LSI TR-875-9

REFURBISHMENT OF ONE-PERSON REGENERATIVE AIR REVITALIZATION SYSTEM

FINAL REPORT

by

F. T. Powell

March, 1989

Prepared Under Contract NAS8-36435

by

Life Systems, Inc.
Cleveland, OH 44122

for

MARSHALL SPACE FLIGHT CENTER
National Aeronautics and Space Administration

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FOREWORD

The work described herein was conducted by Life Systems, Inc. at Cleveland, Ohio under Contract No. NAS8-36435 during the period July 22, 1985 through April 3, 1989. The program consisted of several discreet tasks involving many individuals. The program manager was Ferolyn T. Powell. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Jeff H. Birkel	Software Design, Test Support
Robert B. Boyda	Engineering Support
Charles T. Bunnell	Engineering and Test Support
Steve Czernec	Mechanical System/Test Support Accessories Assembly
Robert W. Ellacott	Mechanical System/Test Support Accessories Assembly
Jeff R. Hanck	Test Support
Steve P. Hendrix	Software Design, Test Support
Dennis B. Heppner, Ph.D.	Electronic Hardware Design
John O. Jessup	Electronic Assembly and Test Support
Don W. Johnson	Electronic Assembly and Test Support
Joann L. Kandrac	Documentation
James M. Khoury	Electronic Hardware Design and Test Support
Andrew J. Kovach	Engineering and Test Support
M. Gene Lee	Engineering Support
Edward S. Mallinak	Software Design, Test Support
Larry D. Noble	Engineering Support
Ferolyn T. Powell	Program Management and Engineering Support
James D. Powell	Software Design and Test Support
Michael Prokopcak	Design Drafting Support
Dorothy A. Ruschak	Contract Administration
Franz H. Schubert	Engineering Support
Martin Sudar	Engineering and Test Support
Dennis S. Szulinski	Mechanical System/Test Support Accessories Assembly

The contract's Technical Monitor was Dr. Randy Humphries, Chief, Environmental Control and Life Support Branch, National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama.

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LIST OF ACRONYMS

CMIF	Core Module Integrated Facility
ECLSS	Environmental Control and Life Support System
EDC	Electrochemical CO_2 Concentrator
EDCM	Electrochemical Carbon Dioxide Concentrator Module
LEL	Lower Explosive Level
NASA	National Aeronautics and Space Administration
SFE	Static Feed Electrolyzer
VCDS	Vapor Compression Distillation Subsystem

SUMMARY

Regenerative processes for the revitalization of spacecraft atmospheres and reclamation of wastewaters are essential for making long-term manned space missions a reality. Several of these regenerative processes are being developed by Life Systems, Inc. and tested at Marshall Space Flight Center. Processes supported under this contract include Static Feed Water Electrolysis for oxygen generation, Bosch Carbon Dioxide Reduction, Electrochemical Carbon Dioxide Concentration, Vapor Compression Distillation water recovery, and iodine monitoring. The objectives of the present program were to:

1. Provide engineering support to Marshall Space Flight Center personnel throughout all phases of the test program, e.g., planning through data analysis.
2. Fabricate, test and deliver to Marshall Space Flight Center an electrochemical carbon dioxide module and test stand.
3. Fabricate and deliver an Iodine Monitor.
4. Evaluate the electrochemical carbon dioxide concentrator subsystem configuration and its ability to ensure safe utilization of hydrogen gas.
5. Evaluate techniques for recovering oxygen from a product oxygen and carbon dioxide stream.
6. Evaluate the performance of an electrochemical carbon dioxide concentrator module to operate without hydrogen as a method of safe haven operation.

All of these objectives were met. Several discreet tasks were completed under the present program. Each of these tasks were related in that they all focused on providing a better understanding of the function, operation and performance of developmental pieces of environmental control and life support system hardware.

ACCOMPLISHMENTS

The key program accomplishments were as follows:

1. Fabricated and delivered a one-person liquid cooled Electrochemical Carbon Dioxide (CO_2) Concentrator Module (EDCM).
2. Fabricated and delivered a liquid cooled EDCM characterization and endurance test stand.
3. Completed over 12,000 hours of EDCM operation.
4. Fabricated and delivered a compact, lightweight iodine (I_2) monitor.
5. Provided engineering support for Life Systems, Inc.'s (Life Systems) developed Environmental Control and Life Support System (ECLSS) hardware at Marshall Space Flight Center (MSFC), including the following:
    - Static Feed Electrolyzer (SFE) Subsystem
    - Vapor Compression Distillation Subsystem (VCDS)
    - Bosch CO_2 Reduction Subsystem (Bosch)
    - Iodine Monitor
6. Converted the EDCM test stand to enable operation of the EDCM in either with hydrogen (H_2) or without H_2 operating modes.
7. Completed failure mode testing of the Electrochemical CO_2 Concentrator (EDC) subsystem and identified that the procedures necessary for safe operation of an EDC are the same as those required for any other subsystem that utilizes a combustible gas. Specifically, the keys to failsafe operation are ventilation and detection.
8. Identified and evaluated several options for recovering oxygen (O_2) from product CO_2 when the EDC is run in the without H_2 mode.

INTRODUCTION

Regenerative processes for the revitalization of spacecraft atmospheres and reclamation of waste waters are essential for making long-term manned space missions a reality. Several of these regenerative processes are being developed by Life Systems and tested at MSFC as both individual subsystems and integrated in the Core Module Integrated Facility (CMIF). This report describes several discreet tasks performed by Life Systems to support the testing being performed at MSFC. The report also describes development and testing efforts performed at Life Systems. The report is organized according to each of the major tasks of the program as follows:

1. EDC Module Fabrication
2. EDCM Test Stand Fabrication
3. Engineering Support

4. Iodine Monitor Fabrication
5. EDC Test Stand Conversion
6. EDC Failure Mode Testing
7. O_2 Recovery from Product CO_2 Study

EDC MODULE FABRICATION

The EDC is a most promising technique for concentrating low level CO_2 from spacecraft cabin atmospheres without incurring large weight, volume and power penalties. The EDC removes CO_2 continuously from a flowing stream of low CO_2 partial pressure (pCO_2) atmosphere. The CO_2 exhaust, premixed with H_2, can be sent to a CO_2 reduction subsystem for recovery of the O_2, or vented, as required. The EDC also produces electric power that can be utilized by other spacecraft subsystems (e.g., O_2 generation by a SFE). Life Systems fabricated, tested and delivered to MSFC a one-person EDCM.

Electrochemical CO_2 Removal Process Mechanisms

In electrochemical CO_2 removal processes air containing CO_2 passes through the air compartment of an electrochemical cell and CO_2 diffuses to the entrances of the gaseous pores and diffuses through the pores to the electrolyte-air interface of the cathode where it is absorbed. An expanded view of a portion of a cell showing the various mass transport processes for operation with and without H_2 which occur in its structure in shown in Figure 1.

