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REGENERATIVE CO_2 REMOVAL FOR PLSS APPLICATION

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FINAL REPORT

by

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

October, 1979

Prepared Under Contract NAS9-15218

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Life Systems, Inc.
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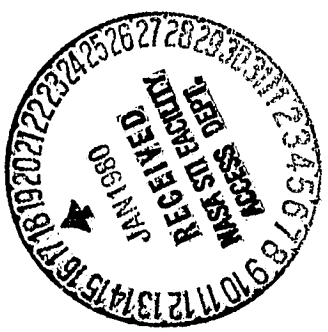

for

LYNDON B. JOHNSON SPACE CENTER
National Aeronautics and Space Administration

TR-319-31-6

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FOREWORD

This report was prepared by Life Systems, Inc. for the National Aeronautics and Space Administration Lyndon B. Johnson Space Center in accordance with the requirement of Contract NAS9-15218. The period of performance for the work completed and summarized in this report was December, 1978 to September, 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 Dennis B. Heppner, Ph.D. Technical Support was provided by Richard R. Woods, Franz H. Schubert and Richard D. Marshall. The program Technical Monitors were Mr. Hoot Gibson and Mr. Nick Lance, Johnson Space Center, Houston, TX, 77058.

All measurements and calculation 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
ARS	Air Revitalization System
AUE	Absorbent Utilization Efficiency
CCC	Contaminant Control Cartridge
C/M I	Control/Monitor Instrumentation
CRS	CO_2 Reduction Subsystem
EDC	Electrochemical Depolarized CO_2 Concentrator
EE	Extraction Efficiency
ERCA	Electrochemically Regenerable CO_2 Absorber
ERCAR	ERCA Regenerator
EVA	Extravehicular Activities
HFM	Hollow Fiber Membranes
PLSS	Portable Life Support Systems
RE	Regeneration Efficiency
RH	Relative Humidity
TAU	Total Absorbent Utilization
WES	Water Electrolysis Subsystem

SUMMARY

Regenerative carbon dioxide removal concepts are needed to sustain people undertaking extravehicular activities during the Space Shuttle era. This requirement is prompted by the anticipated large increases in number and duration of spacesuit missions outside of spacecraft or proposed space platforms. For example, with some missions there could be ten people-hours of extravehicular activity in 1980, 100 in 1983, 1,000 in 1986 and 10,000 by 1990. Concepts that reduce the expendables and logistics of such missions are required. A program to evaluate regenerable carbon dioxide removal concepts has been underway at the National Aeronautics and Space Administration and Life Systems, Inc. for the past five years. The work reported here is a portion of the overall program.

The Electrochemically Regenerable Carbon Dioxide Absorber consists of an aqueous alkaline absorbent confined within a support structure of an absorption bed. Metabolic carbon dioxide produced during extravehicular activity is absorbed by a reaction of the alkaline solution similar to the absorption chemistry of lithium hydroxide. The expended absorbent is then removed and used as the electrolyte for an electrochemical regeneration process. This process regenerates the expended absorbent solution for replacement in the absorber 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 vehicle's Carbon Dioxide Reduction Subsystem or overboard venting.

An electrochemically regenerative absorption bed concept was designed, built and tested under prior in-house and contract work to demonstrate the overall approach. That concept incorporated the required electrochemical regeneration components in the absorber permitting the absorbent to be regenerated within the absorption bed. The hardware size 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 a mass of 30 kg (66 lb).

Because of the size and weight characteristics of the electrochemical absorber hardware, a second hardware concept was evaluated and is the subject of this report. This concept, defined as the nonelectrochemical absorber, separates the functional components of the regeneration and absorption processes. It minimizes the extravehicular activity component volume by eliminating regeneration hardware components within the absorber. This absorber, when sized for a seven hour extravehicular activity mission, is projected to have a component volume of 15 dm^3 (0.53 ft^3) and a mass of 18 kg (40 lb). The projected total absorbent utilization efficiency is 61%.

Various concepts for the design of the nonelectrochemical absorber were defined and evaluated. A preliminary design based on the use of hollow fiber membranes was developed. Small scale bench testing demonstrated the carbon dioxide removal capability and provided design data for scale-up to the one-person level.

A full-scale conceptual design of the absorbent regeneration hardware using six electrochemical cells was also completed. The design was supported by single-cell testing and showed that a full-scale regeneration system, operating continuously over 24 hours, can regenerate the absorbent from one extravehicular activity mission. The single-cell regeneration hardware was operated for over 800 hours.

The Electrochemically Regenerable Carbon Dioxide Absorber concept satisfies the requirements of the regenerable carbon dioxide scrubber for future Portable Life Support System applications. The primary features of the concept are its regenerability without degradation, its projected low backpack component volume and its low total equivalent launch weight.

