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EVALUATION OF A LIQUID AMINE SYSTEM FOR SPACECRAFT CARBON DIOXIDE CONTROL


Unclas

74-10178
September 1974

Prepared Under Contract NAS1-11895

for

Ames Research Center
National Aeronautics and Space Administration

AIRESSEAR CH MANUFACTURING COMPANY OF CALIFORNIA
EVALUATION OF A LIQUID AMINE SYSTEM FOR SPACECRAFT CARBON DIOXIDE CONTROL

Final Report
by

74-10178
September 1974

Prepared Under Contract NAS1-11895

for
Ames Research Center
National Aeronautics and Space Administration

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA
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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EVALUATION OF A LIQUID AMINE SYSTEM
FOR SPACECRAFT CARBON DIOXIDE CONTROL

by D. K. Breaux, P. Friedel, K. C. Kwang, Ph.D.,
G. Probert, J. M. Ruder, and L. Sawamura

Heat Transfer and Cryogenic Systems Department
AIResearch Manufacturing Company
A Division of The Garrett Corporation

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/m² (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**

<table>
<thead>
<tr>
<th>CARBON DIOXIDE REMOVAL SYSTEM REQUIREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Men</td>
</tr>
<tr>
<td>( \text{CO}_2 ) rate, kg/s (lb/hr)</td>
</tr>
<tr>
<td>Cabin Environment:</td>
</tr>
<tr>
<td>Pressure, ( \text{N/m}^2 \times 10^{-3} )</td>
</tr>
<tr>
<td>Temperature, ( ^{\circ} \text{K} \left( ^{\circ} \text{F} \right) )</td>
</tr>
<tr>
<td>Dew Point, ( ^{\circ} \text{K} \left( ^{\circ} \text{F} \right) )</td>
</tr>
<tr>
<td>( \text{CO}_2 ) Partial Pressure, ( \text{N/m}^2 ) (mm Hg)</td>
</tr>
</tbody>
</table>
Figure 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 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 CO₂ 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt Percent</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Aminoethanol</td>
<td>24.7</td>
<td>Matheson Coleman Bell, Catalog No. TX-345</td>
</tr>
<tr>
<td>Tetrahydrothiophene 1, 1-dioxide</td>
<td>48.4</td>
<td>Matheson Coleman Bell, Catalog No. AX-905</td>
</tr>
<tr>
<td>Deionized water</td>
<td>26.9</td>
<td>-</td>
</tr>
</tbody>
</table>

*On a CO₂-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 CO₂-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-CO₂-cooled trap. The condensate weight was added to the final weight of the reaction mixture to determine the weight of CO₂ absorbed. Absorption capacity measurements results are given in Table 2-6.
### TABLE 2-2

**SPECIFIC GRAVITY**

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Solution (kg/m³)</th>
<th>CO₂-Saturated</th>
<th>CO₂-Free</th>
<th>Light Phase</th>
<th>Heavy Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>294 (70)</td>
<td>1130</td>
<td>1210</td>
<td>1230</td>
<td></td>
<td></td>
</tr>
<tr>
<td>311 (100)</td>
<td>1120</td>
<td>1140</td>
<td>1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>339 (150)</td>
<td>1110</td>
<td></td>
<td>1120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>367 (200)</td>
<td>1080</td>
<td></td>
<td>1110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>394 (250)</td>
<td>1060</td>
<td></td>
<td>1090</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 2-2

**VISCOSITY**

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Solution (m²/s)</th>
<th>CO₂-Saturated</th>
<th>CO₂-Free</th>
<th>Light Phase</th>
<th>Heavy Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>311 (100)</td>
<td>3.3 X 10⁻⁶</td>
<td>3.5 X 10⁻⁶</td>
<td>2.85 X 10⁻⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>339 (150)</td>
<td>1.7 X 10⁻⁶</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>367 (200)</td>
<td>1.0 X 10⁻⁶</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 2-4

**SPECIFIC HEAT**

<table>
<thead>
<tr>
<th>Temperature $^{\circ}K$ $^{(\circ)F}$</th>
<th>$\text{Cu}_2$-Free</th>
<th>CO$_2$-Saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Light Phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy Phase</td>
</tr>
<tr>
<td>311 ($^{100}$)</td>
<td>2530 (0.603)</td>
<td>3290 (0.784)</td>
</tr>
<tr>
<td>339 ($^{150}$)</td>
<td>2960 (0.706)</td>
<td>-</td>
</tr>
<tr>
<td>367 ($^{200}$)</td>
<td>3360 (0.802)</td>
<td>-</td>
</tr>
</tbody>
</table>