Absorbed CO_2 reacts with hydroxyl (OH^-) ions to form bicarbonate (HCO_3^-) ions and then carbonate ($CO_3^=$) ions. The conversion can be described by two consecutive reactions:

$$CO_2 + OH^- \rightarrow HCO_3^{\overset{=}{-}} \qquad (1)$$

$$HCO_3 \mp OH^- \rightarrow CO_3 + H_2O \qquad (2)$$

The second reaction occurs instantaneously, so the first reaction is the rate-determining step. Therefore, the conversion can be described by a single step.

$$CO_2 + 2\ OH^- \rightarrow CO_3^= + H_2O \qquad (3)$$

The hydroxyl (OH^-) ions are generated by water molecules combining with O_2 and electrons by

$$H_2O + 1/2\ O_2 + 2e^- \rightarrow 2OH^- \qquad (4)$$

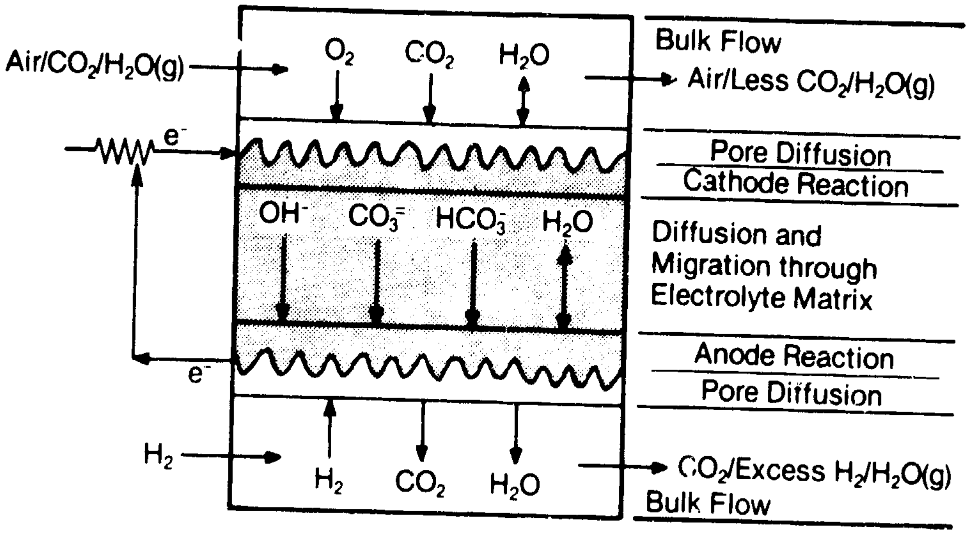
When the concentration of OH^- is depleted, additional CO_2 can be absorbed by

$$CO_2 + CO_3^= + H_2O \rightarrow 2HCO_3^- \qquad (5)$$

resulting in an overall absorption reaction of

$$2CO_2 + 2\ OH^- \rightarrow 2HCO_3^- \qquad (6)$$

Operation With Hydrogen



Operation Without Hydrogen

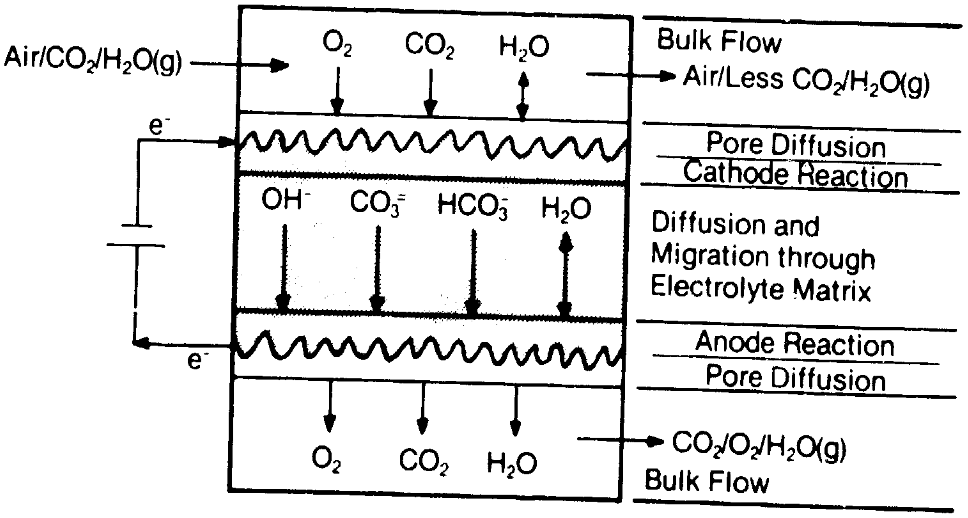


FIGURE 1 ELECTROCHEMICAL CO_2 REMOVAL MASS TRANSFER PHENOMENA

The diffusion and ionic migration for $CO_3^=$, HCO_3^- and OH^- occur in the matrix. The matrix, which is a highly microporous, hydrophilic and densely compressed material, when wetted by aqueous electrolyte solution containing carbonate ions, provides electrical insulation between the two electrodes, a barrier for the separation of anode and cathode gases and passages for the diffusion and migration of ionic and liquid species.

At the anode, when H_2 is supplied, dissolved H_2 reacts at the electrode to form hydronium ions (H_3O^+), lowing pH in the region to cause the evolution of CO_2 from $CO_3^=$. When H_2 is not supplied, water provides the source of H_3O^+. In the case of HCO_3^-, water is formed in addition to CO_2 and O_2. The individual electrode reactions and overall reactions for the cases of with and without H_2 at the anode and the cases of $CO_3^=$ and HCO_3^- as the CO_2-transferring ions are summarized by Figure 2. The performance of the electrochemical CO_2 removal process has been characterized by defining 100% efficiency as the transfer of 2.75 lb of CO_2 per pound of O_2 consumed. This is based on the CO_2 transfer mechanisms as shown in Figure 2. The HCO_3^- transfer mechanisms also shown in the same figures would, on this basis, provide CO_2 transfer at a 200% efficiency. Transfer of CO_2 by HCO_3^- represents the theoretical limit of process efficiency.

Advantages of Electrochemical CO_2 Removal

Advantages of an EDC CO_2 concentrator include:

1. The technology is mature. It has been tested continuously for over 18 years in applications ranging from single cell test fixtures to integrated atmosphere revitalization systems.

