027	-0.14628	-1.12113	1.64119	-0.68311
9	0.77419	0.99027	0.59459	5.44136	1.64119	3.31548
10	0.77419	0.99027	-0.15334	-1.18363	1.64119	-0.72119
11	0.00000	0.73029	-0.05358	-0.69999	2.19407	-0.31904
12	0.00000	0.73029	0.08132	1.06249	2.19407	0.48425
13	0.00000	0.73029	-0.05453	-0.71249	2.19407	-0.32473
14	0.00000	0.73029	-0.02104	-0.27499	2.19407	-0.12533
15	0.00000	0.73029	0.04592	0.59999	2.19407	0.27346
16	0.00000	0.73029	-0.06410	-0.83749	2.19407	-0.38170
17	0.77419	0.99027	-0.12935	-0.97113	1.64119	-0.59172
DEPENDENT						
7	6.81934	9.54090				

INTERCEPT 5.14285

MULTIPLE CORRELATION 0.74075

STD. ERROR OF ESTIMATE 8.77629

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	14	1498.49145	107.03509	1.38964
DEVIATION FROM REGRESSION	16	1232.37475	77.02342	
TOTAL	30	2730.86621		

Table A-13

Comparison of Responses

for Power at p_{CO_2} equal 7.6 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 3

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	2.00000	9.45415	-7.45415
2	3.80000	10.63748	-6.83748
3	2.50000	11.00415	-8.50415
4	3.20000	9.38748	-6.18748
5	2.90000	1.52082	1.37917
6	6.10000	6.95415	-0.85415
7	3.40000	1.97082	1.42917
8	7.30000	4.60415	2.69584
9	3.60000	12.08747	-8.48747
10	4.10000	10.42081	-6.32081
11	12.00000	16.03747	-4.03747
12	4.40000	11.57081	-7.17081
13	2.10000	0.80415	1.29584
14	6.10000	3.38748	2.71251
15	4.70000	3.65415	1.04584
16	6.00000	3.43749	2.56251
17	7.10000	0.77499	6.32500
18	6.10000	1.74166	4.35833
19	6.80000	-0.14166	6.94166
20	5.20000	1.45833	3.74166
21	57.10000	34.94164	22.15836
22	7.40000	18.87497	-11.47497
23	6.50000	-0.32499	6.82499
24	5.00000	1.14166	3.85833
25	4.50000	5.14285	-0.64285
26	3.50000	5.14285	-1.64285
27	5.00000	5.14285	-0.14285
28	5.60000	5.14285	0.45714
29	6.60000	5.14285	1.45714
30	5.10000	5.14285	-0.04285
31	5.70000	5.14285	0.55714

Table A-14

Reduced Equation for CO_2 Removal Rate at p_{CO_2} equal 3.8 mm Hg

// XEQ REGRE

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 1

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.85280	0.56004	0.02606	0.00556	4.68081
3	0.00000	0.85280	0.25114	0.01168	0.00556	2.09907
9	0.69565	1.14553	-0.42875	-0.01697	0.00420	-4.04129
10	0.69565	1.14553	-0.20479	-0.00997	0.00420	-2.37496
12	0.00000	0.60302	-0.26780	-0.01762	0.00787	-2.23830
17	0.69565	1.14553	-0.19279	-0.00960	0.00420	-2.28570
DEPENDENT						
5	0.09173	0.03968				

INTERCEPT	0.11716
MULTIPLE CORRELATION	0.87804
STD. ERROR OF ESTIMATE	0.02227

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	6	0.02671	0.00445	8.97588
DEVIATION FROM REGRESSION	16	0.00793	0.00049	
TOTAL	22	0.03465		

