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EVALUATION OF A LIQUID AMINE SYSTEM FOR SPACECRAFT CARBON DIOXIDE CONTROL

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Prepared Under Contract NAS1-11895

for

Ames Research Center
National Aeronautics and Space Administration

GARRETT

AIRESEARCH MANUFACTURING COMPANY
OF CALIFORNIA

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Final Report

by

D.K. Breaux, P. Friedel, K.C. Hwang,
G. Probert, J.M. Ruder, L. Sawamura

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FOREWORD

The analytical and test activities described in this report were conducted to determine the feasibility of utilizing a liquid amine sorbent process for removing and concentrating the carbon dioxide generated during manned spacecraft missions. The work was performed under NASA contract NAS1-11895 at the Torrance facility of the AiResearch Manufacturing Company, a division of The Garrett Corporation. Shortly after the program started in October 1972, the contract was transferred from the NASA Langley Research Center to the NASA Ames Research Center.

The contract Technical Monitor was Dr. Charles Malick, of the Life Support - Protective System Branch, NASA Ames Research Center, Moffett Field, California. At AiResearch, the program was directed by Mr. D. K. Breaux. Major contributors to the program were P. Friedel, K. C. Hwang, G. Probert, J. Ruder and L. Sawamura.

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SUMMARY

This report describes the results of analytical and experimental studies which were directed toward the acquisition of basic information on utilizing a liquid amine sorbent for in use in a CO_2 removal system for manned spacecraft. Although liquid amine systems have been successfully used on submarines for control of CO_2 generated by the crew, liquid amines could not be considered for spacecraft applications due to lack of development of satisfactory rotary phase separators. Recent developments in this area now make consideration of liquid amines practical for spacecraft system CO_2 removal. Also, the Naval Research Laboratory has identified a new type of amine solution which offers potential important advantages over standard monoethanolamine-water solutions.

During the program, the following major tasks were performed to evaluate liquid amine systems for spacecraft:

(1) Characterization, through testing, of the basic physical and thermodynamic properties of the new solution identified by the Naval Research Laboratory.

(2) Determination of the dynamic characteristics of a cocurrent flow absorber.

(3) Evaluation, synthesis and selection of a liquid amine system concept oriented toward low power requirements.

A low weight, low power system concept was developed. Numerical and graphical data presented in this report are accompanied by pertinent observations. Suggestions for further research and development activity are given.

SECTION 1

INTRODUCTION

There is a trend toward lower allowable levels of carbon dioxide in the atmospheric system of manned spacecraft. One method that shows promise in attaining lower carbon dioxide levels uses liquid amines in a sorbent solution. Liquid amine systems have been successfully used in submarines for control of carbon dioxide levels generated by the crew. Developments in rotary phase separators now allow evaluation of this continuous process system for use aboard spacecraft in zero-g environments.

The liquid amine system recirculates a basic sorbent solution between an absorber, operating at ambient temperature, and a desorber, operating at elevated temperatures. Cabin air comes in contact with the recirculating solution in the absorber, where the carbon dioxide is removed from the air and forms a weak salt with the solution. After being heated in the desorber, the carbon dioxide evolves from the solution and leaves the system. The carbon dioxide-free solution is then directed back to the absorber. The system provides a low power, continuous means of removing and concentrating the carbon dioxide in the cabin air. By further processing the concentrated carbon dioxide in a separate system, oxygen can be recovered and recycled back to the cabin atmosphere.

A new type of amine solution has been identified by the Naval Research Laboratory (References 1, and 2) which offers important advantages over the standard monoethanolamine (MEA) - water solution. This new three-component solution contains sulfolane, which results in a lower vapor pressure solution. Not only does this additive tend to improve desorption characteristics but the post-treatment requirements are also reduced.

Evaluation of the liquid amine system for spacecraft consisted of the following tasks:

(1) Characterization through testing of the basic physical and thermodynamic properties of the new solution.

(2) Determination of the dynamic characteristics of a cocurrent flow absorber.

(3) Evaluation, synthesis and selection of a system concept oriented toward low power requirements.

One of the more important sorbent tests in this program was to determine the carbon dioxide absorption capacity of the three component solution as a function of carbon dioxide partial pressure. It was found, that unlike other types of sorbents, there was no appreciable change in absorption capacity down to the lower limit of carbon dioxide tested, 133 N/m^2 (1 mm Hg).

Submarine liquid amine carbon dioxide removal systems use counter current liquid-to-gas absorption columns. For spacecraft zero-g usage, a cocurrent absorber is required. Here, the liquid and gas stream flow in the same direction and the pressure difference across the unit is the driving force. A cocurrent unit was tested to determine the absorption mass transfer rate between the carbon dioxide in the air stream and the three component solution. High mass transfer rates, with low pressure drop, were achieved using McMahon saddles for the column packing.

Data were obtained on the desorption characteristics of the solution with respect to composition of the various constituents in the liquid and gas phase. As expected, the three component solution had a very low vapor pressure resulting in a very small quantity of amine in the vapor phase, and thus low system losses.

A simplified schematic of the system, that meets the design requirements given in Table 1-1, is shown in Figure 1-1. The system features a cocurrent absorber where the carbon dioxide is absorbed in the amine solution. The two-phase fluid flows into a cabin air separator/pump; where the liquid phase is separated and pumped to a higher pressure. A major portion of this liquid is recirculated and the remainder is directed to the desorption circuit. Air is returned to the cabin by the separator unit which contains an integral fan to overcome the pressure loss of the absorption section.

TABLE 1-1

CARBON DIOXIDE REMOVAL SYSTEM REQUIREMENTS

No. of Men	9	
CO_2 rate, kg/s (lb/hr)	1.04×10^{-4}	(0.825)
Cabin Environment:		
Pressure, $N/m^2 \times 10^{-3}$	101	(14.7)
Temperature, ^oK (^oF)	298	(75)
Dew Point ^oK (^oF)	284	(50)
CO_2 Partial Pressure, N/m^2 (mm Hg)	400	(3)

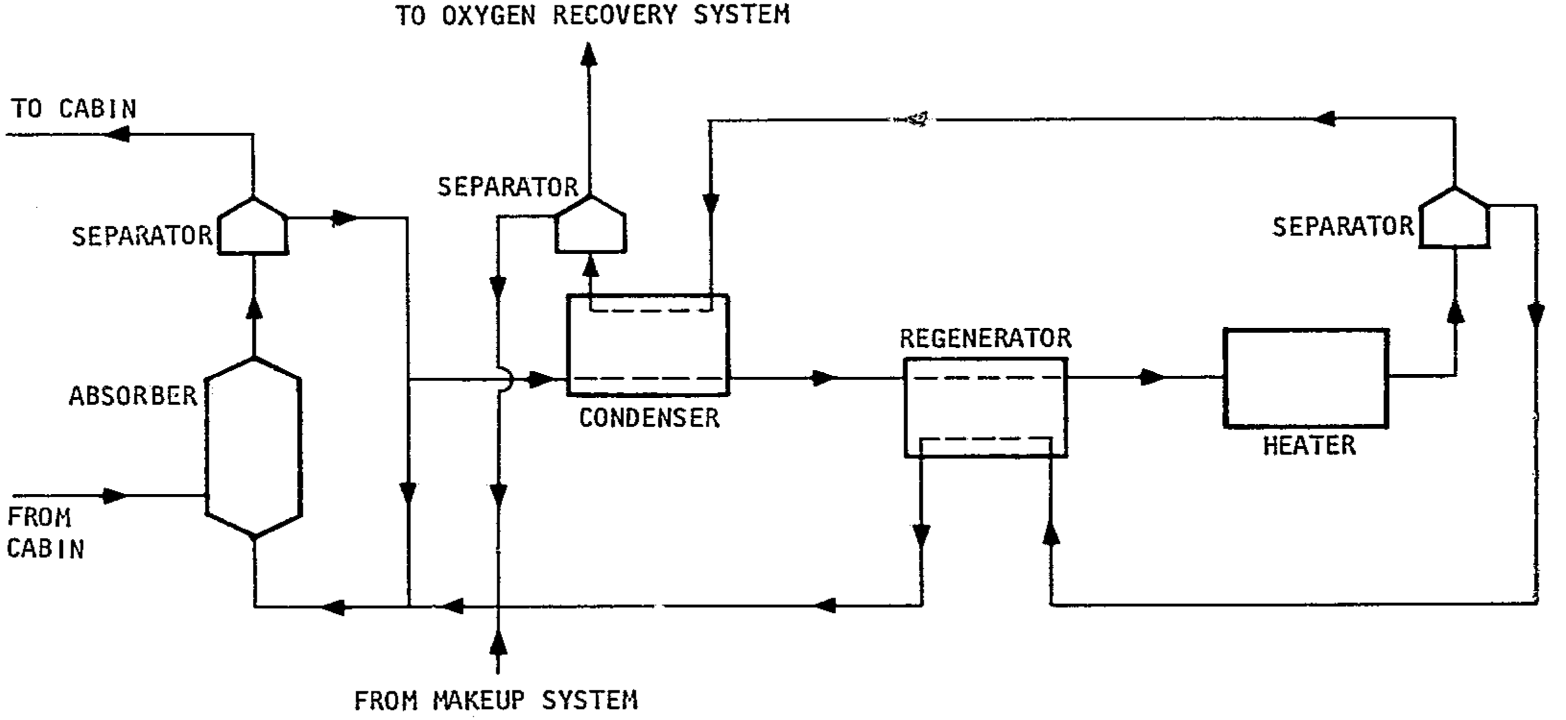

Figure 1-1 Liquid Amine System Simplified Schematic.

By heat exchange in a vapor condenser, the solution containing carbon dioxide is initially heated with further heating being provided in the regenerator. Here, heat exchange occurs between the returning liquid stream and the liquid stream to be desorbed. Final heating to the desired desorption temperature, 422°K (300°F), occurs in an electrical heater. The liquid/vapor mixture is then separated; the liquid is cooled in the regenerator and returns to the absorber circuit. Composition of the vapor is primarily carbon dioxide and water; the vapor is cooled and partially condensed in the condenser and again the two phases are separated. The liquid stream is directed to the absorption circuit while the vapor, containing 99.2 percent carbon dioxide, is directed to an oxygen recovery system.

Overall characteristics of the system are a weight of 55.2 kg (121.6 pounds) with a continuous power requirement of 710 watts. The weight includes individual components, system ducting, wire harnesses, and brackets. The power requirement of 79 watts/man is lower than other carbon dioxide removal/concentration systems because the system is a continuous process and the desorbed carbon dioxide does not require compression.

The remaining sections of the report are organized as follows. Section 2 describes the test program used to obtain basic properties and dynamic data. A system concept is described in Section 3. Characteristics of the various components of the conceptual system are given in Appendix A.

SECTION 2

TEST PROGRAM

INTRODUCTION

The test program was conducted to determine the basic properties as well as the dynamic absorption characteristics of a three-component liquid amine solution. The composition of the solution tested is given in Table 2-1; the liquid amine solution was 4.5 N in both 2-aminoethanol and tetrahydrothiophene 1, 1-dioxide. The Naval Research Laboratory originally investigated this solution (References 1 and 2) as a possible improvement over two-component liquid amine solutions currently in use. The addition of the third component, tetrahydrothiophene 1, 1-dioxide, offers three improvements: the sorbent mixture has a lower volatility than a 2-aminoethanol (MEA) solution; oxidation of MEA is inhibited; and foaming tendency is reduced.

PROPERTY DATA

Introduction

Absorption of carbon dioxide by the solution causes a second heavier phase to form which increases as the dissolved carbon dioxide concentration increases and decreases with increasing temperature. At room temperature and complete saturation with carbon dioxide, the ratio of the volume of the upper phase to the lower phase is 1.5 to 1. As 367°K (200°F) is approached, phase differentiation disappears. It was found that there is no path-dependency in the final CO_2 equilibrium concentration, i.e., absorption and desorption lead to the same solution concentration.

Test Results

Specific Gravity Measurements.-Specific gravity at various temperatures was determined by heating the fluid in a standard volume-calibrated cup inside an oven set at the desired temperature. After heating, the cup plus fluid were weighed. Specific gravity measurement results are given in Table 2-2.

Fluid Viscosity Measurements.-Fluid viscosity was measured with an Ostwald kinematic viscometer utilizing standardized kinematic viscosity flow tubes per ASTM D2515. Fluid viscosity measurement results are given in Table 2-3.

Specific Heat Measurements.-The specific heat measurements utilized a gradient layer calorimeter into which the test samples were placed. The gradient layer calorimeter, which is six sided, contains thermo-electric gradient layer thermopiles connected in series so that all heat flow into or out of the enclosure is monitored by the calorimeter sensor. The calorimeter constant is

TABLE 2-1

COMPOSITION OF THREE-COMPONENT LIQUID AMINE SOLUTION

Component		Wt Percent*	Manufacturer
Name	Synonym		
2-Aminoethanol	Monoethanolamine	24.7	Matheson Coleman Bell, Catalog No. TX-345
Tetrahydrothiophene 1, 1-dioxide	Sulfolane	48.4	Matheson Coleman Bell, Catalog No. AX-905
Deionized water	-	26.9	-

*On a CO_2-free basis

determined by calibration utilizing an electrical heater inside the calorimeter. During measurements the calorimeter and enclosed sample were allowed to attain equilibrium at some initial temperature level (determined by the zero reading of the calorimeter sensor). Then, the environmental temperature of the calorimeter system was changed to a new value. During the transient process, heat flowed into or out of the calorimeter until a new equilibrium temperature was attained. A second experiment was performed with an empty calorimeter. From the data obtained in the two experiments, the desired specific heat was determined from the corresponding heat balance equations involving integrated heat flow, temperature level changes, and sample mass. During the course of these measurements, the specific heat of water was determined to verify the apparatus. Measured values agreed within a few percent of the literature values. Specific heat measurement results are given in Table 2-4.

Thermal Conductivity Measurements.-The thermal conductivity measurements were made in a flat plate cell system into which the liquids were carefully added, so that no gas bubbles or air spaces existed in the liquid layer. An electrical heater provided the heat that was circulated through the test cell containing a sample. The test cell was instrumented with a differential temperature sensor to obtain the temperature drop across the specimen. Electrical power was monitored with precision ammeters and voltmeters. Thermal conductivity measurement results are given in Table 2-5.

Absorption Capacity Measurements.-Absorption capacity was measured by bubbling a known concentration of CO_2-in-nitrogen mixture through a known quantity of liquid solution, until the concentration of the effluent gas approached that of the incoming gas. Such concentrations were analyzed by infrared spectroscopy. Vapors lost from the reaction vessel during absorption were condensed in a solid-CO_2-cooled trap. The condensate weight was added to the final weight of the reaction mixture to determine the weight of CO_2 absorbed. Absorption capacity measurements results are given in Table 2-6.