### TABLE 2-5

**THERMAL CONDUCTIVITY**

<table>
<thead>
<tr>
<th>Temperature $^{\circ}K$ $^{(\circ)F}$</th>
<th>$\text{CO}_2$-Free</th>
<th>CO$_2$-Saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Light Phase</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heavy Phase</td>
</tr>
<tr>
<td>300 ($^{80}$)</td>
<td>-</td>
<td>0.355 (0.205)</td>
</tr>
<tr>
<td>311 ($^{100}$)</td>
<td>0.139 (0.080)</td>
<td>-</td>
</tr>
<tr>
<td>339 ($^{150}$)</td>
<td>0.121 (0.070)</td>
<td>-</td>
</tr>
<tr>
<td>367 ($^{200}$)</td>
<td>0.116 (0.067)</td>
<td>-</td>
</tr>
<tr>
<td>CO₂ Partial Pressure, N/m² (mm Hg)</td>
<td>Weight-Percent Absorbed and (°K)</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>133 (1.0)</td>
<td>7.99 (301.1)</td>
<td>7.98 (313.2)</td>
</tr>
<tr>
<td>507 (3.8)</td>
<td>8.05 (300.2)</td>
<td>7.90 (311.5)</td>
</tr>
<tr>
<td>1013 (7.6)</td>
<td>8.09 (302.2)</td>
<td>7.12 (315.2)</td>
</tr>
<tr>
<td>3013 (22.6)</td>
<td>9.26 (300.9)</td>
<td>7.87 (312.15)</td>
</tr>
<tr>
<td>5066 (38.0)</td>
<td>9.38 (300.7)</td>
<td>8.63 (316.2)</td>
</tr>
<tr>
<td></td>
<td>9.23 (300.2)</td>
<td>8.73 (308.2)</td>
</tr>
</tbody>
</table>
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 evacuated. 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**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Pressure</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>OK °C (°F)</td>
<td>N/m$^2$</td>
<td>(mm HgA)</td>
</tr>
<tr>
<td>295 (72)</td>
<td>1970</td>
<td>14.8</td>
</tr>
<tr>
<td>311 (100)</td>
<td>5080</td>
<td>38.1</td>
</tr>
<tr>
<td>339 (150)</td>
<td>1730</td>
<td>130</td>
</tr>
<tr>
<td>367 (200)</td>
<td>5200</td>
<td>390</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Parameter</th>
<th>Value Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid amine flow rate</td>
<td>0.00252 to 0.00756 kg/s (20 to 60 lb/hr)</td>
</tr>
<tr>
<td>Air flow rate</td>
<td>0.00189 to 0.00566 m$^3$/s (4 to 12 scfm)</td>
</tr>
<tr>
<td>Liquid amine temperature</td>
<td>295°K (71°F)</td>
</tr>
<tr>
<td>Inlet CO$_2$ concentration</td>
<td>373 N/m$^2$ (2.8 mm Hg) partial pressure</td>
</tr>
<tr>
<td>Outlet CO$_2$ concentration</td>
<td>&lt; 373 N/m$^2$ (&lt;2.8 mm Hg) partial pressure</td>
</tr>
</tbody>
</table>
TABLE 2-8

VAPOR LIQUID EQUILIBRIUM CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Run Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Temperature, °K (°F)</td>
<td>422 (300)</td>
</tr>
<tr>
<td>Pressure, N/m² X 10⁻⁵ (psia)</td>
<td>2.76 (40)</td>
</tr>
<tr>
<td>Liquid, percent</td>
<td>85.0</td>
</tr>
<tr>
<td>Vapor, percent</td>
<td>15.0</td>
</tr>
<tr>
<td>Liquid composition, percent</td>
<td></td>
</tr>
<tr>
<td>Tetrahydrothiophene 1, 1-dioxide</td>
<td>52.8</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.7</td>
</tr>
<tr>
<td>2-Aminoethanol</td>
<td>26.6</td>
</tr>
<tr>
<td>Water</td>
<td>18.9</td>
</tr>
<tr>
<td>Vapor composition, percent</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>39.3</td>
</tr>
<tr>
<td>2-Aminoethanol</td>
<td>1.7</td>
</tr>
<tr>
<td>Water</td>
<td>59.0</td>
</tr>
</tbody>
</table>

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 CO₂-saturated solution contained approximately 7 percent CO₂
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 diatometer) 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 CO2 loadings in the liquid. These yielded 36 operating data points. During system checkout before these data points were obtained, the effect of varying inlet CO2 partial pressure and temperature were qualitatively evaluated as given in Table 2-11. Finally, after the prime series of tests were 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 CO2 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 CO2 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 CO2 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^-1m^-2 (1850 lb/hr-ft^2). This represents the upper limit that should be used in column design.