MULTIPLE REGRESSION.....CO2CON

Table A-15

Comparison of Responses for

CO_2 Removal Rate for Reduced Equation at p_{CO_2} equal 3.8 mm Hg

SELECTION..... 1

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	0.10000	0.10073	-0.00073
2	0.09500	0.08386	0.01113
3	0.07700	0.10073	-0.02373
4	0.08300	0.08386	-0.00086
5	0.11600	0.11261	0.00338
6	0.03000	0.02523	0.00476
7	0.09200	0.11261	-0.02061
8	0.03800	0.02523	0.01276
9	0.10800	0.07726	0.03073
10	0.05000	0.07726	-0.02726
11	0.07800	0.07263	0.00536
12	0.02400	0.02588	-0.00188
13	0.14200	0.11716	0.02483
14	0.09100	0.11716	-0.02616
15	0.15000	0.13088	0.01911
16	0.01100	0.02663	-0.01563
17	0.15500	0.11716	0.03783
18	0.10800	0.11716	-0.00916
19	0.13800	0.11716	0.02083
20	0.11900	0.11716	0.00183
21	0.09200	0.11716	-0.02516
22	0.09700	0.11716	-0.02016
23	0.11600	0.11716	-0.00116

Table A-16

Results for Reduced Equation for

Water Loss at p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 2

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
4	0.00000	0.85280	-0.37343	-0.13187	0.05816	-2.26742
9	0.69565	1.14553	-0.56397	-0.14826	0.04329	-3.42434
DEPENDENT						
6	0.75565	0.30116				

INTERCEPT 0.85879

MULTIPLE CORRELATION 0.67639

STD. ERROR OF ESTIMATE 0.23264

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	2	0.91290	0.45645	8.43366
DEVIATION FROM REGRESSION	20	1.08245	0.05412	
TOTAL	22	1.99536		

Table A-17

Comparison of Responses for Water Loss for Reduced Equation at p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 2

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	0.41000	0.57865	-0.16865
2	0.35000	0.84240	-0.49240
3	0.89000	0.84240	0.04759
4	0.40000	0.57865	-0.17865
5	0.57000	0.57865	-0.00865
6	0.60000	0.84240	-0.24240
7	1.11000	0.84240	0.26759
8	0.60000	0.57865	0.02134
9	0.63000	0.59504	0.03495
10	1.20000	1.12254	0.07745
11	0.22000	0.26572	-0.04572
12	0.50000	0.26572	0.23427
13	0.81000	0.85879	-0.04879
14	0.80000	0.85879	-0.05879
15	0.84000	0.85879	-0.01879
16	1.20000	0.85879	0.34120
17	1.00000	0.85879	0.14120
18	1.00000	0.85879	0.14120
19	1.09000	0.85879	0.23120
20	1.00000	0.85879	0.14120
21	0.38000	0.85879	-0.47879
22	1.13000	0.85879	0.27120
23	0.65000	0.85879	-0.20879

Table A-18

Results for Reduced Equation for Power at p_{CO_2} equal to 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 3

VARIABLE NO.	MEAN	STANDARD DEVIATION	CORRELATION X VS Y	REGRESSION COEFFICIENT	STD. ERROR OF REG.COEF.	COMPUTED T VALUE
1	0.00000	0.85280	-0.61218	-15.52499	1.66612	-9.31802
15	0.00000	0.60302	-0.14699	12.34999	2.35625	5.24136
17	0.69565	1.14553	0.59052	6.71445	0.87706	7.65558
DEPENDENT						
7	12.83477	13.02506				

INTERCEPT 8.16384

MULTIPLE CORRELATION 0.94177

STD. ERROR OF ESTIMATE 4.71251

ANALYSIS OF VARIANCE FOR THE REGRESSION

SOURCE OF VARIATION	DEGREES OF FREEDOM	SUM OF SQUARES	MEAN SQUARES	F VALUE
ATTRIBUTABLE TO REGRESSION	3	3310.40137	1103.46704	49.68825
DEVIATION FROM REGRESSION	19	421.94830	22.20780	
TOTAL	22	3732.34961		

Table A-19

Comparison of Responses for Power for Reduced Equation at p_{CO_2} equal 3.8 mm Hg