TABLE 2-2

SPECIFIC GRAVITY

Temperature °K	(°F)	Solution (kg/m^3)		
			CO_2-Saturated	
		CO_2-Free	Light Phase	Heavy Phase
294	(70)	1130	1210	1230
311	(100)	1120	1140	1200
339	(150)	1110	1120	
367	(200)	1080	1110	
394	(250)	1060	1090	

TABLE 2-3

VISCOSITY

Temperature °K	(°F)	Solution (m^2/s)		
			CO_2-Saturated	
		CO_2-Free	Light Phase	Heavy Phase
311	(100)	3.3×10^{-6}	3.5×10^{-6}	2.85×10^{-6}
339	(150)	1.7×10^{-6}	-	-
367	(200)	1.0×10^{-6}	-	-

TABLE 2-4

SPECIFIC HEAT

Temperature °K	(°F)	Solution ($Jkg^{-1}K^{-1}$ (Btu/lb-°F))		
			CO_2-Saturated	
		CO_2-Free	Light Phase	Heavy Phase
311	(100)	2530 (0.603)	3290 (0.784)	1950 (0.465)
339	(150)	2960 (0.706)	-	-
367	(200)	3360 (0.802)	-	-

TABLE 2-5

THERMAL CONDUCTIVITY

Temperature °K	(°F)	Solution (Wm^{-1} K^{-1} (Btu/hr-ft-°F))		
			CO_2-Saturated	
		CO_2-Free	Light Phase	Heavy Phase
300	(80)	-	0.355 (0.205)	0.120 (0.069)
311	(100)	0.139 (0.080)	-	-
339	(150)	0.121 (0.070)	-	-
367	(200)	0.116 (0.067)	-	-

TABLE 2-6

CO_2 ABSORPTION CAPACITY

CO_2 Partial Pressure, N/m^2 (mm Hg)		Weight-Percent Absorbed and (^oK)			
		1	2	3	4
133	(1.0)	7.99 (301.1)	7.98 (313.2)	-	-
507	(3.8)	8.05 (300.2)	7.90 (311.5)	4.19 (339.4)	1.62 (365.8)
1013	(7.6)	8.09 (302.2)	7.12 (315.2)	4.81 (339.2)	1.88 (366.4)
3013	(22.6)	9.26 (300.9)	7.87 (312.15)	6.89 (338.7) 6.44 (337.4)	2.19 (366.4)
5066	(38.0)	9.38 (300.7) 9.23 (300.2)	8.63 (316.2) 8.73 (308.2)	6.60 (344.2)	3.07 (366.2)

Vapor Pressure Measurements.-Vapor pressure measurements were made using a pressure transducer connected to a previously evacuated stainless steel chamber which contained the liquid absorbent. The vapor line to the transducer was heated to prevent condensation in the line while the rest of the system was contained in an oven. Vapor pressure measurement results are given in Table 2-7.

Vapor-Liquid Equilibrium Composition Measurements.-Vapor-liquid equilibrium composition measurements at possible system desorption conditions were accomplished by using a stainless steel spherical chamber. A thermocouple, pressure transducer and needle valve were attached to the chamber. Downstream of the needle valve, a solid-CO_2-cooled (dry ice) trap collected the condensable vapors. Further downstream, a solid absorbent trap was used to collect the carbon dioxide. The chamber was filled with a CO_2 saturated liquid amine solution, and then placed in a circulating air oven and evaculated. Thermocouple and pressure transducers were located in the oven. The needle valve was adjustable from outside the oven and the exit port was also outside of the oven. The valve body was heated to 433°K (310°F) to prevent condensation of vapors upstream of the needle valve in the oven. Condensate formed downstream of the needle valve was swept into the traps after each run by purging with dry nitrogen. The procedure used to determine the equilibrium composition in each phase is described below.

After the CO_2 saturated amine solution was placed in the spherical chamber the pressure was rapidly reduced below 3320 N/m^2 (25 mm HgA). The needle valve was closed and the oven was turned on. When the required pressure was reached, the needle valve was opened and modulated to maintain a constant pressure. Escaping vapor passed through the cold and sorbent traps. Constant pressure was maintained in the chamber while the solution temperature increased to the equilibrium temperature. After evaporation stopped and equilibrium was attained, the needle valve was closed and the lines to the traps purged with dry nitrogen.

TABLE 2-7

VAPOR PRESSURE

Temperature		Pressure	
°K	(°F)	N/m^2	(mm HgA)
295	(72)	1970	14.8
311	(100)	5080	38.1
339	(150)	1730	130
367	(200)	5200	390

Equilibrium composition of the vapor and liquid phases were then determined. For the vapor phase, the quantity of evolved CO_2 was determined from the weight gain of the sorbent trap. The cold trap contained 2-aminoethanol (MEA) and water; tetrahydrothiophene 1, 1-dioxide was assumed to remain in the liquid phase because of its very low vapor pressure. MEA was determined by titration, with the remainder of the weight gain in the cold trap due to water. The constituents remaining in the liquid phase in the chamber were determined by subtracting the individual quantities of each constituent found in the vapor from that in the original CO_2-saturated amine solution. A verification check was obtained by acidifying a sample and trapping the evolved CO_2 and by titrating another sample to determine the MEA content. Vapor-liquid equilibrium composition measurement results are given in Table 2-8.

DYNAMIC DATA

Test Description

The dynamic test program was conducted to obtain data on the mass transfer rate of carbon dioxide to the amine solution under cocurrent flow conditions. This was done by spraying an amine solution over a packed column while simultaneously flowing air containing carbon dioxide in the same direction through the column.

Air and CO_2 was mixed with a resultant partial pressure of 373 N/m^2 (2.8 mm Hg) of CO_2 and allowed to flow through the absorber. Liquid amine sprayed into the column absorbed the CO_2. Composition of the liquid amine solution was previously given in Table 2-1. The outlet air was examined using the CO_2 analyzer.

The ranges of the important test parameters are given in Table 2-9.

TABLE 2-9

TEST PARAMETER RANGES

Parameter	Value Range
Liquid amine flow rate	0.00252 to 0.00756 kg/s (20 to 60 lb/hr)
Air flow rate	0.00189 to 0.00566 m^3/s (4 to 12 scfm)
Liquid amine temperature	295°K (71°F)
Inlet CO_2 concentration	373 N/m^2 (2.8 mm Hg) partial pressure
Outlet CO_2 concentration	$<$ 373 N/m^2 ($<$2.8 mm Hg) partial pressure

TABLE 2-8

VAPOR LIQUID EQUILIBRIUM CHARACTERISTICS

Characteristic	Run Number				
	1	2	3	4	5
Temperature, ^oK (^oF)	422 (300)	411 (280)	411 (280)	422 (300)	411 (280)
Pressure, $N/m^2 \times 10^{-5}$ (psia)	2.76 (40)	2.76 (40)	1.72 (25)	1.72 (25)	2.76 (40)
Liquid, percent	85.0	92.3	73.4	70.3	91.9
Vapor, percent	15.0	7.7	26.6	29.7	8.1
Liquid composition, percent					
Tetrahydrothiophene 1, 1-dioxide	52.8	48.8	61.3	64.0	49.0
Carbon dioxide	1.7	2.4	1.7	0.7	2.6
2-Aminoethanol	26.6	24.8	29.2	27.9	24.7
Water	18.9	24.0	7.8	7.3	23.7
Vapor composition, percent					
Carbon dioxide	39.3	63.0	21.8	22.1	57.9
2-Aminoethanol	1.7	0.5	5.7	11.0	2.2
Water	59.0	36.5	72.5	66.9	39.9

NOTES

1. Run No. 1 was a checkout run
2. For Runs No. 3, 4 and 5, the needle valve was heated to prevent reflux
3. Initial CO_2-saturated solution contained approximately 7 percent CO_2

Test Setup Description

A schematic of the test setup is shown in Figure 2-1. Figure 2-2 shows a photograph of the setup, and Figure 2-3 presents a photograph of the cocurrent absorber. The cocurrent absorber column was 0.0508 m (2 in.) in diameter, loaded with a saddle type packing to a depth of 0.305 m (12 in.). Test setup components and functional descriptions are given in Table 2-10.

Test Results

Results of the dynamic cocurrent absorber test measurements are given in Table 2-11.

All absorption tests, except for the last three tests given in Table 2-11, were conducted using 0.0095 m (3/8 in.) stainless steel (100 mesh, 1.1 x 10^{-4} m (0.0045 in.) wire diatemer) McMahon saddles for the column packing. The prime series of tests were run at air rates of 1.9, 3.8 and 5.7 x 10^{-3} m^3/s (4, 8 and 12 scfm) with 0.0025, 0.005 and 0.0075 kg/s (20, 40 and 60 lb/hr of liquid and at four different CO_2 loadings in the liquid. These yielded 36 operating data points. During system checkout before these data points were obtained, the effect of varying inlet CO_2 partial pressure and temperature were qualitatively evaluated as given in Table 2-11. Finally, after the prime series of testswere completed, the column packing was changed to 0.0064 m (1/4 in.) ceramic Berl saddles and a test was conducted at three different air flow rates.

The prime data given in Table 2-11 is shown in Figure 2-4. (Prime data refers to data obtained with McMahon saddles at 295°K (71°F) and an inlet CO_2 partial pressure of approximately 373 N/m^2 (2.8 mm Hg). A check of all data points indicates that two data points may be in error. These two points are 3 weight percent of CO_2 in the liquid at an air flow of 5.7 x 10^3 m^3/s (12 cfm) with a liquid flow of 0.0047 kg/s (37.5 lb/hr; and 6.6 weight percent of CO_2 in the liquid at an air flow of 1.9 x 10^{-3} m^3/s (4 cfm) with a liquid flow of 0.0078 kg/s (62 lb/hr).

Removal efficiency is nearly constant (Figure 2-4) above liquid rates of 0.005 kg/s (40 lb/hr), equal to a nominal liquid flux of 2.51 $kgs^{-1}m^{-2}$ (1850 $lb/hr\text{-}ft^2$). This represents the upper limit that should be used in column design.

The major parameter that effects CO_2 removal efficiency is the weight percent of CO_2 in the liquid, as shown in Figure 2-5. Removal efficiency drops rapidly with increased CO_2 loading and indicates that loadings above 5 percent are probably excessive except at low air rates (1.9 x 10^{-3} m^3/s = 0.94 m/s) (4 scfm = 3.08 ft/sec, nominal)).

Actual quantity of CO_2 removed is shown in Figure 2-6. At high CO_2 levels in the liquid, the removal rate is quite low and is not strongly influenced by the air rate.