The major parameter that affects CO2 removal efficiency is the weight percent of CO2 in the liquid, as shown in Figure 2-5. Removal efficiency drops rapidly with increased CO2 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 CO2 removed is shown in Figure 2-6. At high CO2 levels in the liquid, the removal rate is quite low and is not strongly influenced by the air rate.
Figure 2-1. Co-current Absorber Test Setup Schematic
Figure 2-2. Test Setup
Figure 2-3. Cocurrent Absorber.
<table>
<thead>
<tr>
<th>Item No.</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oil Vapor Trap</td>
<td>Removes oil vapors from inlet air flow to prevent contamination.</td>
</tr>
<tr>
<td>2</td>
<td>Water Trap</td>
<td>Removes water droplets from inlet air flow.</td>
</tr>
<tr>
<td>3</td>
<td>VOL-O-FLO Air Flowmeter</td>
<td>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).</td>
</tr>
<tr>
<td>4</td>
<td>AP Gauge</td>
<td>Measures pressure drop across flowmeter-used with flow curve. Range, 0 to 2500 N/m² (10 in. H₂O), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>5</td>
<td>Pressure Gauge</td>
<td>Measures outlet pressure of flowmeter-used with flow curve. Range, 0 to 1.14 x 10⁶ N/m² (150 psig), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>6</td>
<td>Thermocouple</td>
<td>Connected to 24 channel recorder, measures outlet temperature of flowmeter-used with flow curve. Accuracy ±0.56 K (10°F) on readout.</td>
</tr>
<tr>
<td>7</td>
<td>Scales</td>
<td>Used to measure net quantity of CO₂ removed from CO₂ bottle. Range, 0 to 45 kg (100 lbs), smallest increment of measurement 0.0045 kg (0.0116) accuracy ±0.0045 kg (0.116).</td>
</tr>
<tr>
<td>8</td>
<td>CO₂ Bottle</td>
<td>Contains 0 to 9 kg (20 lbs) liquid CO₂.</td>
</tr>
<tr>
<td>9</td>
<td>VOL-o-FLO CO₂ Flowmeter</td>
<td>Measures gaseous CO₂ into the test setup. Range, 0 to 2.4 x 10⁵ m³/s (0.05 scfm) at 1 x 10⁵ N/m² (14.7 psia), total accuracy ±1 percent FS.</td>
</tr>
<tr>
<td>10</td>
<td>AP Gauge</td>
<td>Measures pressure drop across flowmeter-used with flow curve. Range, 0 to 2500 N/m² (10 in. H₂O), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>11</td>
<td>Pressure Gauge</td>
<td>Measures outlet pressure of flowmeter-used with flow curve. Range, 0 to 6.5 x 10⁵ N/m² (80 psig), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>Item No.</td>
<td>Component</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>12</td>
<td>Thermocouple</td>
<td>Connected to 24 channel recorder, measures outlet temperature of flowmeter—used with flow curve. Accuracy 0.56 °K (1°F) on readout.</td>
</tr>
<tr>
<td>13</td>
<td>Gas Mixing Chamber</td>
<td>Mixes the air and CO₂ gases.</td>
</tr>
<tr>
<td>14</td>
<td>Ice Bath</td>
<td>Removes moisture from sample gas entering CO₂ analyzer.</td>
</tr>
<tr>
<td>15</td>
<td>Flowmeter</td>
<td>Measures quantity of sample gas entering CO₂ analyzer. Range, 0 to 6.7 × 10⁻³ m³/s (400 sccm), total accuracy ±2 percent FS.</td>
</tr>
<tr>
<td>16</td>
<td>CO₂ Analyzer</td>
<td>Analyzes gas for partial pressure of CO₂. Beckman Model 315B. Range 0 to 1010 N/m³ (7.6 mm Hg), total accuracy ±3 percent FS.</td>
</tr>
<tr>
<td>17</td>
<td>Recorder</td>
<td>Records output of CO₂ analyzer. L and N Speedomax recorder. Range, 0 to 1300 N/m² (10 mm Hg CO₂).</td>
</tr>
<tr>
<td>18</td>
<td>Thermocouple</td>
<td>Connected to 24 channel recorder, measures temperature of gas exiting the absorber. Accuracy ±0.56 °K (±1°F) on readout.</td>
</tr>
<tr>
<td>19</td>
<td>Thermocouple</td>
<td>Connected to 24 channel recorder, measures temperature of gas entering the absorber. Accuracy ±0.56 °K (±1°F) on readout.</td>
</tr>
<tr>
<td>20</td>
<td>Thermocouple</td>
<td>Connected to 24 channel recorder, measures temperature of liquid amine entering the absorber. Accuracy ±0.56 °K (±1°F) on readout.</td>
</tr>
<tr>
<td>21</td>
<td>Pressure Gauge</td>
<td>Measures pressure of liquid amine entering absorber. Range, 0 to 1.1 × 10⁶ N/m² (150 psig), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>22</td>
<td>Pressure Gauge</td>
<td>Measures pressure of gas entering absorber. Range 0 to 6.9 × 10⁴ N/m² (10 psig), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>23</td>
<td>ΔP Gauge</td>
<td>Measures gas pressure drop across the absorber. Range 0 to 1.15 × 10⁴ N/m² (60 in. H₂O), total accuracy ±0.5 percent FS.</td>
</tr>
<tr>
<td>24</td>
<td>Spray Nozzle</td>
<td>Directs the liquid amine in a spray pattern over the absorber to increase wetting capability.</td>
</tr>
</tbody>
</table>
TABLE 2-10 (Continued)

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Absorber</td>
<td>Filled with McMahan packing (saddles) to produce a large wetted surface for exposure to the gas.</td>
</tr>
<tr>
<td>26</td>
<td>Liquid Collector</td>
<td>Collects the liquid amine after it passes through the absorber.</td>
</tr>
<tr>
<td>27</td>
<td>Water Bath</td>
<td>Cools the liquid amine to room ambient.</td>
</tr>
<tr>
<td>28</td>
<td>Liquid Amine Supply</td>
<td>0.02 m³ (5 gallons) Millipore supply can, stainless steel. Contains 0.02 m³ (5 gallons) of liquid amine.</td>
</tr>
<tr>
<td>29</td>
<td>Scales</td>
<td>Used to measure net quantity of liquid amine removed from can. Range 0 to 45 lb (100 lbs), smallest increment of measurement 0.0045 kg (0.01 lb), accuracy &lt;0.0045 kg (0.0116).</td>
</tr>
<tr>
<td>30</td>
<td>Recirculating Pump</td>
<td>Used to stir the amine in the supply can to maintain the proper mixture.</td>
</tr>
<tr>
<td>31</td>
<td>Pressure Gauge</td>
<td>Measures liquid amine supply pressure. Range, 0 to 1.5 x 10⁶ N/m² (200 psig), total accuracy ±5 percent FS.</td>
</tr>
<tr>
<td>32</td>
<td>Thermocouple</td>
<td>Connected to 24 channel recorder, measures temperature of liquid amine in tank. Accuracy ±0.56°C (±1°F) on readout.</td>
</tr>
<tr>
<td>33</td>
<td>Flow Measuring Device</td>
<td>Measures the quantity of liquid amine flowing from the tank. The flowmeter is a flow 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.</td>
</tr>
<tr>
<td>34</td>
<td>Ambient Thermocouple</td>
<td>Connected to temperature readout, measures temperature of ambient air. Accuracy ±0.56°C (±1°F) on readout.</td>
</tr>
<tr>
<td>35</td>
<td>Temperature Readout</td>
<td>Connected to ambient thermocouple or other thermocouples as required. Accuracy ±0.56°C (±1°F).</td>
</tr>
<tr>
<td>36</td>
<td>Temperature Recorder</td>
<td>24 Channel recorder for recording temperature from thermocouples.</td>
</tr>
</tbody>
</table>

