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ELECTROCHEMICALLY REGENERABLE CARBON DIOXIDE ABSORBER

FINAL REPORT

by

R. R. Woods, R. D. Marshall,
F. H. Schubert and D. B. Heppner

August, 1979

Prepared Under Contract NAS2-8666

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Life Systems, Inc.
Cleveland, OH 44122

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AMES RESEARCH CENTER
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FOREWORD

This report was prepared by Life Systems, Inc. for the National Aeronautics and Space Administration Ames Research Center in accordance with the requirement of Contract NAS2-8666. The period of performance for the work completed and summarized in this report was January, 1977 to August, 1979. The objective of the program was to demonstrate the feasibility of the Electrochemically Regenerable Carbon Dioxide Absorber for Portable Life Support System application.

The overall program manager was R. D. Marshall. Technical Support was provided by R. R. Woods and J. D. Powell. The program Technical Monitors were Mr. Mark Leban and Mr. Phil Quattrone, Ames Research Center, Moffett Field, CA, 94035.

All measurements and calculations contained in this report are expressed in SI (metric) units; conventional units, when applicable, are given in parentheses.

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AE	Absorption Efficiency
AEPS	Advanced Extravehicular Protective System
ARS	Air Revitalization System
AUE	Absorbent Utilization Efficiency
CRS	Carbon Dioxide Reduction Subsystem
EDC	Electrochemical Depolarized Carbon Dioxide Concentrator
EE	Extraction Efficiency
ERC	Electrochemically Regenerable Carbon Dioxide
ERCA	Electrochemically Regenerable Carbon Dioxide Absorber
ERCAR	Electrochemically Regenerable Carbon Dioxide Absorber Regenerator
EVA	Extravehicular Activities
HFM	Hollow Fiber Membrane
PLSS	Portable Life Support Systems
RE	Regeneration Efficiency
RH	Relative Humidity
TAU	Total Absorbent Utilization
TSA	Test Support Accessories

SUMMARY

The Electrochemically Regenerable Carbon Dioxide Absorber consists of an aqueous alkaline absorbent confined within the support structure of the absorption bed. Metabolic carbon dioxide produced during extravehicular activity is absorbed by reaction with the alkaline solution similar to the absorption chemistry of lithium hydroxide. The expended absorbent is then used as the electrolyte for the electrochemical regeneration process. This process regenerates the expended absorbent solution and recovers the metabolic carbon dioxide stored in the absorbent. During the regeneration process the carbon dioxide is evolved into a flowing hydrogen stream for direct integration with the primary space vehicles' Carbon Dioxide Reduction Subsystem.

Preliminary designs were generated for two Electrochemically Regenerable Carbon Dioxide Absorber concepts. Initially, an electrochemically regenerable absorption bed concept was designed. This concept incorporated the required electrochemical regeneration components in the absorber design, permitting the absorbent to be regenerated within the absorption bed. The hardware sized to satisfy the carbon dioxide removal requirements of an eight-hour extravehicular activity mission resulted in a component volume of 23 dm^3 (0.80 ft^3) and mass of 30 kg (66 lb). This hardware was identified as the electrochemical absorber hardware and was sized with a projected total absorbent utilization efficiency of 53%.

The second hardware concept separated the functional components of the regeneration and absorption process. This design approach minimized the extravehicular activity component volume by eliminating regeneration hardware components within the absorber. This type of hardware was defined as the nonelectrochemical absorber. This absorber, when sized for an equivalent eight-hour extravehicular activity mission, resulted in a component volume of 15 dm^3 (0.53 ft^3) and a mass of 20 kg (45 lb). The projected total absorbent utilization efficiency used was 77%.

The electrochemical absorber hardware has been extensively characterized for major operating parameters such as inlet carbon dioxide partial pressure, process air flow rate, operational pressure, inlet relative humidity, regeneration current density and absorption/regeneration cycle endurance testing. This hardware demonstrated 200 absorption/regeneration cycles without degradation in absorbent utilization efficiencies.

The Electrochemically Regenerable Carbon Dioxide Absorber concept satisfied the requirements of the regenerable carbon dioxide scrubber for future Portable Life Support System applications based on its regenerability without degradation, its projected minimum component volume and its low total equivalent weight.

INTRODUCTION

As the length of man's space missions increase, more ambitious extravehicular activities (EVA) will be attempted. Current state-of-the-art Portable Life Support Systems (PLSS) involve the use of expendables. For projected longer missions these expendables will become prohibitive due to increased weight and volume penalties. The removal of metabolically generated carbon dioxide (CO_2) in a PLSS is currently performed using expendable chemicals (i.e., lithium

hydroxide (LiOH)).[1] The development of the regenerable CO_2 scrubber for PLSS application is therefore desirable.

One promising concept is the Electrochemically Regenerable CO_2 (ERC) Absorber (ERCA).[2] This concept is based on absorbing CO_2 into an alkaline absorbent as is done with LiOH. The absorbent is an aqueous solution which can electrochemically be regenerated on-board the primary space vehicle. The absorbent can be either regenerated in place as in the electrochemical ERC Absorber design or can be extracted from the absorption bed and transferred to the electrochemical regeneration hardware. The regeneration process is based on Electrochemical Depolarized CO_2 Concentrator (EDC) technology[3-5] and evolves the CO_2 absorbed during the EVA into a flowing hydrogen (H_2) stream for direct integration with the primary space vehicle's CO_2 Reduction Subsystem (CRS). With the metabolic CO_2 recovery, the ERCA concept results in a totally regenerable CO_2 scrubber.

Background

A typical block diagram of the PLSS application depicting the atmospheric revitalization, the liquid coolant loop and the controller connection for the various PLSS components is presented in Figure 1. The CO_2 scrubber is shown as the second component in the atmospheric revitalization loop although alternate locations are possible. The inlet process air to the absorber is warm, moist and debris-free air containing CO_2. The absorber functions as a passive absorber bed which effectively removes metabolically-generated CO_2 at an absorption efficiency of 100%.

Regenerative CO_2 Removal Concepts

In the past, several concepts were investigated for the development of a regenerable CO_2 scrubber for the PLSS application. Initially direct replacement of the LiOH by metallic oxide or metallic hydroxide pellets was attempted.[6] Compounds of zinc, silver and magnesium were investigated for their CO_2 absorption and regeneration characteristics. These concepts were eliminated due to loss of pellet structural integrity with repeated regeneration.

Other concepts based on the reaction chemistry of alkaline carbonate material reacting with CO_2 to form bicarbonate materials have been investigated.[7] The regeneration method of these concepts is based on the thermal and/or vacuum decomposition of bicarbonate species to its original carbonate form. Similar to the metallic oxide or hydroxide concept, structural integrity as a solid pellet is lost upon repeated regeneration. One method which overcomes the loss of absorbent integrity upon regeneration suspends the carbonate absorbent into a porous polymer sheet.[8-10] Testing of this concept has demonstrated a reduction in CO_2 absorption capacity of about 25% after 60 regeneration cycles. Also, high gas void volumes are required resulting in excessive EVA volumes for the backpack application.

The ERCA concept has been designed to eliminate the shortcomings observed in other potential regenerative CO_2 scrubbers. The ERCA concept is based on the same reaction chemistry as LiOH. This provides the similar high CO_2 absorption

(1) References cited at end of this report.

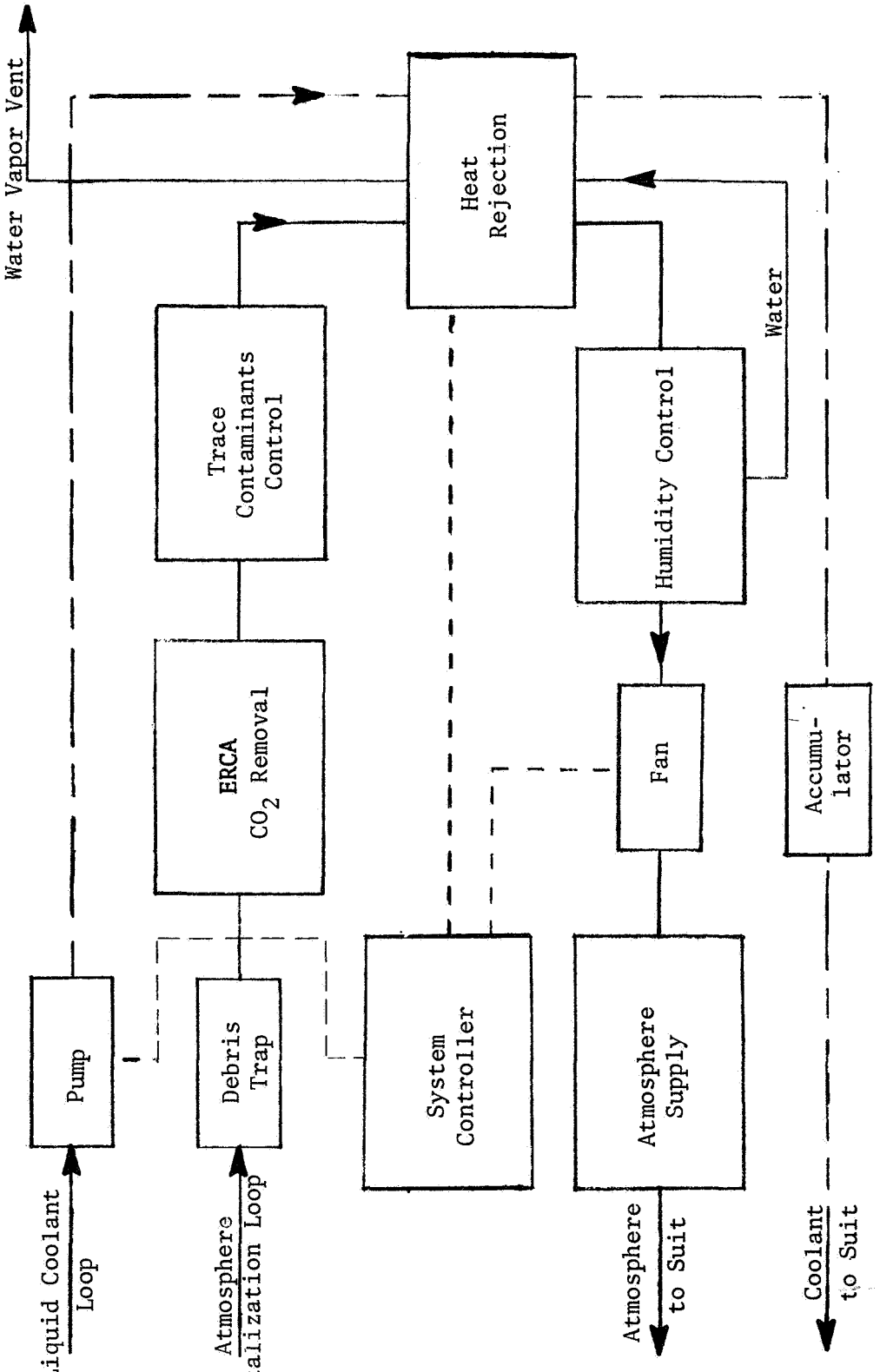


FIGURE 1 PLSS BLOCK DIAGRAM

rate capabilities and low absorbent volume requirements for efficient storage of metabolic CO_2 generated during EVA. Maintaining structural integrity and proper containment of the absorbent is not a problem because the absorbent is an aqueous solution supported in a porous interface. The aqueous solution also provides for the exchange of CO_2 and fresh absorbent at the gas/absorbent interface. This mechanism decreases the gas void volume requirement and total gas/absorbent surface area requirements for the ERCA concept compared to the solid absorbents such as LiOH or the alkaline carbonates. At the completion of the EVA the aqueous absorbent becomes the electrolyte for the electrochemical regeneration process on-board the primary space vehicle. The electrochemical process results in a totally regenerative concept of which the product gas is directly integratable into the vehicles' CRS.

The initial developmental program activities conducted under Contract NAS2-8666[2] evaluated the electrochemical ERC absorber hardware's absorption and regeneration performance through multiple cycles. The cyclic testing demonstrated no performance degradation during the initial 60 cycles of testing. A maximum absorption utilization of 75% and a regeneration efficiency of 63% were observed for the test hardware. These performance levels justified the program extension for the design and development of lightweight, low volume ERCA hardware.

Program Objectives and Organization

The objective of the work completed was the evaluation of lightweight, low volume ERCA hardware to meet future EVA CO_2 scrubber requirements. The evaluation initially included only the preliminary design of electrochemical ERC Absorber hardware. With the completion of this design the projected minimum absorber volume for the electrochemical ERC Absorber hardware was approximately 16 dm^3 (0.57 ft^3). Present nonregenerable LiOH CO_2 scrubber volumes range from 4 to 8 dm^3 (0.14 to 0.28 ft^3). As a result the program emphasis was redirected toward the evaluation of nonelectrochemical ERC Absorber designs. These designs illustrated the potential for a minimum absorber volume of 8 to 10 dm^3 (0.28 to 0.35 ft^3) which could result in as much as a 50% reduction in the ERC Absorber EVA volume.

Also included in the program was the completion of the ERC Absorber data base by testing breadboard electrochemical ERC Absorber hardware. This testing included characterization of ERC Absorber performance as a function of operation pressure, inlet relative humidity (RH) and an additional 100 absorption/regeneration cycles.

To accomplish the above, the work was organized into five tasks and program documentation and management functions. The specific objectives of the five tasks were to:

1. Design lightweight and low volume ERCA hardware to illustrate the electrochemical ERC Absorber concept. Assemble and functionally checkout a ten-cell breadboard ERC Absorber for use in characterizing electrochemical ERC Absorber performance as a function of inlet RH, pressure and cycle time.

2. Evaluate several alternate nonelectrochemical ERC Absorber design approaches. Select an approach and complete a preliminary design on the selected concept.

3. Maintain product assurance activities required through all phases of the contractual performance, including design, fabrication, purchasing, assembly and testing.

4. Conduct a test program to characterize the ten-cell electrochemical ERC Absorber hardware as a function of inlet RH, pressure and cycle time. Design, fabricate, assemble and functionally check out the Test Support Accessories (TSA) required for the testing of the breadboard ERC Absorber.

5. Conduct various analyses in support of the ERCA development.

CONCEPT DESCRIPTION

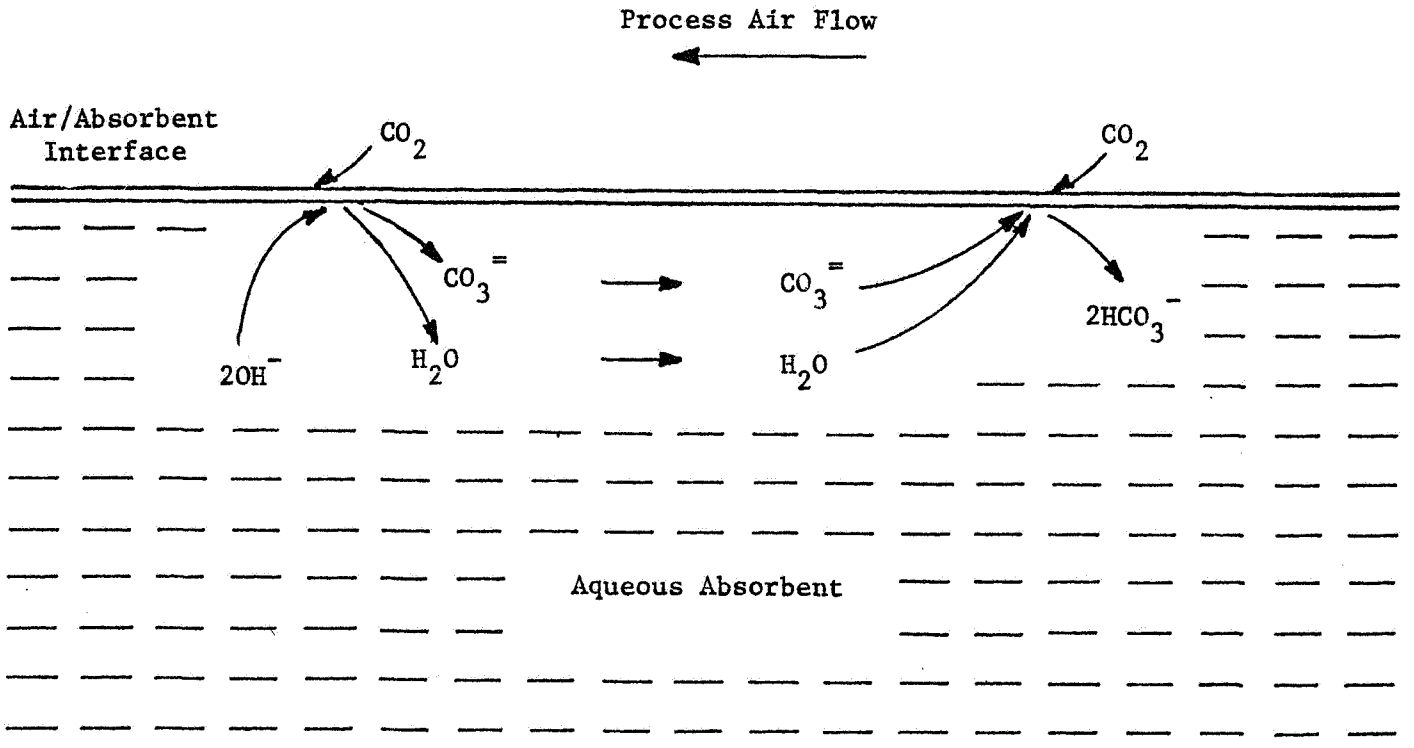
The ERCA concept encompasses a wide range of ERC Absorber designs, all of which are electrochemically regenerable. Conceptually the simplest design is the electrochemical absorber hardware. This absorber consists of a dense packing of electrochemical cells which function as both the ERC absorption bed during the EVA and the electrochemical hardware necessary for regeneration. A general description of the absorption and regeneration mechanisms of this absorber hardware is applicable to all ERCA concepts. Concept differences between the electrochemical and nonelectrochemical approaches are cited where applicable.