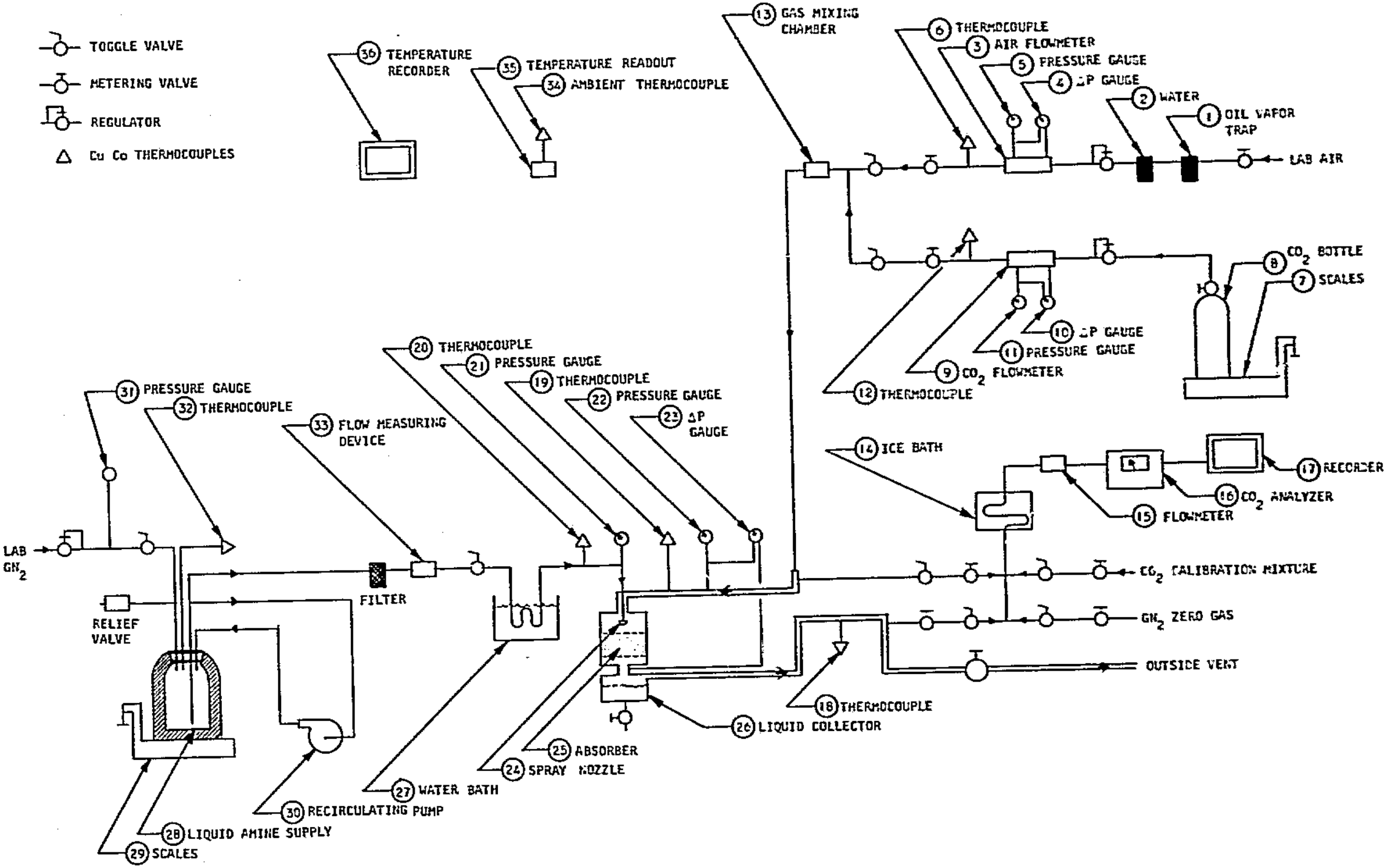

Figure 2-1. Cocurrent Absorber Test Setup Schematic

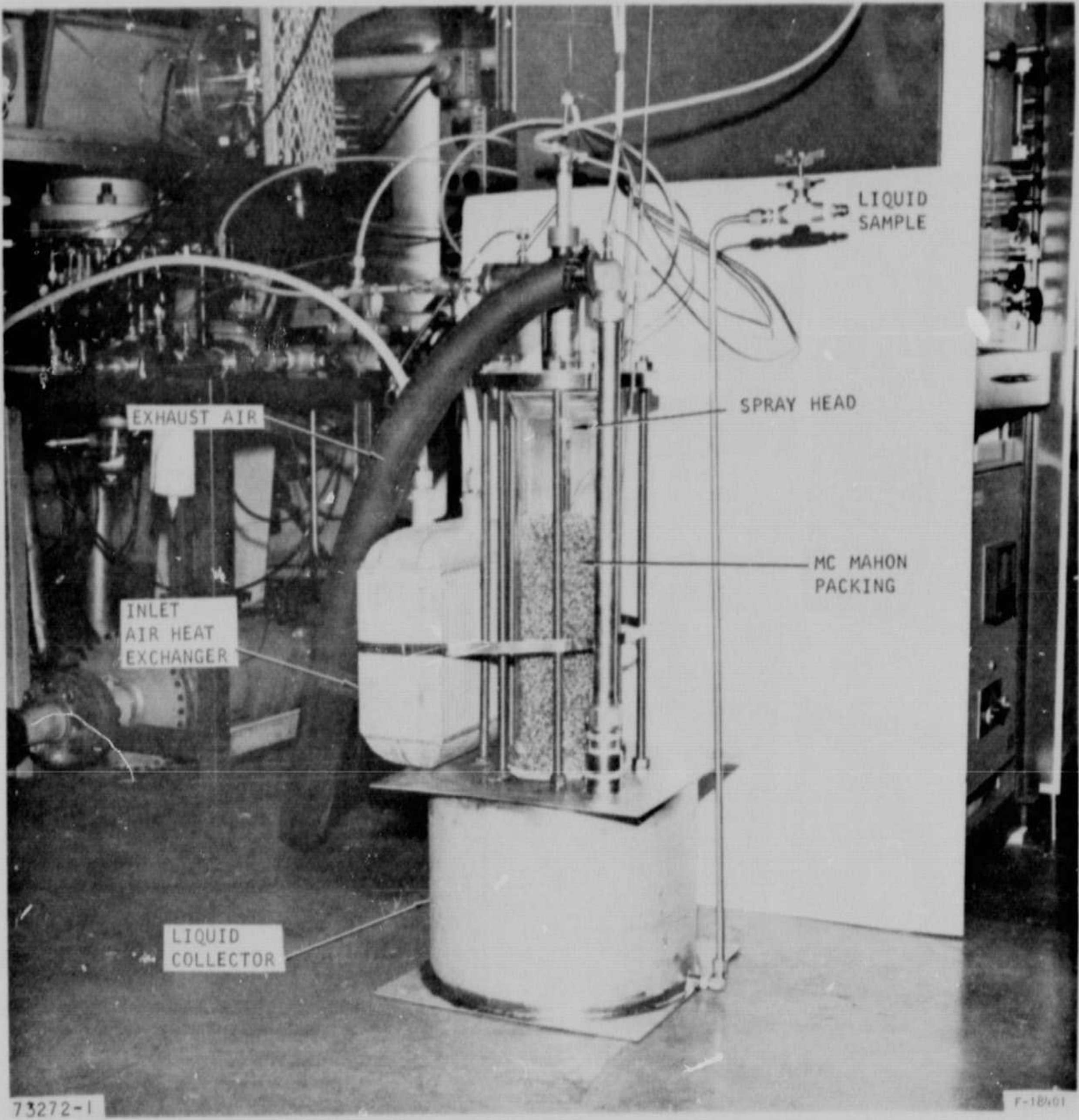

Figure 2-2. Test Setup

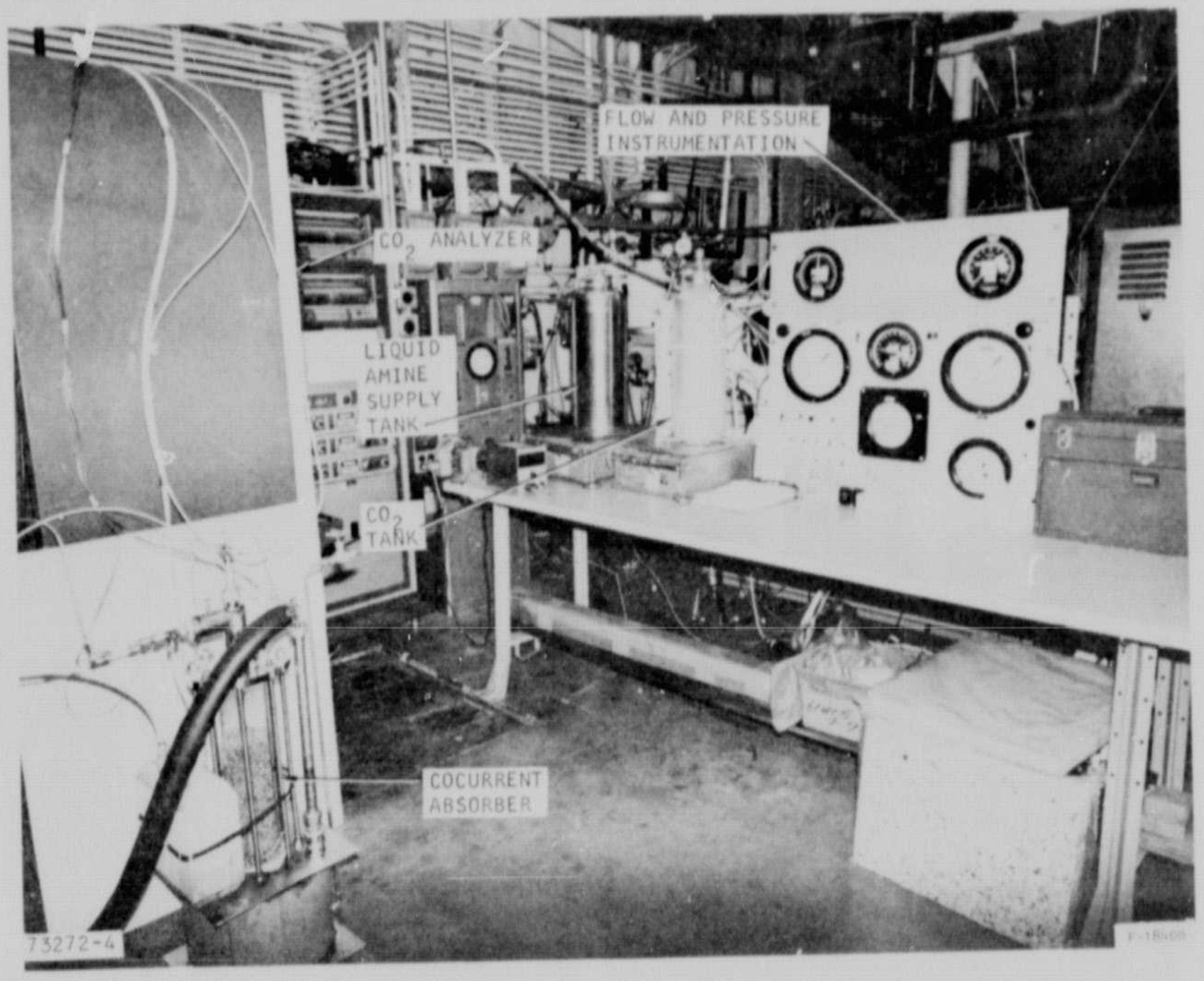

Figure 2-3. Cocurrent Absorber

TABLE 2-10

TEST SETUP COMPONENTS AND FUNCTIONAL DESCRIPTIONS

Item No.	Component	Description
1	Oil Vapor Trap	Removes oil vapors from inlet air flow to prevent contamination.
2	Water Trap	Removes water droplets from inlet air flow.
3	VOL-O-FLO Air Flowmeter	Measures air flow into the test setup. Range 0 to 0.45 kg/s (1.0 lb/min) total accuracy ±1 percent FS (Full Scale).
4	ΔP Gauge	Measures pressure drop across flowmeter-used with flow curve. Range, 0 to 2500 N/m^2 (10 in. H_2O), total accuracy ±0.5 percent FS.
5	Pressure Gauge	Measures outlet pressure of flowmeter-used with flow curve. Range, 0 to 1.14×10^6 N/m^2 (150 psig), total accuracy ±0.5 percent FS.
6	Thermocouple	Connected to 24 channel recorder, measures outlet temperature of flowmeter-used with flow curve. Accuracy ±0.56°K (1°F) on readout.
7	Scales	Used to measure net quantity of CO_2 removed from CO_2 bottle. Range, 0 to 45 kg (100 lbs), smallest increment of measurement 0.0045 kg (0.0116) accuracy ±0.0045 kg (0.116).
8	CO_2 Bottle	Contains 0 to 9 kg (20 lbs) liquid CO_2.
9	VOL-O-FLO CO_2 Flowmeter	Measures gaseous CO_2 into the test setup. Range, 0 to 2.4×10^5 m^3/s (0.05 scfm) at 1×10^5 N/m^2 (14.7 psia), total accuracy ±1 percent FS.
10	ΔP Gauge	Measures pressure drop across flowmeter-used with flow curve. Range, 0 to 2500 N/m^2 (10 in. H_2O), total accuracy ±0.5 percent FS.
11	Pressure Gauge	Measures outlet pressure of flowmeter-used with flow curve. Range, 0 to 6.5×10^5 N/m^2 (80 psig), total accuracy ±0.5 percent FS.

TABLE 2-10 (Continued)

Item No.	Component	Description
12	Thermocouple	Connected to 24 channel recorder, measures outlet temperature of flowmeter-used with flow curve. Accuracy 0.56°K (1°F) on readout.
13	Gas Mixing Chamber	Mixes the air and CO_2 gases.
14	Ice Bath	Removes moixture from sample gas entering CO_2 analyzer.
15	Flowmeter	Measures quantity of sample gas entering CO_2 analyzer. Range, 0 to 6.7 X 10^{-6} m^3/s (400 sccm), total accuracy ±2 percent FS.
16	CO_2 Analyzer	Analyzes gas for partial pressure of CO_2. Beckman Model 315B. Range 0 to 1010 N/m^3 (7.6 mm Hg), total accuracy ±3 percent FS.
17	Recorder	Records output of CO_2 analyzer. L and N Speedomax recorder. Range, 0 to 1300 N/m^2 (10 mm Hg CO_2).
18	Thermocouple	Connected to 24 channel recorder, measures temperature of gas exiting the absorber. Accuracy ±0.56°K (±1°F) on readout.
19	Thermocouple	Connected to 24 channel recorder, measures temperature of gas entering the absorber. Accuracy ±0.56°K (±1°F) on readout.
20	Thermocouple	Connected to 24 channel recorder, measures temperature of liquid amine entering the absorber. Accuracy ±0.56°K (±1°F) on readout.
21	Pressure Gauge	Measures pressure of liquid amine entering absorber. Range, 0 to 1.1 X 10^6 N/m^2 (150 psig), total accuracy ±0.5 percent FS.
22	Pressure Gauge	Measures pressure of gas entering absorber. Range 0 to 6.9 X 10^4 N/m^2 (10 psig), total accuracy ±0.5 percent FS.
23	ΔP Gauge	Measures gas pressure drop across the absorber. Range 0 to 1.15 X 10^4 N/m^2 (60 in. H_2O), total accuracy ±0.5 percent FS.
24	Spray Nozzle	Directs the liquid amine in a spray pattern over the absorber to increase wetting capability.

TABLE 2-10 (Continued)

Item No.	Component	Description
25	Absorber	Filled with McMahon packing (saddles) to produce a large wetted surface for exposure to the gas.
26	Liquid Collector	Collects the liquid amine after it passes through the absorber.
27	Water Bath	Cools the liquid amine to room ambient.
28	Liquid Amine Supply	0.02 m^3 (5 gallons) Millipore supply can, stainless steel. Contains 0.02 m^3 (5 gallongs) of liquid amine.
29	Scales	Used to measure net quantity of liquid amine removed from can. Range 0 to 45 kg (100 lbs), smallest increment of measurement 0.0045 kg (0.01 lb), accuracy ±0.0045 kg (0.0116).
30	Recirculating Pump	Used to stir the amine in the supply can to maintain the proper mixture.
31	Pressure Gauge	Measures liquid amine supply pressure. Range, 0 to 1.5 X 10^6 N/m^2 (200 psig), total accuracy ±5 percent FS.
32	Thermocouple	Connected to 24 channel recorder, measures temperature of liquid amine in tank. Accuracy ±0.56°K (1°F) on readout.
33	Flow Meausring Device	Measures the quantity of liquid amine flowing from the tank. The flowmeter is a Cox measuring section which is read out on an Hewlett Packard 5221A counter. Range 0 to 0.57 kg/s (75 lb/hr). Accuracy ±1 percent FS.
34	Ambient Thermocouple	Connected to temperature readout, measures temperature of ambient air. Accuracy ±0.56°K (1°F) on readout.
35	Temperature Readout	Connected to ambient thermocouple or other thermocouples as required. Accuracy ±0.56°K (1°F).
36	Temperature Recorder	24 Channel recorder for recording temperature from thermocouples.

NOTE: "Total Accuracy" is the stated accuracy of the instrument plus the hysteresis and repeatability.

TABLE 2-11

COCURRENT ABSORBER TEST RESULTS

CO_2 In Liquid St. %	Liquid Rate kg/s x 10^3 (lb/hr)	Air Rate $m^3/s \times 10^3$ (SCFM)	Bed ΔP $N/m^2 \times 10^{-3}$ (In. H_2O)	CO_2 Partial Pressure $N/m^2 \times 10^{-2}$ (mm Hg)		CO_2 Removal Efficiency %
				Inlet	Outlet	
	PERFORMANCE TEST WITH MCMAHON SADDLES					
1.5	7.81 (62.0)	5.66 (12.0)	2.1 (8.5)	3.73 (2.8)	1.67 (1.25)	55.4
1.5	7.56 (60.0)	3.72 (7.89)	1.1 (4.5)	3.73 (2.8)	1.20 (0.9)	67.9
1.5	7.56 (60.0)	1.91 (4.05)	0.37 (1.5)	3.60 (2.7)	0.47 (0.35)	87.0
1.5	2.43 (19.3)	1.89 (4.01)	0.25 (1.0)	3.60 (2.7)	0.47 (0.35)	87.0
1.5	2.46 (19.5)	3.68 (7.80)	0.87 (3.5)	3.87 (2.9)	1.27 (0.95)	67.2
1.5	2.58 (20.5)	5.76 (12.2)	1.9 (7.5)	3.60 (2.7)	1.73 (1.3)	51.9
1.5	5.04 (40.0)	5.71 (12.1)	2.0 (8.0)	3.67 (2.75)	1.67 (1.25)	54.5
1.5	4.91 (39.0)	3.73 (7.90)	1.0 (4.0)	3.73 (2.8)	1.20 (0.9)	67.9
1.5	4.83 (38.3)	1.91 (4.05)	0.25 (1.0)	3.67 (2.75)	0.47 (0.35)	87.3
3.0	2.52 (20.0)	1.91 (4.05)	0.25 (1.0)	3.60 (2.7)	0.93 (0.7)	74.1
3.0	4.91 (39.0)	1.92 (4.06)	0.25 (1.0)	3.60 (2.7)	0.73 (0.55)	79.6
3.0	7.31 (58.0)	1.88 (3.98)	0.37 (1.5)	3.67 (2.75)	0.64 (0.48)	82.5
3.0	2.52 (20.0)	3.69 (7.81)	0.87 (3.5)	3.80 (2.85)	1.87 (1.4)	50.9
3.0	4.85 (38.5)	3.66 (7.75)	1.0 (4.0)	3.80 (2.85)	1.60 (1.2)	57.9
3.0	7.09 (56.3)	3.69 (7.81)	1.1 (4.5)	3.80 (2.85)	1.60 (1.2)	57.9
3.0	2.58 (20.5)	5.62 (11.9)	1.5 (6.0)	3.73 (2.80)	2.66 (2.0)	28.6
3.0	4.73 (37.5)	5.62 (11.9)	1.9 (7.5)	3.64 (2.73)	2.27 (1.7)	37.7
3.0	6.87 (54.5)	5.62 (11.9)	2.1 (8.5)	3.60 (2.70)	2.07 (1.55)	42.6
5.0	2.47 (19.6)	1.92 (4.06)	0.25 (1.0)	3.81 (2.86)	2.07 (1.55)	45.8
5.0	4.83 (38.3)	1.92 (4.06)	0.37 (1.5)	3.81 (2.86)	1.73 (1.30)	54.5
5.0	7.31 (58.0)	1.91 (4.05)	0.37 (1.5)	3.93 (2.95)	1.67 (1.25)	57.6
5.0	2.58 (20.5)	3.72 (7.90)	1.0 (4.0)	3.84 (2.88)	2.80 (2.1)	27.1
5.0	4.93 (39.1)	3.75 (7.95)	1.1 (4.5)	3.79 (2.84)	2.53 (1.9)	33.1
5.0	7.56 (60.0)	3.75 (7.95)	1.2 (5.0)	3.75 (2.81)	2.47 (1.85)	34.2
5.0	2.47 (19.6)	5.76 (12.2)	2.0 (8.0)	3.65 (2.74)	2.87 (2.15)	21.6
5.0	5.04 (40.0)	5.76 (12.2)	2.2 (9.0)	3.65 (2.74)	2.77 (2.08)	24.1
5.0	7.09 (56.3)	5.71 (12.1)	2.2 (9.0)	3.68 (2.76)	2.71 (2.03)	26.4
6.6	2.52 (20.0)	1.92 (4.07)	0.37 (1.5)	3.63 (2.72)	2.93 (2.2)	19.1
6.6	5.04 (40.0)	1.92 (4.07)	0.37 (1.5)	3.63 (2.72)	2.80 (2.1)	22.8
6.6	7.81 (62.0)	1.87 (3.97)	0.50 (2.0)	3.87 (2.90)	3.13 (2.35)	19.0
6.6	2.52 (20.0)	3.72 (7.89)	1.0 (4.0)	3.78 (2.84)	3.53 (2.65)	6.7
6.6	5.04 (40.0)	3.72 (7.89)	1.1 (4.5)	3.78 (2.84)	3.40 (2.55)	10.3
6.6	7.56 (60.0)	3.63 (7.77)	1.4 (5.5)	3.80 (2.85)	3.33 (2.50)	12.3

TABLE 2-11 (Cont.)