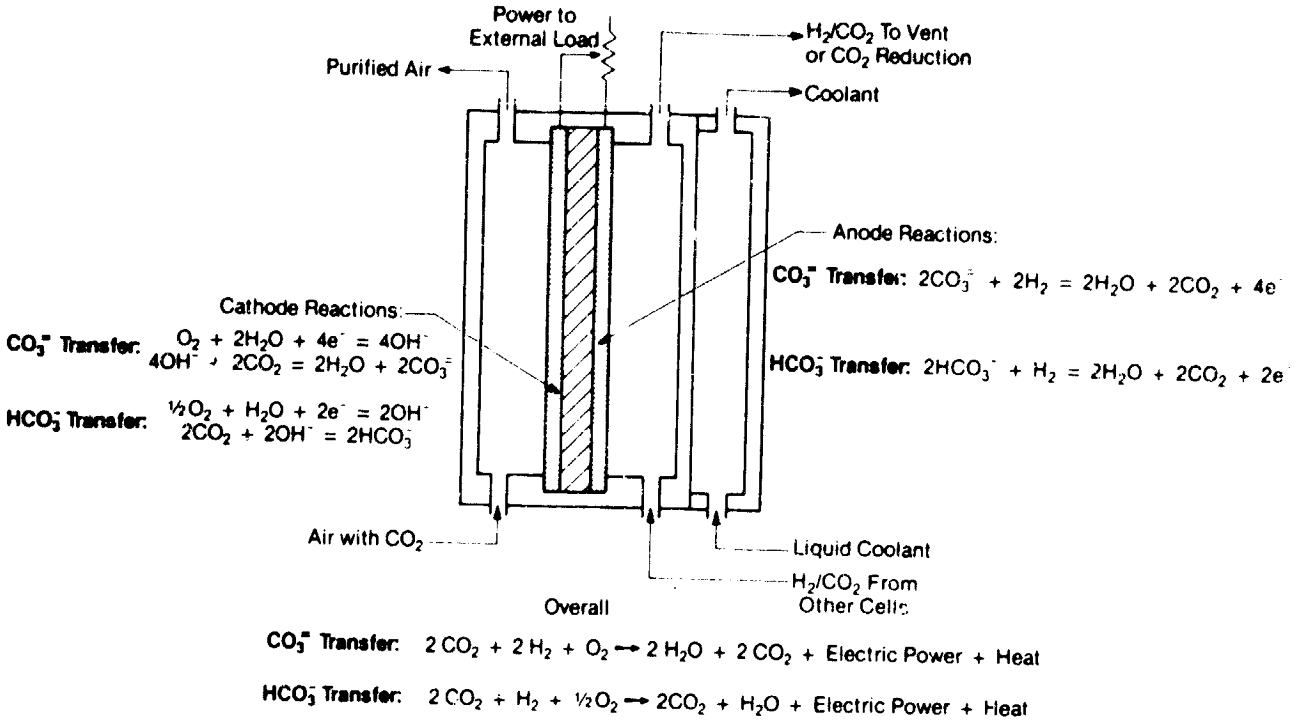
2. The EDC subsystems function as a continuous process. Continuous operation minimizes the number of moving parts and eliminates the need for a CO_2 compressor and accumulator.

3. The EDC subsystems are rate flexible. The use of electric current flow to regulate the CO_2 concentration rate allows EDC subsystems to maintain a constant cabin pCO_2 environment during periods of varying crew activity and number. This flexibility includes the ability to operate pCO_2 levels ranging from less than 267 Pa (2.0 mm Hg) to 1,600 Pa (12.00 mm Hg) or greater.

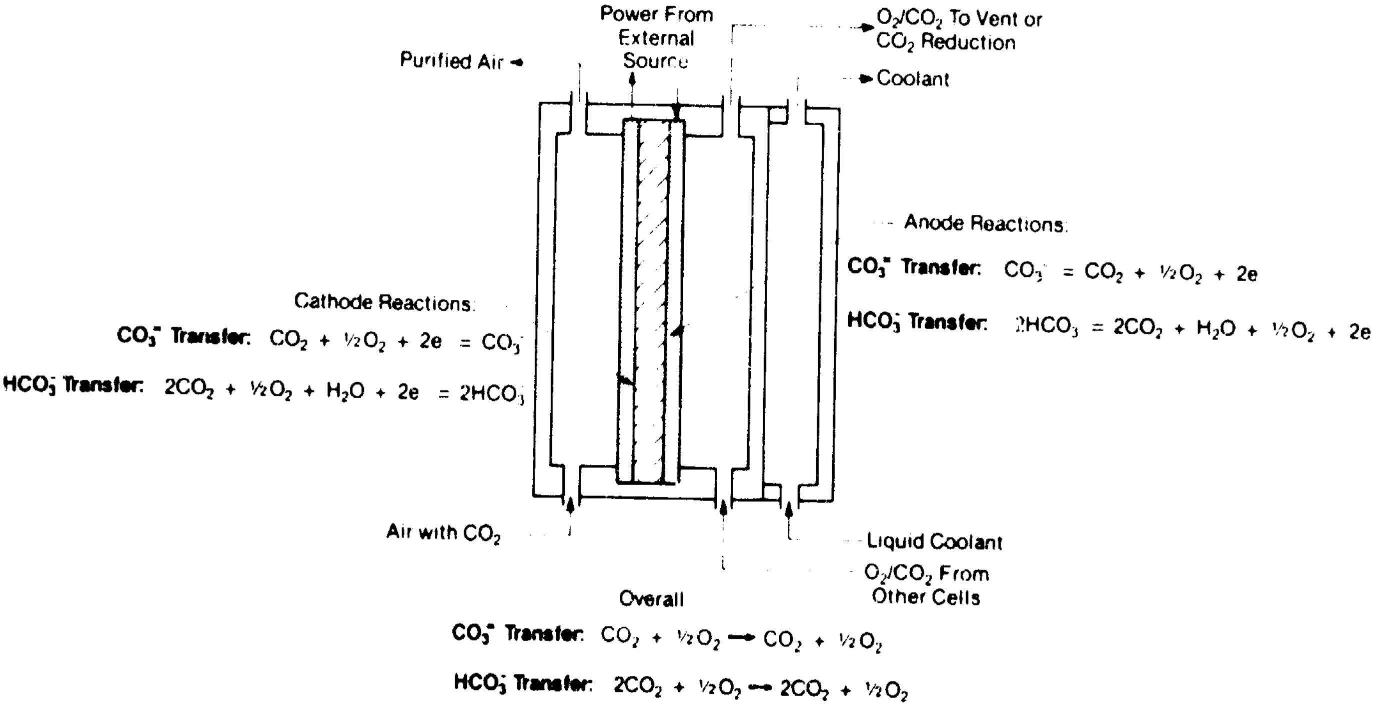
4. The EDC subsystems are flight efficient. Operation of an EDC CO_2 concentrator is light weight and require a minimum amount of power and volume. This is achieved by the use of integrated components which also simplify subsystem maintainability.