Absorption Mechanism

The ERC Absorber functions as a passive absorption bed for the removal of CO_2 from a process air stream. The absorber is composed of a porous media containing the aqueous absorbent solution. The cavities adjacent to the porous media provide for the distribution of the process gases.

The absorption mechanism includes the CO_2 reaction chemistry with both hydroxyl ions (OH^-) and carbonate ions ($CO_3^=$). The CO_2 in the air transfers to the gas/liquid interface where it reacts with two OH^- to form $CO_3^=$ and water. The ionic concentration gradients resulting from the CO_2 absorption at the interface are the driving forces for the exchange of $CO_3^=$ and OH^- between the gas/liquid interface and the bulk absorbent. As the OH^- concentration is reduced, a second absorption reaction occurs. Carbon dioxide is absorbed and reacts with $CO_3^=$ and water to form two bicarbonate ions (HCO_3^-). The two absorption reactions occur simultaneously along the active interfacial area, depending on the localized pH of the absorbent. The $CO_3^=/HCO_3^-$ equilibrium established is based on the pCO_2 of the process air. The functional schematic illustrating the two absorption processes is provided in Figure 2.

The solution in which the absorption process occurs allows fresh absorbent to transfer by diffusion to the gas/liquid interface from the bulk absorbent in the matrix. This internal transport mechanism minimizes gas void volume and gas/absorbent interface surface area requirements as compared to a solid absorbent bed. The interface construction provides for extremely high gas/



Hydroxyl Ion Absorption

$CO_2 + 2OH^- = CO_3^= + H_2O$

Carbonate Ion Absorption

$CO_2 + CO_3^= + H_2O = 2HCO_3^-$

FIGURE 2 ABSORPTION MECHANISM FOR ERCA CONCEPTS

liquid interfacial areas for the absorption process and results in the effective and efficient absorption bed design. The small pore structure provides additional capillary forces to the porous retention media for separation of gas and liquid phases, and proper containment of the absorbent.

Absorption performance is evaluated with three parameters. The first is Absorption Efficiency (AE) which is defined as the percent ratio of the change in CO_2 mass flow through the absorber to the inlet CO_2 mass flow rate. An AE of 100% implies an absorber outlet pCO_2 of zero. The second performance parameter is the Absorbent Utilization Efficiency (AUE). This parameter is defined as the percentage utilization of the maximum regenerated CO_2 absorption capacity of the absorber. A third term used in evaluating ERCA performance is breakthrough. This parameter is defined as the time during the absorption process when the absorption efficiency decreases from its initial performance level of 100% to a reduced level, e.g., 95%.

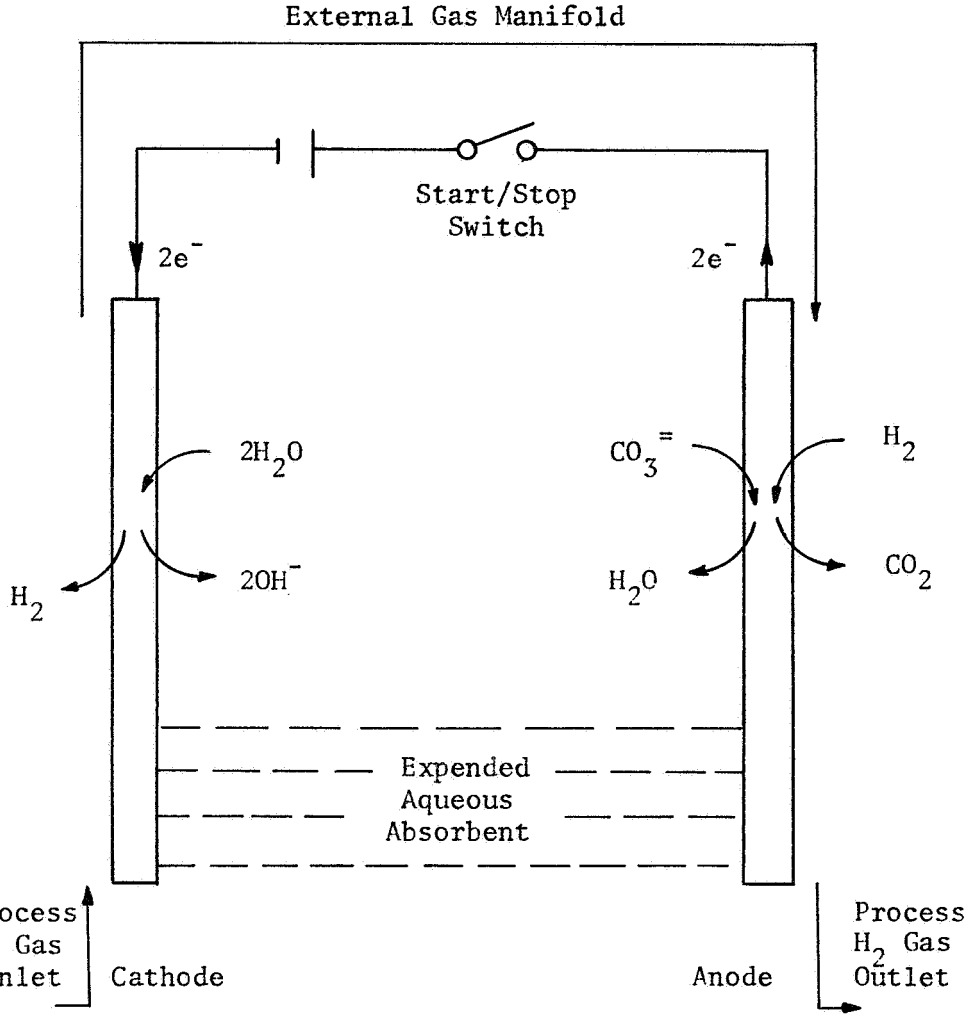
Regeneration Mechanism

The regeneration process evolves the metabolic CO_2 stored in the expended absorbent and replenishes the OH^- concentration of the absorbent. The ERCA regeneration module basically functions as a H_2 concentrator, consuming H_2 gas at the anodes and regenerating it at the cathodes. A side reaction of the H_2 consumption occurring at the anode is the evolution of CO_2 from the expended absorbent solution. Similarily, a side reaction of the H_2 generation process at the cathode is the production of the regenerated absorbent solution.

The process occurs in four steps for the electrochemical ERC Absorber hardware. First, a nitrogen (N_2) purge is used to remove oxygen (O_2) remaining from the absorption process. Second, a H_2 purge is completed to assure H_2 contact with the electrode surfaces before initiation of the regeneration process. The third step is the actual desorption mode defined as the active process of applying current for absorbent regeneration. During this step, the expended aqueous absorbent becomes the electrolyte for the electrochemical regeneration process. A final N_2 purge is then used to remove H_2 from the ERC Absorber prior to reabsorption.

The electrochemical and chemical reactions which occur when power is supplied to the electrodes are presented in Figure 3. During desorption H_2 gas flows in series over the cathode and anode as illustrated in Figure 3. Hydrogen and OH^- are electrochemically consumed at the anode to form water. This reaction decreases the pH of the anolyte which results in the evolution of CO_2 through the reaction listed in Figure 3. At the cathode water is consumed to produce the H_2 gas and OH^-. The H_2 gas is evolved into the process stream where it returns to the anode cavity for reconsumption. The OH^- remains in the electrolyte to chemically transport the current from the cathode to the anode. As the OH^- concentration of the electrolyte increases the CO_2 evolution rate decreases due to the increase in anolyte pH. The product of the desorption mode is a mixture of CO_2 and H_2 in the gas phase ready for direct integration with a CRS.

The regeneration process for the nonelectrochemical ERC Absorber hardware occurs in two steps. First, the expended absorbent solution within the ERC Absorber is extracted from the absorber and replaced by regenerated absorbent



Cathode Reaction

$$2H_2O + 2e^- = 2OH^- + H_2$$

Anode Reaction

$$2OH^- + H_2 = 2H_2O + 2e^-$$

$$CO_3^= + H_2O = HCO_3^- + OH^-$$

$$HCO_3^- = CO_2 + OH^-$$

Overall Reactions

$$CO_3^= + H_2O + \text{Electrical Energy} = 2OH^- + CO_2 + \text{Heat}$$

Overall Anode Reaction

$$CO_3^= + H_2 = H_2O + CO_2 + 2e^-$$

FIGURE 3 REGENERATION MECHANISM FOR ERCA CONCEPTS

solution. The second step is the regeneration of the expended absorbent solution which is performed on a continuous basis with the regeneration hardware. The electrode reactions are identical to those defined in Figure 3. However, the bulk absorbent passes through the cell during regeneration rather than being stationary within a matrix. Expended absorbent solution is continuously fed into the anode electrode through a feed plate assembly. A differential pressure is established across the electrochemical cell resulting in bulk liquid flow across the electrochemical cell. This bulk flow causes the regenerated absorbent solution to exit the electrochemical cell at the cathode where it is separated from the H_2 gas generated at the cathode and collected for the extraction/replacement process of the ERC Absorber.

Performance of the regeneration mechanism is evaluated as Regeneration Efficiency (RE). This efficiency is defined as the ability of the hardware to convert the $CO_3^=$ in the expended absorbent to OH^-. This definition implies 100% RE is equivalent to a pure OH^- solution. Two other terms are required to complete the description of ERCA performance. Extraction Efficiency (EE) is defined as the ability to replace the expended absorbent solution within the ERC Absorber hardware with regenerated absorbent solution. Extraction Efficiencies are used in describing the performance of the nonelectrochemical ERC Absorber design only since the electrochemical ERC Absorber design does not require the removal and replacement of absorbent solution. The final term for describing ERCA performance is Total Absorbent Utilization (TAU) which is defined as the product of the independent performance parameters for each concept. For the electrochemical ERC Absorber TAU is the product of the AUE and RE. For the nonelectrochemical ERC Absorber it is the product of the AUE, EE and RE.

ELECTROCHEMICAL ERC ABSORBER DESIGN

The block diagram of the CO_2 scrubber, as integrated within the PLSS, was presented in Figure 1. This figure depicted the atmospheric revitalization loop, the liquid coolant loop and the controller connections to the various PLSS components. The scrubber was shown as the second component in the atmospheric revitalization loop although alternate locations were possible. The inlet process air is warm, moist and debris-free air containing CO_2. The ERC Absorber functions as a passive absorption bed which effectively removes metabolically-generated CO_2. At the completion of an EVA the aqueous absorbent solution becomes the electrolyte for the electrochemical regeneration process on-board the primary space vehicle.

Design Specifications

The design specifications for the PLSS CO_2 scrubber are provided in Table 1. These specifications are based on previously completed studies to define Advanced Extravehicular Protective System (AEPS) requirements.[11,12] The specifications include CO_2 removal requirements, the length and frequency of EVA missions and atmospheric data projected for the PLSS air revitalization loop. An illustration of a typical CO_2 generation rate during an EVA[1] is provided in Figure 4.

There are several major differences between the PLSS specifications and those of the primary space vehicle Air Revitalization System (ARS). The nominal

TABLE 1 PLSS CO_2 SCRUBBER DESIGN SPECIFICATIONS

Crew Data	
Number of Crew	1
Metabolic Rates, J/h-person (Btu/h-person)	
Average	1.3×10^6 (1200)
Maximum Sustained	1.7×10^6 (1600)
Maximum	3.7×10^6 (3500)
CO_2 Generation Rate, kg/h-person (lb/h-person)	
Average	0.118 (0.260)
Maximum Sustained	0.159 (0.350)
Maximum	0.341 (0.752)
O_2 Consumption, kg/h-person (lb/h-person)	
Average	0.088 (0.195)
Maximum Sustained	0.119 (0.262)
Maximum	0.256 (0.564)
Respiratory Quotient Base, Vol. CO_2 Exhaled/Vol. O_2 Inhaled	0.97
Mission Data	
Mission Length	
Maximum, h	12
Nominal, h	4 to 8
Frequency of Mission	
Maximum/d	3
Nominal/d	1
Maximum Number of EVA	250
Atmosphere Data	
Operational Gravity Range, N/kg (g)	0 to 9.8 (0 to 1)
Total Pressure, kPa (psi)	48 to 55 (7 to 8)
Suit Gas Composition	
Pure O_2, kPa (psi)	48 to 55 (7 to 8)
O_2-N_2 Mixture, kPa (psi)	48 to 55 (7 to 8)
CO_2 Partial Pressure	
Nominal, kPa (mm Hg)	0.53 (4.0)
Maximum, kPa (mm Hg)	1.00 (7.5)
Emergency Maximum, kPa (mm Hg)	2.00 (15.0)
O_2 Partial Pressure	
Nominal, kPa (psi)	25.5 to 55.2 (3.7 to 8)
Ventilation	
Inlet Flow Rate, dm^3/s (cfm)	
Nominal	3.4 (7.2)
Emergency	4.2 (9.0)

continued -

Table 1 - continued

Inlet Temperature, K (F)	
Nominal	283 to 294 (50 to 70)
Emergency	283 (50)
Inlet Dew Point, K (F)	
Minimum	277 (40)
Nominal	280 (45)
Maximum	289 (60)
Relative Humidity, %	70 to 40
Liquid Coolant Transport Loop Data	
Flow Rate, kg/h (lb/h)	109 (240)
Temperature, K (F)	
Minimum	277 (40)
Maximum	289 (60)