CO_2 In Liquid St. %	Liquid Rate kg/s x 10^3 (lb/hr)	Air Rate $m^3/s \times 10^3$ (SCFM)	Bed ΔP $N/m^2 \times 10^{-3}$ (In. H_2O)	CO_2 Partial Pressure $N/m^2 \times 10^{-2}$ (mm Hg) Inlet	Outlet	CO_2 Removal Efficiency %
PERFORMANCE TEST WITH MCMAHON SADDLES						
6.6	2.52 (20.0)	5.76 (12.2)	2.1 (8.5)	3.68 (2.76)	3.47 (2.60)	5.8
6.6	5.17 (41.0)	5.76 (12.2)	2.2 (9.0)	3.68 (2.76)	3.40 (2.55)	7.6
6.6	7.81 (62.0)	5.71 (12.1)	2.5 (10.0)	3.67 (2.75)	3.33 (2.50)	9.1
VARYING INLET PARTIAL PRESSURE						
(1)	4.83 (38.3)	3.68 (7.80)	1.0 (4.0)	3.73 (2.8)	2.33 (1.75)	37.5
(1)	4.98 (39.5)	3.68 (7.80)	1.0 (4.0)	2.67 (2.0)	1.53 (1.15)	42.5
(1)	4.93 (39.1)	3.68 (7.80)	1.0 (4.0)	1.33 (1.0)	0.67 (0.5)	50.0
HIGH TEMPERATURE RUNS, 130-135°F						
(2)	5.04 (40.0)	5.66 (12.0)	2.0 (8.0)	3.60 (2.70)	2.47 (1.85)	31.5
(2)	5.04 (40.0)	3.68 (7.80)	1.0 (4.0)	3.67 (2.75)	2.07 (1.55)	43.6
(2)	4.91 (39.0)	1.84 (3.90)	0.35 (1.4)	3.60 (2.70)	1.67 (1.25)	53.7
HIGH TEMPERATURE RUNS, 116-122°F						
2.5	3.78 (30.0)	1.84 (3.90)	0.25 (1.0)	3.60 (2.7)	0.31 (0.23)	91.5
2.5	4.04 (32.1)	3.70 (7.83)	1.0 (4.0)	3.60 (2.7)	1.0 (0.75)	72.2
2.5	4.04 (32.1)	5.66 (12.0)	2.0 (8.1)	3.73 (2.8)	1.53 (1.15)	58.9
PERFORMANCE TEST WITH BERL SADDLES						
6.6	6.39 (66.6)	1.80 (3.82)	1.5 (6.0)	4.00 (3.0)	3.27 (2.45)	18.3
6.6	7.81 (62.0)	3.71 (7.86)	3.6 (14.5)	3.73 (2.8)	3.40 (2.55)	8.9
6.6	7.81 (62.0)	5.90 (12.5)	6.2 (25.0)	3.60 (2.7)	3.27 (2.45)	9.3

(1) Estimated at 3-4%
(2) Estimated at 1.8-2.5%

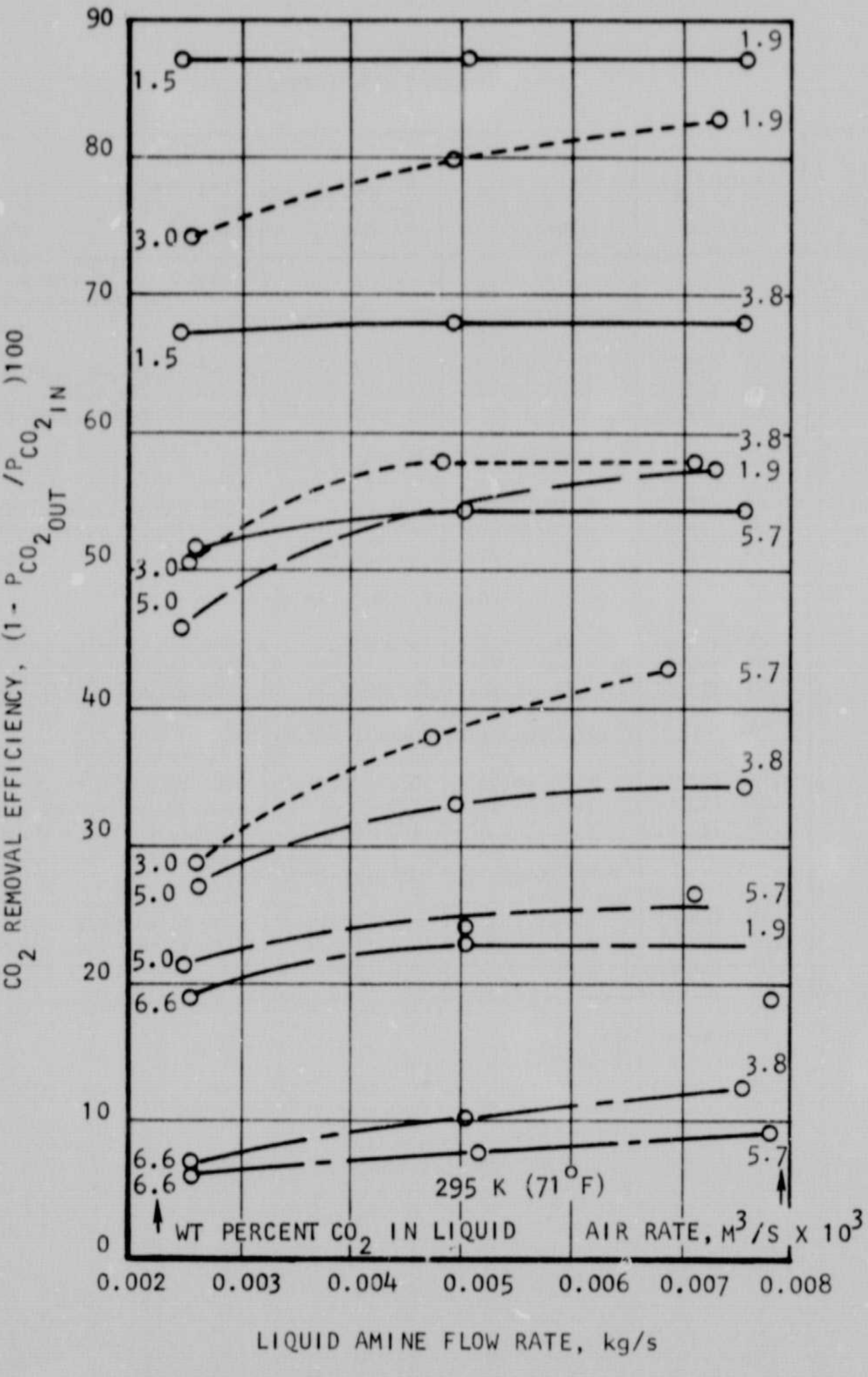

Figure 2-4. Cocurrent Absorber Removal Efficiency

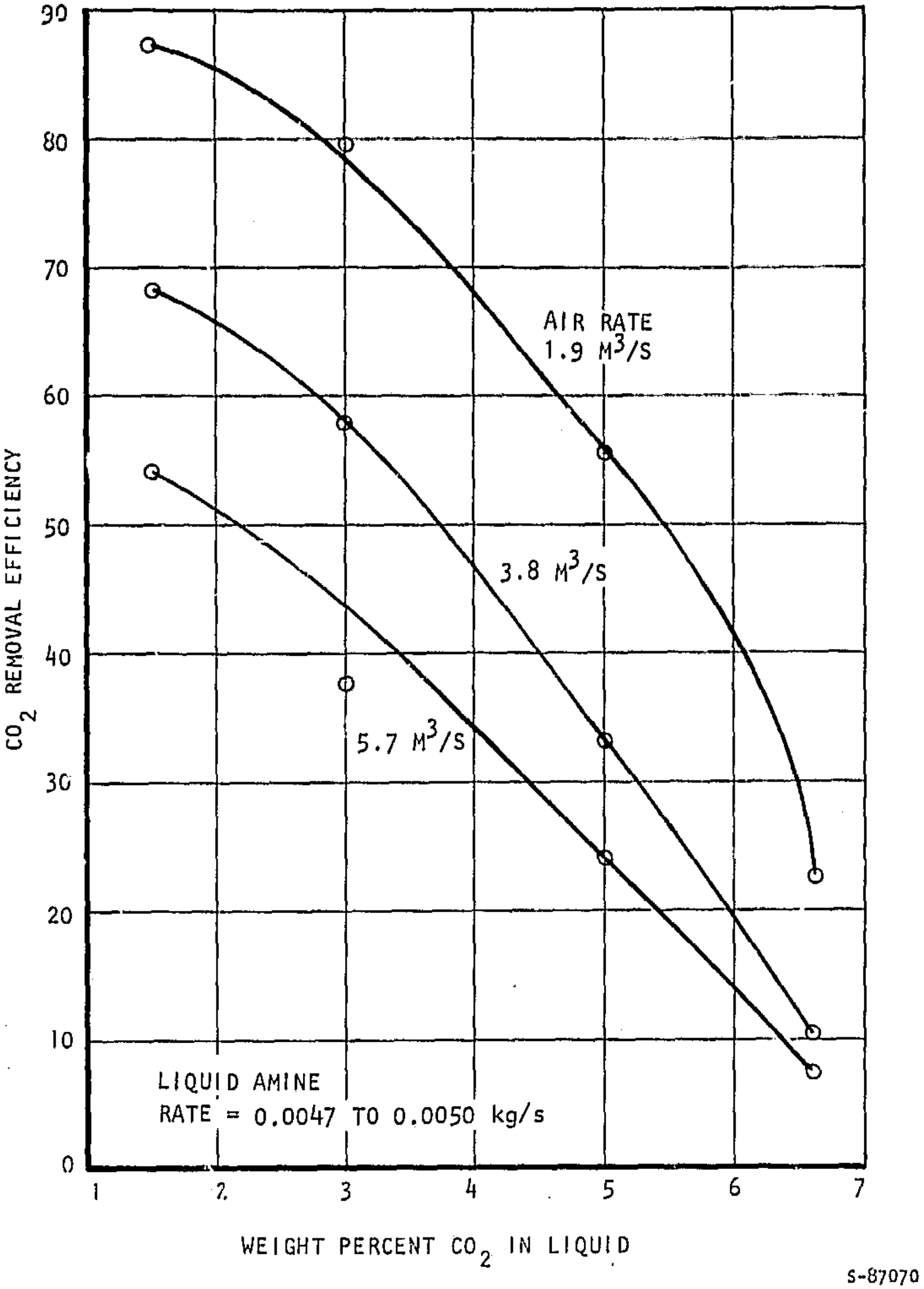

Figure 2-5. Effect of CO_2 Absorbed in Liquid

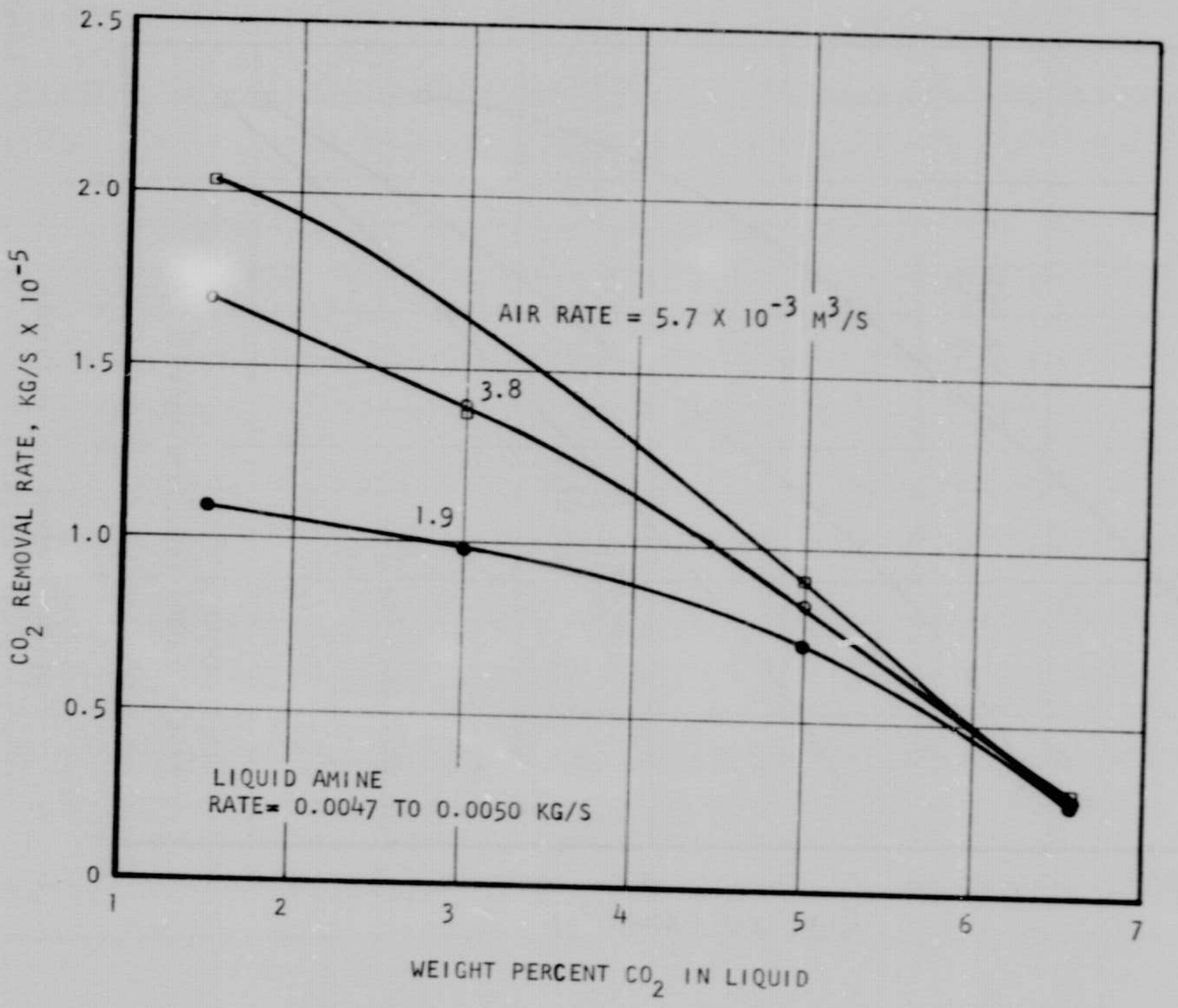

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Figure 2-6. CO_2 Removal Rate

The advantage of McMahon over Berl saddles for column packing is shown in Figure 2-7. Although the CO_2 removal efficiency is approximately the same for both packings, the pressure drop for the McMahon saddles is less than half that of the Berl saddles. Use of McMahon saddles will thus reduce the absorber air circulation fan power requirements by a significant amount. In addition, the weight of the McMahon saddles is only 22.8 percent that of Berl saddles. The two inch column contained 0.142 kg of McMahon saddles; when the column was repacked with Berl saddles, the packing weight was 0.590 kg.