INTRODUCTION

As the Space Shuttle becomes operational and the length of space missions increase, more numerous, lengthy and ambitious extravehicular activities (EVA) will be desired. 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 the associated increased weight and volume penalties. The major expendables are oxygen (O_2) for crew metabolic needs, lithum hydroxide (LiOH) for absorbing metabolic carbon dioxide (CO_2) and water for thermal control through evaporation.[1] A regenerative CO_2 removal concept has promise for significantly reducing the expendable penalties of the CO_2 removal function. At present, O_2 generation and water reclamation at the one-person level do not trade favorably. Therefore, the development of a regenerable CO_2 scrubber for PLSS application is timely and desirable.

One promising concept is the Electrochemically Regenerable CO_2 (ERC) Absorber.[2] This concept, termed ERCA, is based on absorbing CO_2 into an alkaline absorbent as is done with LiOH. The absorbent is an aqueous solution which can be regenerated electrochemically on-board the primary space vehicle (Space Shuttle). The absorbent can be either regenerated in place, that is, within the absorber, or can be extracted from the absorption bed and transferred to separate electrochemical regeneration hardware. This regeneration process developed by Life Systems is based on the Electrochemical Depolarized CO_2 Concentrator (EDC) technology[3-5] and evolves the CO_2 that was 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). If a CRS is not available on early missions the H_2/CO_2 stream can be vented overboard. Clearly, two savings are possible: (1) expendables for removing CO_2 and (2) O_2 in the form of recovered CO_2. With the metabolic CO_2 recovery, the ERCA concept results in a totally regenerable CO_2 scrubber. The ERCA system concept, as shown in Figure 1, shows the ERC Absorber located on the PLSS backpack and the ERCA Regenerator (ERCAR) located within the primary space vehicle.

Background

A typical block diagram of the PLSS application depicting the atmospheric revitalization loop, the liquid coolant loop and controller connections for the various PLSS components is presented in Figure 2.[1] The ERC Absorber is

(1) References cited are found at the end of this report.