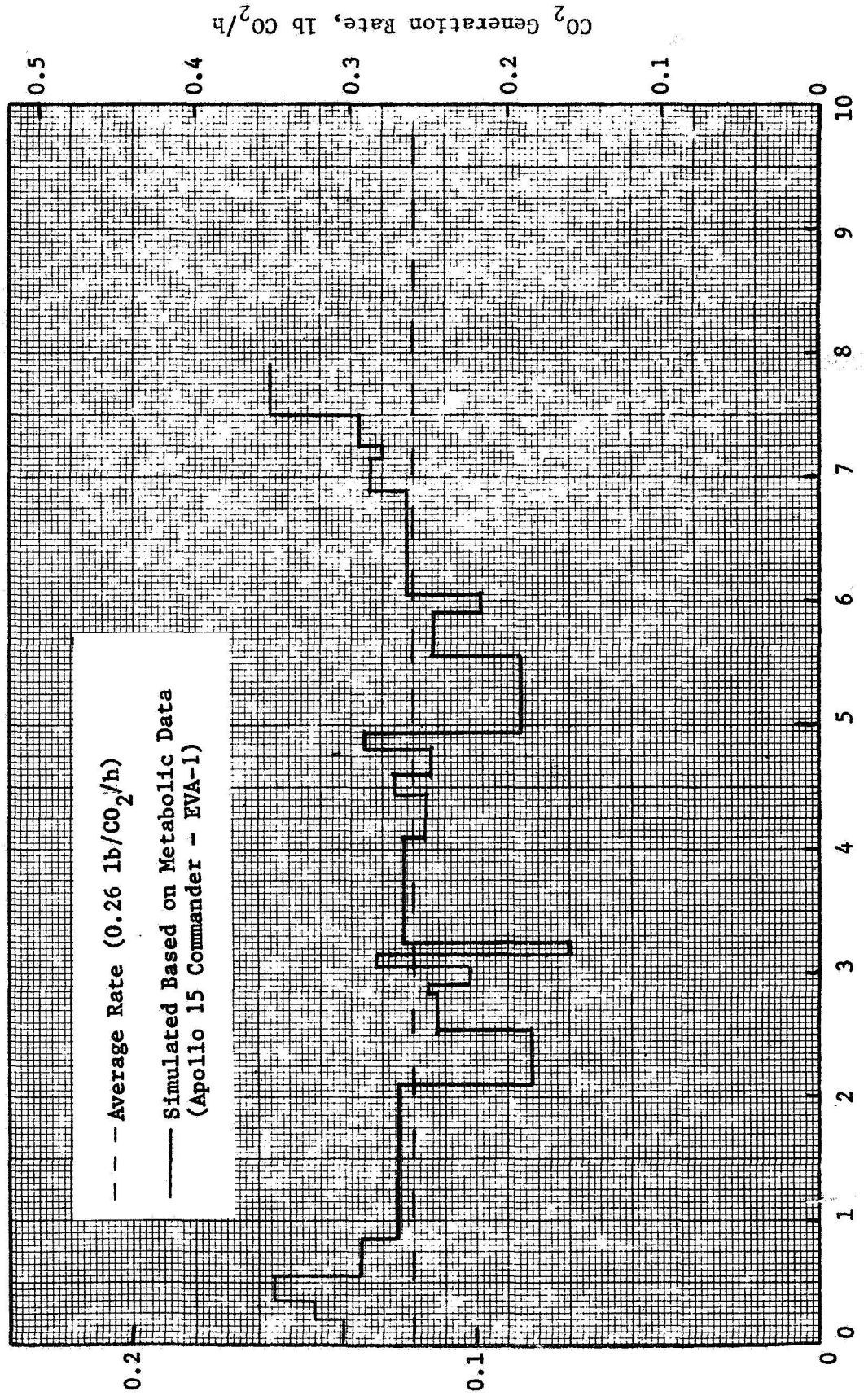


FIGURE 4 SIMULATED CO_2 GENERATION RATES DURING EVA

PLSS CO_2 removal requirement of 0.118 kg/h (0.260 lb/h) per person is 2.8 times the ARS CO_2 removal requirement of 0.042 kg/h (0.092 lb/h) per person. The low PLSS process air flow rate and small total suit volume requires that CO_2 be removed at the same rate that it is produced since there is no large volume to damp out sudden increases in CO_2 production. The high nominal CO_2 removal requirement and the requirement to suddenly increase the CO_2 removal rate up to three times to match increased metabolic rates severely limits the type of CO_2 absorption process that can be used. In general, the high and variable CO_2 removal requirements and the finite time of an EVA mission implies the use of a passive, capacity-limited process for CO_2 absorption. A capacity-limited CO_2 absorber must still be sized to ensure that the peak removal requirements can be met at the end of an EVA mission.

The PLSS application dictates the criteria for evaluation of totally regenerable absorption concepts. The highest priority for comparison of potential concepts is placed on total equivalent launch weight and EVA volume. Secondary criteria include EVA mass and total equivalent launch volume. The total equivalent launch weight includes: (1) CO_2 scrubber hardware and spares, (2) regeneration subsystem hardware and spares, (3) power and heat rejection penalties for regeneration, (4) total expendables and (5) recovery penalties for CO_2 and water on-board the primary space vehicle during regeneration.

The EVA volume is of primary importance for backpack application. Present LiOH canister volumes for EVA range from 4 to 8 dm^3 (0.14 to 0.28 ft^3). Since most EVAs are performed in zero gravity, only secondary importance is placed on EVA component mass although considerations for momentum and center of gravity are still required.

Electrochemical ERC Absorber

The initial hardware development efforts concentrated on the miniaturization of the electrochemical ERC Absorber hardware. The miniaturization was limited to decreasing cell gas cavity heights, decreasing electrode thicknesses, and the elimination of hardware components which did not directly increase absorbent capacity or perform gas contacting requirements. Within these restrictions several concepts were proposed. From the choice of proposed concepts the flat plate baseline cell hardware design was selected based on its minimum edge sealing requirements, proven fabrication techniques for the electrodes and the matrices and the direct correlations with the performance characteristics of the ten-cell module previously tested in this program.

Absorber Design

The projected design characteristics are provided in Table 2 for the flat plate, electrochemical ERC Absorber hardware. The absorber was designed to satisfy the CO_2 removal capacity and rate requirements for the AEPS specification defined in Table 1. These projections are based on an absorbent utilization efficiency of 90% and a regeneration efficiency of 59%. The projected 90% absorbent utilization efficiency is based on the results of the feasibility test data and improvements projected as a result of hardware modifications and flow path designs. The regeneration efficiency and the power required for regeneration were based directly on the feasibility test data. The results of these sizings demonstrate an absorber volume of 23 dm^3 (0.80 ft^3) and mass of

TABLE 2 DESIGN CHARACTERISTICS FOR AN ELECTROCHEMICAL ERCA CONCEPT ABSORBER

CO_2 Capacity, kg (lb)	0.95 (2.1)
Absorber Volume, dm^3 (ft^3)	23 (0.8)
Absorber Mass, kg (lb)	30 (66)
Absorber Dimensions, m (ft)	0.23 x 0.23 x 0.44 (0.75 x 0.75 x 1.44)
Total Surface Area, m^2 (ft^2)	35 (380)
Absorbent Volume, dm^3 (in^3)	9.0 (550)
Absorbent Utilization Efficiency, %	90
Regeneration Efficiency, %	59
Extraction Efficiency, %	N/A
Total Absorbent Utilization, %	53
Power Required for Regeneration, W	200
Extraction/Replace Volume Ratio	N/A

30 kg (66 lb) for the electrochemical ERC Absorber. A sketch of the ERC Absorber hardware is provided in Figure 5.

Table 3 illustrates the baseline cell configuration. Each electrode matrix combination is fabricated into a unitized cell. An epoxy seal between the electrodes and matrix provide the edge sealing and electrode separation. The unitized cell construction technique provides for both cell quality assurance checking prior to module assembly and uniform alignment of cells during module assembly. The electrodes are LSI proprietary composition and design.

The gas cavity spacer/bipolar current collector was designed for fabrication from a thin sheet of nickel material with a dense pattern of alternating up and down dimples. This gas cavity spacer, when assembled between two unitized cells, produces two isolated gas cavities and a bipolar current collector. The dimples function as both the contact points for the current transfer and as cavity spacers providing gas passages. The nickel sheet material effectively isolates the anode gas cavity of a cell from the cathode gas cavity of the next cell. This isolation is required to eliminate the potential for regeneration inefficiencies which results from CO_2 reabsorption at the cathode after evolution from the anode during the regeneration process.

The ERCA flat plate hardware cell design utilizes the cathode-to-anode series flow path of 170 cm (68 in) in length. The design calls for each electrode gas cavity to be divided into four serpentine flow paths. A figure illustrating the gas and liquid flow path design is provided in Figure 6. A Teflon cord material is utilized to produce the serpentine flow path geometry of the gas cavities.

Heat removal during the absorption mode can be accomplished by internal liquid coolant or allowing water evolution from the absorbent solution. Both methods should maintain process air RH conditions within the acceptable limits. The heat and mass balance of the ERCA regeneration process identified the requirement for active cooling during regeneration. The internal liquid coolant method was selected for the design based on its minimum effect on the EVA volume and the potential for uniform heat removal over the plane of the cell. Calculations determined that one coolant plate assembly for every ten cells was sufficient to satisfy the ERCA regeneration heat removal requirements.

Regeneration Hardware

The regeneration hardware for the electrochemical ERCA concept simply consists of a fluids control assembly and control/monitoring instrumentation. A block diagram of the regeneration process is shown in Figure 7. The fluids control assembly, consisting of valving, regulators and flow control orifices, provides interfaces with the space vehicles' N_2, H_2 and liquid coolant supplies and connects the absorber outlet with the CRS or vacuum vent. The control/monitoring instrumentation provides the fluid control and power sequencing required for the regeneration process and the necessary monitoring and protective instrumentation.

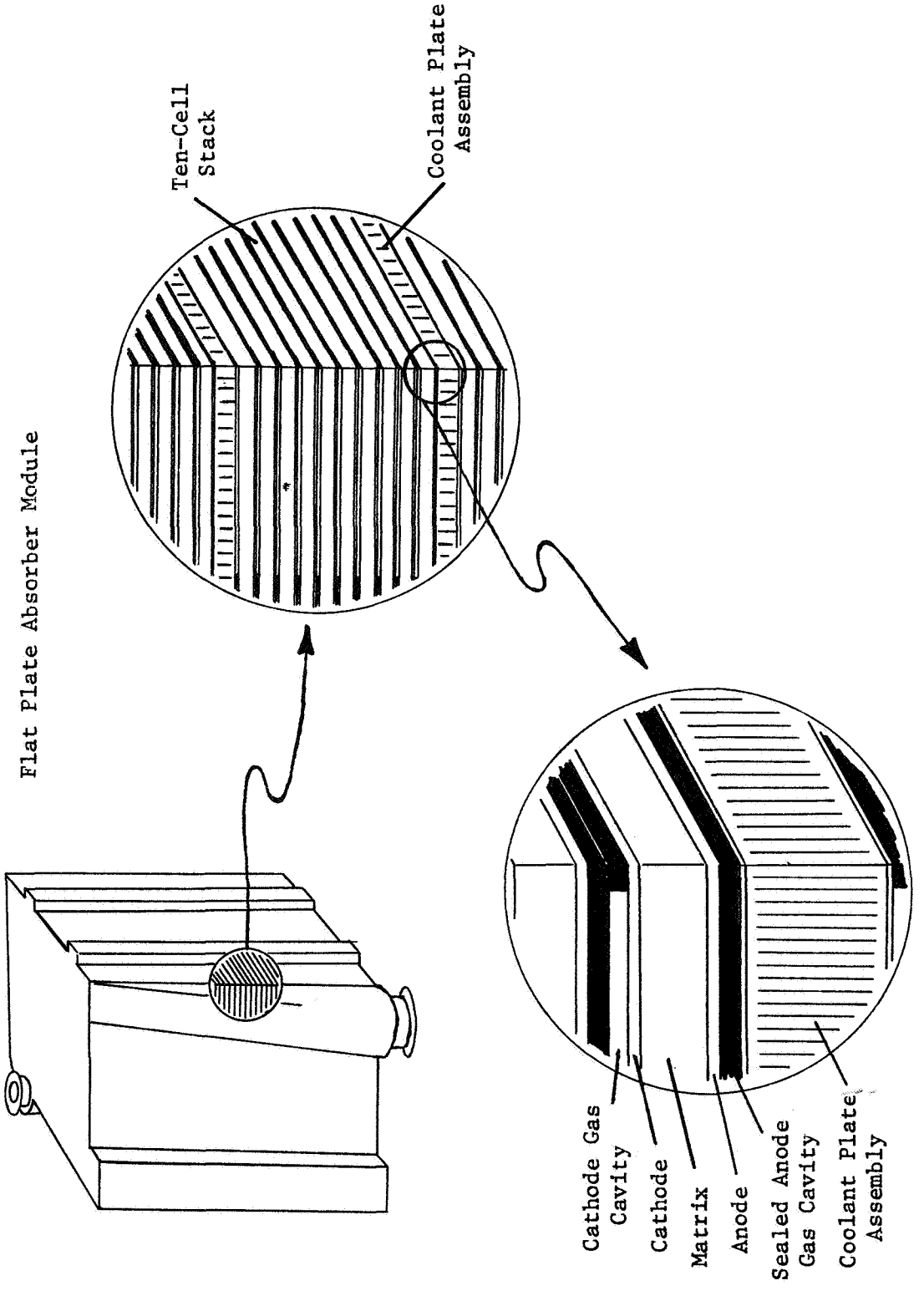


FIGURE 5 FLAT PLATE ELECTROCHEMICAL ERC ABSORBER HARDWARE

TABLE 3 CELL CONFIGURATION FOR THE ELECTROCHEMICAL ERC ABSORBER

Cathode	
Thickness, cm (in)	0.010 (0.004)
Surface Area, cm^2 (ft^2)	460 (0.50)
Anode	
Thickness, cm (in)	0.010 (0.004)
Surface Area, cm^2 (ft^2)	460 (0.50)
Matrix	White Asbestos
Thickness, cm (in)	0.051 (0.020)
Gas Cavity Height, cm (in)	0.015 (0.006)
Absorption Surface Area, cm^2 (ft^2)	930 (1.0)
Cooling Method	Internal Liquid Cooling
Absorbent	EA-1
Flow Path	Cathode to Anode in series
Flow Path Length, cm (in)	170 (68)