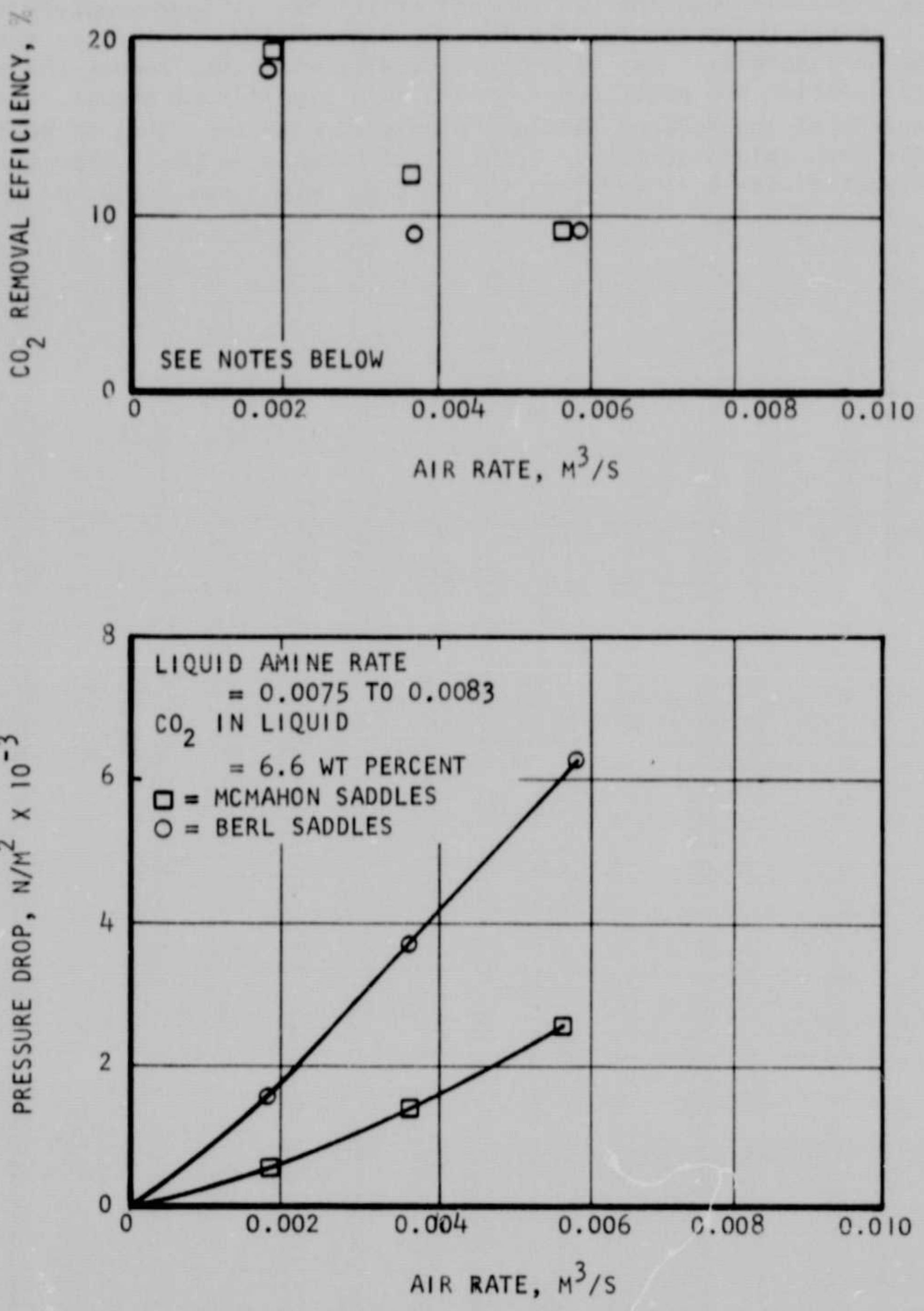

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Figure 2-7. Performance Characteristics of McMahon and Berl Saddles

SECTION 3

SYSTEM SYNTHESIS

INTRODUCTION

Regenerable carbon dioxide removal systems used on United States submarines are continuous process systems which employ aqueous solutions of 2-aminoethanol (monoethanolamine or MEA). A simple schematic of such a system is shown in Figure 3-1. The absorber is a packed column through which the air and liquid solution flow counter-currently. Desorption occurs in the regenerator, which is also a packed column with a reboiler section at the bottom. External heat and cooling water are required by this system.

The spacecraft liquid amine carbon dioxide system synthesized in this section is a zero-g adaption of the submarine system. Dynamic phase separators have been added for liquid/vapor control and absorption occurs in a cocurrent absorber. In addition, a three-component liquid amine solution is used. The basic requirements for a spacecraft carbon dioxide removal and recovery system are given in Table 3-1.

TABLE 3-1

CARBON DIOXIDE REMOVAL SYSTEM REQUIREMENTS

No. of Men	9	
CO_2 rate, kg/s (lb/hr)	1.04×10^{-4}	(0.825)
Cabin environment		
Pressure, $N/m^2 \times 10^{-3}$ (psia)	101	(14.7)
Temperature, ^oK (^oF)	298	(75)
Dew Point, ^oK (^oF)	284	(50)
CO_2 Partial pressure, N/m^2 (mm Hg)	400	(3)

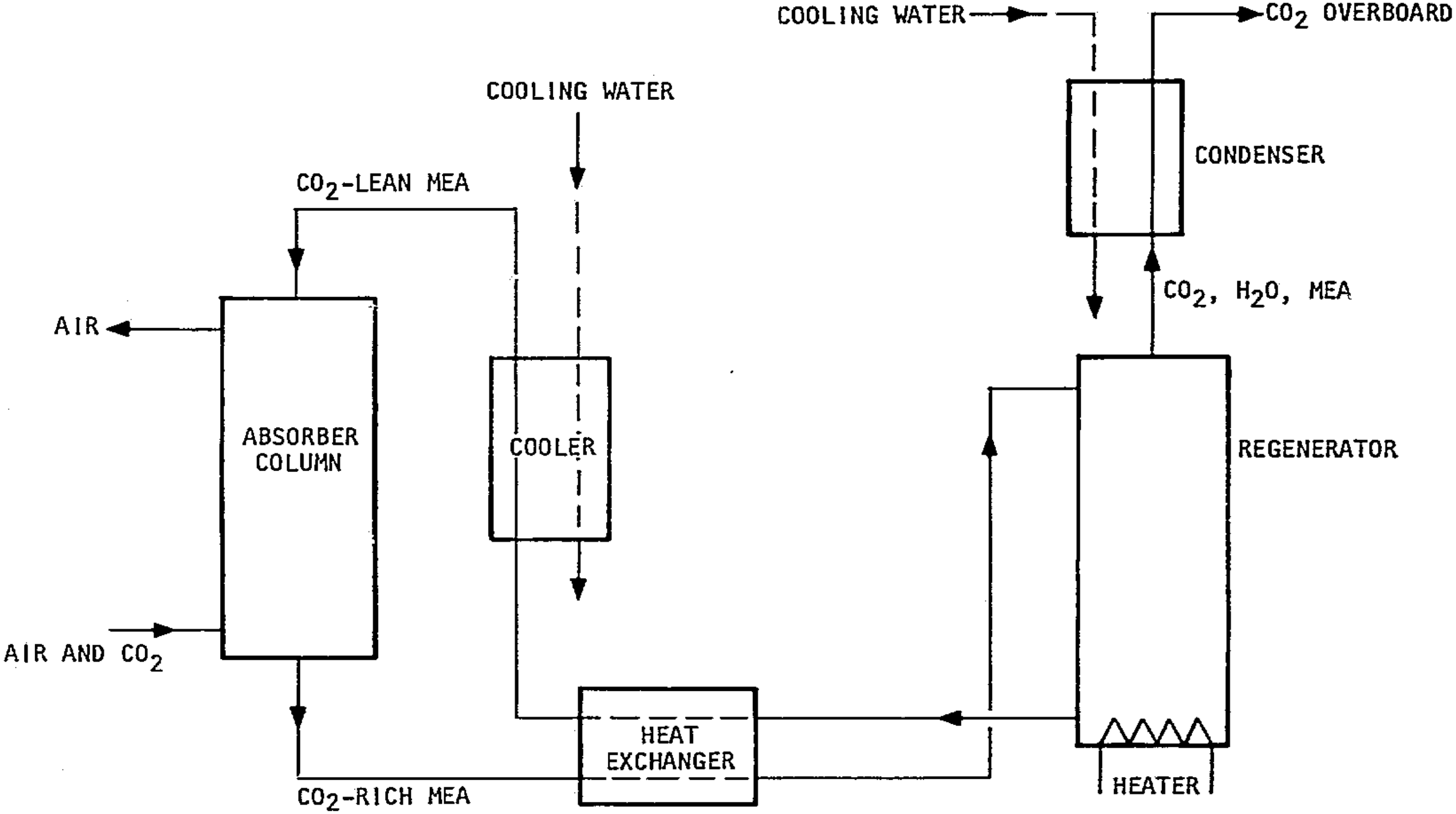

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Figure 3-1 CO_2 Removal System Used on Submarines.

SYSTEM DESIGN CONSIDERATIONS

Absorption test data shows that improved absorption efficiencies are obtained as the liquid-to-gas mass flow ratios are increased, but that liquid mass velocities above 2.51 kg s^{-1} m^{-2} (1850 lb/hr-ft^2) through the cocurrent flow absorption column will not result in appreciable gains in absorption efficiencies (Figure 2-4) also an initial concentration of greater than 4 percent carbon dioxide in the entering liquid will cause a disproportionate increase in the gas flow rate to achieve higher carbon dioxide absorption efficiencies as shown in Figure 3-2. Higher desorption efficiencies are achieved by obtaining higher inlet carbon dioxide concentration of the entering liquid and a combination of higher desorption pressures and temperatures.

The net effect of these absorption and desorption variables results in a system design with a recirculation loop around the cocurrent absorber. The recirculation loop functions to obtain reasonable absorption efficiencies by maintaining a high liquid flux through the absorption column.

Liquid-vapor phase separation is required at the outlet of the absorber and the desorber, and immediately upstream of the exit carbon dioxide line. Since each of the phase separators is capable of providing the pumping head for the circulating liquid, the pumping function is incorporated into the particular phase separator. Reliability is also improved by eliminating the circulating pumps since they would be part of the series link in a reliability logic diagram.

Vapor recompression was initially considered to minimize the electrical heater power requirements and recover the latent heat of evaporation. Due to the reduced amount of water vapor formed during the desorption operation in the presently proposed system and the differences in flow rates, analysis indicated a net power saving of only 9 watts for the vapor compression system.

The mechanical design problems of building a vapor compressor with a volumetric flow rate of less than 2.4×10^{-6} m^3/s (0.05 cfm) and a pressure ratio 1.5 or greater requires a small positive displacement compressor or a centifugal compressor operating at speeds in excess of 1600 rps. Either design presents bearing design and cooling problems in addition to the material compatibility with the amine at elevated temperatures. Because of these design problems, it was evident that for a small savings in electrical power the vapor recompression system design would not be practical.

Inspection of the desorption data (Table 2-8) shows that less water vapor is produced at higher desorption operating pressures. The reduction in electrical heater requirements due to the reduced amount of water evaporated is greater than the increase in pumping power required for the higher desorption pressure. Thus a net reduction in power required results when operating at higher desorption pressure. Also, system calculations were performed to study the effects of desorption temperatures of 411 and 422°K (280 and 300°F) at a constant desorption pressure of 2.75×10^5 N/m^2 (40 psia). The higher desorption temperature of 422°K (300°F) showed the minimum system total power consumption would be lower. This was due to the increased desorption efficiency which resulted in lower desorber flow rates and lower heater power input.

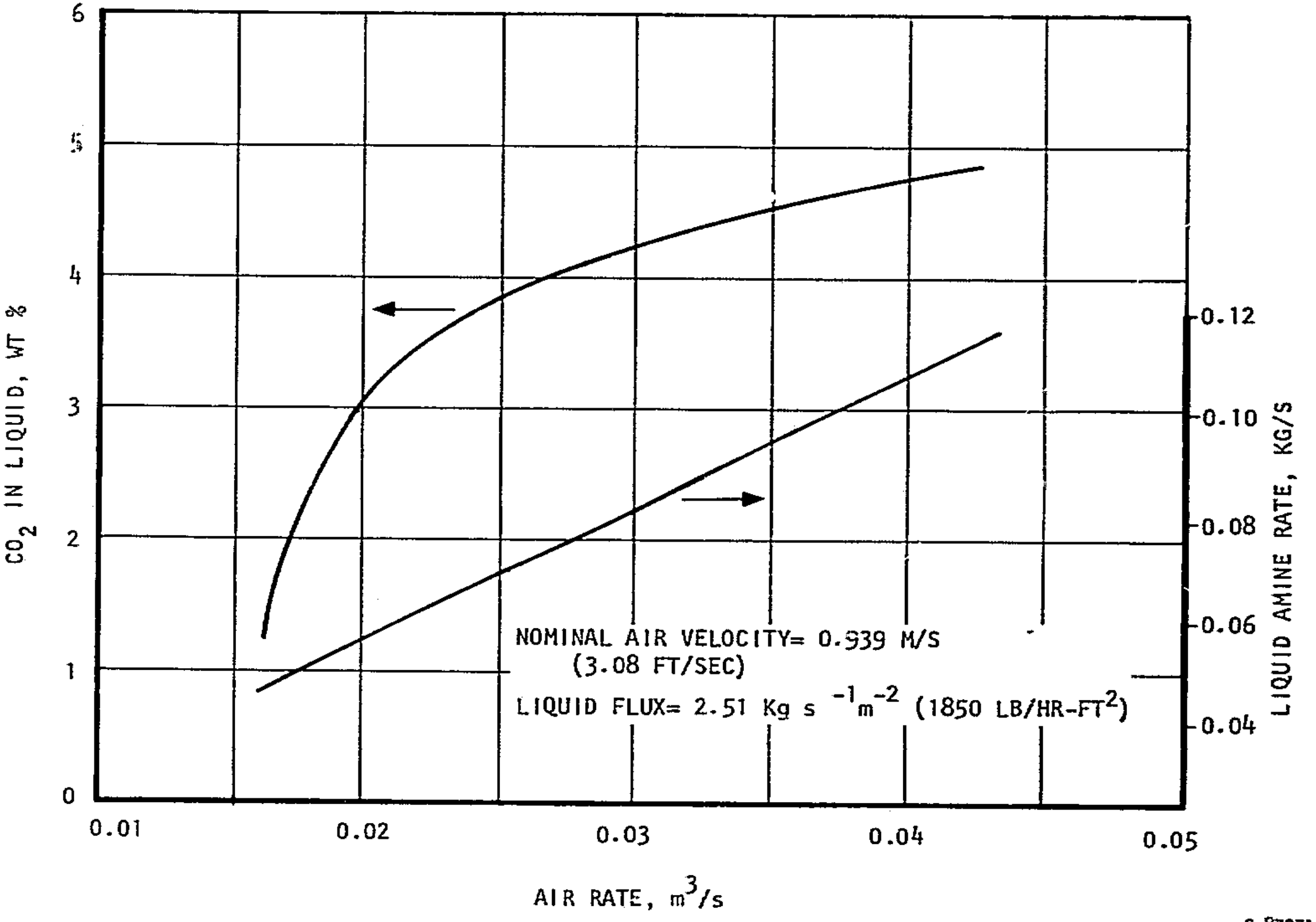

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Figure 3-2. Absorber Design Conditions

In order to obtain a good liquid spray pattern in the absorber, the liquid amine pressure into the unit must be, as a minimum, approximately 3.1 x 10^5 N/m^2 (45 psia). With the desorber operating condition established at 2.75 x 10^5 N/m^2 (40 psia) and 422°K (300°F), there is only a difference of 3.4 x 10^4 N/m^2 (5 psi) between the pressure requirements of the liquid solutions in the absorber and desorber. Since the pressure requirements are so similar, there is no incentive for adding a separate boost pump in the recirculating loop around the absorber.