MULTIPLE REGRESSION.....CO2CON

SELECTION..... 3

TABLE OF RESIDUALS

CASE NO.	Y VALUE	Y ESTIMATE	RESIDUAL
1	8.30000	11.70330	-3.40330
2	12.60000	18.05330	-5.45330
3	13.60000	11.70330	1.89669
4	11.00000	18.05330	-7.05330
5	7.10000	11.70330	-4.60330
6	27.00000	18.05330	8.94669
7	8.10000	11.70330	-3.60330
8	11.90000	18.05330	-6.15330
9	8.30000	8.16384	0.13615
10	14.00000	8.16384	5.83615
11	14.00000	8.16384	5.83615
12	16.70000	8.16384	8.53615
13	5.30000	8.16384	-2.86384
14	8.80000	8.16384	0.63615
15	6.40000	3.97168	2.42831
16	68.50001	66.07167	2.42834
17	5.50000	8.16384	-2.66384
18	8.30000	8.16384	0.13615
19	6.50000	8.16384	-1.66384
20	6.70000	8.16384	-1.46384
21	8.70000	8.16384	0.53615
22	9.30000	8.16384	1.13615
23	8.60000	8.16384	0.43615

APPENDIX B

INSTRUMENTATION

AND

EQUIPMENT

INSTRUMENTATION AND EQUIPMENT

The following instrumentation and equipment was used to control, read, and record the various parameters encountered in the program.

B.1 Temperature

Type T (Copper-Constantan) thermocouples were used for all temperature measurement except for the four dial thermocouples which are built into the GAT-O-SORB system for measuring the temperature of the liquid entering and exiting each of the two absorbent beds. The thermocouples sensing the temperature of the gas at the inlet of the fan in the GAT-O-SORB system, and the temperature of the gas leaving the absorbent bed were read out and recorded on a Bristol Dynamaster multipoint recorder (range -50° to +150°F). Other thermocouples which sensed the temperature inside of the absorbent beds, temperature of the chamber, and temperature of the coolant at the inlet connection to the GAT-O-SORB system were read out and recorded on a Daystrom-Weston model 6702 multipoint recorder (range 0-300°F). The temperature of the gas entering the GAT-O-SORB system was controlled at 50°F by passing chamber air through a gas-liquid heat exchanger. The air entering the heat exchanger varied from 65° to 80°F. The temperature of the gas leaving the heat exchanger was controlled by the temperature of the glycol-water solution which passed through the liquid side. This liquid was recycled through a refrigeration unit outside of the chamber.

The temperature of the water flowing to the absorbing bed's internal heat exchanger was 50°F. This liquid left the absorbing bed and was heated with an electric cartridge heater to 180°F and flowed to the bed being regenerated. A Fenwal thermostatic switch turned the electric heater on or off.

B.2 Dew Point

The dew point of the gas entering or exiting the GAT-O-SORB system was sensed with a Cambridge Systems Model 992-C1 hygrometer. This sensor has a type T thermocouple output which was read out and recorded on the same Bristol recorder used for recording temperatures. A three way solenoid valve was used to control the sample point, i.e., inlet gas or outlet gas. The dew point of the gas entering the GAT-O-SORB system was controlled by passing chamber gas through a gas-liquid heat exchanger to condense excess moisture and lower the dew point to 45°. The temperature of the liquid flowing through the heat exchanger controlled both the dew point and the temperature of the gas leaving the heat exchanger.

B.3 Vacuum for Regeneration

A Precision Scientific Model 150 vacuum pump (5.3 cfm free air) was used to evacuate the bed in the regeneration mode. A mercury manometer indicated the absolute pressure of the regenerating bed and a Matheson Lab-Stat controller was used to open or close a solenoid valve in the line between the vacuum pump and the chamber. This controller has a dielectric sensor attached to the mercury manometer. Thus changes in the level of mercury were transmitted to the controller. Also two dry ice-acetone traps were placed in series in the vacuum line between the solenoid valve and the chamber. These traps prevented moisture from reaching the vacuum pump and provided a method of measuring the amount of moisture lost from the sorbent during regeneration.