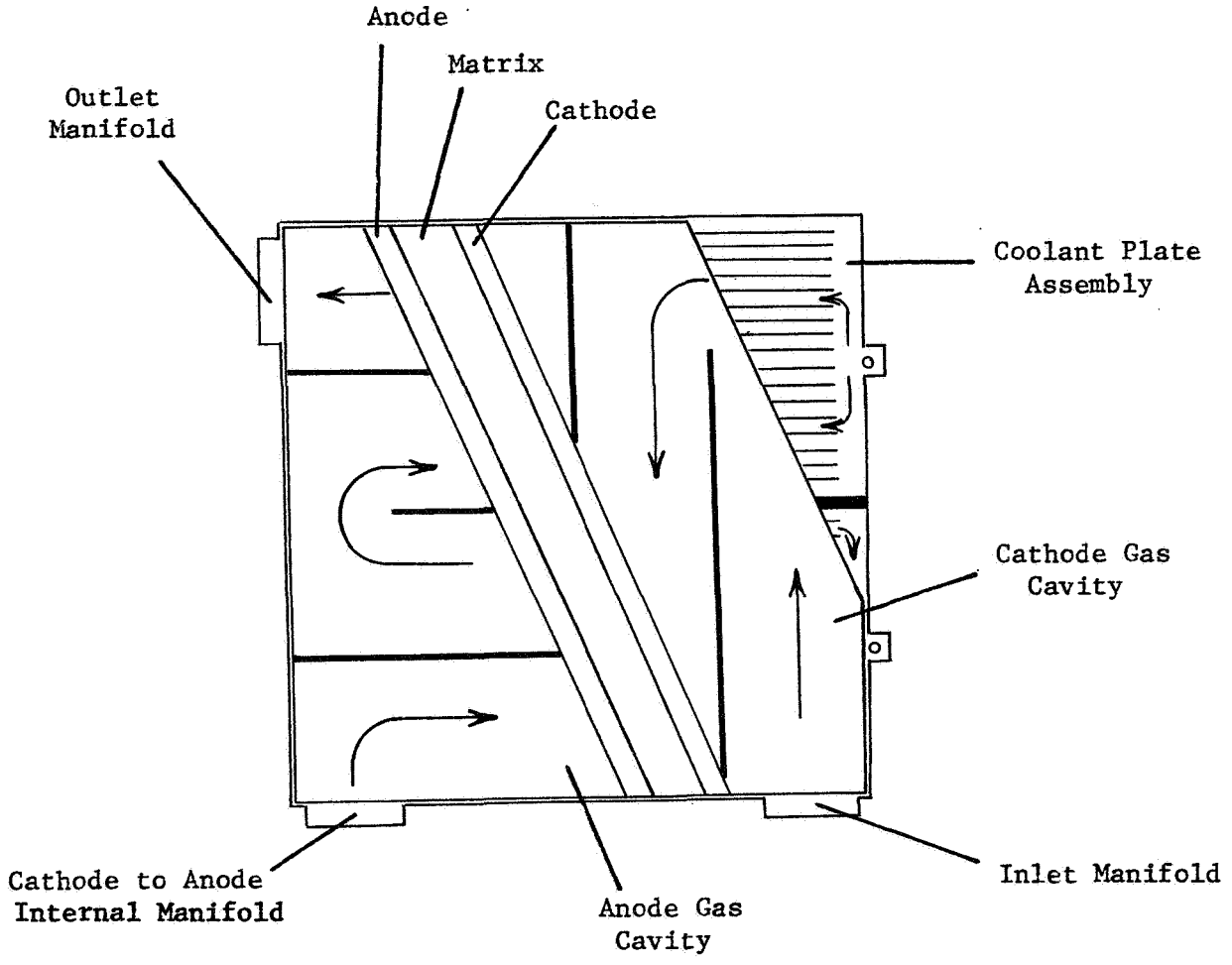


FIGURE 6 FLOW PATH ILLUSTRATION OF ELECTROCHEMICAL ERC ABSORBER CELL

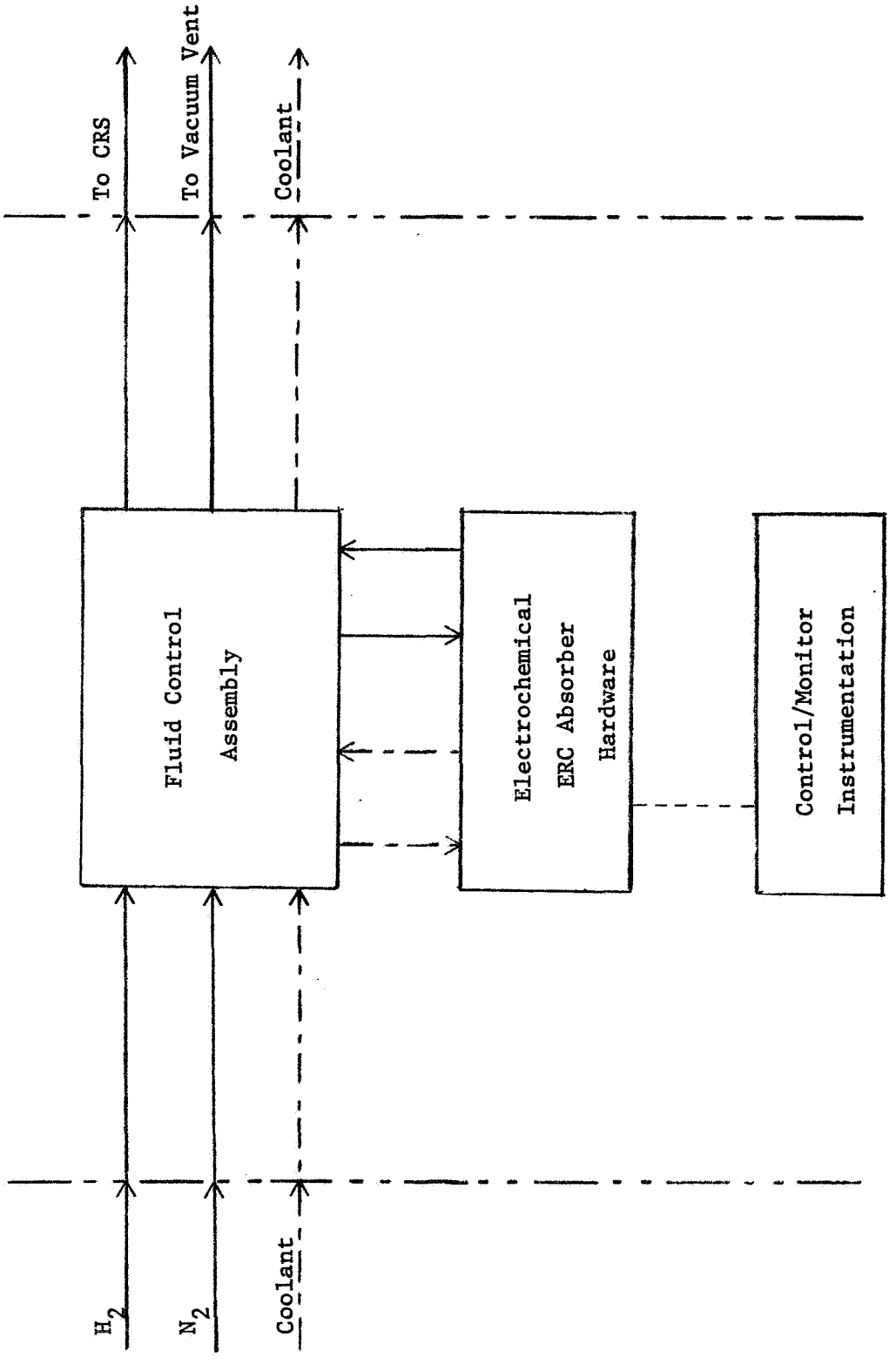


FIGURE 7 BLOCK DIAGRAM OF THE REGENERATION PROCESS FOR AN ELECTROCHEMICAL ERC ABSORBER

NONELECTROCHEMICAL ERC ABSORBER EVALUATION

With the completion of the preliminary design of the electrochemical ERC Absorber the program emphasis was directed to the evaluation of nonelectrochemical ERC Absorber designs. Improvements in the ERC Absorber volume and mass can result by removing nonessential components from the absorption hardware such as the electrodes and current collectors. These modifications define the nonelectrochemical ERC Absorber hardware. This hardware requires the extraction and replacement of aqueous absorbent solution from the absorption bed for regeneration. A comparison of the two types of ERC Absorbers is provided in Table 4.

Alternate Design Concepts

The evaluation of the nonelectrochemical ERC Absorber designs was performed in three steps. The first step was to define alternate design concepts based on various approaches to solving the problems of absorbent/gas contact and absorbent retention during EVA. The second step was the generation of conceptual designs for each approach. The final step was the selection of a concept to be carried to a preliminary design level.

The five major concept approaches which satisfy the absorbent/gas contact and absorbent retention requirements are: (1) the porous pellet absorption bed, (2) the shell and tube contactor, (3) the aerosol contactor, (4) the fiber bed contactor, and (5) the plate absorption bed. A comparison of these approaches, including advantages/disadvantages, is provided in Table 5. A conceptual design was generated for each approach. Each design consisted of a sketch of the absorber bed, a description of the hardware, a list of projected advantages/disadvantages and potential risks, a schematic of the absorption process and a projected sizing for the absorber volume and mass. A summary of the nonelectrochemical ERC absorber conceptual designs is contained in Table 6. The regeneration power requirements were based on the power necessary to generate the volume of absorbent solution needed to achieve the projected extraction efficiencies by a flush-through method.

Two methods, the porous pellet and fiber bed contactor, were eliminated based on their ineffective extraction methods which resulted in high regeneration power requirements. A representative sketch of either concept is provided in Figure 8. The porous pellets were projected to be solid porous polysulfone pellets. The fiber bed was envisioned as a tight honeycomb structure weave of fibrous material.

A sketch of a plate absorption bed approach is provided in Figure 9. This design utilized hydrophobic membranes to provide the absorbent/air interface. The membranes were fabricated into disk-shaped, spiral bags which contained the absorbent solution and provided a simple and direct method for extraction of the absorbent. Although this approach maintained a high AUE the extra volume required for the membranes and gas cavity spacers resulted in a slightly higher projected volume then the shell and tube contactor approach.

The aerosol contactor approach is shown in Figure 10. This design utilized a parallel flow of fine absorbent mist directly contacting the process air.

TABLE 4 BASIC ABSORBER CONCEPT COMPARISON

Hardware Concepts	Description	Major Advantages	Major Disadvantages
Electrochemical Absorber Concept	Any concept in which the absorbent is regenerated within the confines of the absorption bed	• Does not require absorbent solution transfer	• Lower absorbent regeneration efficiencies (Range 40 to 70% OH^- production) and higher electrochemical power consumption for absorbent regeneration (Range 100 to 300 W) • Extra hardware mass and volume required in absorber
Nonelectrochemical Absorber Concept	Any concept in which the absorbent must be extracted from the absorption bed for regeneration	• Projected higher regeneration efficiencies (Range 60 to 100% OH^- production) and lower electrochemical power consumption for absorbent regeneration (Range 30 to 100 W) • Minimal absorber volume and mass	• Tranferring absorbent solution which requires positive isolation disconnects and additional power consumption

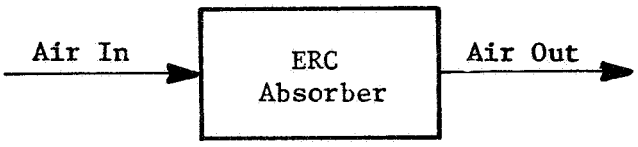
TABLE 5 ALTERNATE ABSORBER DESIGN CONCEPTS

Concept Approaches	Description	Major Advantages	Major Disadvantages
Porous Pellet Absorption Bed	Absorbent is contained within pore structure of the pellet	High absorption surface area	Difficult absorbent extraction for regeneration
Shell and Tube Contactor	Hydrophobic tubes form the separation between the air passages and the bulk absorbent	High gas phase mass transport, high liquid phase mass transport within bulk absorbent and easy absorbent extraction for regeneration	Reliability of the tubes
Aerosol Contactor	Absorbent is mixed with gas stream to form an aerosol, then separated	Very efficient gas-liquid contacting technique and high absorbent utilization	Zero gravity gas-liquid absorbent separation
Fiber Bed Contactor	Absorbent is retained in micropore structure and gas flows through macropore structure of the fibrous mesh	Efficient gas-liquid contacting technique	Gas-liquid separation, high pressure drop and difficult extraction/recharge procedure
Plate Absorption Bed	Absorbent is positively contained within flat plates which are separated by gas cavities	High absorbent utilization for a captive absorbent concept	Gas flow distribution over the flat plates

TABLE 6 SUMMARY OF NONELECTROCHEMICAL ERC ABSORBER CONCEPTUAL DESIGNS

Concept Approach	Absorber Design	EVA Sizing		TAU,[a] %	EE, %	AUE, %	Regeneration Power, W
		Volume, dm^3 (ft^3)	Mass, kg (lb)				
Porous Pellet Absorption Bed	Porous Polysulfone Pellet	12 (0.43)	10.4 (22.9)	68	95	72	210
Shell and Tube Contactor	Hollow Fiber Membrane (HFM) Absorber	11 (0.39)	8.8 (19.4)	86	98	88	90
Aerosol Contactor	Co-current Mist	7 (0.28)[b]	8.9 (19.6)[b]	90	98	92	70
Fiber Bed Contactor	Honeycomb Weave	16 (0.56)	10.5 (23.1)	72	98	73	120
Plate Absorption Bed	Hydrophobic Disk	12 (0.44)	8.2 (18.1)	93	98	95	90

(a) Regeneration Efficiency of 100% was assumed for all absorber concepts.
(b) Additional hardware and EVA power is required for absorbent pumping during EVA; therefore, an additional 3.6 kg (7.9 lb) and 4.8 dm^3 (0.17 ft^3) must be added to this sizing.



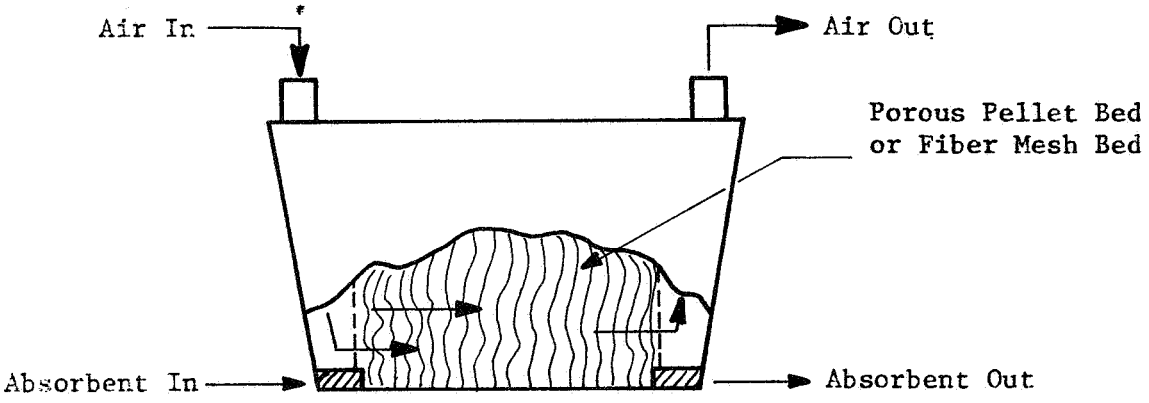
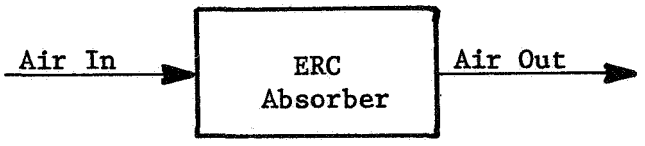


FIGURE 8 POROUS PELLET OR FIBER BED CONTACTOR APPROACH



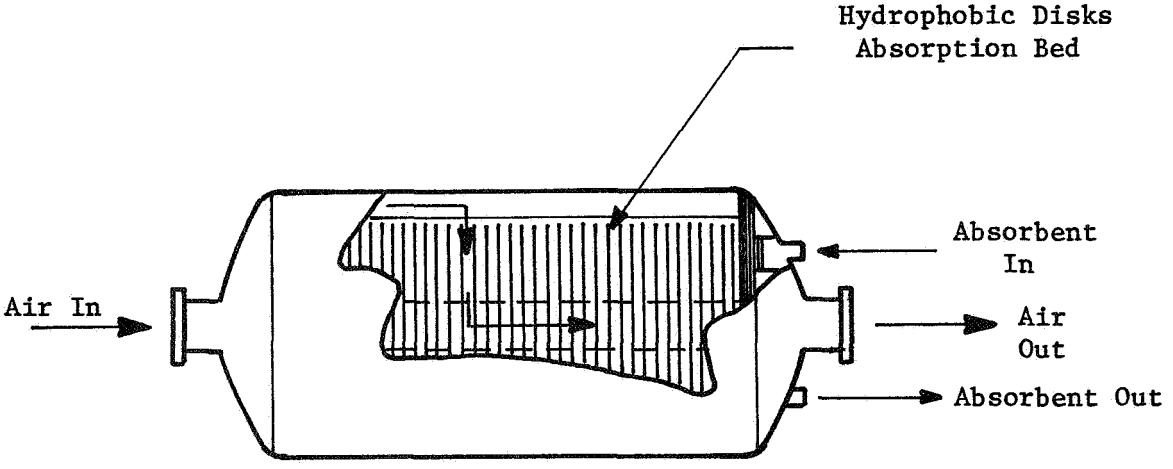
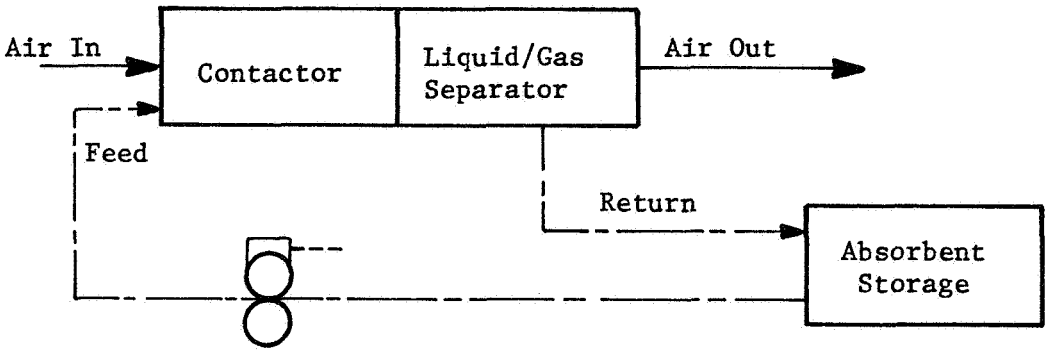


FIGURE 9 PLATE ABSORPTION BED APPROACH



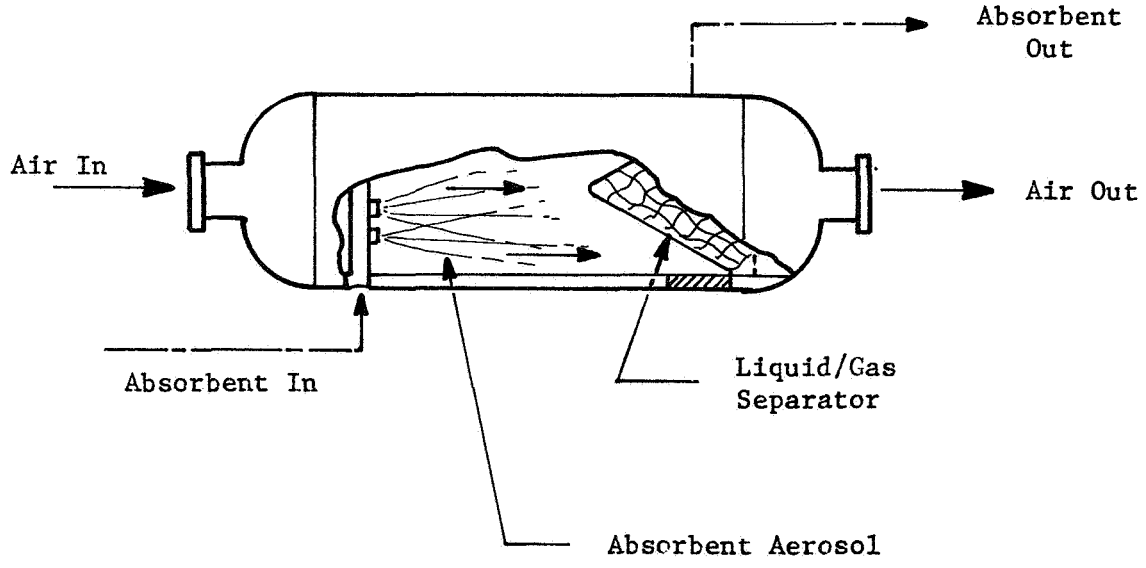


FIGURE 10 AEROSOL CONTACTOR APPROACH

After contact the liquid and gas are separated by a combination hydrophobic/ hydrophilic separator. This approach results in the minimum absorber component size although additional EVA hardware and power requirements are necessary to operate the pump and controls. These requirements increase its net component size to levels equal to those of the other approaches. The reliability and development requirements of the gas/absorbent separator for this approach eliminated it from consideration at this level of development.