SYSTEM DESCRIPTION

The conceptual liquid amine carbon dioxide removal system schematic is shown in Figure 3-3. Carbon dioxide in the cabin air is brought into intimate contact with the liquid amine solution in a cocurrent flow absorber which removes approximately two thirds of the carbon dioxide contained in the air. The cabin air is returned to the cabin air purification system and the liquid amine solution is desorbed by adding electrical heat which is supplemented by heat-recovery heat exchangers. The concentrated carbon dioxide gas flows to the oxygen recovery system and the liquid amine solution returns to the absorber in a continuous flow process.

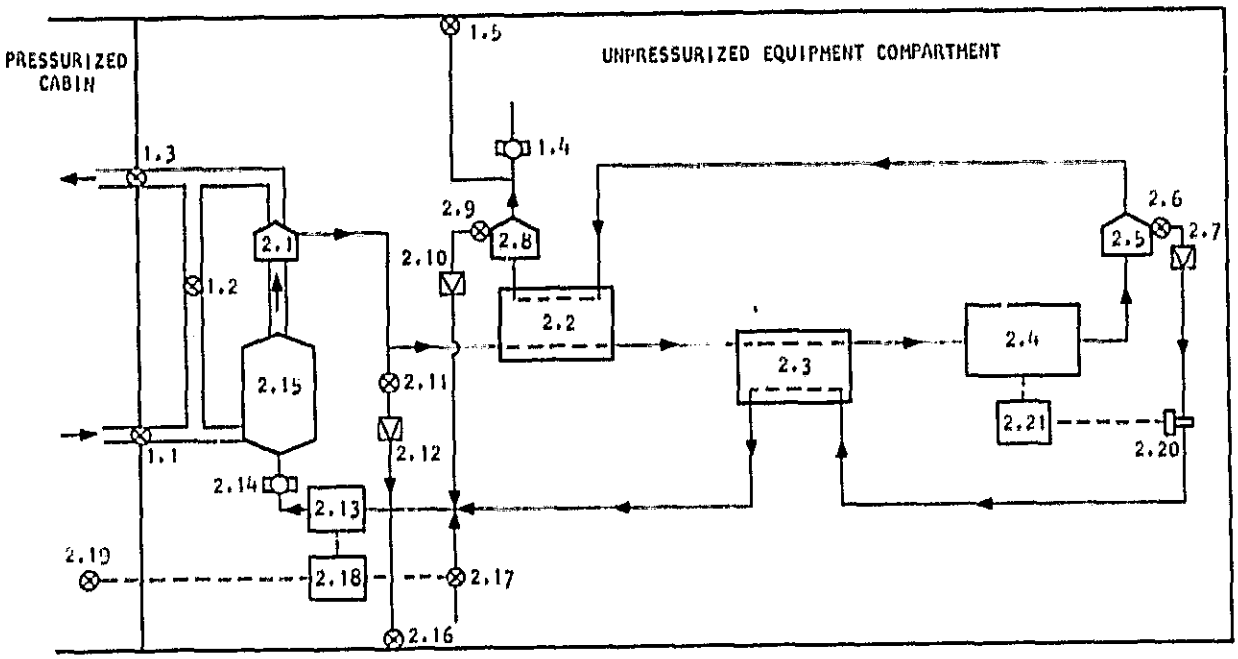
Because monoethanolamine (MEA) is mildly toxic and may cause moderate skin irritation, or serious eye injury upon contact, all of the liquid lines are located in an equipment compartment external to the pressurized, manned compartment. This provides an added measure of safety.

Although this system is designed for zero-g operation, it must be capable of operating in a normal 1-g gravity field, during boost into orbit, and during acceleration and deceleration which result from changes in orbit or flight path.

Ground servicing, ground operation and normal system operation are described in greater detail in the following paragraphs.

SERVICING AND GROUND OPERATION

The design of various components of this system must be such that the liquid level within each of the three phase separators will not be permitted to completely flood the fan section of the device. This will minimize the motor overload sizing problems and will prevent pump cavitation. The cabin air ducts should also be located to prevent liquid flow into the cabin in the event of malfunctions that could occur during ground servicing. A check valve (Item 2.12), backed up by a shutoff valve (Item 2.11), provides redundancy to prevent check valve leakage into the cabin during shutdown for ground servicing.



1.1, 1.3	SHUTOFF VALVE
1.2	BYPASS VALVE
1.4	PRESSURE REGULATOR AND SHUTOFF VALVE
1.5	VENT VALVE
2.1	CABIN AIR SEPARATOR PUMP
2.2	VAPOR CONDENSER
2.3	REGENERATIVE HEAT EXCHANGER
2.4	HEATER - DESORBER
2.5	VAPOR SEPARATOR PUMP
2.6, 2.9 2.11 AND 2.17	SHUTOFF VALVE
2.7, 2.10, AND 2.12	SHUTOFF VALVE
2.8	CARBON DIOXIDE SEPARATOR PUMP
2.15	ABSORBER
2.16	FILL VALVE
2.18	LIQUID LEVEL CONTROLLER
2.19	LIQUID LEVEL INDICATOR
2.20	OVERTEMPERATURE SWITCH
2.21	TEMPERATURE CONTROLLER

S-67093

Figure 3-3. Conceptual Liquid Amine Carbon Dioxide Removal System Schematic

Charging System With Liquid

To charge the system with liquid, the following valve conditions are established:

Valve	Condition
Cabin Loop Shutoff (1.1, 1.3)	Closed
Bypass (Item 1.2)	Open
Pressure Regulator and Shutoff Valve (Item 1.4)	Closed
Vent Valve (Item 1.5)	Open
Liquid Shutoff Valves (Items 2.6, 2.9, 2.11)	Open

With these valve conditions established, the ground servicing equipment is connected to the fill valve (Item 2.16).

Prior to initiating liquid flow to the system, the phase separators (Items 2.1, 2.5 and 2.8) must be operating to purge the system of air and avoid flooding of the phase separators. Liquid filling may now be initiated and continues until the liquid reservoir (Item 2.13) is full as indicated by the liquid level indicator (Item 2.19). The phase separator-pump assemblies (Items 2.1, 2.5 and 2.8) continue to operate and power is applied to the desorber (Item 2.4) until the reservoir requires no further topping off. At this time, the fill and vent valves (Items 2.16 and 1.5) are closed and capped; the cabin loop shutoff valves (Items 1.1, 1.3) are opened; the pressure regulator and shutoff valve (Item 1.4) is opened; and the bypass valve (Item 1.2) is opened.

Shutdown After Charging and Operation

If it becomes necessary to shut down after the liquid system is fully charged and operating, the shutdown procedure requires that the pressurizing reservoir (Item 2.13) be isolated from the gaseous side of the system by closing shutoff valves (Items 2.6, 2.9, and 2.11) and removing power from the phase separators (Items 2.1, 2.5, and 2.8). The cabin is protected from contamination by closing the shutoff valves (Items 1.1 and 1.3) and opening bypass valve, Item 1.2. The oxygen recovery system is isolated by closing the pressure regulator and shutoff valve (Item 1.4). The makeup liquid source is automatically isolated by closing shutoff valve (Item 2.17).

Startup of Fully-Charged System

The startup procedures with a fully charged system are similar to the startup and filling procedure of an empty system except that the fill and vent valves are closed. The cabin air shutoff valves (Items 1.1 and 1.3) are closed and the bypass valve (Item 1.2 is opened). The liquid shutoff valves (Items 2.14, 2.6, 2.9, and 2.11 are opened and the three phase-separator pumps (Items

2.1, 2.5, and 2.8) are activated and power is applied to the electric heater (Item 2.4). When the liquid levels stabilize, the shutoff valves (Items 1.1, 1.3, and 1.4) are opened and shutoff valve (Item 1.2) is closed. With these conditions established, the system is now in the normal operating mode.

Protective Devices

A thermal switch (Item 2.20) is included to protect the system from excessive liquid temperatures due to changes in operating conditions or failure of the temperature controller (Item 2.21). The fluid level controller (Item 2.18) automatically opens the shutoff valve (Item 2.17) to makeup the water and amine lost through normal operation of the system when the fluid level within the liquid reservoir (Item 2.13) reaches the low limit switch. Makeup liquid flows from the makeup fluid tank into the reservoir (Item 2.13) until the liquid level reaches the high limit switch.

NORMAL SYSTEM OPERATION

With the cabin carbon dioxide partial pressure maintained at 400 N/m^2 (3 mm Hg), 0.0236 m^3/s (50 cfm) of cabin air and 0.052 kg/s (410 lb/hr) amine solution are mixed in the cocurrent flow absorber (Item 2.15); refer to Figure 3-4 and Table 3-2. The carbon dioxide partial pressure of the air returning to the cabin atmosphere revitalization system is reduced to 133 N/m^2 (1 mm Hg) with an air dew point of approximately 290°K (62°F). Phase separation between the gas and liquid is accomplished in the integral separator pump (Item 2.1) which is described in greater detail in Appendix A (Component Descriptions).

The fan portion of the cabin air separator pump has a pressure rise of 1243 N/m^2 (5 in. of H_2O) to overcome the pressure losses of the absorber, ducting, and valves. The pump has a total pressure rise of approximately 40 psi, to overcome the pressure drop of the valves and ducting and to provide the recirculation flow for the absorber. The amine solution pressure, referenced to the cabin pressure, is established by the pressure regulator (Item 2.14).

Air returning to the cabin will contain amine vapor at concentrations levels of a few parts per million. This vapor may be removed by ion exchange resins (as presently accomplished aboard submarines Reference 3), or by passing the vapor-laden gases through an activated charcoal bed impregnated with phosphoric acid; or a combination of these two techniques. A post-scrubbing wash solution technique investigated by the Navy is effective, but in a zero-g application it would involve another subsystem similar to the proposed amine system.

The carbon dioxide concentration, by weight, in the liquid entering the absorber is approximately 3.5 percent and exiting the absorber is approximately 3.7 percent. About 7 percent by weight of the liquid flowing through the absorber flows into the desorber portion of the amine system. The liquid is heated by removing the latent heat of vaporization in the condenser

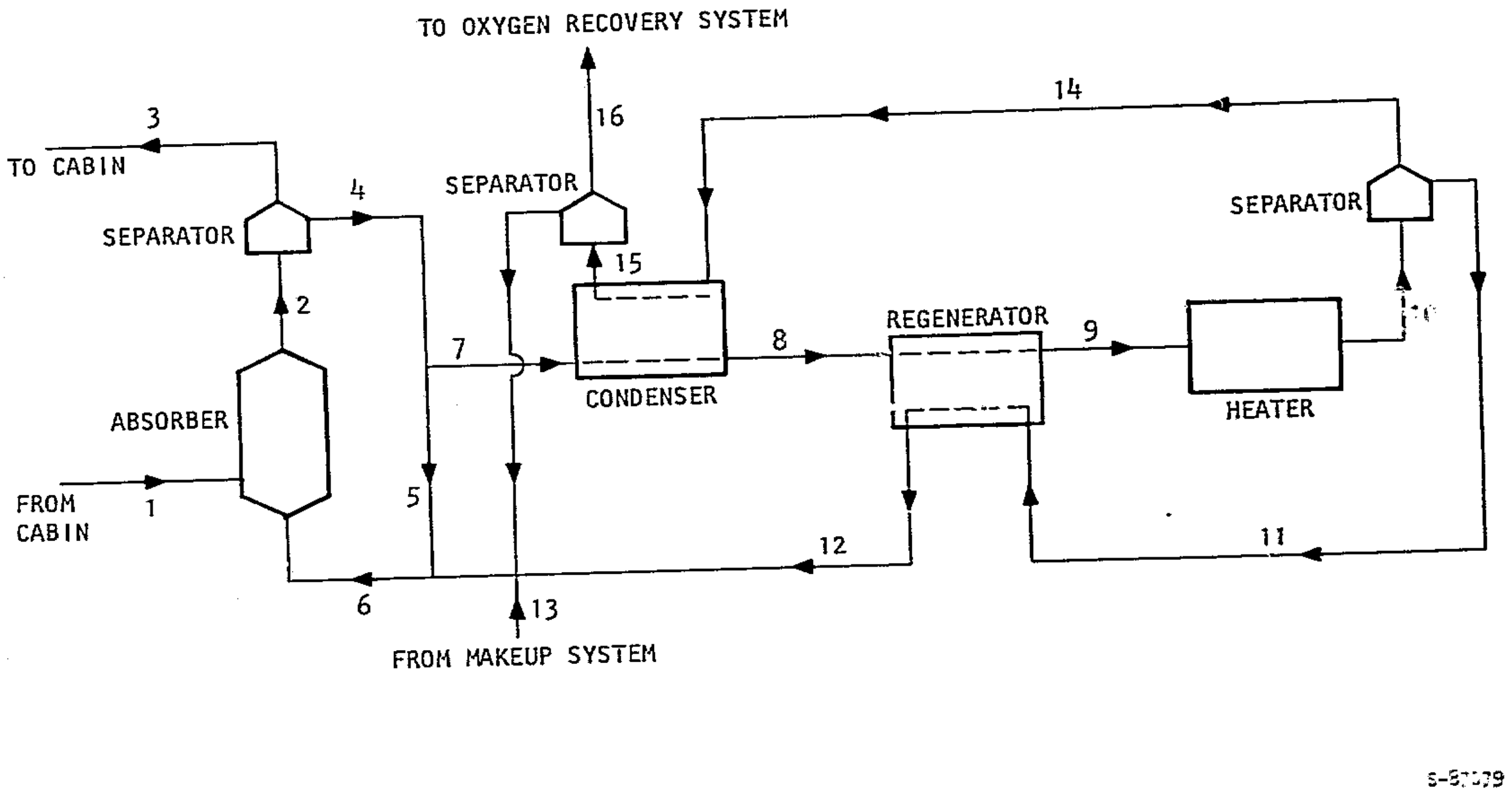


Figure 3-4. System Process Station Identification

TABLE 3-2

SYSTEM PROCESS CONDITIONS

FLUID CONDITIONS (SI UNITS)

Station No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Pressure, $N/M^2 \times 10^{-5}$	1.01	1.01	1.01	3.79	3.79	3.45	3.79	3.65	3.52	2.76	3.79	3.65	3.65	2.76	2.76	2.76	3.65
Temperature, K	297	299	302	299	299	303	299	348	414	422	423	352	297	449	307	330	327
Flow, kg/s	0.0287	0.0803	0.0287	0.0516	0.0480	0.0517	0.00359	0.00359	0.00359	0.00359	0.00333	0.00333	0.000134	[illegible]	[illegible]	0.000105	[illegible]
Flow m^3/s	0.0236	-	0.0233	-	-	-	-	-	-	-	-		-	-	-	-	-

FLUID CONDITIONS (BRITISH UNITS)

Station No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Pressure, psia	14.7	14.7	14.7	55	55	50	55	53	51	40	55	53	53	40	40	40	53
Temperature, ^{o}F	75	78	83	79	79	85	79	167	285	300	301	174	75	349	93	134	128
Flow, lb/hr	227.4	637.4	227.7	409.7	381.2	410	28.5	28.5	28.5	28.5	26.4	26.4	1.1	2.1	2.1	0.83	1.25
Flow, scfm	50	-	50.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-

INLET AND OUTLET CONDITIONS (SI UNITS)

Station No.	1	2	16	13
CO_2, kg/s	1.69×10^{-4}	6.43×10^{-5}	1.04×10^{-4}	-
H_2O, kg/s	2.07×10^{-4}	3.45×10^{-4}	8.4×10^{-6}	1.4×10^{-4}
MEA, kg/s	-	6.3×10^{-10}	8.8×10^{-10}	15.1×10^{-10}

INLET AND OUTLET CONDITIONS (BRITISH UNITS)

Station No.	1	2	16	13
CO_2, lb/hr	1.34	0.51	0.825	-
H_2O, lb/hr	1.64	2.74	0.0065	1.11
MEA, lb/hr	-	5×10^{-6}	7×10^{-6}	12×10^{-6}

(Item 2.2) and removing sensible heat in the regenerative heat exchanger (Item 2.3). The final stage of desorption is accomplished in the electrically heated desorber (Item 2.4) which heats the liquid and vapor to 422°K (300°F).