NOTE: "Total Accuracy" is the stated accuracy of the instrument plus the hysteresis and repeatability.
## Perforrmance Test With McMahon Saddles

<table>
<thead>
<tr>
<th>CO₂ In Liquid Rate (kg/s x 10⁴)</th>
<th>Liquid Rate (gpm x 10⁴)</th>
<th>Air Rate (SCFM)</th>
<th>Bed ΔP (In. H₂O)</th>
<th>CO₂ Partial Pressure (kPa)</th>
<th>CO₂ Removal Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>7.81 (62.0)</td>
<td>5.66 (12.0)</td>
<td>2.1 (8.5)</td>
<td>3.73 (2.8)</td>
<td>1.67 (1.25)</td>
</tr>
<tr>
<td>1.5</td>
<td>7.66 (60.0)</td>
<td>3.72 (7.89)</td>
<td>1.1 (4.5)</td>
<td>3.73 (2.8)</td>
<td>1.20 (0.9)</td>
</tr>
<tr>
<td>1.5</td>
<td>7.56 (60.0)</td>
<td>1.91 (4.05)</td>
<td>0.37 (1.5)</td>
<td>3.60 (2.7)</td>
<td>0.47 (0.35)</td>
</tr>
<tr>
<td>1.5</td>
<td>2.43 (19.3)</td>
<td>1.89 (4.01)</td>
<td>0.25 (1.0)</td>
<td>3.60 (2.7)</td>
<td>0.47 (0.35)</td>
</tr>
<tr>
<td>1.5</td>
<td>2.46 (19.5)</td>
<td>3.68 (7.80)</td>
<td>0.87 (3.9)</td>
<td>3.87 (2.9)</td>
<td>1.27 (0.95)</td>
</tr>
<tr>
<td>1.5</td>
<td>2.58 (20.5)</td>
<td>3.76 (12.2)</td>
<td>1.9 (7.5)</td>
<td>3.60 (2.7)</td>
<td>1.73 (1.3)</td>
</tr>
<tr>
<td>1.5</td>
<td>5.04 (40.0)</td>
<td>5.71 (12.1)</td>
<td>2.0 (8.0)</td>
<td>3.67 (2.75)</td>
<td>1.67 (1.25)</td>
</tr>
<tr>
<td>1.5</td>
<td>4.91 (39.0)</td>
<td>3.73 (7.90)</td>
<td>1.0 (4.0)</td>
<td>3.73 (2.8)</td>
<td>1.20 (0.9)</td>
</tr>
<tr>
<td>1.5</td>
<td>4.83 (38.3)</td>
<td>1.91 (4.05)</td>
<td>0.25 (1.0)</td>
<td>3.60 (2.7)</td>
<td>0.93 (0.7)</td>
</tr>
<tr>
<td>3.0</td>
<td>2.52 (20.0)</td>
<td>1.91 (4.05)</td>
<td>0.25 (1.0)</td>
<td>3.60 (2.7)</td>
<td>0.73 (0.55)</td>
</tr>
<tr>
<td>3.0</td>
<td>4.91 (39.0)</td>
<td>1.92 (4.06)</td>
<td>0.25 (1.0)</td>
<td>3.60 (2.7)</td>
<td>0.47 (0.35)</td>
</tr>
<tr>
<td>3.0</td>
<td>7.31 (58.0)</td>
<td>1.88 (3.98)</td>
<td>0.37 (1.5)</td>
<td>3.67 (2.75)</td>
<td>0.47 (0.35)</td>
</tr>
<tr>
<td>3.0</td>
<td>2.62 (20.0)</td>
<td>3.69 (7.81)</td>
<td>0.87 (3.5)</td>
<td>3.80 (2.86)</td>
<td>1.87 (1.4)</td>
</tr>
<tr>
<td>3.0</td>
<td>4.85 (38.5)</td>
<td>3.66 (7.75)</td>
<td>1.0 (4.0)</td>
<td>3.80 (2.85)</td>
<td>1.60 (1.2)</td>
</tr>
<tr>
<td>3.0</td>
<td>7.09 (56.0)</td>
<td>3.69 (7.81)</td>
<td>1.1 (4.5)</td>
<td>3.80 (2.85)</td>
<td>1.60 (1.2)</td>
</tr>
<tr>
<td>3.0</td>
<td>2.58 (20.5)</td>
<td>5.62 (11.9)</td>
<td>1.5 (6.0)</td>
<td>3.73 (2.80)</td>
<td>2.66 (2.0)</td>
</tr>
<tr>
<td>3.0</td>
<td>4.71 (37.5)</td>
<td>5.62 (11.9)</td>
<td>1.9 (7.5)</td>
<td>3.64 (2.73)</td>
<td>2.27 (1.7)</td>
</tr>
<tr>
<td>3.0</td>
<td>6.87 (44.5)</td>
<td>5.62 (11.9)</td>
<td>2.1 (8.5)</td>
<td>3.60 (2.70)</td>
<td>2.07 (1.53)</td>
</tr>
<tr>
<td>5.0</td>
<td>2.47 (19.6)</td>
<td>1.92 (4.06)</td>
<td>0.25 (1.0)</td>
<td>3.81 (2.86)</td>
<td>2.07 (1.55)</td>
</tr>
<tr>
<td>5.0</td>
<td>4.83 (38.3)</td>
<td>1.92 (4.06)</td>
<td>0.37 (1.5)</td>
<td>3.81 (2.86)</td>
<td>1.73 (1.30)</td>
</tr>
<tr>
<td>5.0</td>
<td>7.31 (58.0)</td>
<td>1.91 (4.05)</td>
<td>0.37 (1.5)</td>
<td>3.93 (2.95)</td>
<td>1.67 (1.25)</td>
</tr>
<tr>
<td>5.0</td>
<td>2.58 (20.5)</td>
<td>3.72 (7.90)</td>
<td>1.0 (4.0)</td>
<td>3.84 (2.88)</td>
<td>2.80 (2.1)</td>
</tr>
<tr>
<td>5.0</td>
<td>4.90 (39.1)</td>
<td>3.75 (7.95)</td>
<td>1.1 (4.5)</td>
<td>3.79 (2.84)</td>
<td>2.53 (1.9)</td>
</tr>
<tr>
<td>5.0</td>
<td>7.56 (60.0)</td>
<td>3.75 (7.95)</td>
<td>1.2 (5.0)</td>
<td>3.75 (2.81)</td>
<td>2.47 (1.85)</td>
</tr>
<tr>
<td>5.0</td>
<td>2.47 (19.6)</td>
<td>5.76 (12.2)</td>
<td>2.0 (8.0)</td>
<td>3.65 (2.74)</td>
<td>2.87 (2.15)</td>
</tr>
<tr>
<td>5.0</td>
<td>5.04 (40.0)</td>
<td>5.76 (12.2)</td>
<td>2.2 (9.0)</td>
<td>3.65 (2.74)</td>
<td>2.77 (2.08)</td>
</tr>
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| CO₂ In Liquid St. | Liquid Rate kg/s x 10^4 (lb/hr) | Air Rate m³/s x 10^3 (SCFM) | Bed ΔP N/m² x 10⁻² (in. H₂O) | CO₂ Parti., Pressure N/m² x 10⁻² (mm Hg) | CO₂ Removal Efficiency | }