5. The concentrated CO_2 product stream from an EDC contains no inerts. All gases from an EDC (i.e., CO_2, $H_2O_{(v)}$ and H_2 are reactive in a CO_2 reduction subsystem. This eliminated the need to vent the CO_2 reduction subsystem.

6. The EDC subsystems are safe. The EDC subsystems operate at low temperature and pressures. The total amount of H_2 contained in a three-person EDC is less than two standard liters.



(a) Electrochemical CO_2 Removal With H_2



(b) Electrochemical CO_2 Removal Without H_2

FIGURE 2 ELECTROCHEMICAL CO_2 REMOVAL WITH AND WITHOUT H_2

The one-person EDC module fabricated and delivered to MSFC is shown in Figure 3, installed onto the EDCM Test Stand. The EDCM characterization and endurance test stand is described in the next section.

THE EDC TEST STAND FABRICATION

A test stand was fabricated under this program to facilitate the testing of the EDCM. The liquid-cooled EDCM test stand, shown in Figure 3 and 4, consists of five main sections. These are:

1. Test stand control
2. The EDCM air control and monitor
3. The EDC pressure control and monitor
4. Gas supply control and monitor
5. The EDCM voltage and current monitor

Components on the test stand's front panel are grouped according to these sections and are shown in Figure 3. The test stand mechanical schematic is given in Figure 5. An Operations Manual, Life Systems' document TR-875-4B, was written and delivered with the EDCM test stand. The Operations Manual included information related to:

1. Test stand design - information pertinent to understanding the capabilities of the test stand.

2. Installation instructions and initial test stand start-up procedures.

3. Operating instructions - outlining the required steps for the operator to run the test stand following installation and initial start-up.

4. Maintenance instructions.

The Operations Manual also included information relative to the operation of the test stand, e.g., calibration curves, gas humidifier operation description, diverter valve and controller description, and data acquisition system interface connections.

ENGINEERING SUPPORT

Life Systems provided support to MSFC in all aspects of the MSFC ECLSS test program, including both individual subsystem tests and the integrated system tests. Specific activities performed by Life Systems included: test planning, subsystem operation, subsystem maintenance and data analysis. The work included direct on-site participation in the test program and a home office effort as was necessary to support the efforts of the Life Systems' personnel and hardware in the field.