The desorbed liquid exiting from the vapor separator pump is returned to the absorber after being cooled in the regenerative heat exchanger (Item 2.3). A weak aqueous amine solution is periodically added to the liquid from the desorber to compensate for the water and amine lost to the cabin air and the oxygen recovery systems.

The composition of the vapors leaving the desorber are (by weight), 59 percent water vapor, 39.5 percent carbon dioxide, and 1.5 percent MEA. Almost all of the water and amine vapors are condensed in the condenser (Item 2.2) with the liquid being pumped back to the absorber by the carbon dioxide separator-pump (Item 2.8). The almost pure carbon dioxide gas is delivered through the pressure regulator (Item 1.4) which establishes the system pressure level in the gaseous portion of the desorbing cycle.

Since this system is a continuous flow system, any variations of the cabin carbon dioxide partial pressures from the nominal design condition will automatically change the chemical equilibrium conditions within the absorber and desorber. This will tend to damp out large fluctuations in carbon dioxide concentrations. With current spacecraft cabin volumes of greater than 6 m^3/man (210 ft^3/man) and a fixed flow rate liquid amine system, sudden changes in the crew metabolic rates probably will not result in changes in the cabin carbon dioxide partial pressure of more than a few millimeters of mercury.

Component performance and design data are given in the Appendix. Power requirements (continuous) total 710 watts; the major power consuming item is the heater-desorber (Item 2.4) which requires 519 watts. The remaining power is for the separator/pumps, liquid level controller and temperature controller. If the spacecraft contains a heat source at approximately 300°F, power requirements could be drastically reduced since the heater-desorber could operate off the heat source.

Total component weight of all the items shown in Figure 3-3 is 46 Kg (101 lb). Ducting, wire harness and brackets were assumed to be twenty percent of total component weight, thus overall weight of the system shown in Figure 3-3 is 55.2 (121.6 lb).

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Analytical and test activities described in this report resulted in the following conclusions.

1. The three-component liquid amine solution has a high capacity for carbon dioxide even at low cabin carbon dioxide partial pressure.
2. Dynamic absorption rates are high, allowing the efficient use of a cocurrent absorber.
3. Power requirements for the continuous processing of carbon dioxide using a liquid amine solution are quite low, resulting in 79 watts/man for this design. The liquid amine system is competitive on a weight and power basis, with other carbon dioxide removal/concentration approaches.

RECOMMENDATIONS

It is recommended that a breadboard system be designed and tested to demonstrate a continuous carbon dioxide removal/concentration process. Initially, the process could be evaluated without utilizing the phase separators and regenerative heat exchangers. Here, the emphasis would be to obtain process performance data to demonstrate the process and validate the system analyses. Later, the separators and heat exchangers could be added to demonstrate the feasibility of operating at zero-g with low power requirements.

REFERENCES

1. Gadomski, S. T., et al, <u>Desorption of CO_2 from a Three-Component Solution</u>, NRL Report 6976, Naval Research Laboratory, Washington, 1969.

2. Gustafson, P. R., and R. R. Miller, <u>Investigation of Some New Amines as Regenerative Carbon Dioxide Absorbent</u>, NRL Report 6926. Naval Research Laboratory, Washington, 1969.

3. Carey, R.B. and I.C. Jacobs, <u>Washer Tower to Eliminate Contaminants from CO_2 Scrubbers and CO-H_2 Burners in Nuclear Submarines</u>, NRD Report 2858, Naval Ship Research and Development Center, Washington 1969.

APPENDIX A

COMPONENT DESCRIPTIONS

This appendix contains functional descriptions and performance and design data for all components of the liquid amine carbon dioxide recovery system shown in Figure 3-3 (Section 3). Components described in this appendix are listed below.

Item No.	
1.1, 1.3	Shutoff Valve
1.2	Bypass Valve
1.4	Pressure Regulator and Shutoff Valve
1.5	Vent Valve
2.1	Cabin Air Separator Pump
2.2	Vapor Condenser
2.3	Regenerative Heat Exchanger
2.4	Heater-Desorber
2.5	Vapor Separator Pump
2.6, 2.9, 2.11 and 2.17	Shutoff Valve
2.7, 2.10, and 2.12	Check Valve
2.8	Carbon Dioxide Separator Pump
2.13	Liquid Reservoir
2.14	Pressure Regulator and Shutoff Valve
2.15	Absorber
2.16	Fill Valve
2.18	Liquid Level Controller
2.19	Liquid Level Indicator
2.20	Overtemperature Switch
2.21	Temperature Controller

APPENDIX A (Continued)

ITEMS 1.1 AND 1.3 - SHUTOFF VALVE

FUNCTION AND DESCRIPTION

This normally-open shutoff valve is closed during servicing or shutdown of the liquid amine carbon dioxide removal system to prevent the monoethanolamine vapors from contaminating the cabin atmosphere.

The valve is a spoon type shutoff valve with a nominal diameter of 0.0508 m (2-in.). It is similar to vent valve P/N 397582-1-1 developed for the Gemini Program. The valve has a pneumatically actuated and electrically controlled head device which allows for remote control with an automatic sensing device.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0287 (228) minimum with 302°K (83°F) air at sea level
Max pressure drop, N/m^2 (in H_2O)	75 (0.3) at design flow
Max operating pressure, N/m^2 (psia)	0.103×10^6 (15)
Proof pressure, N/m^2 (psia)	0.207×10^6 (30)
Burst pressure, N/m^2 (psia)	0.414×10^6 (60)
Weight, kg (lb)	1.41 (3.1)
Overall dimensions, m (in.)	0.178 (7) X 0.178 (7) X 0.152 (6)
Service media	Air
Power, watts	28 at 28 vdc
Availability	Modified Gemini valve

ITEM 1.2 - BYPASS VALVE

FUNCTION AND DESCRIPTION

This normally closed valve is opened when the shutoff valves (Items 1.1 and 1.3) are closed. This allows for circulation of the absorber gases during servicing or shutdown of the liquid amine carbon dioxide removal system when the cabin air separator pump is in operation.

The valve body is a spoon-type shutoff valve with a nominal diameter of 0.0508 m (2-in.) similar to the vent valve P/N 397582-1-1 developed for the Gemini Program. It has a pneumatically actuated and electrically controlled head device that provides for remote control with an automatic sensing device.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0287 (228) minimum with 302°K(83°F) air at sea level
Max pressure drop, N/m^2 (in H_2O)	75 (0.3) at design flow
Max operating pressure, N/m^2 (psia)	0.103×10^6 (15)
Proof pressure, N/m^2 (psia)	0.207×10^6 (30)
Burst pressure, N/m^2 (psia)	0.414×10^6 (60)
Weight, kg (lb)	1.41 (3.1)
Overall dimensions, m (in.)	0.178 (7) X 0.178 (7) X 0.152 (6)
Service media	Air
Power, watts	28 at 28 vdc
Availability	Modified Gemini valve

ITEM 1.4 - PRESSURE REGULATOR AND SHUTOFF VALVE

FUNCTION AND DESCRIPTION

The pressure regulator and shutoff valve maintains the carbon dioxide delivery pressure to the oxygen recovery system at approximately 0.262 X 10^6 N/m^2 (38 psia) referenced to cabin pressure.

The design of the valve is similar to the Apollo water pressure relief valve, AiResearch P/N 827830-1, with an electrically actuated selector valve in lieu of the manual selector valve. The unit consists of two redundant, spring-loaded poppet valves, which allow flow through the valve when a differential pressure of 0.262 X 10^6 N/m^2 (38 psia) is sensed by the valve. An integral selector valve provides for: simultaneous operation of both poppet valves; single operation of either poppet valve; or complete shutoff of flow to both poppet valves.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	1.04 X 10^{-4} (0.83) at a temperature of 330°K (134°F)
Control pressure, N/m^2 (psia)	0.262 X 10^6 ±0.0207 X 10^6 (38)
Proof pressure, N/m^2 (psia)	0.393 X 10^6 (57)
Burst pressure, N/m^2 (psia)	0.524 X 10^6 (76)
Weight, kg (lb)	0.68 (1.5)
Dimensions, m (in.)	0.0508 (2) X 0.0762 (3) X 0.0889 (3.5)
Power, watts	28 at 28 vdc
Service media	Carbon dioxide
Availability	New

ITEM 1.5 - VENT VALVE

FUNCTION AND DESCRIPTION

This quick disconnect vent valve is only used during ground servicing when the liquid lines are being purged of air.

With the exception of change in material from aluminum to stainless steel, this valve is identical to the oxygen vent valve, AiResearch P/N 630054-1-2 developed for the Gemini Program. The connection consists of the nipple half of a self-sealing type, quick disconnect gas coupling.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.00076 (6) at 311°K (100°F) and 0.101×10^6 N/m^2 (14.7 psia)
Max pressure drop, N/m^2 (psig)	6.891×10^3 (1) at design flow
Max operating pressure, N/m^2 (lb/hr)	0.0103×10^6 (15)
Proof pressure, N/m^2 (psig)	0.207×10^6 (30)
Burst pressure, N/m^2 (psig)	0.414×10^6 (60)
Weight, kg (lb)	0.363 (0.8)
Dimensions, m (in.)	0.0538 (2.12) X 0.1046 (4.12)
Availability	Same as 630054 except material

APPENDIX A (Continued)

ITEM 2.1 - CABIN AIR SEPARATOR PUMP

FUNCTION AND DESCRIPTION

The cabin air separator pump provides the necessary pressure rise for both the liquid and cabin air to overcome the system pressure losses and separates the liquid from the gas as the mixture exits from the cocurrent flow absorber.

The air-liquid mixture flows axially into a rotating drum which centrifugally separates the liquid from the air. A stationary pitot tube at the outer radius of the rotating drum uses the kinetic velocity of the rotating liquid for the pumping head as it collects in the drum for recirculation through the absorber. The air flows through a series of baffles into a centrifugal fan and its diffuser and hence axially over the motor housing to cool the motor. The motor is magnetically coupled to the separator so that that motor is not exposed to the corrosive amine vapors.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0516 (409.2) liquid flow 0.0287 (227.7) air flow at 0.101 X 10^6 N/m^2 (14.7 psia) and 299°K (78°F)
Fan pressure rise, N/m^2 (in. H_2O)	1243 (5)
Pump pressure rise, N/m^2 (psia)	0.177 X 10^6 (25.6)
Max operating pressure, N/m^2 (psia)	0.278 X 10^6 (40.3)
Proof pressure, N/m^2 (psia)	0.417 X 10^6 (60)
Burst pressure, N/m^2 (psia)	0.556 X 10^6 (80.6)
Weight. kg (lb)	8.16 (18)
Overall dimensions, m (in.)	0.2032 (8) dia X 0.2794 (11)
Speed, rps	95.8
Power, watts	165
Availability	New

APPENDIX A (Continued)

ITEM 2.2 - VAPOR CONDENSER

FUNCTION AND DESCRIPTION

The vapor condenser function to remove condensable water vapor and amine vapor from the carbon dioxide being delivered to the oxygen recovery system.

The vapor condenser is a tubular, counterflow heat exchanger design with the vapor flowing inside of the tubes and the cooling liquid solution flowing outside of the tubes. The unit is fabricated from stainless steel tubing 48.8 m (160 ft) in length of 0.0064 m (0.25-in.) diameter which is spirally wound into 68 coils of 0.229 m (9-in.) diameter with a coil pitch of 0.0074 m (0.29-in.). A cylindrical shell is brazed to the inside surface of this coil and another cylindrical shell is brazed to the outside of this cylindrical coil. The coolant liquid flows in a counterflow direction through ports attached to the outer shell and within the confines of the space created by the two concentric shells and the spirally wound tubing.

PERFORMANCE AND DESIGN DATA

	Cold Side	Hot Side
Design flow, kg/s (lb/hr)	0.0036 (28.57)	0.00026 (2.088)
Max pressure drop, N/m^2 (psi)	3450 (0.5)	13800 (2.0)
Max operating pressure, N/m^2 (psia)	0.3791×10^6 (55)	0.276×10^6 (40)
Proof pressure, N/m^2	0.569×10^6 (82.5)	0.414×10^6 (60)
Burst pressure, N/m^2	0.758×10^6 (110)	0.552×10^6 (80)
Inlet temperature, °K (°F)	299 (79)	449 (349)
Outlet temperature, °K, (°F)	348 (167)	307 (93)
Weight, kg (lb) wet	5.72 (12.6)	
Overall dimensions, m (in.)	0.2286 (9) dia x 0.5009 (19.72)	
Availability	New	

APPENDIX A (Continued)

ITEM 2.3 - REGENERATIVE HEAT EXCHANGER

FUNCTION AND DESCRIPTION

The regenerative heat exchanger conserves system thermal energy by heating the liquid flowing to the desorber while simultaneously cooling the liquid returning to the absorber.

The regenerative heat exchanger is a tubular, counterflow heat exchanger design with the hot liquid flowing outside of the tubes. The unit is fabricated from stainless steel tubing 23.9 m (78.5 ft) in length of 0.0095 m (0.375 in.) diameter which is spirally wound into 50 coils of 0.1524 m (6 in.) diameter with a coil pitch of 0.0105 m (0.415 in.). A cylindrical shell is brazed to the inside surface of this coil and another cylindrical shell is brazed to the outside of this cylindrical coil. The coolant liquid flows in a counterflow direction through ports attached to the outer shell and within the confines of the space created by the two concentric shells and the spirally wound tubing.