B.4 Chamber Pressure

After the chamber was evacuated to the specified operating pressure of 360 mm Hg, the pressure was maintained at this level with a trim pump that corrected for in-leakage. Generally in-leakage ranged from 20 to 30 scfh. The trim pump used was a Speedaire model 1Z943 (free air 1.9 cfm). A Barksdale Model D1H-H18 Pressure-Vacuum switch was used to open or close a solenoid valve in the line between the trim pump and chamber. A Sprague model 175 gas meter was used to measure the amount of gas that the trim pump removed from the chamber. Therefore the amount of CO_2 removed could be calculated.

The pressure within the chamber was readout on a Wallace-Tiernan absolute pressure gauge, model FA 160 (range 0-800 mm Hg).

B.5 Carbon Dioxide Concentration

The concentration of carbon dioxide within the chamber and fed to the GAT-O-SORB system, and the concentration of carbon dioxide leaving the GAT-O-SORB system which indicates how efficiently the absorbent performs, were measured with MSA LIRA infrared analyzers (Model 300).

The signal from the LIRA which measured chamber CO_2 concentration was sent to a Leeds/Northrup model "H" AZAR recording controller. When the CO_2 concentration fell below the set-point, the controller opened a solenoid valve between the CO_2 supply and the chamber.

The signal from the LIRA which measured the CO_2 concentration at the exit of the GAT-O-SORB system was sent to a Bausch and Lomb strip chart recorder.

B.6 Carbon Dioxide Gas

The purity of the carbon dioxide fed to the chamber was 99.5 percent. The amount of CO_2 used was measured with a wet test meter which was pre-saturated with CO_2 to prevent errors due to CO_2 absorption in the water within the meter.

B.7 Power

All electrical power for the GAT-O-SORB system was measured with a watt-hour meter. Also a ammeter was used to indicate periods of peak power demand when the water heater was turned on. The ammeter also indicated the proper functioning, based on current output, of electrical components such as the blower and the heater.

B.8 Gas Flow

The amount of air which is blown through the absorbing bed was measured with a Sprague model 1000 gas meter that was placed inside the test chamber. Thus measured flows are at chamber pressure rather than standard conditions.

B.9 Coolant Flow

A Dwyer rotameter and a needle valve were used to read and control water flowing to the heat exchangers in the absorbent canisters. The calibration also was checked during each run with a graduated cylinder and stop-watch.

APPENDIX C

EXPERIMENTAL TEST PLAN

The Box-Wilson central composite design was the test plan specified for the experimental evaluation of the GAT-O-SORB system. The composite design consists of a factorial design which yields only linear relationships plus additional tests for the determination of second order effects.

In a central composite design a point exists at the center of the factorial design and "2K" addition tests for determination of second order effects (called star points) are symmetrically located around the center point where K equals the number of independent variables.

A non-central composite design is used only if the results of the factorial design suggest that a point of maximum is closer to one factor combination than it is to others. In this case K extra points will be tested around the factorial point suspected to be near a maximum point.

The central composite design yields the regression coefficients for a quadratic polynomial expression. Additional tests are run at the center point of the design so that the standard error can be determined and is uniformly distributed between all test points.

C.1 Designs Used

The GAT-O-SORB system was operated under two design test plans. The first was with a fixed CO_2 partial pressure of 7.6 mm Hg. Under these conditions, the composite design was made up of a 16-test full two level factorial for 4 variables, plus 8 star points, and 7 center points for a total of 31 tests.

The second test plan was run with a fixed CO_2 partial pressure of 3.8 mm Hg. The composite design consisted of 8 tests for a 1/2 replicate two level factorial design for 4 variables plus 8 star points, and 7 center points for a total of 23 tests.

C.2 Method of Data Analysis

The relationship between the independent variables and the responses is determined as a polynomial in the form

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_{11}X_1^{\ 2} + B_{22}X_2^{\ 2} + B_{33}X_3^{\ 2} + B_{44}X_4^{\ 2} +$$

$$B_{12}X_1X_2 + B_{13}X_1X_3 + B_{14}X_1X_4 + B_{23}X_2X_3 + B_{24}X_2X_4 + B_{34}X_3X_4$$

The quantity Y is the performance characteristic of the system such as CO_2 removal rate; the "B" s are the coefficients which are to be determined and the X's are the independent variables of cycle time, precool time, flow, or air flow. Only first and second order terms are considered significant. Higher order terms are neglected. The coefficients are determined by fitting the data to a multiple linear regression.