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<td>3.60 (2.7)</td>
<td>3.27 (2.45)</td>
<td>9.3</td>
</tr>
</tbody>
</table>

(1) Estimated at 3-4''
(2) Estimated at 1.8-2.5'
Figure 2-4. Cocurrent Absorber Removal Efficiency
Figure 2-5. Effect of CO₂ Absorbed in Liquid

AIR RATE
1.9 M³/S

3.8 M³/S

5.7 M³/S

LIQUID AMINE RATE = 0.0047 TO 0.0050 kg/s

WEIGHT PERCENT CO₂ IN LIQUID
Figure 2-6. CO₂ Removal Rate
The advantage of McMahon over Berl saddles for column packing is shown in Figure 2-7. Although the CO₂ 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.
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 adaptation 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) | $1.04 \times 10^{-4}$ (0.825) |
| Cabin environment |
| Pressure, N/m$^2 \times 10^{-3}$ (psia) | 101 (14.7) |
| Temperature, °K (°F) | 298 (75) |
| Dew Point, °K (°F) | 284 (50) |
| CO$_2$ Partial pressure, N/m$^2$ (mm Hg) | 400 (3) |
Figure 3-1 CO₂ 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-ft²) 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 x 10⁻⁶ m³/s (0.05 cfm) and a pressure ratio 1.5 or greater requires a small positive displacement compressor or a centrifugal 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°C (780 and 796°F) at a constant desorption pressure of 2.75 x 10⁵ N/m² (40 psia). The higher desorption temperature of 422°C (796°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.
Figure 3-2. Absorber Design Conditions

NOMINAL AIR VELOCITY = 0.939 m/s
(3.08 ft/sec)

LIQUID FLUX = 2.51 kg s⁻¹ m⁻² (1850 lb/hr-FT²)
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 \(3.1 \times 10^5\) N/m\(^2\) (45 psia). With the desorber operating condition established at \(2.75 \times 10^5\) N/m\(^2\) (40 psia) and 422\(^\circ\)K (300\(^\circ\)F), there is only a difference of \(3.4 \times 10^4\) 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.
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:

<table>
<thead>
<tr>
<th>Valve</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Loop Shutoff (1.1, 1.3)</td>
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</tr>
<tr>
<td>Bypass (Item 1.2)</td>
<td>Open</td>
</tr>
<tr>
<td>Pressure Regulator and Shutoff Valve (Item 1.4)</td>
<td>Closed</td>
</tr>
<tr>
<td>Vent Valve (Item 1.5)</td>
<td>Open</td>
</tr>
<tr>
<td>Liquid Shutoff Valves (Items 2.6, 2.9, 2.11)</td>
<td>Open</td>
</tr>
</tbody>
</table>

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 open.