PERFORMANCE AND DESIGN DATA

	Cold Side	Hot Side
Design flow, kg/s (lb/hr)	0.0036 (28.57)	0.0033 (26.482)
Pressure drop, N/m^2 (psi)	0.0276 X 10^6 (4)	0.00689 X 10^6 (1)
Operating pressure, N/m^2 (psia)	0.379 X 10^6 (55)	0.365 X 10^6 (53)
Proof pressure, N/m^2 (psia)	0.569 X 10^6 (82.5)	0.548 X 10^6 (79.5)
Burst pressure N/m^2 (psia)	0.758 X 10^6 (110)	0.731 X 10^6 (106)
Inlet temperature, ^{o}K (^{o}F)	348 (167)	423 (301)
Outlet temperaure, ^{o}K (^{o}F)	416 (289)	352 (174)
Weight (total), kg (lb) wet	7.44 (16.4)	
Dimensions, m (in.)	0.1524 (6) dia X 0.5271 (20.75)	
Availability	New	

ITEM 2.4 - HEATER-DESORBER

FUNCTION AND DESCRIPTION

The heater-desorber utilizes electrical power to provide the latent heat of evaporization to desorb the carbon dioxide from the amine solution.

The heater-desorber consists of a single-pass, single-core, plate-fin heat exchanger with strip heaters on both sides of the tube plates. The unit is of all stainless steel construction with 0.0019 m (0.075-in.) high fins. The fins are rectangular of 0.00254 m (0.1-in) offset, with 788 fins/m (20 fins/in.).

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0036 (28.57)
Max press drop, N/m^2 (psi)	0.00689 X 10^6 (1)
Max operating pressure, N/m^2 (psia)	0.345 X 10^6 (50)
Proof press, N/m^2 (psia)	0.517 X 10^6 (75)
Burst press, N/m^2 (psia)	0.690 X 10^6 (100)
Inlet temperature ^{o}K (^{o}F)	414 (285)
Outlet temperature, ^{o}K (^{o}F)	422 (300)
Weight, kg (lb)	0.27 (0.6)
Dimensions, m (in.)	0.00223 (0.087) X 0.0813 (3.2) X 0.305 (12)
Power, watts	519
Availability	New

APPENDIX A (Continued)

ITEM 2.5 - VAPOR SEPARATOR PUMP

FUNCTION AND DESCRIPTION

The vapor separator pump provides the necessary pressure rise to overcome the system pressure losses for both the liquid and desorbed vapors and gas as they exit from the heater-desorber.

The vapor-liquid mixture flows axially into a rotating drum which centrifugally separates the liquid from the gas. A stationary pitot tube at the outer radius of the rotating drum uses the kinetic velocity of the rotating liquid for the pumping head as it collects in the drum for circulation through the regenerative heat exchanger. The vapors flow through a series of baffles into a centrifugal fan and its diffuser to the condenser. The unit is magnetically coupled to the motor which it shares with the carbon dioxide separator pump. This motor is liquid cooled by the amine solution exiting from the cabin air separator pump.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0033 (26.482) liquid flow; 0.00026 (2.088) vapor flow; at 0.276 X 10^6 N/m^2 (40 psia) and 422°K (300°F)
Fan pressure rise, N/m^2 (in. H_2O)	1243 (5)
Pump pressure rise, N/m^2 (psia)	0.103 X 10^6 (15)
Max operating pressure, N/m^2 (psia)	0.379 X 10^6 (55)
Proof pressure, N/m^2 (psia)	0.569 X 10^6 (82.5)
Burst pressure, N/m^2 (psia)	0.758 X 10^6 (110)
Weight, kg (lb)	2.73 (6.02) Includes Item 2.8
Overall dimensions, m (in.)	0.0699 (2.75) dia X 0.203 (8.0) (includes Item 2.8)
Speed, rps	388
Power watts	10 (Includes Item 2.8)
Availability	New

ITEMS 2.6, 2.9, 2.11 and 2.17 - SHUTOFF VALVE

FUNCTION AND DESCRIPTION

The solenoid-operated shutoff valves are used to isolate various portions of the liquid amine solution during shutdown and also as a on-off control valve for the weak aqueous amine makeup solution.

This valve design is a latching solenoid type, which utilizes a slide-type port valve to control the fluid flow.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.048 (380.6)
Max pressure drop, N/m^2 (psi)	0.0138×10^6 (2)
Max operating pressure, N/m^2 (psia)	0.379×10^6 (55)
Proof pressure, N/m^2 (psia)	0.569×10^6 (82.5)
Burst pressure, N/m^2 (psia)	0.758×10^6 (110)
Max temperature, $^{\circ}K$ ($^{\circ}F$)	423 (301)
Weight, kg (lb)	1.09 (2.4)
Dimensions, m (in.)	0.1016 (4) X 0.1016 (4) X 0.0762 (3)
Power, watt	23 at 28 vdc
Availability	New

ITEMS 2.7, 2.10 and 2.12 - CHECK VALVE

FUNCTION AND DESCRIPTION

These check valves function to prevent flow reversal through the phase separators and complete flooding of the separators with liquid, upon system shutdown.

This design is a diaphragm-type check valve. The diaphragm is an umbrella shaped elastomer, slightly preloaded to seal at the outer periphery. If pressure is applied in the flow direction, the elastomer is forced away from the seat allowing the liquid to flow through the hole in the valve seat. A retainer prevents the valve from tearing away from its seat in the event that a high-pressure transient occurs in the flow direction.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.048 (380.6)
Max pressure drop, N/m^2 (psi)	0.0138×10^6 (2)
Max operating pressure, N/m^2 (psia)	0.379×10^6 (55)
Proof pressure, N/m^2 (psia)	0.569×10^6 (82.5)
Burst pressure, N/m^2 (psia)	0.758×10^6 (110)
Max temperature, °K (°F)	423 (301)
Weight, kg (lb)	0.14 (0.30)
Dimensions, m (in.)	0.0295 (1.16) dia X 0.0467 (1.84)
Availability	New

ITEM 2.8 - CARBON DIOXIDE SEPARATOR PUMP

FUNCTION AND DESCRIPTION

The carbon dioxide separator pump provides the necessary pressure rise to overcome the system pressure losses for both the liquid and uncondensed gas exiting from the vapor condenser.

The gas-liquid mixture flows axially into a rotating drum which centrifugally separates the liquid from the gas. A stationary pitot tube at the outer radius of the rotating drum uses the kinetic velocity of the rotating liquid for the pumping head as it collects in the drum for recirculation back to the absorber. The gases flow through a series of baffles into a centrifugal fan and its diffuser to the oxygen recovery system. The unit is magnetically coupled to the motor which it shares with the vapor separator-pump. This motor is liquid cooled by the amine solution exiting from the cabin air separator-pump.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.00016 (1.256) liquid flow 0.00010 (0.831) gas flow at 0.276 X 10^6 N/m^2 (40 psia) and 307°K (93°F)
Fan pressure rise, N/m^2 (in. H_2O)	497 (2)
Pump pressure rise, N/m^2 (psia)	0.103 X 10^6 (15)
Max operating pressure, N/m^2 (psia)	0.379 X 10^6 (55)
Proof pressure, N/m^2 (psig)	0.569 X 10^6 (82.5)
Burst pressure, N/m^2 (psig)	0.758 X 10^6 (110)
Weight, kg (lb)	2.73 (6.02) includes Item 2.5
Overall dimensions, m (in.)	0.0699 (2.75) dia X 0.203 (8.0) (Includes Item 2.5)
Speed, rps	388
Power, watts	10 (Includes Item 2.5)
Availability	New

APPENDIX A (Continued)

ITEM 2.13 - LIQUID RESERVOIR

FUNCTION AND DESCRIPTION

The liquid reservoir provides storage capacity for additional amine solution to compensate for minor leakage, system volumetric changes with temperature change, and to maintain a minimum liquid supply pressure for the absorber.

This unit is composed of two separate metallic bellows-type assemblies which act as a spring-loaded piston to move up or down as the system pressure fluctuates. It is identical to the Gemini coolant reservoir, AiResearch P/N 640230. There is continuous flow through this unit. Additional pressurizing force on the liquid is obtained by a trapped volume of a Freon-11/gas mixture on the opposite side of the bellows.

PERFORMANCE AND DESIGN DATA

Capacity, m^3 (cu. in.)	868 X 10^{-6} (53)
Design flow, kg/s (lb/hr)	0.0517 (410)
Max pressure drop, N/m^2 (psi)	0.004826 X 10^{-6} (0.7)
Max operating pressure, N/m^2 (psia)	0.379 X 10^{6} (55)
Proof pressure, N/m^2 (psia)	0.569 X 10^{6} (87.2)
Burst pressure, N/m^2 (psia)	0.758 X 10^{6} (110)
Inlet temperature, $^{\circ}$K ($^{\circ}$F)	303 (85)
Weight, kg (lb)	5.99 (13.2)
Dimensions, m (in.)	0.2096 (8.25) X 0.1359 (5.35) X 0.2896 (11.4)
Availability	P/N 640230

ITEM 2.14 - PRESSURE REGULATOR AND SHUTOFF VALVE

FUNCTION AND DESCRIPTION

The pressure regulator and shutoff valve maintains the liquid pressure to the absorber nozzle above 0.288 X 10^6 N/m^2 (41.7 psia) with the regulator being fully open at 0.343 X 10^6 N/m^2 (49.7 psig) at the rated flow of 0.0517 kg/s (410 lb/hr). The shutoff valve provides a means for isolating the absorber from the liquid portion of the system.

The design of this valve is similar to the Apollo water pressure relief valve. AiResearch P/N 827830-1, with an electrically actuated selector valve in lieu of the manual selector valve. The unit consists of two redundant, spring-loaded poppet valves, which allows flow through the valve when a differential pressure of 0.288 X 10^6 N/m^2 (41.7 psia) is sensed by the valve. An integral selector valve provides for: simultaneous operation of both poppet valves; single operation of either poppet valve; or complete shutoff of flow to both poppet valves.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0517 (410)
Control pressure, N/m^2 (psig)	0.288 X 10^6 (41.7)
Max operating pressure, N/m^2 (psia)	0.379 X 10^6 (55)
Proof pressure, N/m^2 (psia)	0.567 X 10^6 (82.5)
Burst pressure, N/m^2 (psia)	0.758 X 10^6 (110)
Inlet temperature, °K (°F)	303 (85)
Weight, kg (lb)	0.68 (1.5)
Dimensions, m (in.)	0.0508 (2) X 0.0762 (3) X 0.0889 (3.5)
Power, watts	28 at 28 vdc
Availability	New

ITEM 2.15 - ABSORBER

FUNCTION AND DESCRIPTION

The absorber is a packed column in which the cabin air and the three-component solution are contacted in a cocurrent flow arrangement. Carbon dioxide is removed from the air and absorbed in the solution. The liquid amine solution is sprayed into the absorber; the packing material to provide the mass transfer area is 0.0095 m (0.375 in.) stainless steel (100 mesh) McMahon saddles.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0286 (227) air 0.0517 (410) amine solution
CO_2 removal rate, kg/s (lb/hr)	0.000104 (0.825) of carbon dioxide from air containing 400 N/m^2 (3 mm Hg) carbon dioxide partial pressure
Max air pressure drop, N/m^2 (in. H_2O)	830 (3.5)
Max operating pressure, N/m^2 (psia)	0.103×10^6 (15)
Proof pressure, N/m^2 (psia)	0.207×10^6 (30)
Burst pressure, N/m^2 (psia)	0.414×10^6 (60)
Weight, kg (lb)	3.62 (8 lb)
Overall dimensions, m (in.)	0.165 (6.5) OD X 0.546 m (21.5)
Service media	Air and liquid amine solution
Power	0
Availability	New

ITEM 2.16 - FILL VALVE

FUNCTION AND DESCRIPTION

This quick disconnect fill valve is only used during ground servicing for charging the system with liquid amine solution.

The connection consists of the nipple half of a self-sealing-type, quick disconnect fluid coupling. This part is identical to AiResearch P/N 828350 developed for Project Apollo for use as a coolant fill valve.

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.0378 (300)
Max pressure drop, N/m^2 (psia)	0.03447×10^6 (5)
Max operating pressure, N/m^2 (psia)	0.414×10^6 (60)
Proof pressure, N/m^2 (psia)	0.621×10^6 (90)
Burst pressure, N/m^2 (psia)	0.827×10^6 (120)
Inlet temperature, ^oK (^oF)	311 (100)
Weight, kg (lb)	0.11 (0.25)
Dimensions, m (in.)	0.0339 (1.335) dia X 0.0682 (2.687)
Availability	Apollo P/N 828350

ITEM 2.18 - LIQUID LEVEL CONTROLLER

FUNCTION AND DESCRIPTION

The liquid level controller uses the signal from the liquid reservoir low-limit switch to modulate the makeup amine shutoff valve to refill the reservoir until cutoff by the reservoir high-limit switch.

The control is an electronic relay which furnishes power to the normally-closed, solenoid-operated shutoff valve. The control is triggered "ON" by the low-limit switch and triggered to the standby mode of operation by the high-limit switch.

PERFORMANCE AND DESIGN DATA

Output power, watts	23 at 28 vdc
Standby power, va	8
Input power, vac	115 at 400 Hz
Weight, kg (lb)	0.45 (1)
Dimensions, m (in.)	0.0917 (3.61) X 0.0594 (2.34) X 0.0572 (2.25)
Availability	Similar to Apollo P/N 820910 with higher output power

APPENDIX A (Continued)

ITEM 2.19 - LIQUID LEVEL INDICATOR

FUNCTION AND DESCRIPTION

The liquid level indicator is a part of the caution and warning system at the spacecraft operating console. A yellow indicator shows that the makeup liquid valve is open. A red indicator shows that the fluid reservoir is depleted.

The indicator is a space-qualified type with brightness control and press-to-test features.

PERFORMANCE AND DESIGN DATA

Weight, kg (lb)	0.057 (0.13)
Dimensions, m (in.)	0.025 (1) X 0.019 (0.75) X 0.056 (2.19)
Power, watts	2 max at 28 vdc
Availability	Space-qualified part available

ITEM 2.20 - OVERTEMPERATURE SWITCH

FUNCTION AND DESCRIPTION

The overtemperature switch automatically triggers shutdown of the desorber heater to prevent excessive temperature buildup in the liquid exiting from the desorber.

The unit consists of a solid state temperature sensor and switching element. The unit is mounted in the liquid line so that liquid flows around the temperature sensor. The Project Gemini thermal switch is suitable for this application with a change in material to stainless steel and a temperature setting of 436°K (325°F).

PERFORMANCE AND DESIGN DATA

Design flow, kg/s (lb/hr)	0.00334 (26.5)
Max pressure drop, N/m^2 (psi)	0.0138×10^6 (2)
Max operating pressure, N/m^2 (psia)	0.379×10^6 (55)
Proof pressure, N/m^2 (psia)	0.569×10^6 (82.5)
Burst pressure, N/m^2 (psia)	0.758×10^6 (110)
Max temperature, °K (°F)	450 (350)
Weight, kg (lb)	0.23 (0.5)
Dimensions, m (in.)	0.1321 (5.20) X 0.0533 (2.10) X 0.0295 (1.16)
Power, watts	0.70 at 28 vdc (ON) 700×10^{-6} at 28 vdc (OFF)
Availability	Modified P/N 646048

ITEM 2.21 - TEMPERATURE CONTROLLER

FUNCTION AND DESCRIPTION

The temperature controller uses the signal from the temperature sensor to maintain the desorber exit temperature at 422°K (300°F) by modulating the desorber heater input power.

Control achieved by an electronic relay which interrupts the input power to a normally "ON" electrically operated heater element. The controller is turned "OFF" by the over temperature switch and remains off until a reset button is pushed.

PERFORMANCE AND DESIGN DATA

Output power, watts	519 at 28 vdc
Standby power, vac	8
Input power, vac	115 at 400 Hz
Weight, lbs	0.45 (1)
Dimensions, m (in.)	0.0917 (3.61) X 0.0594 (2.34) 0.057 (2.25)
Availability	Similar to Apollo P/N 820190 with higher output power