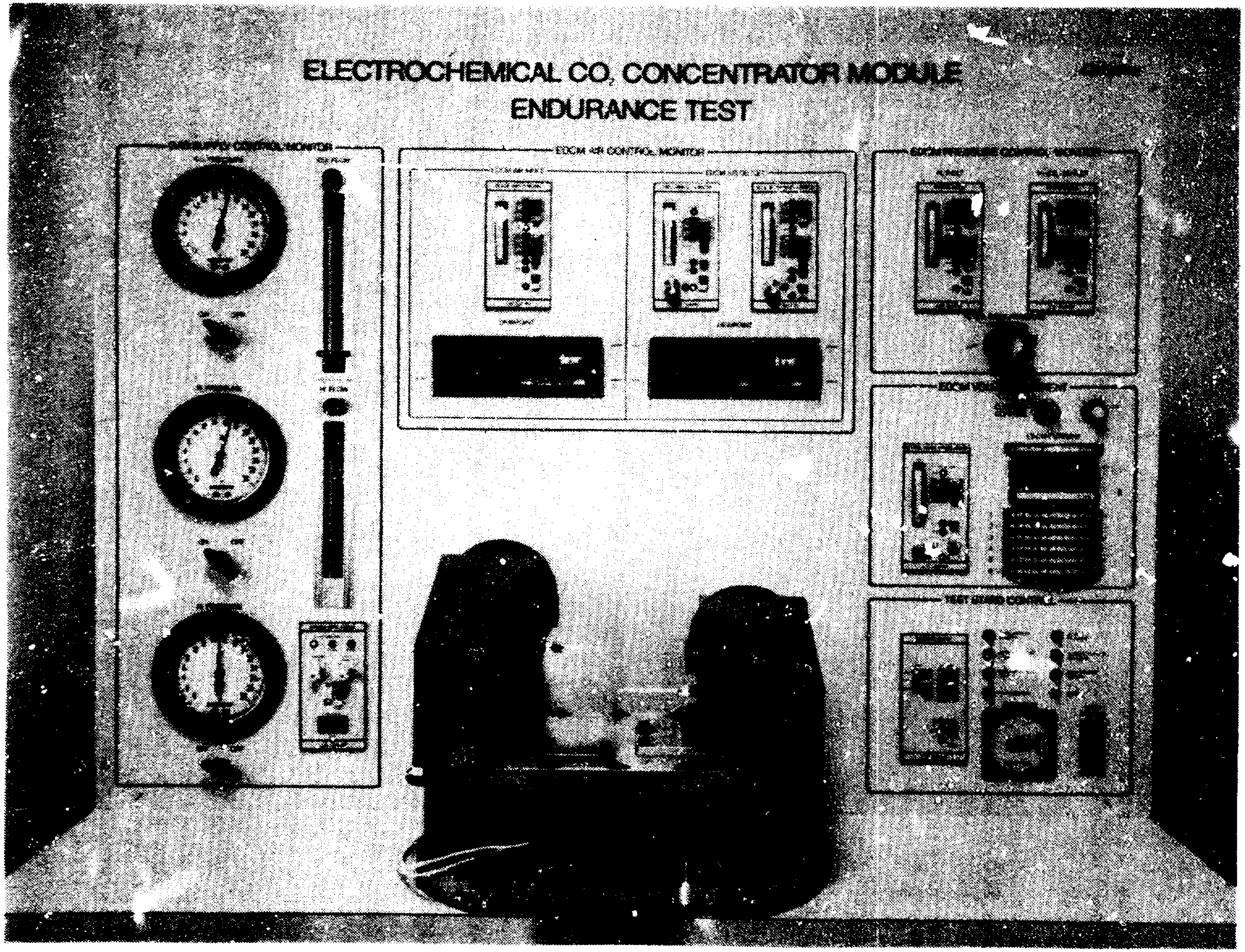


FIGURE 3 ELECTROCHEMICAL CO_2 CONCENTRATOR MODULE ENDURANCE TEST STAND FRONT PANEL

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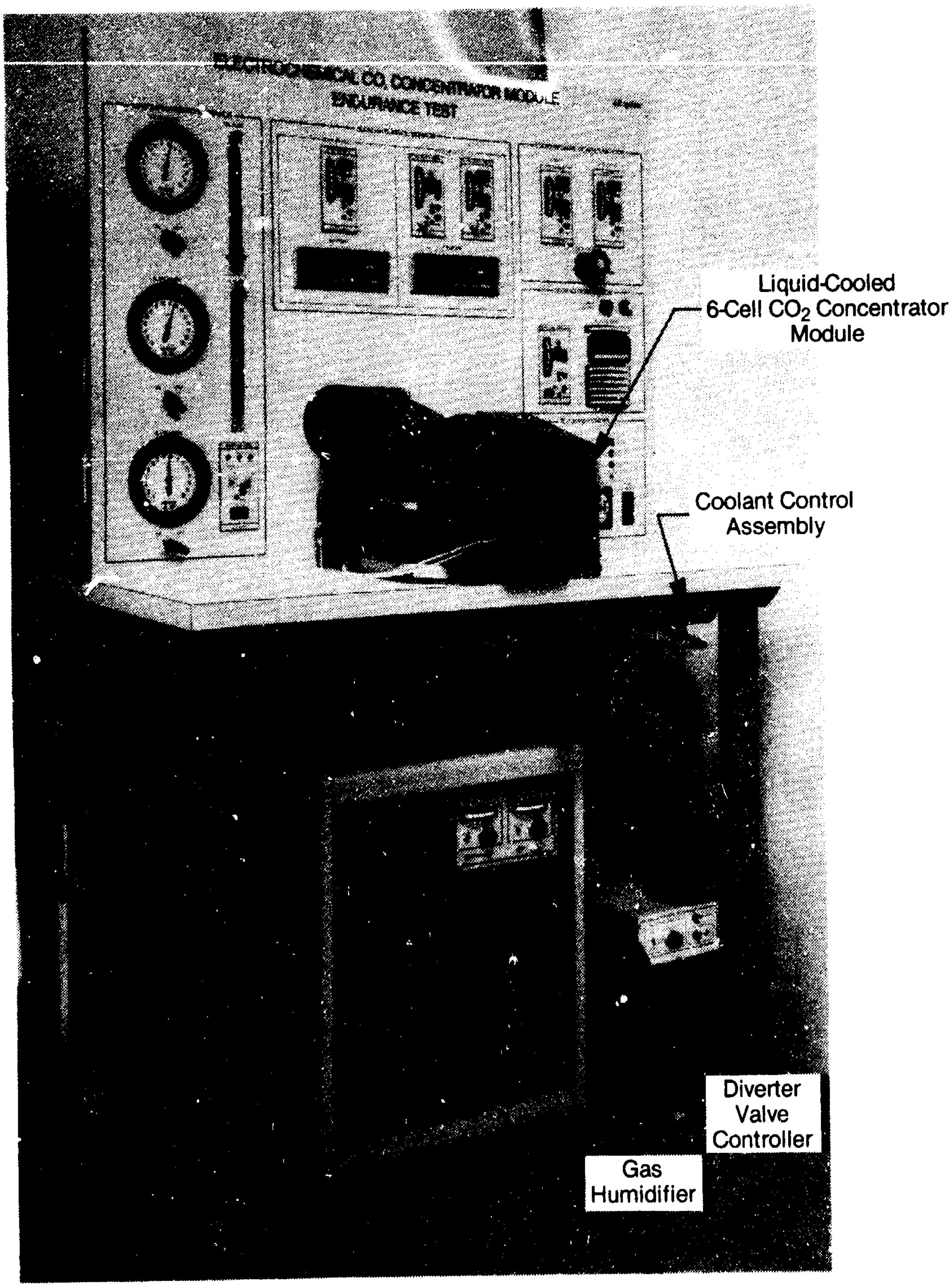