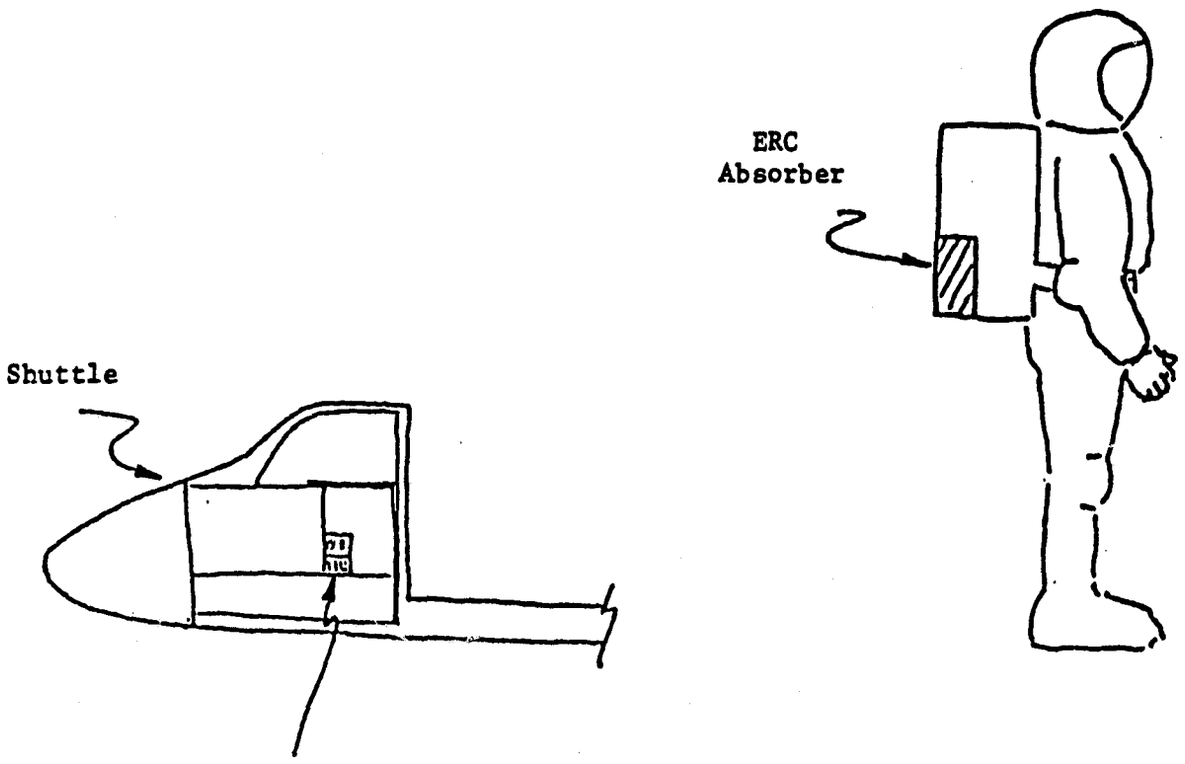


FIGURE 1 ERCA SYSTEM CONCEPT

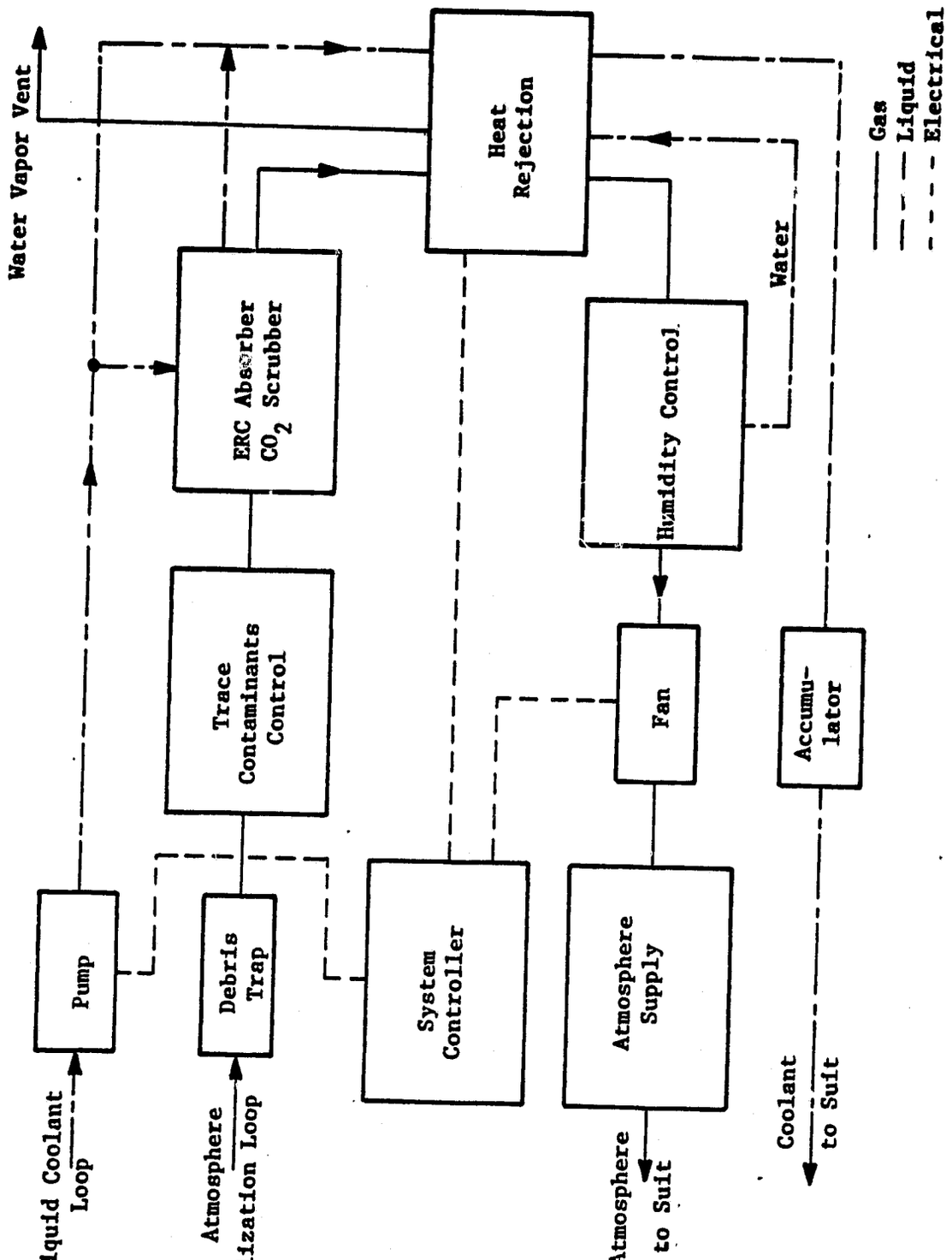


FIGURE 2 FUNCTIONAL PLSS BLOCK DIAGRAM

shown as the component in the atmospheric revitalization loop where the process air coming directly from the breathing mask enters the loop. The debris trap and trace contaminant control functions can be combined with the absorber component. The inlet process air to the absorber is warm, moist and debris-free containing metabolic CO_2. The ERC Absorber functions as a passive absorber bed which effectively removes metabolically generated CO_2 at an absorption efficiency of nearly 100%.

Prior Concepts

In the past, several concepts were investigated for the development of a regenerable CO_2 scrubber for 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 the loss of pellet structural integrity and fragmentation with repeated regeneration.

Other concepts based on the reaction chemistry of alkaline carbonate materials 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 concepts, the structural integrity of the solid form is lost upon repeated regeneration. One method which overcomes the loss of absorbent integrity upon regeneration suspends the carbonate absorbent in 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.