The concept approach selected was a shell and tube contactor for which a hollow fiber membrane (HFM) was selected to perform the absorbent/gas separation. This concept was selected based on projected EVA volumes, ease of absorbent extraction/replacement, reliability, flexibility of design parameters, ease of fabrication, including sealing techniques, and finally, material availability. A detailed description is provided in the following section.

Nonelectrochemical ERC Absorber

The discussion of a nonelectrochemical ERC Absorber design is divided into two sections. The first section covers the selected absorber hardware design. The second section discusses the regeneration hardware design. The regeneration hardware is applicable to any nonelectrochemical ERC Absorber concept.

Absorber Design

The characteristics projected for the nonelectrochemical ERC Absorber are presented in Table 7. The absorber design uses HFM tubing to separate the absorbent and process air during the absorption process. The absorber was designed to satisfy the CO_2 removal capacity and rate requirements of the PLSS specifications defined in Table 1. A projected AUE of 90% and RE of 95% was used for the sizing. The EE was estimated at 90% and required a 1.5 stoichiometric regenerated absorbent volume to perform the replacement process.

A functional block diagram of the ERC Absorber is provided in Figure 11 and a sketch in Figure 12. The ERC Absorber consists of two major assemblies, the tube bundle assembly and the coolant assembly. The tube bundle assembly consists of three sections, each containing eight subassemblies of HFM tubes. Fabrication of the tubes into subassemblies allows quality control of these subassemblies prior to the fabrication of the total assembly. The absorbent solution is stored within the tube wall and inside diameter of the HFM tubing. The subassemblies are manifolded into a series absorbent flow path for efficient extraction efficiencies at low regeneration power requirements. The coolant assembly consists of two heat exchanger cores positioned between the three tube sections. These heat exchangers function to remove the heat generated by the absorption of metabolic CO_2. A mock-up of this absorber was fabricated. A photo of the mock-up is provided in Figure 13.

Regeneration Hardware Design

The regeneration hardware design is applicable to all nonelectrochemical ERC Absorber hardware approaches and not specific to the HFM absorber approach. A block diagram of the ERCA Regenerator (ERCAR) system is provided in Figure 14. The functions of the ERCAR module are to evolve the metabolic CO_2 from the expended absorbent solution and to regenerate the CO_2 absorption capability of

TABLE 7 DESIGN CHARACTERISTICS FOR A NONELECTROCHEMICAL ERCA CONCEPT ABSORBER

CO_2 Capacity, kg (lb)	0.95 (2.1)
Absorber Volume, dm^3 (ft^3)	15 (0.53)
Absorber Mass, kg (lb)	20 (45)
Absorber Dimensions, m (ft)	0.36 x 0.28 x 0.16 (1.17 x 0.92 x 0.50)
Total Surface Area, m^2 (ft^2)	48 (520)
Absorbent Volume, dm^3 (in^3)	7.4 (450)
Absorbent Utilization Efficiency, %	90
Regeneration Efficiency, %	95
Extraction Efficiency, %	90
Total Absorbent Utilization, %	77
Power Required for Regeneration, W	40 to 80
Extraction/Replace Volume Ratio	1.5