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 make up 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/m² (3 mm Hg), 0.0236 m³/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/m² (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/m² (5 in. of H₂O) 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**

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**Outlet and Outlet Conditions (STP, mol/L)**

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<td>-</td>
<td>-</td>
<td>12 x 10⁻⁴</td>
</tr>
<tr>
<td>H₂S, lb/hr</td>
<td>-</td>
<td>5 x 10⁻⁵</td>
<td>7 x 10⁻⁵</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
(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


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.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0287 (228) minimum with 302°K (83°F) air at sea level</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (in H₂O)</td>
<td>75 (0.3) at design flow</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.103 x 10⁶ (15)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.207 x 10⁶ (30)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.414 x 10⁶ (60)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>1.41 (3.1)</td>
</tr>
<tr>
<td>Overall dimensions, m (in.)</td>
<td>0.178 (7) x 0.178 (7) x 0.152 (6)</td>
</tr>
<tr>
<td>Service media</td>
<td>Air</td>
</tr>
<tr>
<td>Power, watts</td>
<td>28 at 28 vdc</td>
</tr>
<tr>
<td>Availability</td>
<td>Modified Gemini valve</td>
</tr>
</tbody>
</table>
APPENDIX A (Continued)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0287 (228) minimum with 302K (83°F) air at sea level</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (in H₂O)</td>
<td>75 (0.3) at design flow</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.103 X 10⁶ (15)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.207 X 10⁶ (30)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.414 X 10⁶ (60)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>1.41 (3.1)</td>
</tr>
<tr>
<td>Overall dimensions, m (in.)</td>
<td>0.178 (7) X 0.178 (7) X 0.152 (6)</td>
</tr>
<tr>
<td>Service media</td>
<td>Air</td>
</tr>
<tr>
<td>Power, watts</td>
<td>28 at 28 vdc</td>
</tr>
<tr>
<td>Availability</td>
<td>Modified Gemini valve</td>
</tr>
</tbody>
</table>
APPENDIX A (Continued)

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 \times 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 \times 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

<table>
<thead>
<tr>
<th>Design flow, kg/s (lb/hr)</th>
<th>1.04 \times 10^{-4} (0.83) at a temperature of 330^oK (134^oF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control pressure, N/m^2 (psia)</td>
<td>0.262 \times 10^6 \pm 0.0207 \times 10^6 (38)</td>
</tr>
<tr>
<td>Proof pressure, N/m^2 (psia)</td>
<td>0.393 \times 10^6 (57)</td>
</tr>
<tr>
<td>Burst pressure, N/m^2 (psia)</td>
<td>0.524 \times 10^6 (76)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>0.68 (1.5)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.0508 (2) \times 0.0762 (3) \times 0.0889 (3.5)</td>
</tr>
<tr>
<td>Power, watts</td>
<td>28 at 28 vdc</td>
</tr>
<tr>
<td>Service media</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>

48
**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, AlResearch 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**

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0516 (409.2) liquid flow</td>
</tr>
<tr>
<td></td>
<td>0.0287 (227.7) air flow at 0.101 X 10^6 N/m² (14.7 psia) and 299 K (78°F)</td>
</tr>
<tr>
<td>Fan pressure rise, N/m² (in. H₂O)</td>
<td>1243 (5)</td>
</tr>
<tr>
<td>Pump pressure rise, N/m² (psia)</td>
<td>0.177 X 10^6 (25.6)</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.278 X 10^6 (40.3)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.417 X 10^6 (60)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.556 X 10^6 (80.6)</td>
</tr>
<tr>
<td>Weight, lb (kg)</td>
<td>8.16 (18)</td>
</tr>
<tr>
<td>Overall dimensions, m (in.)</td>
<td>0.2032 (8) dia X 0.2794 (11)</td>
</tr>
<tr>
<td>Speed, rps</td>
<td>95.8</td>
</tr>
<tr>
<td>Power, watts</td>
<td>165</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
**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**

<table>
<thead>
<tr>
<th></th>
<th>Cold Side</th>
<th>Hot Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0036 (28.57) 0.00026 (2.088)</td>
<td></td>
</tr>
<tr>
<td>Max pressure drop, N/m² (psi)</td>
<td>3450 (0.5) 13800 (2.0)</td>
<td></td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.3791 X 10⁶ (55) 0.276 X 10⁶ (40)</td>
<td></td>
</tr>
<tr>
<td>Proof pressure, N/m²</td>
<td>0.569 X 10⁶ (82.5) 0.414 X 10⁶ (60)</td>
<td></td>
</tr>
<tr>
<td>Burst pressure, N/m²</td>
<td>0.758 X 10⁶ (110) 0.552 X 10⁶ (80)</td>
<td></td>
</tr>
<tr>
<td>Inlet temperature, °K (°F)</td>
<td>299 (79) 449 (349)</td>
<td></td>
</tr>
<tr>
<td>Outlet temperature, °K (°F)</td>
<td>348 (167) 307 (93)</td>
<td></td>
</tr>
<tr>
<td>Weight, kg (lb) wet</td>
<td>5.72 (12.6)</td>
<td></td>
</tr>
<tr>
<td>Overall dimensions, m (In.)</td>
<td>0.2286 (9) dia x 0.5009 (19.72)</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>Cold Side</th>
<th>Hot Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0036 (28.57)</td>
<td>0.0033 (26.482)</td>
</tr>
<tr>
<td>Pressure drop, N/m² (psi)</td>
<td>0.0276 X 10⁶ (4)</td>
<td>0.00689 X 10⁶ (1)</td>
</tr>
<tr>
<td>Operating pressure, N/m² (psia)</td>
<td>0.379 X 10⁶ (55)</td>
<td>0.365 X 10⁶ (53)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.569 X 10⁶ (82.5)</td>
<td>0.548 X 10⁶ (79.5)</td>
</tr>
<tr>
<td>Burst pressure N/m² (psia)</td>
<td>0.758 X 10⁶ (110)</td>
<td>0.731 X 10⁶ (106)</td>
</tr>
<tr>
<td>Inlet temperature, °K (°F)</td>
<td>348 (167)</td>
<td>423 (301)</td>
</tr>
<tr>
<td>Outlet temperature, °K (°F)</td>
<td>416 (289)</td>
<td>352 (174)</td>
</tr>
<tr>
<td>Weight (total), kg (lb) wet</td>
<td>7.44 (16.4)</td>
<td></td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.1524 (6) dia X 0.5271 (20.75)</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX A (continued)