First the independent variables are put in a "coded" form. The advantage of putting the dependent variables in coded form is that the equations are easier to work with because only plus or minus integers and zero are used for independent variables.

The following coding equations were used in this program:

$$X_1 = \frac{A-30}{10}$$

where X_1 is the coded value for cycle time, and A is the measured cycle time in minutes, 30 is the cycle time in minutes at the center of the design, and 10 is the difference between levels of cycle time.

$$X_2 = \frac{B-3.0}{1.5}$$

where X_2 is the coded value for precool time, and B is the measure precool time in minutes 3.0 is the precool time at the center of the design, and 1.5 is the difference between levels of precool time

$$X_3 = \frac{C-3}{1}$$

where X_3 is the coded value for water flow, and C is the measured water flow in gal per hour, 3 is the water flow at the center of the design, and 1 is the difference between levels of water flow,

$$X_4 = \frac{D-10}{2}$$

where X_4 is the coded value for air flow, and D is the measured air flow in cfm, 10 is the air flow at the center of the design and 2 is the difference between levels of air flow. The coded values of the independent variables are summarized in Table 3.

TABLE C-1. CODED VALUES FOR INDEPENDENT VARIABLES

Coded Value	+2	+1	0	-1	-2
Cycle Time, minutes	50	40	30	20	10
Precool Time, minutes	6.0	4.5	3.0	1.5	0
Water Flow, gph	5	4	3	2	1
Air Flow, cfm	14	12	10	8	6

The matrix of coded X values and the corresponding Y vectors which are the measured responses are listed in Tables C-2 and C-3 for the corresponding test plans. Then least squares estimates of the coefficients are chosen so as to minimize the sum of squares of deviations between the data points and the estimated response surface.

These least squares estimates can be derived by (1) solving simultaneous normal equations, (2) by use of matrix algebra in which a matrix for the normal equations, the vectors, and an inverse matrix are calculated or (3) by using a digital computer.

A computer solution was used for this program to minimize the time required to utilize test data. In addition the computer program furnished estimates of standard error, t values of the significance of each coefficient, and a comparison of the estimated and measured responses.

C.3 Test Program at p_{CO_2} = 7.6 mm Hg

The central composite design for tests run at p_{CO_2} equal to 7.6 mm Hg is summarized in the array in Table C-2. This table shows the coded values of the independent variables and the measured responses of the three dependent variables. The X_0 column always has the value (+1) and is used to determine the constant of the regression equation.

C.4 Test Program at p_{CO_2} = 3.8 mm Hg.

The central composite design for tests run at p_{CO_2} equal to 3.8 mm Hg is summarized in the array in Table C-3. This table shows the coded values for the independent variables and the measured response for the dependent variables.