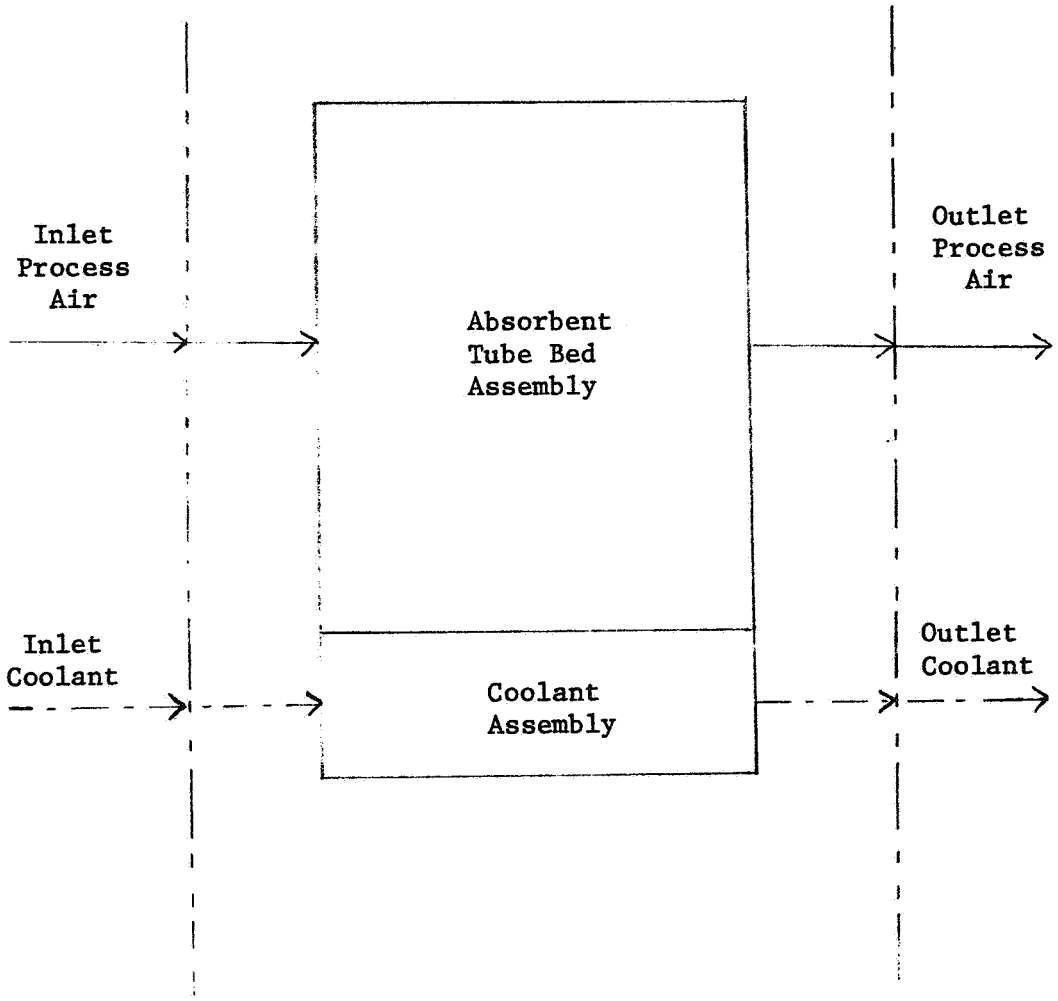


FIGURE 11 FUNCTIONAL BLOCK DIAGRAM OF NONELECTROCHEMICAL ERC ABSORBER

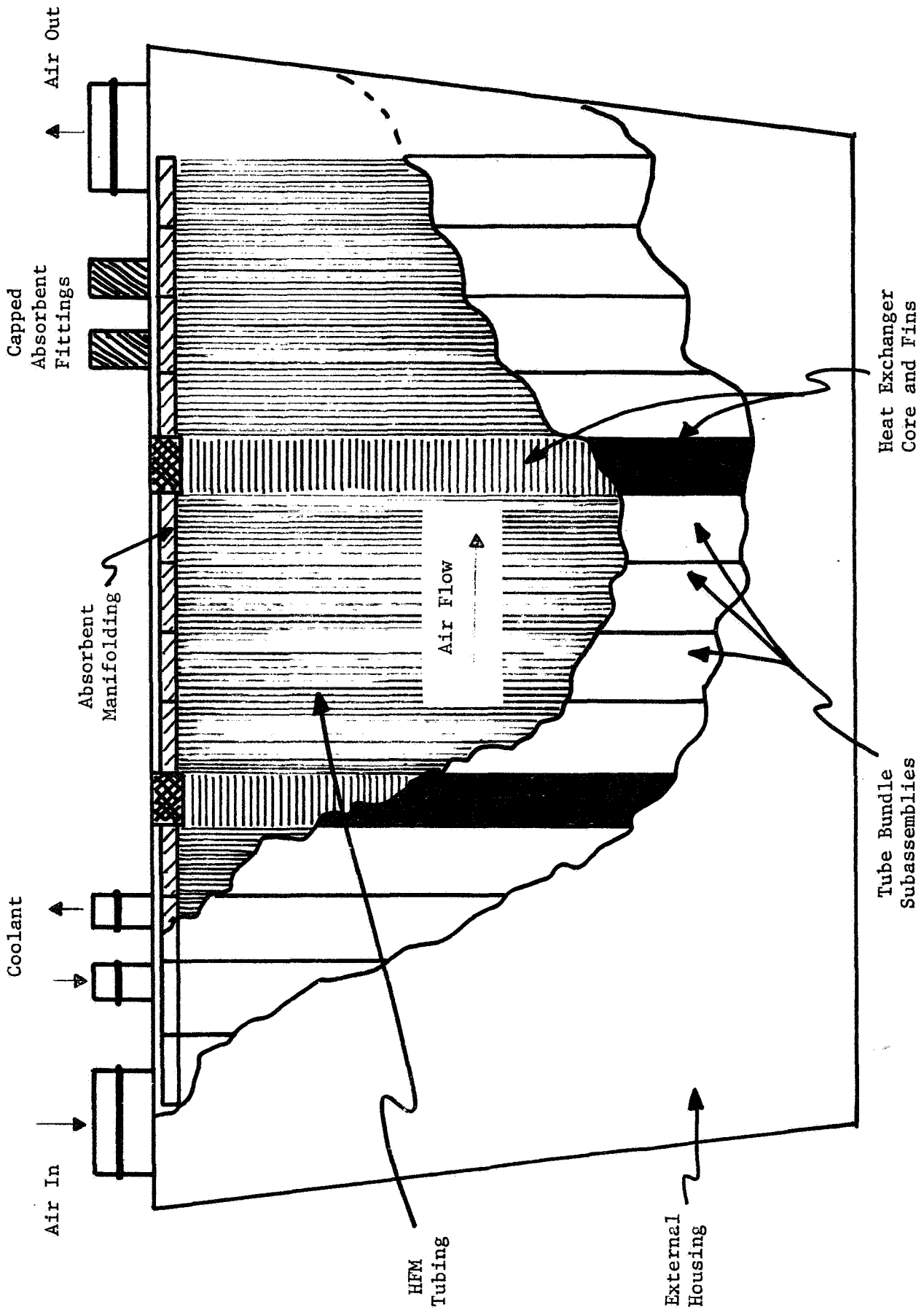


FIGURE 12 ERC ABSORBER

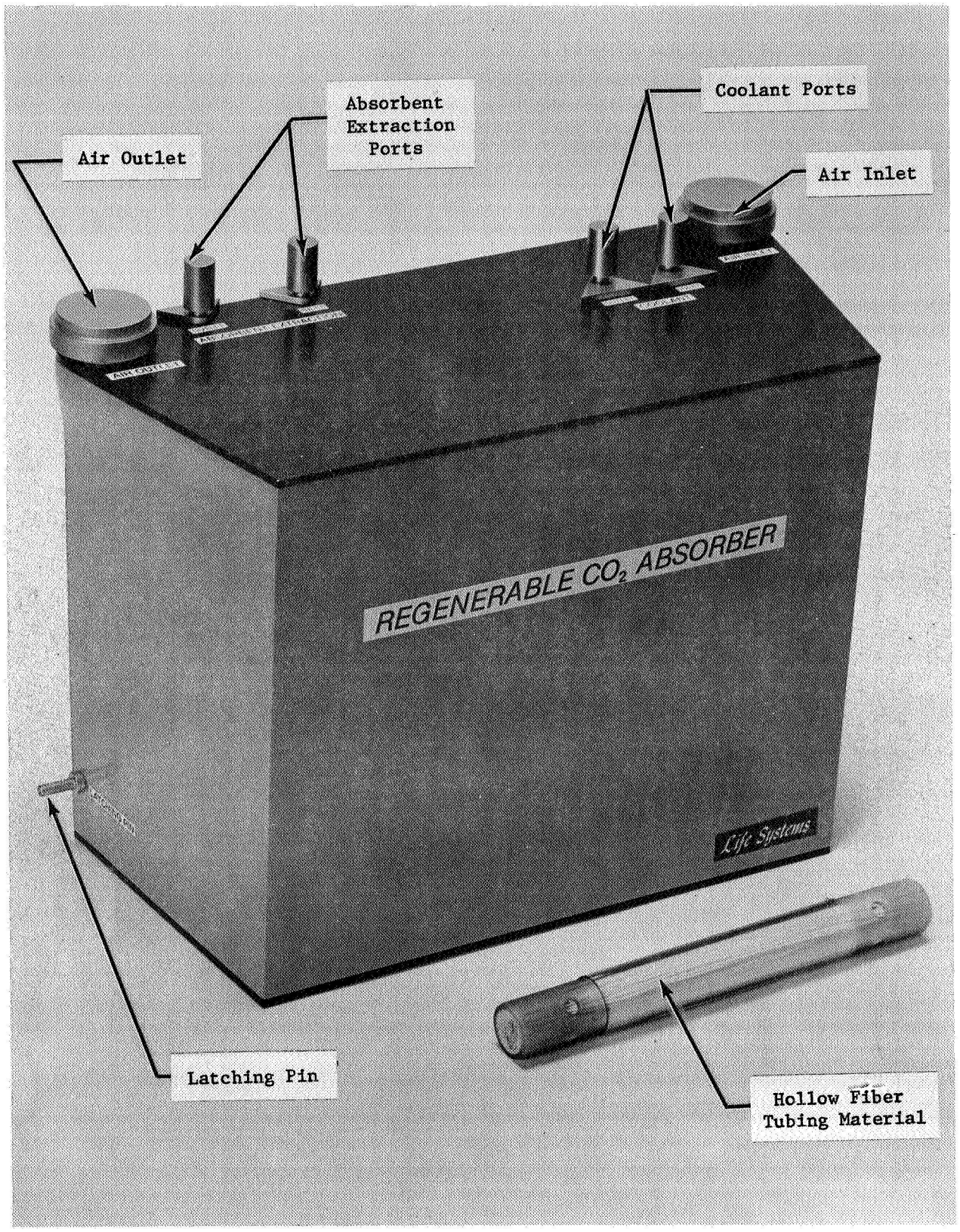


FIGURE 13 ERC ABSORBER MOCK-UP

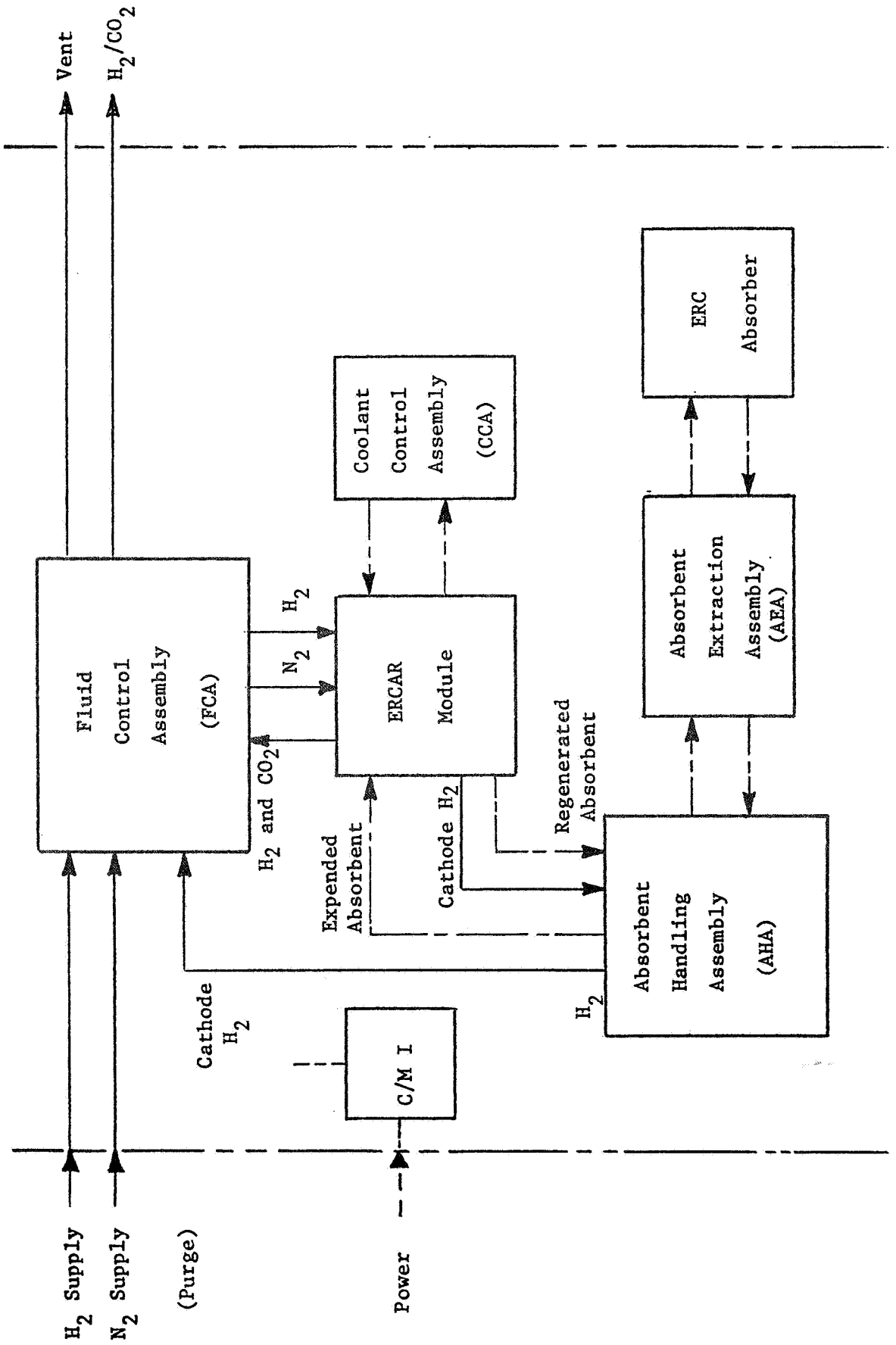


FIGURE 14 ERCAR SUBSYSTEM BLOCK DIAGRAM

the absorbent. The functions of the fluid control assembly are to provide H_2 and N_2 interfaces to the module, to maintain module pressure levels and to provide CRS or vacuum vent interfaces. The coolant control assembly provides thermal control for the module. The absorbent extraction assembly is designed to efficiently extract the spent absorbent solution from the absorber while replacing it with regenerated absorbent. The absorbent handling assembly stores expended and regenerated absorbent solution and interfaces with the ERCAR module by providing proper absorbent feed rates. The cross section view of the regeneration cell hardware is provided in Figure 15. This figure illustrates the assembly of the cell electrodes and matrix with the feed plate assembly. Also demonstrated is the dimpled design of the feed plate which provides the gas cavity for the anode electrode.

CONCEPT COMPARISON

The applicability of the ERCA concept to the PLSS application requires the evaluation of the three major selection criteria: total equivalent launch weight, EVA absorber volume and the ability of the absorbent to be regenerated without performance degradation. The ERCA feasibility testing illustrated the last requirement by demonstrating multiple absorption/regeneration cycles without performance degradation.[2]

The total equivalent launch weight comparisons of various ERCA concepts to the present LiOH CO_2 scrubber are provided in Figure 16. The projected range for the ERCA concept total equivalent weight is applicable for both the electrochemical and the nonelectrochemical ERC Absorber concepts. The data illustrates a crossover point of 91 kg (200 lb) at approximately 26 EVA missions.

The range of EVA absorber volume illustrated in Figure 17 for both the electrochemical and nonelectrochemical ERC Absorber illustrates acceptability for the regenerative PLSS application. The nonelectrochemical ERC Absorbers have smaller EVA volumes mainly due to the elimination of electrodes and current collectors from the absorption hardware. Potentially the nonelectrochemical ERC Absorber could achieve an EVA volume comparable to the present nonregenerable LiOH absorber.

PRODUCT ASSURANCE PROGRAM

The Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, fabrication, purchasing and testing. The Product Assurance included Quality Assurance, Reliability, Safety and Materials Control activities.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definitions and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action. These activities consisted of inspecting all vendor-supplied parts when received and ensuring compliance with assembly techniques specified in the design drawings.

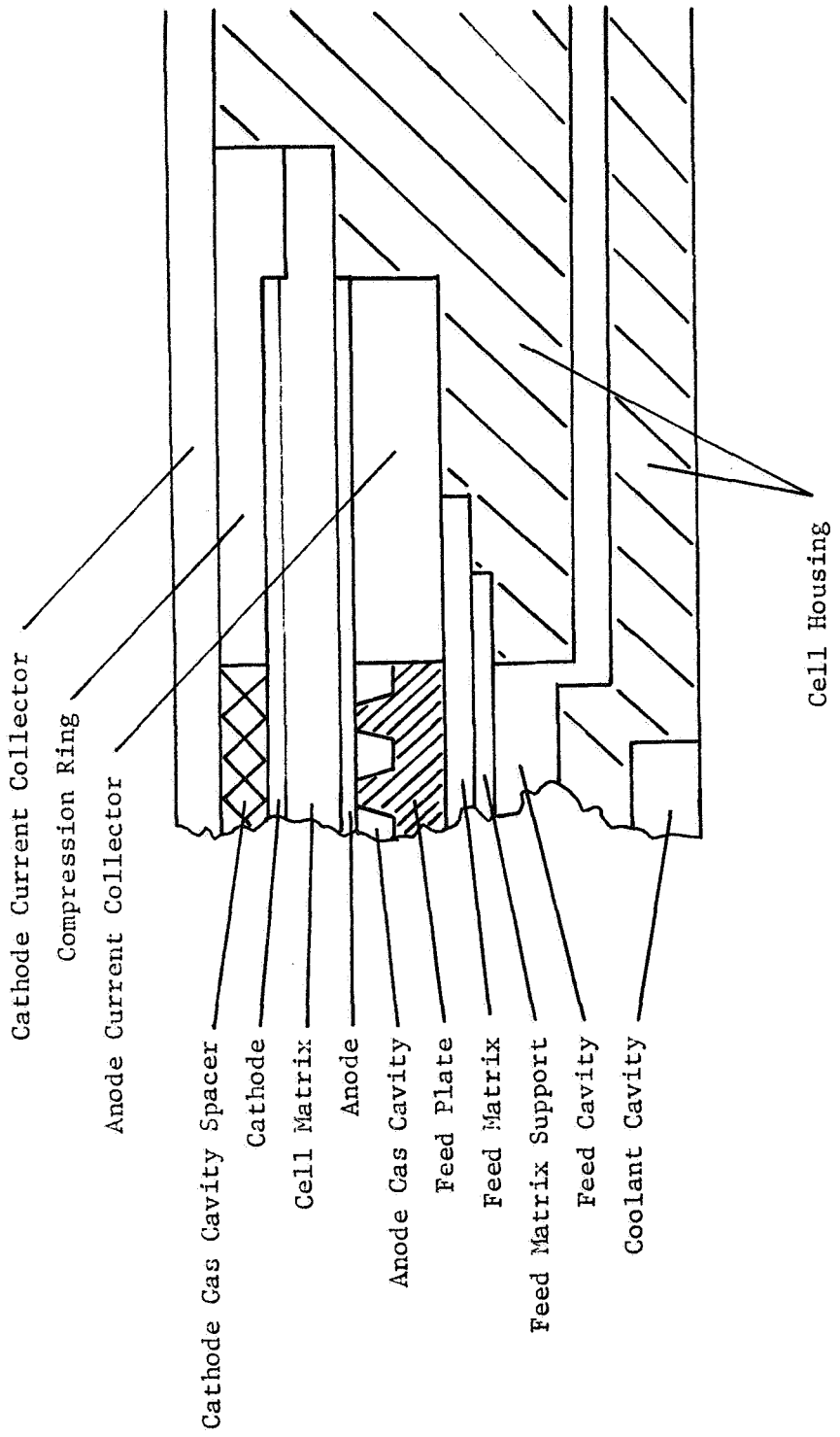


FIGURE 15 CROSS SECTIONAL VIEW OF REGENERATION HARDWARE

FIGURE 16 COMPARISON OF PROJECTED ERCA CONCEPT TOTAL EQUIVALENT LAUNCH WEIGHTS

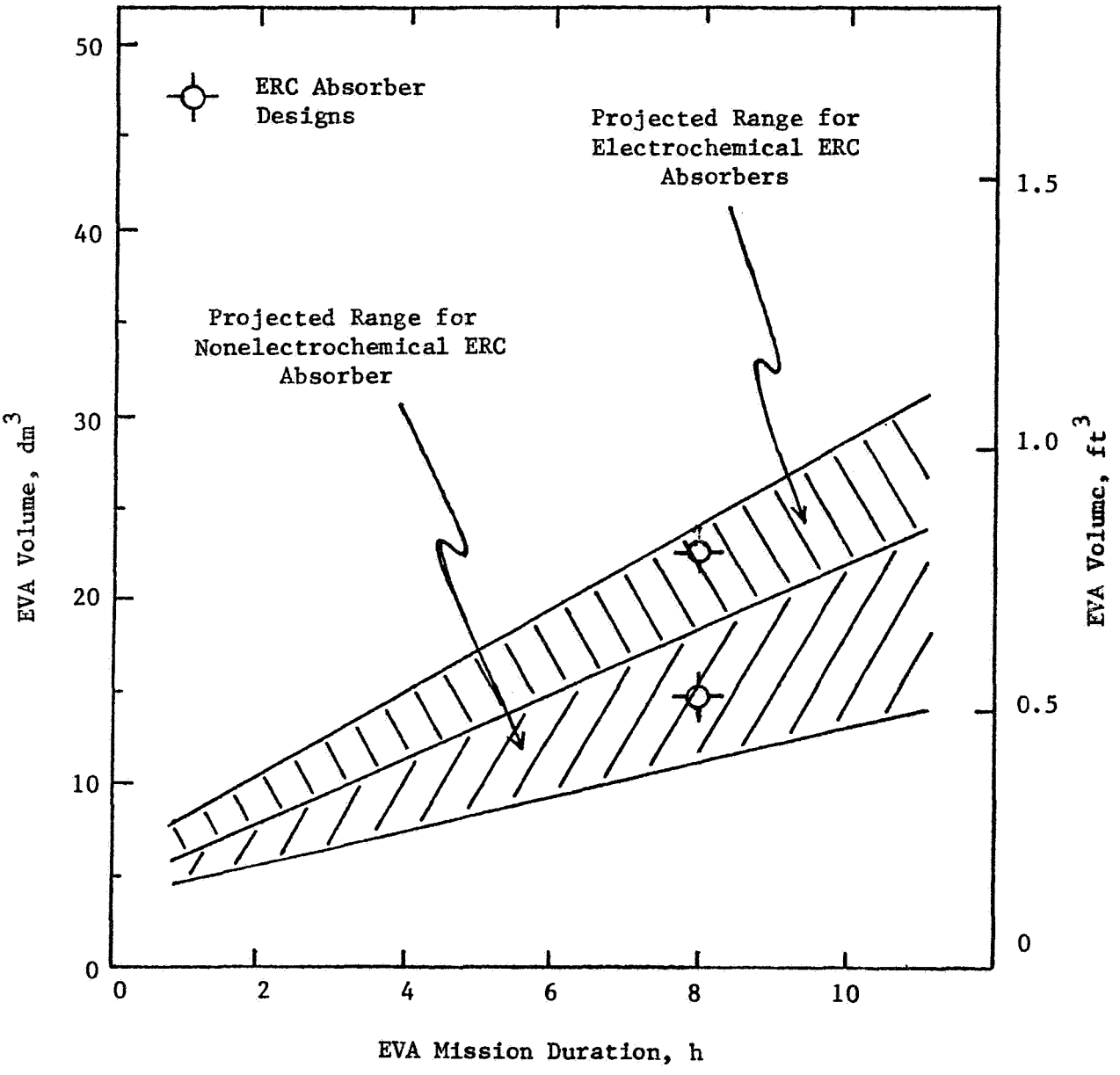


FIGURE 17 COMPARISON OF PROJECTED ERC ABSORBER VOLUMES

Reliability

Reliability activities consisted of (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations.

A survey of the system and TSA design was performed to determine the calibration requirements for testing. Applicable components were calibrated during assembly and after installation (e.g., the CO_2 analyzers and mass flowmeters). All major testing required that a test plan be completed and approved. A test procedure was followed to ensure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures.

The major area of concern was ensuring constant absorbent CO_2 concentration at the start of the absorption tests. Constant CO_2 concentration was accomplished by consistent shutdown conditions of the previous cycle. For the absorption mode testing, desorption was performed at baseline conditions and shutdown occurred approximately one hour after startup when the outlet CO_2 evolution rate was approximately 20 cm^3/min.

Safety

A safety program was initiated to assure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of identifying possible adverse system characteristics, reviewing design and design changes for potential safety hazards, reviewing NASA Alerts for safety information and defining and incorporating the equipment's protective features.

The primary safety consideration was with the alternate use of O_2 and H_2 in a cavity containing catalyzed electrodes. A combination of three factors eliminated this as a potential safety hazard: N_2 purge was used before introducing O_2 or H_2 into the cell cavities, total gas void volume was kept at a minimum and operation at ambient pressure limited the mass of reactant present in the cavities. These provisions eliminated potential safety hazards from the operating procedure.

Materials Control

Considering the developmental nature of the program only the materials associated with the ERCA module and projected for application hardware were evaluated from a flight acceptability standpoint. The evaluation was performed in two categories: metallic and nonmetallic. Acceptability for metallic materials was based on the SSP Design Criteria Handbook.[13] The nonmetallic materials were screened for acceptability.[14] All metallic and nonmetallic materials projected for application hardware were evaluated as flight acceptable.

TEST PROGRAM ACTIVITIES

The testing activities of this program were directed toward continued characterization of the electrochemical ERC Absorber concept. Table 8 defines the testing experience of ERCA development by indicating which major performance parameters have been characterized for the operating parameters. The major

TABLE 8 ELECTROCHEMICAL ERC ABSORBER OPERATING EXPERIENCE

Operating Parameter	Effect On: Absorbent Utilization	Regeneration Efficiency	CO_2 Removal Capacity	CO_2 Removal Rate	Regeneration Power
1. CO_2 Partial Pressure	X	N/A	X	X	N/A
2. Relative Humidity	O	-	O	O	-
3. Air Flow Rate	X	N/A	X	X	N/A
4. Temperature	-	-	-	-	-
5. Pressure	O	-	O	O	-
6. Regeneration Current Density	N/A	X	-	N/A	X
7. Regeneration Voltage	N/A	X	-	N/A	X
8. H_2 Flow Rate	N/A	-	-	N/A	-
9. Absorbent (Type)	-	-	-	-	-
10. Operating Time	X,O	X,O	X,O	X,O	X,O
11. Number of Cycles	X,O	X,O	X,O	X,O	X,O

X = Prior Test Experience
O = Test Under Present Development Effort
- = Not Evaluated at This Point of Development
N/A = Operating Parameter Does Not Significantly Effect Performance

accomplishments of prior ERCA testing are: (1) completed 60 absorption/regeneration cycles, (2) demonstrated 100% AE, (3) demonstrated 75% AUE, and (4) demonstrated 60% RE. The present program has been directed to characterizing absorption performance parameters as functions of inlet RH, operating pressure and additional absorption/regeneration cycles.

Test Hardware Description

The breadboard ten-cell ERCA module and test setup was used for the additional electrochemical absorber characterizations. A detailed description of this hardware was provided in the Annual Report.[2] The module maintained an overall cathode/anode series gas flow path with parallel flow through the ten cathode cavities and the ten anode cavities. For the regeneration mode current was transported using bipolar current collectors and thermal control was provided by external fin air cooling. A photograph of the cell components is provided in Figure 18. A high humidity tolerance proprietary absorbent/electrolyte solution, designated EA-1, was used for the testing. The CO_2 solubility and absorption properties of this solution permits long cycle life and high CO_2 capacities for ERCA concept.