Another proposed concept utilizes vacuum to strip the CO_2 from a potassium carbonate (K_2CO_3) absorbent solution.[11] The shortcoming of this concept is that CO_2 and water is continuously lost overboard to the vacuum vent and moisture balance in the absorbent solution is continually altered.

ERCA Concept

The ERCA concept has been designed to eliminate the shortcomings of 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 rate capacities and low absorbent volume requirements for efficient storage of metabolic CO_2 generated during EVA. Structural integrity and proper containment of the absorbent is maintained because the absorbent is an aqueous solution supported in a porous interface. The aqueous solution provides for the exchange of CO_2 and fresh absorbent by diffusion at a gas/absorbent interface. This mechanism decreases the gas void volume 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 regenerable concept in which product gases can be directly integrated into the vehicle's CRS.

Past ERCA Developments

An initial ERCA conceptual study was conducted by Life Systems under company sponsorship. Then a development and test program was funded by NASA under Contract NAS2-8666.[2,12] This program evaluated an ERC Absorber where the electrochemical regeneration hardware was contained within the absorber. Multiple cycles of absorption and regeneration were performed. 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 with the test hardware. These performance levels validated the ERCA concept but left some question as to whether final flight weight and volume objectives could be met.

The present program is an extension of that activity and investigates the concept of removing the absorbent from the absorber and performing the regeneration of the absorbent in separate hardware that is located elsewhere. The volume of the resulting ERC Absorber is shown to be competitive with the existing nonregenerable technique and for multi-missions, clearly has a launch weight performance improvement.

Program Objectives

The objectives of the present program were to:

1. Perform a conceptual design of an ERC Absorber which could replace the existing Contaminant Control Canister (CCC) of the PLSS. This ERC Absorber contains an aqueous absorbent which passively removes the CO_2 and can be subsequently regenerated aboard the space vehicle.

2. Define a regeneration system (ERCAR) that would electrochemically rejuvenate the absorbent for reuse. The emphasis was on the conceptual design of the heart of the system, namely, the electrochemical module.

3. Demonstrate, through bench top testing at the fractional level, the feasibility of the selected ERC Absorber and ERCAR regeneration concepts.

Program Organization

To meet the above objectives the program was divided into four tasks plus the documentation and program management functions. The four tasks were:

1.0 Define the ERC Absorber concept for integration into the PLSS using applicable existing PLSS specifications. Emphasis was placed on the low volume required for PLSS hardware application.

2.0 Define the regeneration concept located aboard the spacecraft required to regenerate the absorbent. Emphasis was placed on the vehicle interfaces and resources required to ensure that no concept limitations existed. Absorbent extraction and replacement techniques required to interface the absorber with the regeneration hardware were also defined.

3.0 Experimentally demonstrate both the absorber and regeneration techniques. This demonstration was at a level sufficient to demonstrate the feasibility of the chosen concept and to provide the engineering confidence necessary to allow scale-up to a practical capacity.

4.0 Establish, implement and maintain a mini-Product Assurance program through all phases of contractual performance consistent with a program in the early stages of development.

Report Organization

This Final Report covers the work performed during the period December, 1978 through September, 1979. The following five sections present the technical results grouped according to (1) Concept Description, (2) ERC Absorber, (3) ERCA Regeneration (ERCAR) System, (4) mini-Product Assurance program and (5) Test Program Activities. These sections are followed by conclusions and recommendations based on the work performed.

CONCEPT DESCRIPTION

The ERCA concept can encompass a wide range of ERC Absorber designs, all of which are electrochemically regenerable in separate ERCAR hardware. Figure 3 shows the overall relationships between the ERCA hardware, the PLSS and the spacecraft. The ERC Absorber interfaces with and is an integral part of the PLSS air loop and removes CO_2. At the end of the EVA, the ERC Absorber is removed from the PLSS hardware or could be serviced in place. Under the assumption of component removal the ERC Absorber is placed within the ERCAR system. Ancillary components such as pumps, accumulators and fluid lines transfer the used absorbent to the ERCAR module and the regenerated absorbent back to the absorber. The ERCAR interfaces with spacecraft resources such as electrical power, H_2, coolant and an exhaust port for the H_2/CO_2. A Control and Monitor Instrumentation (C/M I) package controls the automatic operation of the ERCAR.

The regenerative aspect of the ERCA concept has the absorption processes taking place in the ERC Absorber and regeneration processes taking place in the ERCAR system. A general description of the absorption and regeneration mechanisms of this hardware is discussed below.

Absorption Mechanism

The ERC Absorber functions as a passive absorption bed for the removal of CO_2 from the PLSS 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 actual absorption mechanism occurs at a gas/liquid interface which is located within the porous media.