ITEM 2.4 - HEATER-DESORBER

FUNCTION AND DESCRIPTION

The heater-desorber utilizes electrical power to provide the latent heat of evaporation 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0036 (28.57)</td>
</tr>
<tr>
<td>Max press drop, N/m^2 (psi)</td>
<td>0.00689 \times 10^6 (1)</td>
</tr>
<tr>
<td>Max operating pressure, N/m^2 (psia)</td>
<td>0.345 \times 10^6 (50)</td>
</tr>
<tr>
<td>Proof press, N/m^2 (psia)</td>
<td>0.517 \times 10^6 (75)</td>
</tr>
<tr>
<td>Burst press, N/m^2 (psia)</td>
<td>0.690 \times 10^6 (100)</td>
</tr>
<tr>
<td>Inlet temperature °K (°F)</td>
<td>414 (285)</td>
</tr>
<tr>
<td>Outlet temperature, °K (°F)</td>
<td>422 (300)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>0.27 (0.6)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.00223 (0.087) X 0.0813 (3.2) X 0.305 (12)</td>
</tr>
<tr>
<td>Power, watts</td>
<td>519</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Design flow, kg/s (lb/hr)</th>
<th>0.0033 (26.482) liquid flow; 0.00026 (2.088) vapor flow; at 0.276 $\times 10^6$ N/m$^2$ (40 psia) and 422°F (300°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan pressure rise, N/m$^2$ (in. H$_2$O)</td>
<td>1243 (5)</td>
</tr>
<tr>
<td>Pump pressure rise, N/m$^2$ (psia)</td>
<td>0.103 $\times 10^6$ (15)</td>
</tr>
<tr>
<td>Max operating pressure, N/m$^2$ (psia)</td>
<td>0.379 $\times 10^6$ (55)</td>
</tr>
<tr>
<td>Proof pressure, N/m$^2$ (psia)</td>
<td>0.569 $\times 10^6$ (82.5)</td>
</tr>
<tr>
<td>Burst pressure, N/m$^2$ (psia)</td>
<td>0.758 $\times 10^6$ (110)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>2.73 (6.02) Includes Item 2.8</td>
</tr>
<tr>
<td>Overall dimensions, m (in.)</td>
<td>0.0699 (2.75) dia X 0.203 (8.0) (includes Item 2.8)</td>
</tr>
<tr>
<td>Speed, rps</td>
<td>388</td>
</tr>
<tr>
<td>Power watts</td>
<td>10 (Includes Item 2.8)</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>

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APPENDIX A (Continued)

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 an 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.048 (380.6)</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (psi)</td>
<td>0.0138 X 10⁶ (2)</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.379 X 10⁶ (55)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.569 X 10⁶ (82.5)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.758 X 10⁶ (110)</td>
</tr>
<tr>
<td>Max temperature, °K (°F)</td>
<td>423 (301)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>1.09 (2.4)</td>
</tr>
<tr>
<td>Dimensions, m (In.)</td>
<td>0.1016 (4) X 0.1016 (4) X 0.0762 (3)</td>
</tr>
<tr>
<td>Power, watt</td>
<td>23 at 28 vdc</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.048 (380.6)</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (psi)</td>
<td>0.0138 X 10⁶ (2)</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.379 X 10⁶ (55)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.569 X 10⁶ (82.5)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.758 X 10⁶ (110)</td>
</tr>
<tr>
<td>Max temperature, °K (°F)</td>
<td>423 (301)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>0.14 (0.30)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.0295 (1.16) dia X 0.0467 (1.84)</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
APPENDIX A (Continued)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.00016 (1.256) liquid flow</td>
</tr>
<tr>
<td></td>
<td>0.00010 (0.831) gas flow at 0.276 X 10^6 N/m^2 (40 psia) and 307°K (93°F)</td>
</tr>
<tr>
<td>Fan pressure rise, N/m^2 (in. H_2O)</td>
<td>497 (2)</td>
</tr>
<tr>
<td>Pump pressure rise, N/m^2 (psia)</td>
<td>0.103 x 10^6 (15)</td>
</tr>
<tr>
<td>Max operating pressure, N/m^2 (psia)</td>
<td>0.379 x 10^6 (55)</td>
</tr>
<tr>
<td>Proof pressure, N/m^2 (psig)</td>
<td>0.569 x 10^6 (82.5)</td>
</tr>
<tr>
<td>Burst pressure, N/m^2 (psig)</td>
<td>0.758 x 10^6 (110)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>2.73 (6.02) includes Item 2.5</td>
</tr>
<tr>
<td>Overall dimensions, m (in.)</td>
<td>0.0699 (2.75) dia x 0.203 (8.0) (Includes Item 2.5)</td>
</tr>
<tr>
<td>Speed, rps</td>
<td>388</td>
</tr>
<tr>
<td>Power, watts</td>
<td>10 (Includes Item 2.5)</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
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-II/gas mixture on the opposite side of the bellows.