TABLE C-2 CENTRAL COMPOSITE DESIGN

for Tests at p_{CO_2} = 7.6 mm Hg

		X ARRAY CODED SCALE				Y RESPONSES		
Test No	X_0	X_1 Cycle Time Min.	X_2 Precool Time	X_3 Coolant Flow gph	X_4 Air Flow cfm	Y_1 CO_2 Rate lb/hr	Y_2 H_2O Loss $lbH_2O/lbCO_2$	Y_3 Power $kwhr/lbCO_2$
1	+1	-1	-1	-1	-1	0.30	0.32	2.0
2.	+1	+1	-1	-1	-1	0.19	0.61	3.8
3	+1	-1	+1	-1	-1	0.26	0.50	2.5
4	+1	+1	+1	-1	-1	0.21	0.70	3.2
7	+1	-1	-1	+1	-1	0.33	0.48	2.9
9	+1	+1	-1	+1	-1	0.17	0.96	6.1
8	+1	-1	+1	+1	-1	0.20	0.43	3.4
10	+1	+1	+1	+1	-1	0.14	0.26	7.3
5	+1	-1	-1	-1	+1	0.20	0.67	3.6
14	+1	+1	-1	-1	+1	0.16	0.41	4.1
12	+1	-1	+1	-1	+1	0.10	0.40	12.0
15	+1	+1	+1	-1	+1	0.13	0.62	4.4
13	+1	-1	-1	+1	+1	0.23	0.33	2.1
16	+1	+1	-1	+1	+1	0.16	0.48	6.1
17	+1	-1	+1	+1	+1	0.22	0.37	4.7
19	+1	+1	+1	+1	+1	0.17	0.67	6.0
23	+1	-2	0	0	0	0.075	0.38	7.1
22	+1	+2	0	0	0	0.15	0.65	6.1
24	+1	0	-2	0	0	0.13	0.70	6.8
25	+1	0	+2	0	0	0.17	0.66	5.2
26	+1	0	0	-2	0	0.007	0.52	57.1
27	+1	0	0	+2	0	0.15	0.39	7.4
30	+1	0	0	0	-2	0.13	0.70	6.5
32	+1	0	0	0	+2	0.19	0.71	5.0
11	+1	0	0	0	0	0.20	0.24	4.5
20	+1	0	0	0	0	0.17	0.61	3.5
28	+1	0	0	0	0	0.18	0.85	5.0
29	+1	0	0	0	0	0.17	0.65	5.6
36	+1	0	0	0	0	0.13	0.90	6.6
37	+1	0	0	0	0	0.11	0.96	5.1
46	+1	0	0	0	0	0.15	0.64	5.7

TABLE C-3 CENTRAL COMPOSITE DESIGN

for Tests at p_{CO_2} = 3.8 mm Hg

		X ARRAY CODED SCALE				Y RESPONSES		
Test No	X_0	X_1 Cycle Time Min.	X_2 Precool Time Min.	X_3 Coolant Flow gph	X_4 Air Flow cfm	Y_1 CO_2 Rate lb/hr	Y_2 H_2O Loss $lbH_2O/lbCO_2$	Y_3 Power $kwhr/lbCO_2$
62	+1	+1	+1	+1	+1	0.100	0.41	8.3
68	+1	-1	+1	+1	-1	0.095	0.35	12.6
66	+1	+1	-1	+1	-1	0.077	0.89	13.6
64	+1	-1	-1	+1	+1	0.083	0.40	11.0
63	+1	+1	+1	-1	+1	0.116	0.57	7.1
77	+1	-1	+1	-1	-1	0.030	0.60	27.0
67	+1	+1	-1	-1	-1	0.092	1.11	8.1
65	+1	-1	-1	-1	+1	0.038	0.60	11.9
71	+1	0	0	0	+2	0.108	0.63	8.3
72	+1	0	0	0	-2	0.050	1.20	14.0
56	+1	0	0	+2	0	0.078	0.22	14.0
74	+1	0	0	-2	0	0.024	0.50	16.7
54	+1	0	+2	0	0	0.142	0.81	5.3
55	+1	0	-2	0	0	0.091	0.80	8.8
59	+1	+2	0	0	0	0.150	0.84	6.4
75	+1	-2	0	0	0	0.011	1.20	68.5
53	+1	0	0	0	0	0.155	1.00	5.5
57	+1	0	0	0	0	0.108	1.00	8.3
61	+1	0	0	0	0	0.138	1.09	6.5
70	+1	0	0	0	0	0.119	1.00	6.7
73	+1	0	0	0	0	0.092	0.38	8.7
76	+1	0	0	0	0	0.097	1.13	9.3
78	+1	0	0	0	0	0.116	0.65	8.6

C.5 Polynomial Expressions

The computation of the coefficients for polynomial expression was done by the least squares method. The coefficients are used in the equations shown in Table C-4 and C-5. These equations are in the coded form and must be used in conjunction with the coding equations shown in section C.2, Also the equations in Tables C-6 and C-7 should be considered applicable only within the coded range of +2 to -2. No estimate of accuracy is established for values outside of this range. The coefficients shown in Tables C-6 and C-7 are shown to 3 significant figures because the measured values were reported to two or three significant figures. The extra figures shown in the computer printout in Appendix A are of no significance.