The absorption mechanism includes the CO_2 reaction chemistry with both hydroxyl ions (OH^-) and carbonate ions ($CO_3^=$). The CO_2 in the inlet process air transfers to the gas/liquid interface where it reacts with two hydroxide ions to form $CO_3^=$ and water. The ionic concentration gradients resulting from the CO_2

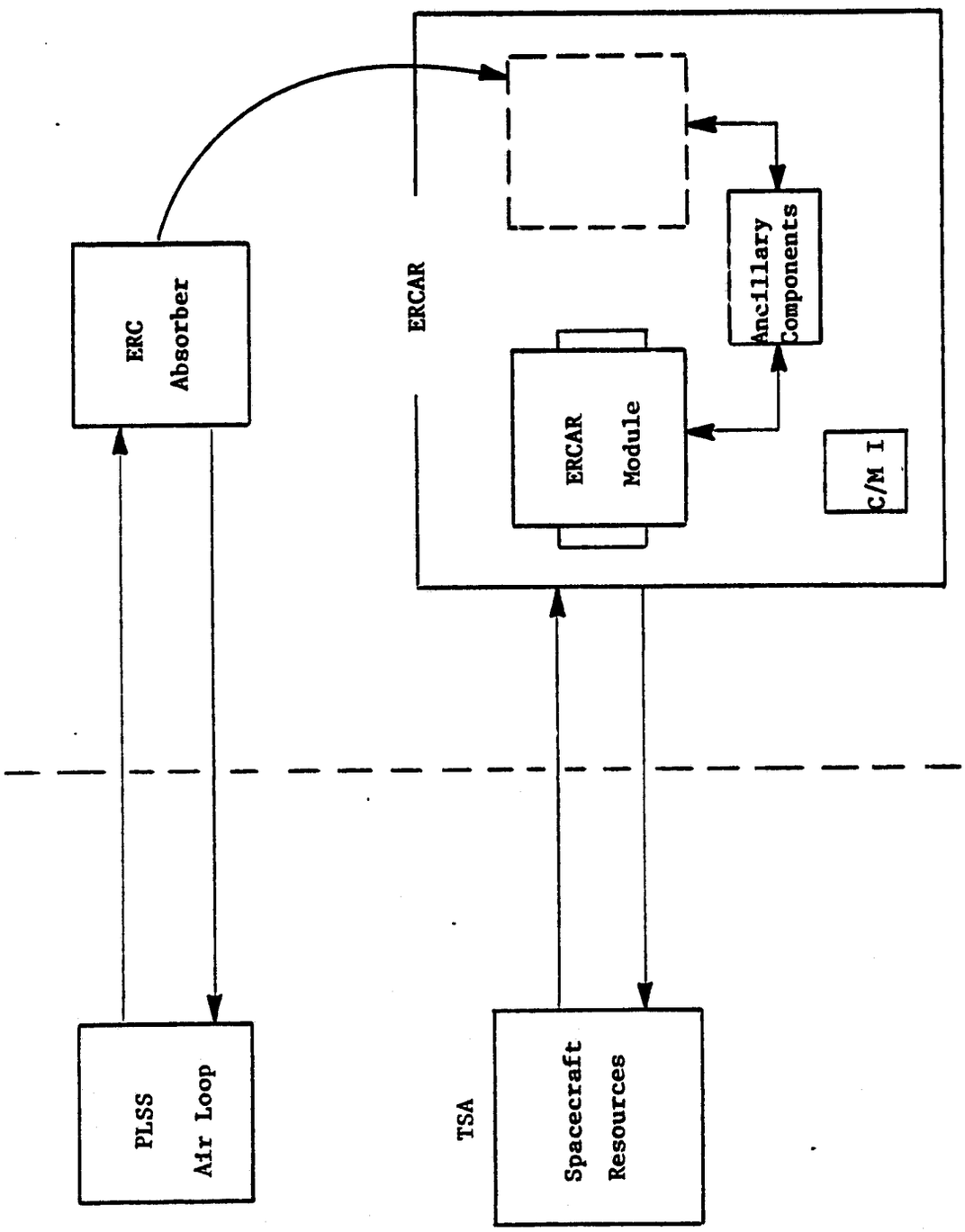


FIGURE 3 ERCA/PLSS/SPACECRAFT RELATIONSHIPS

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^-). These 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 CO_2 partial pressure (pCO_2) of the process air. The functional schematic illustrating the two absorption processes is provided in Figure 4.