PERFORMANCE AND DESIGN DATA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity, m³ (cu. in.)</td>
<td>868 X 10^-6 (53)</td>
</tr>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0517 (410)</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (psi)</td>
<td>0.004826 X 10^-6 (0.7)</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.379 X 10^6 (55)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.569 X 10^6 (87.2)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.758 X 10^6 (110)</td>
</tr>
<tr>
<td>Inlet temperature, °K (°F)</td>
<td>303 (85)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>5.99 (13.2)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.2096 (8.25) X 0.1359 (5.35) X 0.2896 (11.4)</td>
</tr>
<tr>
<td>Availability</td>
<td>P/N 640230</td>
</tr>
</tbody>
</table>
APPENDIX A (Continued)

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 $0.288 \times 10^6\ \text{N/m}^2$ (41.7 psia) with the regulator being fully open at $0.343 \times 10^6\ \text{N/m}^2$ (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 $0.288 \times 10^6\ \text{N/m}^2$ (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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0517 (410)</td>
</tr>
<tr>
<td>Control pressure, N/m$^2$ (psig)</td>
<td>$0.288 \times 10^6$ (41.7)</td>
</tr>
<tr>
<td>Max operating pressure, N/m$^2$ (psia)</td>
<td>$0.379 \times 10^6$ (55)</td>
</tr>
<tr>
<td>Proof pressure, N/m$^2$ (psia)</td>
<td>$0.567 \times 10^6$ (82.5)</td>
</tr>
<tr>
<td>Burst pressure, N/m$^2$ (psia)</td>
<td>$0.758 \times 10^6$ (110)</td>
</tr>
<tr>
<td>Inlet temperature, °K (°F)</td>
<td>303 (85)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>0.68 (1.5)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.0508 (2) x 0.0762 (3) x 0.0889 (3.5)</td>
</tr>
<tr>
<td>Power, watts</td>
<td>28 at 28 vdc</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
APPENDIX A (Continued)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0286 (227) air</td>
</tr>
<tr>
<td></td>
<td>0.0517 (410) amine solution</td>
</tr>
<tr>
<td>CO₂ removal rate, kg/s (lb/hr)</td>
<td>0.000104 (0.825) of carbon dioxide from air containing 400 N/m² (3 mm Hg) carbon dioxide partial pressure</td>
</tr>
<tr>
<td>Max air pressure drop, N/m² (in. H₂O)</td>
<td>830 (3.5)</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.103 X 10⁶ (15)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.207 X 10⁶ (30)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.414 X 10⁶ (60)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>3.62 (8 lb)</td>
</tr>
<tr>
<td>Overall dimensions, m (in.)</td>
<td>0.165 (6.5) OD X 0.546 m (21.5)</td>
</tr>
<tr>
<td>Service media</td>
<td>Air and liquid amine solution</td>
</tr>
<tr>
<td>Power</td>
<td>0</td>
</tr>
<tr>
<td>Availability</td>
<td>New</td>
</tr>
</tbody>
</table>
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 AirResearch P/N 828350 developed for Project Apollo for use as a coolant fill valve.

PERFORMANCE AND DESIGN DATA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.0378 (300)</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (psia)</td>
<td>0.03447 X 10⁶ (5)</td>
</tr>
<tr>
<td>Max operating pressure, N/m² (psia)</td>
<td>0.414 X 10⁶ (60)</td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.621 X 10⁶ (90)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.827 X 10⁶ (120)</td>
</tr>
<tr>
<td>Inlet temperature, °K (°F)</td>
<td>311 (100)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>0.11 (0.25)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.0339 (1.335) die X 0.0682 (2.687)</td>
</tr>
<tr>
<td>Availability</td>
<td>Apollo P/N 828350</td>
</tr>
</tbody>
</table>
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

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

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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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design flow, kg/s (lb/hr)</td>
<td>0.00334 (26.5)</td>
</tr>
<tr>
<td>Max pressure drop, N/m² (psi)</td>
<td>0.0138 X 10⁶ (2)</td>
</tr>
<tr>
<td>Max operating pressure, N/m²</td>
<td>0.379 X 10⁶ (55)</td>
</tr>
<tr>
<td>Max operating pressure, psia</td>
<td></td>
</tr>
<tr>
<td>Proof pressure, N/m² (psia)</td>
<td>0.569 X 10⁶ (82.5)</td>
</tr>
<tr>
<td>Burst pressure, N/m² (psia)</td>
<td>0.758 X 10⁶ (110)</td>
</tr>
<tr>
<td>Max temperature, °K (°F)</td>
<td>450 (350)</td>
</tr>
<tr>
<td>Weight, kg (lb)</td>
<td>0.23 (0.5)</td>
</tr>
<tr>
<td>Dimensions, m (in.)</td>
<td>0.1321 (5.20) X 0.0533 (2.10) X 0.0295 (1.16)</td>
</tr>
<tr>
<td>Power, watts</td>
<td>0.70 at 28 vdc (ON) X 700 X 10⁻⁶ at 28 vdc (OFF)</td>
</tr>
<tr>
<td>Availability</td>
<td>Modified P/N 646048</td>
</tr>
</tbody>
</table>
APPENDIX A (Continued)
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°F (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

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