FIGURE 4 ELECTROCHEMICAL CO_2 CONCENTRATOR MODULE ENDURANCE TEST STAND

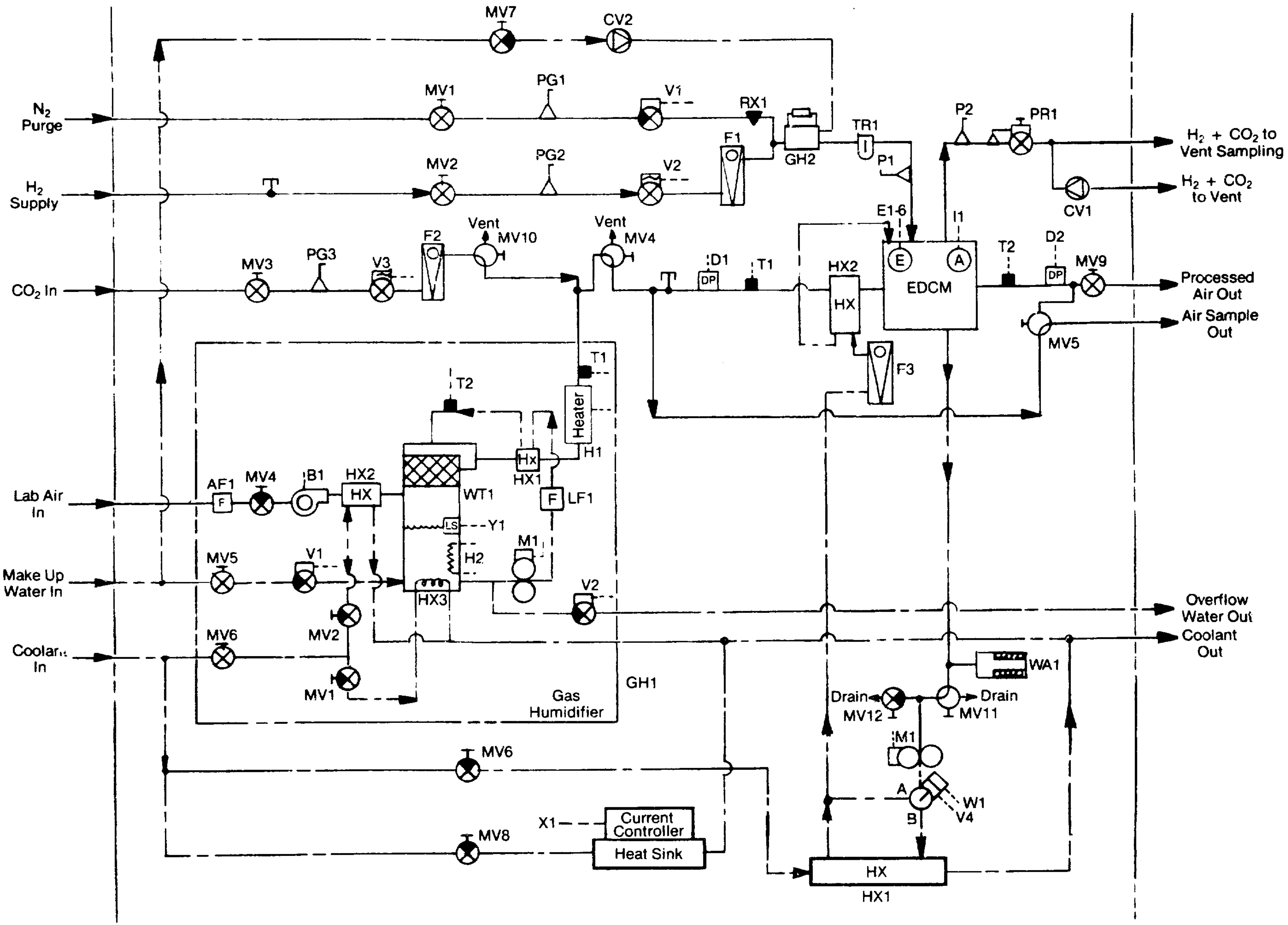

FIGURE 5 LIQUID-COOLED ELECTROCHEMICAL CO_2 CONCENTRATOR MODULE TEST STAND MECHANICAL SCHEMATIC WITH SENSORS

Test Planning

A major element in achieving a successful test program is planning. The planning effort included definition of the data desired, design of the test facility and the preparation of test plans and procedures. This effort also included aiding MSFC personnel in developing a detailed understanding of Life Systems' hardware so that provisions could be made to obtain the data necessary for rigorous evaluations, definition of individual subsystem interface requirements, system integration requirements and subsystem and system safety requirements, participation in the review and preparation of the detailed plans and procedures required for execution of the test program and training of MSFC personnel in the operation of Life Systems' hardware.

Hardware Operation

Field support was also provided during active hardware testing. This support helped in optimizing test results and facilitated subsystem maintenance required during and after testing.

Hardware Maintenance

The ECLSS hardware utilized in the MSFC test program is developmental in nature and as such required more maintenance than would subsystems fabricated to a higher level of flight readiness. Maintenance during the test program was facilitated by the presence of Life Systems' personnel during test operation. This maintenance program included both personnel support and materials.

Data Analysis

Life Systems participated and provided support in a real time analysis of the operating data to verify subsystem performance and that the test goals were being achieved.

IODINE MONITOR FABRICATION

A compact, lightweight I_2 monitor as shown in Figure 6 was fabricated and delivered to MSFC.

Iodine Monitor

Potable water on future long-term manned space missions, like the Space Station Freedom, will be recycled water which will be inherently susceptible to microbial contamination. Iodine has been shown to have a superior microorganism annihilation potential at low dosages and dose rates. In order to verify and control the I_2 content of water, a means is necessary by which the I_2 content of water, in concentrations as low as 0.5 ppm, can be measured. Under contract to NASA, Life Systems developed an instrument that has demonstrated the ability to perform this measurement using a photometric technique.

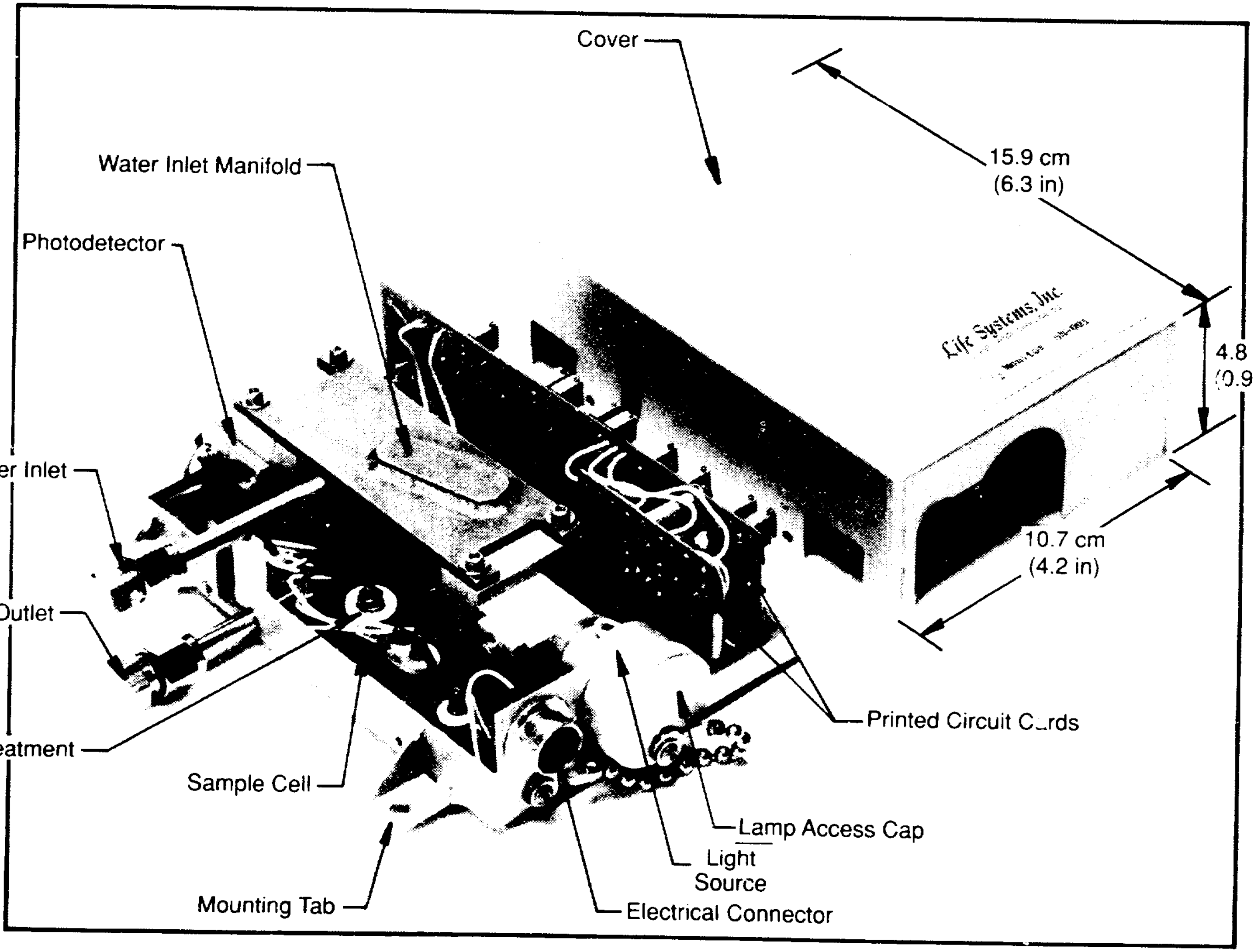

FIGURE 6 I_2 MONITOR

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The I_2 monitor developed by Life Systems is illustrated in Figure 7. As shown, white light is passed through iodinated water. The blue portion of the light is attenuated by the I_2 in water. The intensity level of the blue portion of the light is detected selectively and converted into an electrical signal by a photodetector/filter combination. The red component of the light passing through the iodinated water is unattenuated by the I_2 and therefore, serves as a reference. The intensity of the red component of the light is sensed by a second photodetector/filter combination. A beam splitter focuses equal amounts of light on the two photodetector/filters. A signal corresponding to the unattenuated red light component is scaled to be equivalent to unattenuated blue light (zero I_2 concentration) to compensate for the difference of the intensity of these components in the white light. The ratio of the attenuated blue signal to the equivalent unattenuated blue signal is determined electrically. The resulting readout is proportional to the I_2 concentration, as illustrated on the bottom half of Figure 7.