The function of the breadboard test setup was to provide the fluid interfaces, controls and protective shutdown instrumentation, and data acquisition required for ERCA operation. The test setup was modified to provide low pressure operation as indicated in the schematic provided in Figure 19.

Electrochemical ERC Absorber Testing

The electrochemical ERC Absorber test program was designed to further characterize this ERCA concept. The test program was subdivided into four major areas of investigation: (1) shakedown testing, (2) RH testing, (3) operational pressure testing and (4) cycle testing. The cycle numbers are continued from the initial characterization testing activities since the test hardware was the same.

Shakedown Test

The shakedown test was conducted to familiarize personnel with ERCA operation, data analysis and procedures and to check out and evaluate the reassembled ten-cell electrochemical ERC Absorber module and the reassembled breadboard test setup. The module was operated for 18 cycles during the testing.

Objective. The objective of the shakedown testing was to verify and check out the integrated test setup and ERCA operation, to correct misalignments, to establish and reevaluate operating procedures and to check out, calibrate and set monitoring circuits.

Results. The results of the shakedown testing are presented in Figure 20. Eighteen regeneration/absorption cycles (cycles No. 78 through 95) were completed. A variety of operating conditions were tested and are defined in Table 9. Data provided in Figure 19 illustrates both the mass of CO_2 absorbed at breakthrough and at shutdown for each cycle. The ERCA CO_2 removal capacity demonstrated during the shakedown testing was 2.4 g CO_2/cell.

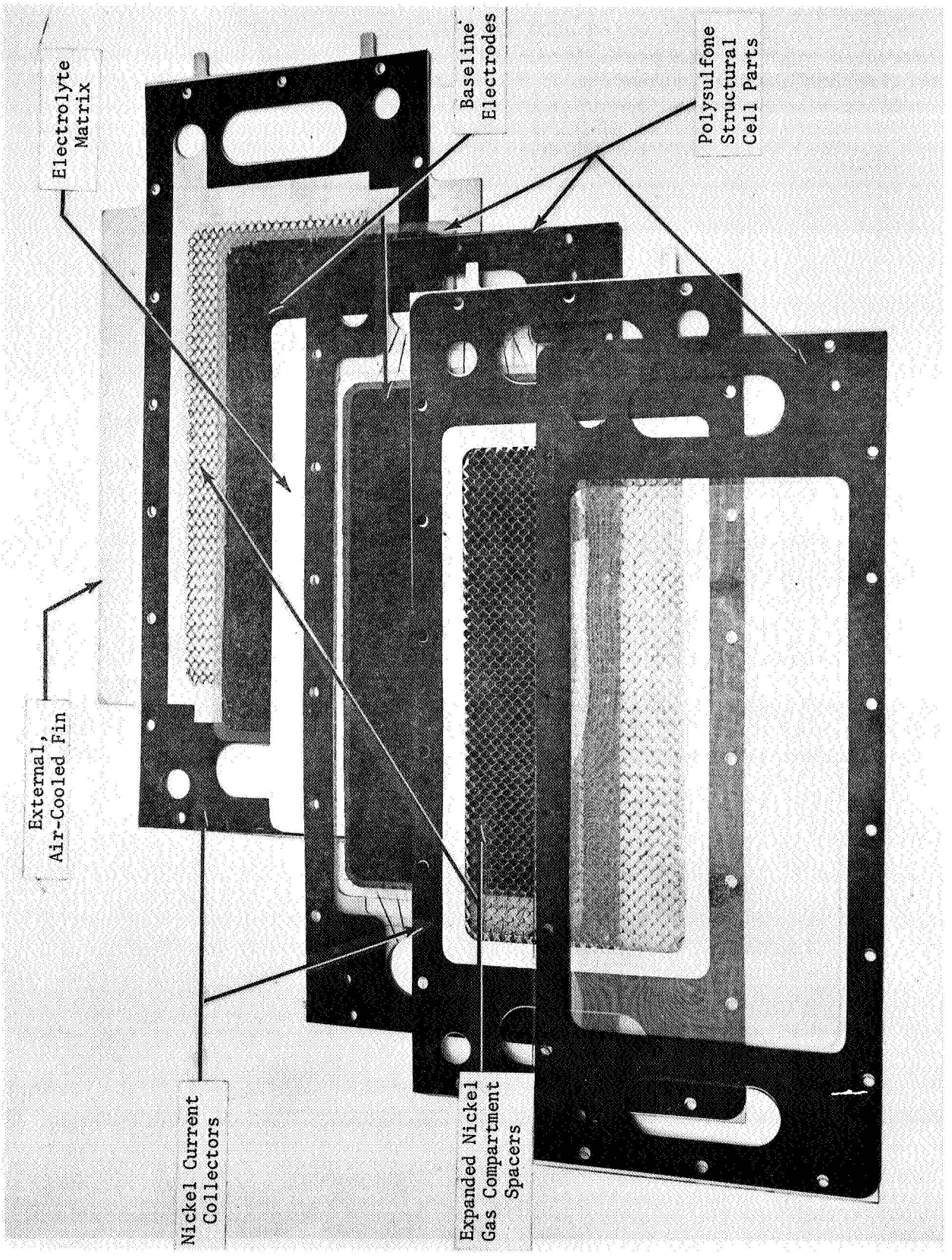


FIGURE 18 ERCA TEST CELL COMPONENTS

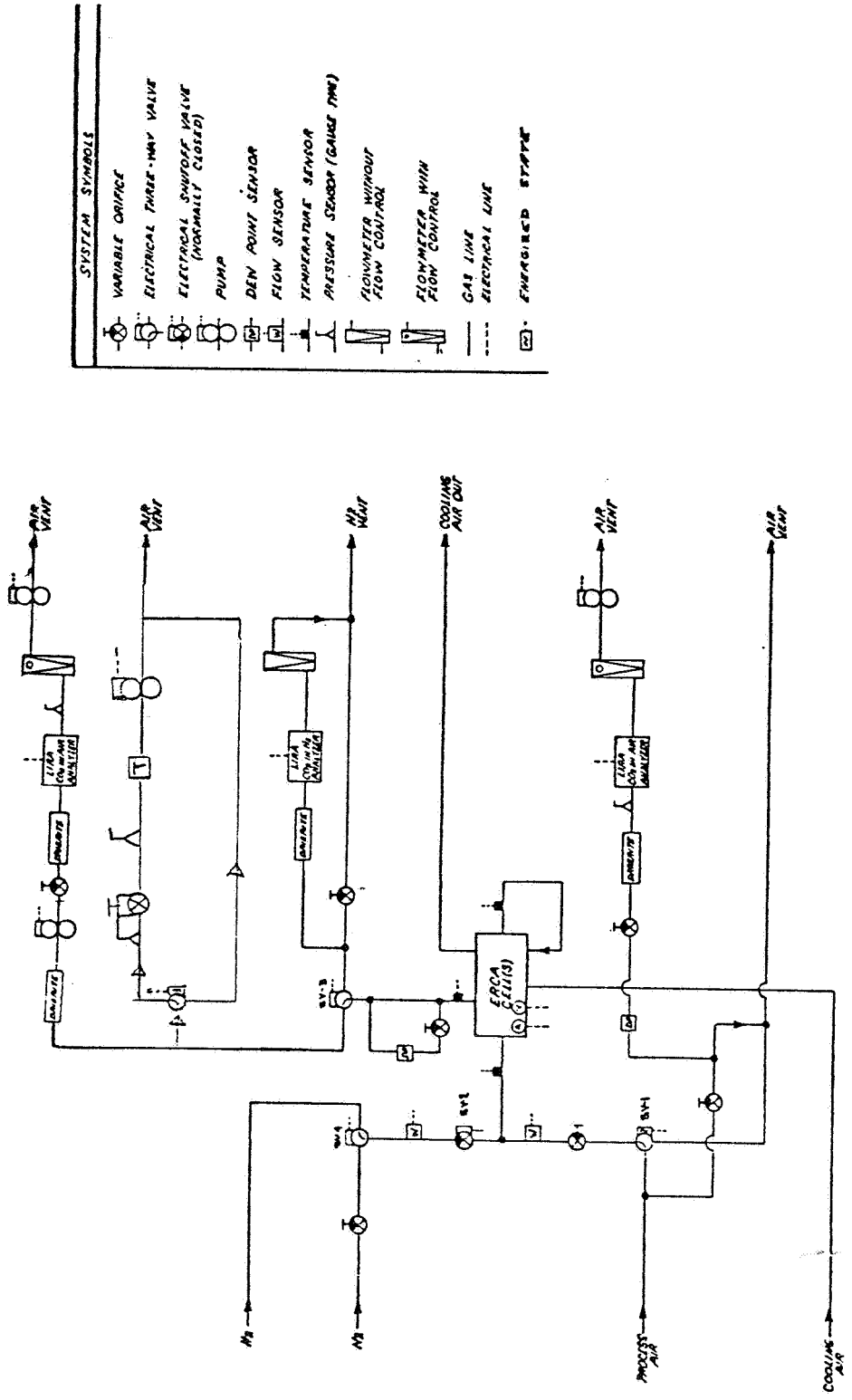


FIGURE 19 TEST SETUP SCHEMATIC FOR ERCA TESTING

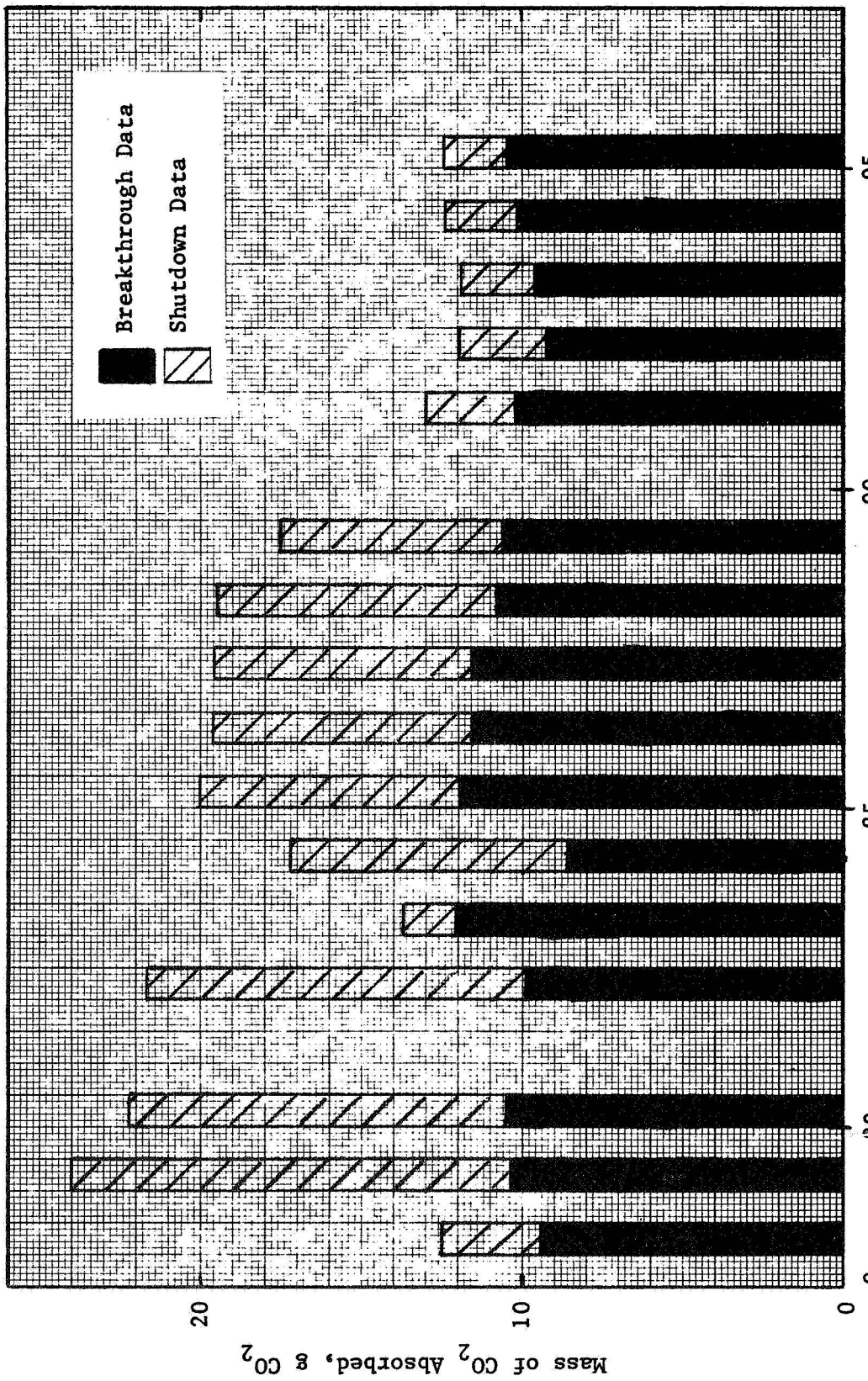


FIGURE 20 SHAKEDOWN TESTING RESULTS

TABLE 9 OPERATING CONDITIONS FOR SHAKEDOWN TESTING

Cycle No.	Desorption Cycle		Absorption Cycle		
	Current Density, mA/cm^2 (ASF)	Time, Min	Air Flow Rate, sccm (scfm)	Inlet pCO_2, Pa (mm Hg)	Time, Min
78	44 (41)	48	8500 (0.30)	480 (3.6)	165
79	44 (41)	63	8500 (0.30)	480 (3.6)	1320
80	44 (41)	183	8500 (0.30)	1040 (7.8)	215
81	44 (41)	55	-	-	-
82	44 (41)	108	8800 (0.31)	1180 (8.9)	207
83 to 89	44 (41)	54	8800 (0.31)	1120 (8.4)	113
90	44 (41)	55	-	-	-
91 to 95	44 (41)	55	10500 (0.37)	520 (3.9)	113

Relative Humidity Test

The RH test was conducted to determine the effects of inlet RH on absorption performance parameters.

Objective. The objective of the RH testing was to determine the effects of process air inlet RH on ERCA absorption performance during a single cycle for inlet RH levels between 50 and 70%.

Results. The results of the RH testing are presented in Figure 21. A total of five regeneration/absorption cycles were performed at the operating conditions defined in Table 10. The figure illustrates the absorption efficiency at breakthrough and the absorption efficiency at the end of the absorption cycle as a function of the average inlet RH of the cycle. The results demonstrate constant absorption efficiencies at breakthrough and at shutdown for single absorption cycles with inlet RH levels from 50 to 70%. Water absorption and evolution by the absorbent solution did occur in an effort to equilibrate the absorbent concentration with the inlet RH. The amount of water transferred during an eight-hour absorption cycle had minimal effect on the average absorbent solution concentration and did not significantly affect absorbent moisture balance.

Operational Pressure Testing

The operational pressure testing was conducted to evaluate ERCA absorption performance at the operational pressure of the PLSS application (48 to 55 kPa (7 to 8 psia)). A total of five regeneration/absorption cycles were performed during this testing.

Objective. The objective of the operational pressure testing was to determine the effects of absolute pressure on absorption performance at PLSS operating pressure.

Results. The results of the operational pressure testing are presented in Figure 22. A total of five regeneration/absorption cycles were performed at the baseline conditions defined in Table 10. The test results illustrate constant absorption efficiencies within the experimental error at both breakthrough and shutdown. A slight decrease in absorbent utilization at shutdown was observed with decreasing pressure, but this decrease is well within the experimental error of ±10%. Testing was performed at two absolute pressures, atmospheric pressure (97 kPa (14 psia)) and approximately half atmospheric pressure (51 kPa (7.4 psia)) while maintaining constant mass CO_2 flow rates. Two types of atmospheric pressure tests were performed as baseline references. The initial baseline reference cycles were performed at atmospheric pressure utilizing 1060 Pa (8.0 mm Hg) pCO_2 level and the same constant process air flow rate at the half atmospheric pressure cycles. The last baseline reference cycle was performed at twice the half atmospheric process air flow rate while maintaining a 530 Pa (4.0 mm Hg) pCO_2 level to achieve the constant mass CO_2 flow rate.