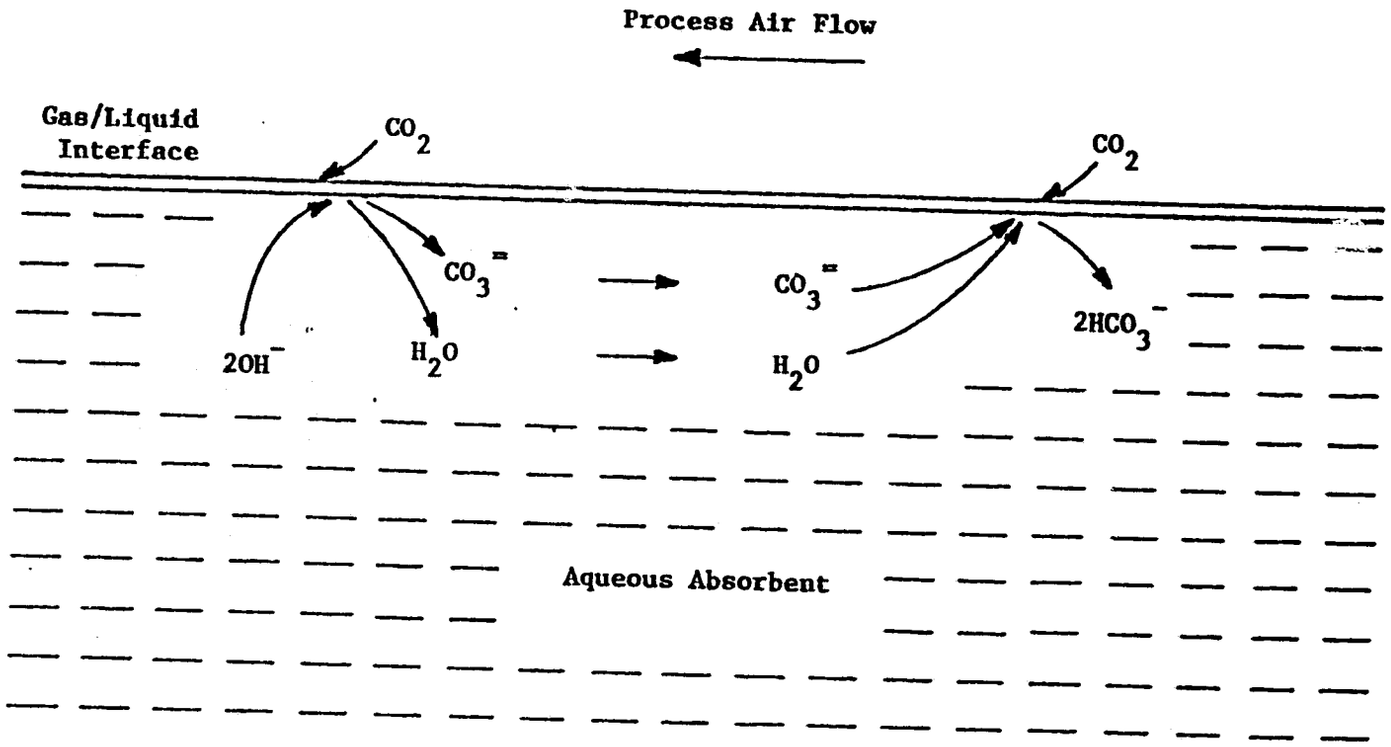
The media in which the absorption process occurs allows fresh absorbent (OH^-) to transfer, by diffusion, to the gas/liquid interface from the bulk absorbent. This internal transport mechanism minimizes gas void volume and gas/absorbent interface surface requirements as compared to a solid absorbent bed. The interface construction provides for high gas/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, proper containment of the absorbent and desired differential pressure capabilities.

Absorption performance is evaluated with three parameters. First is absorption efficiency (AE) which is defined as the percent ratio of the change in CO_2 mass flow through the absorber compared 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 absorbent utilization efficiency (AUE). This parameter is defined as the percentage utilization of the maximum regenerated CO_2 absorption capacity of the absorber. For example, if the maximum amount of CO_2 that the bed could absorb is 1.0 kg (2.2 lb) and the bed actually absorbs 0.85 kg (1.9 lb) then the AUE is 85%. The 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 some reduced level, e.g., 95%. Continued operation will result in increased outlet pCO_2.

Regeneration Mechanism

The regeneration process evolves the metabolic CO_2 stored in the expended absorbent and replenishes the OH^- concentration of the absorbent. The ERCAR basically functions by consuming H_2 gas at the anodes and regenerating it at cathodes of electrochemical cells. A side reaction of the H_2 consumption occurring at the anode is the evolution of CO_2 from the expended absorbent solution. Similarly, a side reaction of the H_2 generating process at the cathode is the production of regenerated absorbent solution.