The I_2 monitor operates on single phase 115 V AC power. The signal generated is a 0 to 5 VDC signal which is proportional to the sensed level of I_2 in the water.

THE EDC TEST STAND CONVERSION

The section entitled "EDC Module Fabrication" described the operation of the EDC operating in either with H_2 or without H_2 operating mode. The EDC test stand as originally configured was for operation of the EDCM in the with H_2 mode. The test stand was converted to allow operation of the EDCM in either mode.

TEST PROGRAM

An extensive characterization and endurance test program was completed under the program. Three modes of EDC operation were investigated during the test program. These included:

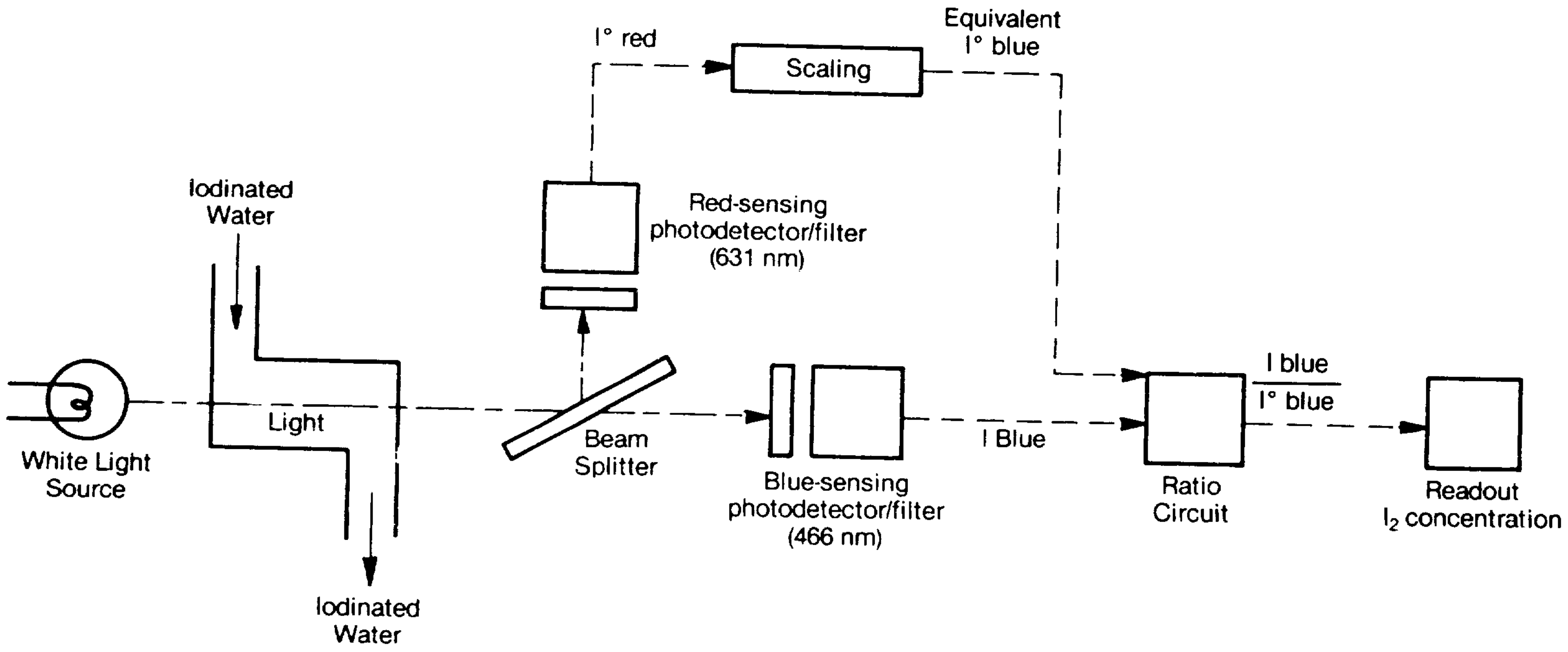
1. Operation of the EDC with H_2.
2. Operation of the EDC without H_2.
3. Operation of the EDC cyclically with H_2 and without H_2.

The EDC Operation With Hydrogen

The EDC operation with H_2 phase of the test program consisted of 12,580 hours of testing. This testing included both parametric and endurance testing. No shutdowns occurred throughout the testing as a result of the EDC process.

The EDC Operation Without Hydrogen

Operation of the EDC without H_2 was performed on the single cell, the one-person module and a one-person subsystem level. Characterization tests were performed to determine optimal operating conditions and to determine



Term definition:

I = light intensity signal attenuated by I_2
I° = light intensity signal unattenuated by I_2
C = concentration of attenuating species (I_2)

Readout is approximately linear because

C α I blue/I° blue, approximately

Beer's Law of
light attenuation: $I/I° = e^{-kc} = 1-kC$ when $kC << 1$ (C = small)
(k = constant)

FIGURE 2-2 I_2 MONITOR FUNCTION

efficiencies versus power consumption. This test program was the first time the EDCM operation without H_2 had ever been extensively characterized and endurance tested. Carbon dioxide removal efficiencies in the without H_2 mode compared well with CO_2 removal efficiencies in the with H_2 operating mode. An objective of the without H_2 testing was to characterize the ability of the EDC to perform without H_2 in a Space Station Freedom safe haven condition. The test results indicated that the EDC could perform sufficiently in the without H_2 mode during the safe haven conditions.

EDC FAILURE MODES TESTING

An effort was performed to evaluate the EDC subsystem configuration and its ability to ensure safe utilization of H_2 gas. The test work performed showed that the procedures necessary for safe operation of an EDC are the same as those required for any other subsystem that utilizes a combustible gas. Specifically, the keys to failsafe operation are ventilation and detection.