Endurance Cycle Testing

The endurance cycle testing was conducted to determine the effects of multiple cycles on ERCA performance. The reliability of the ERCA concept as the regener-

FIGURE 21 INLET RELATIVE HUMIDITY ABSORPTION PERFORMANCE

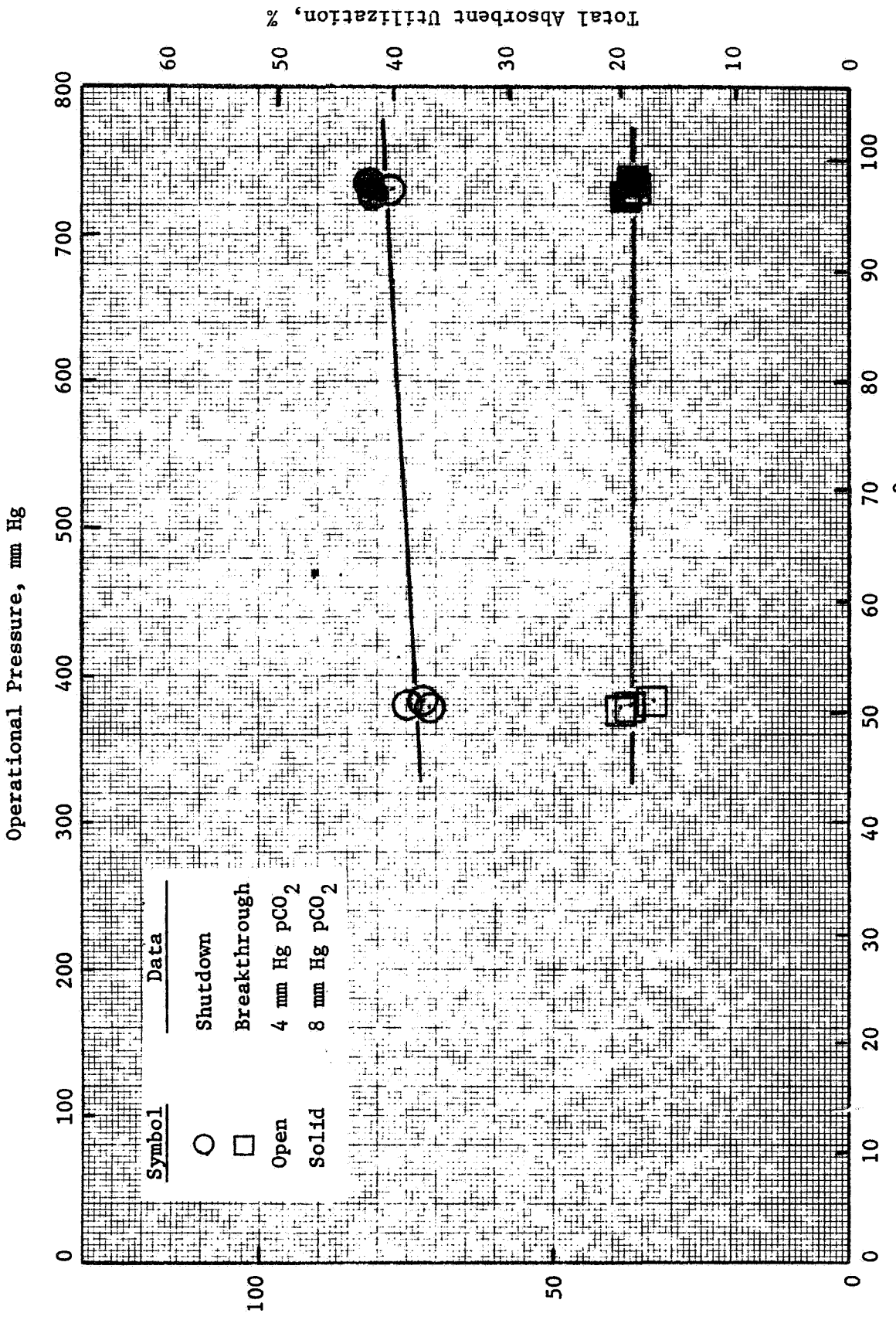


FIGURE 22 OPERATIONAL PRESSURE TEST RESULTS

TABLE 10 BASELINE OPERATING CONDITIONS

Absorption	
Number of Cells	10
Air Flow Rate, cm^3/min (scfm)	10.2 ±1.0 (0.360 ±0.04)
Inlet pCO_2, Pa (mm Hg)	533 ±70 (4.0 ±0.5)
CO_2 Mass Flow, gCO_2/min (lb/h)[a]	0.21 ±0.02 (0.028 ±0.003)
Dry Bulb Temperature, K (F)	297 ±1 (75 ±2)
Relative Humidity, %	60 ±5
Pressure	Ambient
Regeneration	
Regeneration Efficiency, %	52
Current Density, mA/cm^2 (ASF)	44 (41)
H_2 Flow Rate, cm^3/min	600 ±50
N_2 Flow Rate, cm^3/min	300 ±50
N_2 Purges, min	5
Current Delay, min	5
Desorption, min	60
Dry Bulb Temperature, K (F)	296 ±2 (74 ±4)
Relative Humidity, %	60 ±5
Shutdown CO_2 Evolution Rate, cm^3/min	20[b]

(a) CO_2 mass flow was maintained constant during pressure testing allowing variable air flow rates and inlet pCO_2 levels.

(b) This shutdown requirement is to provide constant absorbent regeneration at an efficiency of approximately 52%.

able CO_2 scrubber subsystem for the PLSS can be judged by the ability to regenerate CO_2 absorption capacity without degradation after multiple cycles.

Objective. The objective of the cycle endurance testing was to identify and evaluate any changes in ERCA performance for 100 regeneration/absorption cycles.

Results. The results of the cycle testing are presented in Figure 23. The testing was performed at baseline conditions as defined in Table 10. The test setup controlled the process gases and automatically cycled the ERCA through its regeneration/absorption modes. Data was collected by continuously monitoring the outlet pCO_2 level with a strip chart recorder. This data acquisition procedure provided startup, breakthrough and shutdown times. The results presented in the figure were obtained by multiplying the inlet CO_2 mass flow by the absorption time at which breakthrough occurred. The data illustrated constant AUE at breakthrough for the additional 113 cycles performed. Representative examples of the ERCA module/regeneration voltage performance as a function of time are illustrated in Figure 24. The voltage traces of the desorption mode illustrate a gradual increase in operational voltage which results in the increased power requirements for regeneration of the electrochemical ERC Absorber module. The average peak voltage increased from a level of 0.65 V/cell to an average peak voltage of 0.73 V/cell at the end of the endurance cycle testing. This increase in operation voltage over the 113 endurance cycle testing represents a 12% degradation in the ERCA voltage performance. This decrease in voltage performance would illustrate an increase in the average power requirement for regeneration from 210 to 236 W for regeneration over a 24-hour period.

ANALYTICAL SUPPORT

The analytical support task was performed to define potential concepts for improving electrochemical ERC Absorber performance. Both the absorption and regeneration processes were evaluated from which the potential concepts were identified. A list of the concepts, including a description, is presented in Table 11. Each concept was then evaluated according to the selection criteria established in Table 12.

The selection criteria is divided into two sections: go/no-go criteria and primary selection criteria. Initially, the go/no-go criteria evaluates whether the concept is within the scope of the performance improvement tasks. The primary selection criteria is divided into seven categories. Each criteria was provided a rating value between zero and 0.3. Each value was determined according to the level of importance of the criteria and the maximum amount of performance improvement achievable. The exact value for each rating was obtained by a qualitative estimate of the performance improvements as reference to baseline performance. Each performance improvement was based on the ability of each potential concept to decrease the ERCA hardware volume, mass and power consumption.

The results of the selection process identified the anode masking concept to be evaluated for performance improvements. The anode masking concept is a process by which the anode is decreased in active surface area by inserting

FIGURE 23 ERCA ENDURANCE TEST RESULTS

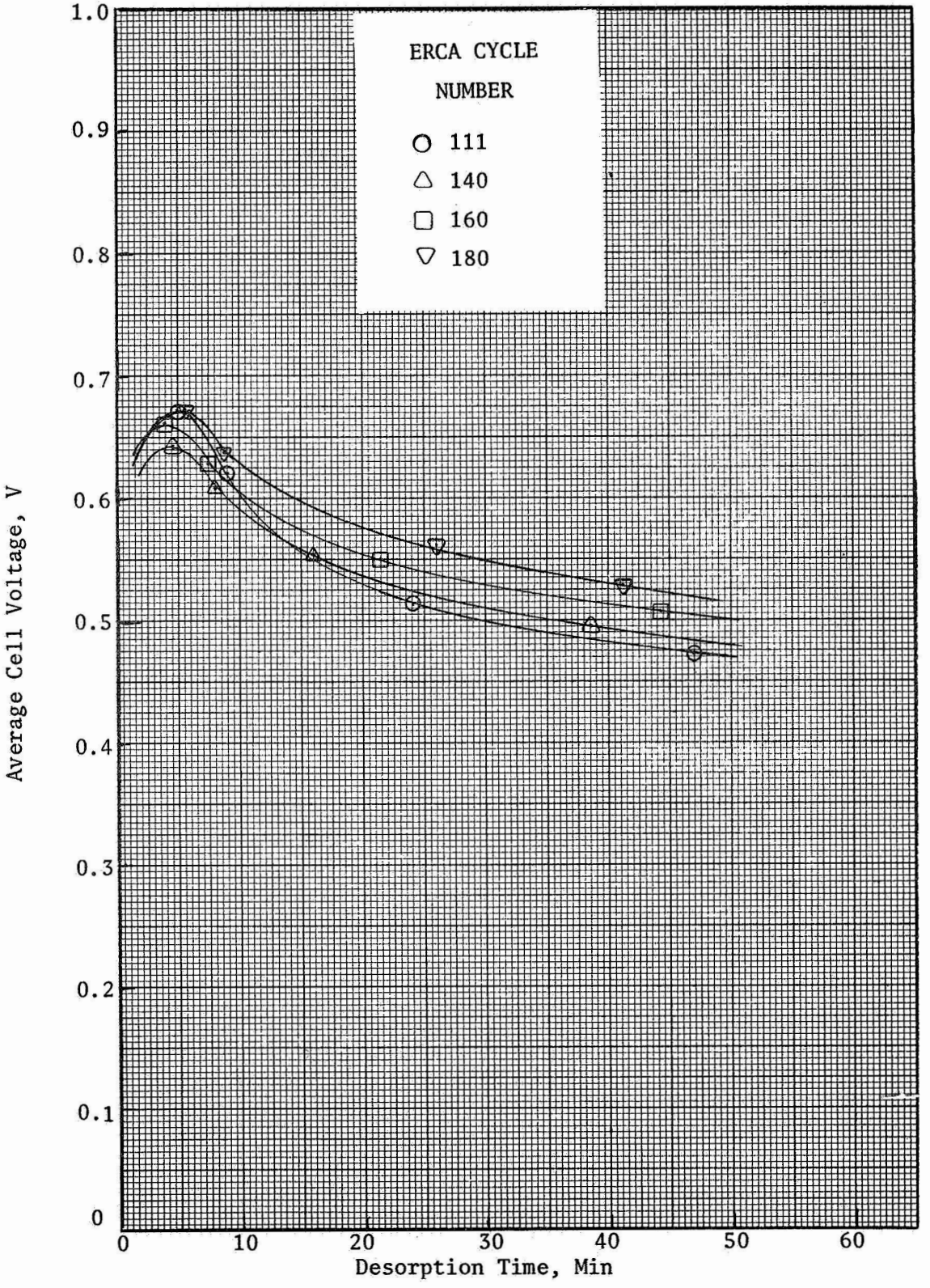


FIGURE 24 ERCA VOLTAGE PERFORMANCE DURING THE CYCLE TESTING

TABLE 11 ERCA PERFORMANCE IMPROVEMENT CONCEPTS

Concept	Description	Advantages	Disadvantages
Anode Masking	Anode masking effectively increases the anode current density	Increases the CO_2 evolution driving force at the anode	Decreases the electrical performance of a cell
Tube Cells	Hardware concept utilizing tubular structures for the	Effectively increases the anode-to-cathode current current density ratio. Increases the ratio of absorption surface area to total absorbent volume	Unproven hardware concept
Selective Membrane Transport	A method of isolating the anode and cathode electrochemical mechanisms utilizing an ionic selective membrane	Efficiently produces a hydroxide solution while independently consuming the carbonate solution of the anode	Highly selective low-resistance ionic membranes are not readily available
Molten Electrolyte	A hardware concept that utilizes the molten electrolyte for the regeneration process	Utilizes a highly efficient electrochemical process for the CO_2 evolution mechanism while providing a low volume solid salt absorption bed for the absorption process	Unproven technology for ERCA application and a usable salt must be identified
Decrease Matrix Thickness and Density	Modify the matrix material to decrease resistance to transport of absorbed CO_2	Should improve the absorption efficiency	Potential for decreasing efficiency by reducing the resistance to hydroxide ion transport during desorption

continued-

Table 11 - continued

Concept	Description	Advantages	Disadvantages
Ionic Polymer Matrix	The utilization of a polymer matrix material which would serve both the function of the matrix material and an absorbent site for carbonate ion	Has the potential of improving the CO_2 absorbent capacity of a cell by 30%	Availability and stability of potential ionic polymer materials must be identified
Insoluable Carbonate Salt Matrix	Incorporating an insoluable carbonate salt into the matrix material	Has the potential of improving the absorption capacity of each cell	Has a low rate for CO_2 absorption at the solid crystal interface and has the potential for salt crystal formation resulting in decreased electrical performance

TABLE 12 SELECTION CRITERIA

GO/NO GO CRITERIA

Improves Performance (Expected)

Baseline Safety

Materials Availability and Cost

PRIMARY SELECTION CRITERIA

	Rating Value
Absorbent Utilization Improvements	0.20
Regeneration Efficiency Improvements	0.30
Power Reduction/Mass CO_2	0.20
Reliability	0.10
Operability	0.05
Hardware Complexity	0.10
Interface Compatibility	0.05
Total	1.00

thin polysulfone strips at the interface of the anode and the matrix. This process will decrease the anode limit to CO_2 evolution by increasing the active current density of the anode.

The test was performed on a single baseline ERCA cell. Desorption testing was performed at constant anode current densities of 32 and 44 mA/cm^2 (30 and 41 ASF). The results of the tests are presented in Table 13 and compared to previously obtained ERCA performance on the ten-cell unit. The comparison is provided at two levels of average desorption power requirements for a 24-hour desorption period. A 5 to 7% increase in regeneration efficiency was observed. The performance gain was marginal. Further evaluation will be required prior to incorporating this concept into future ERCA designs.

CONCLUSIONS

The following conclusions were reached:

1. Both of the ERCA hardware approaches are feasible for the PLSS regenerable CO_2 scrubber based on the criteria established for the PLSS application.

2. The nonelectrochemical ERC Absorber concept is the selected approach to satisfying the hardware requirements based on its lower EVA component volumes.

3. The HFM absorption bed design is the best approach to the design of a nonelectrochemical ERC Absorber based on its projected sizing and minimization of development risks.

4. Regeneration of the EA-1 type absorbent solution by the ERCA process does not cause degradation of the absorbent capacity. The ten-cell ERCA module illustrated this performance by completing 200 absorption/regeneration cycles without degradation in absorption capacity. Since both ERCA concepts use the EA-1 absorbent and similar electrochemical regeneration processes these test results also indicate the regenerability of the nonelectrochemical ERC Absorber hardware.

5. Inlet process air RH and operational pressure level have minimal effects on ERCA CO_2 absorption performance.

RECOMMENDATIONS

The following recommendations are a direct result of the work completed.

1. A development program should be initiated to design, fabricate, assemble and test the selected nonelectrochemical ERC Absorber and continued development of the electrochemical ERC Absorber concept should be delayed.

2. A development and characterization program should be initiated to evaluate the performance of an ERCAR module for use with the nonelectrochemical ERC Absorber hardware. This program should be directed at the characterization and optimization of the regeneration process and identification and development of the ancillary components required to fabricate a complete ERCAR system needed for a nonelectrochemical ERC Absorber design.

TABLE 13 RESULTS OF PERFORMANCE IMPROVEMENT CONCEPT TESTING

Current Density, mA/cm^2 (ASF)	Average Power Required, W	Regeneration Efficiency, %	Performance Improvement, %
	Ten Cell Performance		
32 (30)	100	46.9	-
44 (41)	100	45.8	-
32 (30)	200	51.3	-
44 (41)	200	51.3	-
	Anode Configuration Change Performance		
32 (30)	100	52.9	6.0
44 (41)	100	50.8	5.0
32 (30)	200	58.0	6.7
44 (41)	200	56.5	5.2

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