The regeneration process for the ERCA hardware occurs in two steps. First the expended absorbent solution within the ERC Absorber is extracted from the absorber and replaced by regenerated absorbent solution. The second step is the regeneration of the expended absorbent solution which is performed on a continuous basis with the electrochemical ERCAR hardware. The electrochemical and chemical reactions occur when power is supplied to the cell electrodes as indicated in Figure 5. Hydrogen gas flows over the anode. 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



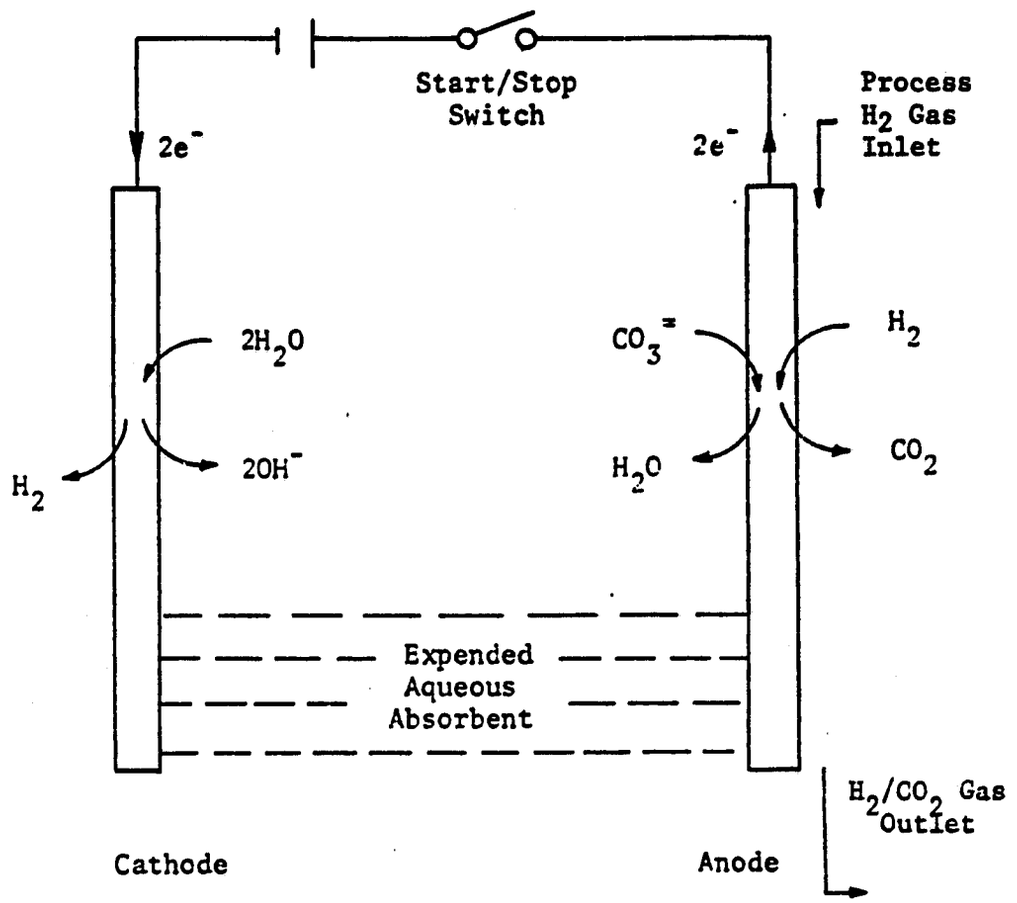
Hydroxyl Ion Absorption

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

Carbonate Ion Absorption

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

FIGURE 4 ABSORPTION MECHANISM FOR ERC ABSORBER



Cathode Reaction

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

Anode Reactions

$$2OH^- + H_2 = 2H_2O + 2e^-$$
$$CO_3^= + H_2O = HCO_3^- + OH^-$$
$$HCO_3^- = CO_2 + OH^-$$

Overall Anode Reaction

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

Overall Reaction

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

FIGURE 5 REGENERATION MECHANISM FOR ERCA CONCEPT

the reaction listed in the figure. At the cathode, water is consumed to produce the H_2 gas and OH^-. The H_2 gas is evolved in the process stream where it can return to the anode cavity through external plumbing for reconsumption. The OH^- remains in the electrolyte to ionically 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 the anolyte pH. The exhaust product of the regeneration is a mixture of CO_2 and H_2 in the gas phase ready for direct integration with a CRS.

For the continuous regeneration of electrolyte, the bulk absorbent passes through the cell during regeneration rather than being stationary within the cell matrix as implied by Figure 5. Expended absorbent solution is continuously fed into the anode electrode through a feed plate assembly (not shown). 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 cell at the cathode where it is separated from the H_2 gas generated at the cathode and collected for replacement in the ERC Absorber. By proper adjustment of flow and current parameters the absorbent OH^- concentration at the cathode can approach 100%.

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 that 100% regeneration efficiency 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 within the ERC Absorber hardware with regenerated absorbent solution. It relates to volumetric removal and replacement. The final term for describing ERCA performance is total absorbent utilization (TAU) which is defined as the product of the independent performance parameters. It is therefore the product of AUE, EE and RE. This parameter is important in sizing the ERC Absorber as it relates to the volume of absorbent required to meet a given specification.