4.3.6 Reduction of Equations to Simpler Form

The polynomial equations in Tables C-4 and C-5 include all first and second order terms whether or not they are significant. All terms of order three or more are assumed to be insignificant. In order to further reduce the number of terms in the equation, a "t" test was applied to each coefficient. From the "t" test terms can be eliminated if their effect is not greater than the effect of random errors at a specified confidence level. Normally a 95 percent confidence level is chosen.

The central composite design which contained a 1/2 replicate factorial design, i.e., the tests run at a 3.8 mm Hg CO_2 level has 8 degrees of freedom, 23 tests were run and 14 regression coefficients plus 1 constant were determined.

At the 95% confidence level and with 8 degrees of freedom, the "t" value must exceed 2.306 in order to be significant. This critical value of "t" can

Table C-4

Polynomial Equation for Responses

at p_{CO_2} equal to 7.6 mm Hg

$$Y_1 \quad \frac{\text{lb } CO_2}{\text{hr}} = 0.1657 - 0.0158\, X_1 - 0.00874\, X_2 + 0.0157\, X_3 - 0.0137\, X_4 -$$
$$0.00094\, X_1^2 + 0.00842\, X_2^2 - 0.00944\, X_3^2 + 0.01091\, X_4^2 + 0.01441\, X_1X_2 -$$
$$0.0120\, X_1X_3 + 0.0169\, X_1X_4 - 0.00062\, X_2X_3 + 0.00187\, X_2X_4 + 0.0181\, X_3X_4$$

$$Y_2 \quad \frac{\text{lb } H_2O}{\text{lb } CO_2} = 0.693 + 0.07291\, X_1 - 0.0162\, X_2 - 0.212\, X_3 - 0.0121\, X_4 -$$
$$0.0571\, X_1^2 - 0.0158\, X_2^2 - 0.0721\, X_3^2 - 0.00956\, X_4^2 - 0.00687\, X_1X_2 +$$
$$0.0194\, X_1X_3 - 0.0244\, X_1X_4 - 0.0456\, X_2X_3 + 0.0406\, X_2X_4 - 0.0156\, X_3X_4$$

$$Y_3 \quad \frac{\text{kwhr}}{\text{lb } CO_2} = 5.14 + 0.242\, X_1 + 0.400\, X_2 - 4.01\, X_3 + 0.367\, X_4 -$$
$$0.971\, X_1^2 - 1.12\, X_2^2 + 5.44\, X_3^2 - 1.18\, X_4^2 - 0.700\, X_1X_2 +$$
$$1.06\, X_1X_3 - 0.713\, X_1X_4 - 0.275\, X_2X_3 + 0.600\, X_2X_4 - 0.838\, X_3X_4$$

TABLE C-5

Polynomial Equations for Responses at

p_{CO_2} equal 3.8 mm Hg

$$
\begin{aligned}
Y_1 = {} & 0.118 + 0.0347\ X_1 + 0.0127\ X_2 + 0.0117\ X_3 + 0.0145\ X_4 - \\
& 0.00969\ X_1^2 - 0.00068\ X_2^2 - 0.0171\ X_3^2 - 0.0101\ X_4^2 - 0.00912\ X_1X_2 - \\
& 0.0176\ X_1X_3 - 0.00637\ X_1X_4 + 0.00237\ X_2X_3 - 0.0174\ X_2X_4 - 0.02262\ X_3X_4
\end{aligned}
$$

$$
\begin{aligned}
Y_2 = {} & 0.893 - 0.0900\ X_1 + 0.00249\ X_2 - 0.0869\ X_3 - 0.142\ X_4 + \\
& 0.0119\ X_1^2 - 0.0418\ X_2^2 - 0.153\ X_3^2 - 0.0143\ X_4^2 + 0.0212\ X_1X_2 + \\
& 0.00874\ X_1X_3 - 0.136\ X_1X_4 + 0.00124\ X_2X_3 + 0.219\ X_2X_4 + 0.0137\ X_3X_4
\end{aligned}
$$

$$
\begin{aligned}
Y_3 = {} & 7.66 - 15.5\ X_1 - 0.875\ X_2 - 0.875\ X_3 - 1.42\ X_4 + \\
& 6.79\ X_1^2 - 0.814\ X_2^2 + 1.26\ X_3^2 + 0.211\ X_4^2 - 1.45\ X_1X_2 + \\
& 2.75\ X_1X_3 + 2.17\ X_1X_4 - 2.22\ X_2X_3 + 12.3\ X_2X_4 + 1.15\ X_3X_4
\end{aligned}
$$