For an EDC these requirements apply both internally and externally. Internally the process air stream limits the maximum possible H_2 concentration to 0.37% or less than 10% of the lower explosive level (LEL). Internal detection is provided by a multiparameter array of sensors of which the most sensitive is a triply redundant H_2 sensor which can detect H_2 in air at a concentration of 0.05%. External safety features required are the same as any other subsystem that utilizes a combustible gas. These are ventilation and detection. Detection will require the use of multiple combustible gas sensors and ventilation is provided by the avionics rack. External subsystem leaks can also be detected by the EDC via flow sensors included.

OXYGEN RECOVERY FROM PRODUCT CARBON DIOXIDE STUDY

As discussed previously, operation of the EDC without H_2 results in a product stream of CO_2 mixed with O_2. A task was undertaken to evaluate O_2/CO_2 separation techniques. The first item was consideration of the system level impacts resulting from operation of the EDC without H_2. The remaining O_2/CO_2 separation technique study tasks included:

1. Identifying technology options for O_2/CO_2 separation and developing an understanding of each technology option.
2. Development of criteria for screening evaluation of the various technology options identified.
3. Screening of the technology options based on the criteria.
4. Definition of operating parameters for the preferred options.

System Level Impacts

Three system level impacts exist when operating the EDC without H_2 as a baseline CO_2 removal subsystem aboard the Space Station Freedom. The first impact is related to input power requirements. An EDC operating with H_2 at a four-person level will generate approximately 117 watts of power. In contrast, the same EDC operating without H_2 would require 413 watts of input power. Second, the EDC operating without H_2 consumes more O_2 than does its counterpart. For example, an EDC operating with H_2 only requires 3.76 lb per day O_2 compared to 4.26 lb O_2 required by the EDC operating without H_2. The third impact is on the product CO_2 mixture leaving the EDC. When the EDC is operated with H_2 the product CO_2 stream contains H_2. This mixture is sent to the Bosch CO_2 Reduction Subsystem for further processing in order to recover the O_2 contained in the CO_2. When operating the EDC without H_2, the typical product stream consists of CO_2 and O_2. Before processing the CO_2 product stream in the Bosch CO_2 Reduction Subsystem, the amount of O_2 must be lowered to a level such that when the stream enters the Bosch reactor, where H_2 is added, the amount of O_2 in the H_2 is conservatively below the LEL of 6.1%. Therefore, it is necessary to reduce the O_2 content from the product CO_2 gas prior to processing in the Bosch.

Oxygen/Carbon Dioxide Separation Technology Options

Technology options identified and selected for evaluation included:

1. Selective polymer membrane diffusion.
2. Liquid absorption of CO_2.
3. Molecular sieve CO_2 absorption.
4. Ion exchange resin CO_2 absorption.
5. Electrochemical O_2 concentration.
6. Carbon dioxide liquification.
7. Organometallic coordination compound for absorption.

A literature search and review was performed to develop an understanding of each of these techniques. Concept schematics were developed for each of the techniques (e.g., see Figure 8).

Technology Options Screening

Screening criteria included weight, power, volume, heat rejection, CO_2 recovery and product CO_2 purity. Technology options were eliminated from further screening when the option failed to meet any one of the absolute criteria requirements. Six of the seven identified technology options passed this preliminary screening. The technique which did not pass this screening was the organometallic coordination compound for O_2 absorption. The reason for this was that a large percentage of the CO_2 would be lost during O_2 desorption. Further analysis on each of the six remaining techniques should be performed. This analysis should include a more detailed definition of the operating parameters for each of the techniques.

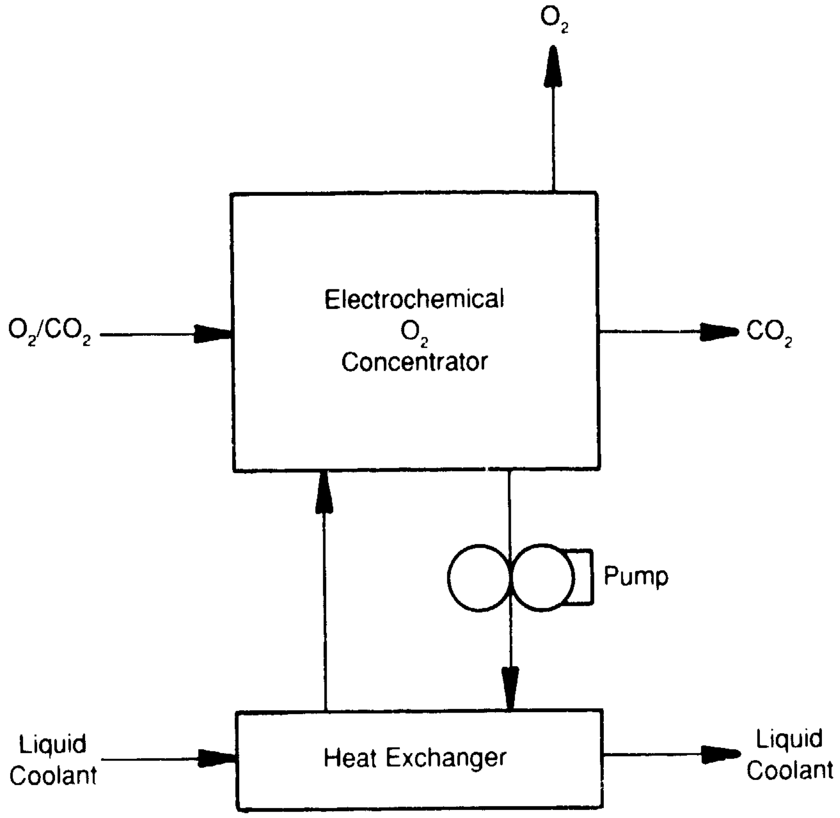


FIGURE 8 ELECTROCHEMICAL O_2 CONCENTRATOR CONCEPTUAL SKETCH

CONCLUSIONS AND RECOMMENDATIONS

The following are conclusions made as a result of the testing and analysis efforts performed under this program:

1. The procedures necessary for safe operation of an EDC are the same as those required for any other subsystem that utilizes a combustible gas.
2. The safety features incorporated into the EDC design, which has been under development since the early 1970s with safety as a key design driver, considered and accounted for many of the failures evaluated in the test program.
3. The EDC subsystem is capable of detecting and shutting down after detection of any internal type leak greater than 10% flow.
4. The hypothetical situation of an undetected 100% H_2 leak from the EDC would not reach the lower explosive level in a Space Station Freedom atmosphere.
5. Further analysis on the six O_2/CO_2 separation techniques should be performed.
6. Iodine Monitors will be needed for monitoring the concentration of the iodinated water at various points throughout the water system. A compact, lightweight I_2 Monitor has been designed, fabricated and assembled by Life Systems which is capable of performing this function.
7. The EDC is capable of providing the safe haven function of CO_2 removal without the use of H_2.
8. Life System's field support activity should continue throughout the MSFC testing activities.