TABLE C-6

Simplified Equations at 95% confidence level

$$p_{CO_2} = 3.8 \text{ mm Hg}$$

$$Y_1 \quad \left(\frac{\text{lb } CO_2}{\text{hr}}\right) = 0.117 + 0.0261\, X_1 + 0.0117\, X_3 - 0.00960\, X_1^2 - 0.0170\, X_3^2 - 0.0100\, X_4^2$$

$$Y_2 \quad \left(\frac{\text{lb } H_2O}{\text{lb } CO_2}\right) = 0.859 - 0.132\, X_4 - 0.148\, X_3^2$$

$$Y_3 \quad \left(\frac{\text{kwhr}}{\text{lb } CO_2}\right) = 8.16 - 15.5\, X_1 + 6.71\, X_1^2 + 12.3\, X_2\, X_4$$

TABLE C-7

Simplified Equations Removed from Coded Form

$p_{CO_2} = 3.8$ mm Hg

95% confidence level

$$Y_1\left(\frac{\text{lb } CO_2}{\text{hr}}\right) = -0.644\text{[illegible]} + 0.0139\text{[illegible]}\,A + 0.165\,C + 0.050\,D - 0.000096\,A^2 - 0.0025\,D^2 - 0.00176\,AC$$

$$Y_2\left(\frac{\text{lb } H_2O}{\text{lb } CO_2}\right) = +0.187 + 0.888\,C - 0.066\,D - 0.148\,C^2$$

$$Y_3\left(\frac{\text{kwhr}}{\text{lb } CO_2}\right) = 238. - 5.576\,A - 41.0\,B - 12.3\,D + 0.0671\,A^2 + 4.1\,BD$$

where	A	=	Cycle Time, minutes
	B	=	Air Valve Delay, minutes
	C	=	Water Flow, gal/hr
	D	=	Air Flow, cfm

be found in most statistics books. The values of "t" for the individual regression coefficients are shown in the computer printout in Appendix A.

Simplified equations can be obtained by dropping the insignificant terms from the equations; however a better method is to select the terms whose "t" values approach or exceed the critical "t" value of 2.306 and to refit the data to these points by the sum of leasts squares methods. New regression coefficients and new "t" values are obtained. The new coefficients give the best fit for the terms used and the new "t" value reconfirm that the appropriate term was chosen. The simplified equations for tests run at a 3.8 mm Hg CO_2 partial pressure are listed in Table C-6.

The simplified equations shown in Table C-6 are in the coded form for the independent variables. These equations can be combined with coding equations given in section C.2 to yield the simplified equations in terms of the measured independent variables. These are shown in Table C-7.

The results from the composite design that was run at a CO_2 partial pressure equal to 3.8 mm Hg showed a high degree of correlation. This is verified by the multiple correlation coefficient which ranged from 0.849 to 0.983 for the overall test design as shown in Appendix A. A multiple correlation coefficient of 1.0 would signify perfect correlation. The multiple correlation coefficients range from 0.676 to 0.942 for the reduced equations. Again the F values verified the high degree of correlation.

The composite design run at a CO_2 partial pressure of 7.6 mm Hg showed poor correlation. This is determined by the multiple correlation coefficient which ranged from 0.614 to 0.741 and the low F values and low "t" values. The terms for Y_1 did not show significance until the confidence level was reduced to 70 percent. The terms for Y_2 showed only one significant term at the 90% confidence level and the terms for Y_3 showed only one significant term at the 95% confidence level. Therefore simplified equations were not determined for the responses for the composite design at 7.6 mm pCO_2.