ERC ABSORBER

The block diagram of the PLSS was presented in Figure 2. The proposed regenerable ERC Absorber would replace the existing CO_2 scrubber. Figure 6 shows the functional block diagram of the ERC Absorber, including its principal parts. The debris trap and charcoal filter assembly remove particulates and gaseous trace contaminants, respectively, prior to entering the absorbent bed assembly. A coolant assembly is required because, as in LiOH, heat is generated due to the absorption of the CO_2 with the liquid absorbent (OH^-). The coolant is an interface presently supplied by the PLSS.

The design for the ERC Absorber must meet the requirements of the existing CO_2 removal component. This section presents a discussion of the ERC Absorber design starting with the specifications and requirements, discussion of the implementation approach and ending with a preliminary design.

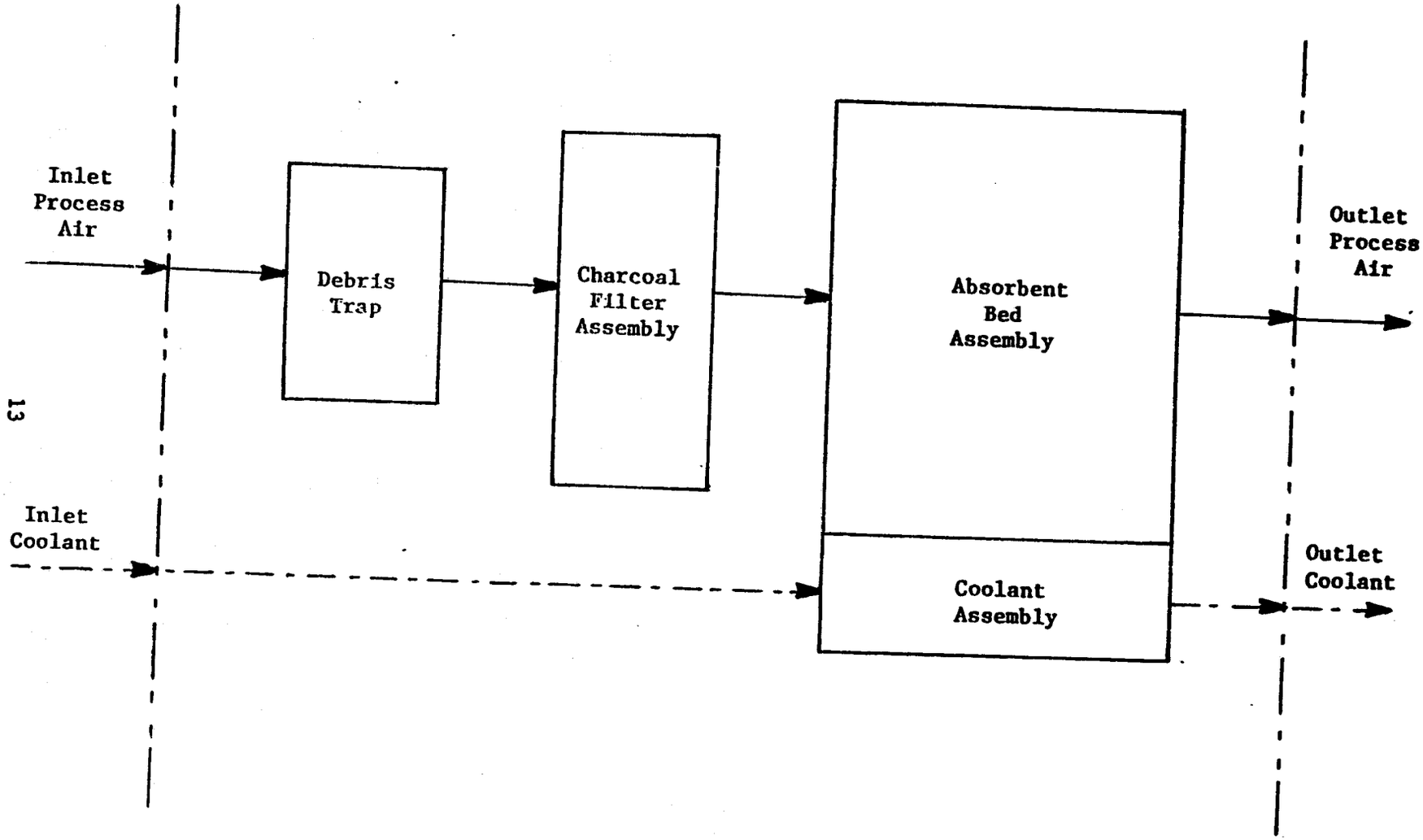


FIGURE 6 FUNCTIONAL BLOCK DIAGRAM OF ERC ABSORBER

Design Requirements

The design specifications for an end application, flight level ERC Absorber are given in Table 1. These specifications were adopted as goals for the ERC Absorber design and are based on the requirements for the existing PLSS Contaminant Control Cartridge (CCC).[11,13,14] The specifications include CO_2 removal requirements, configuration constraints, interface requirements and inlet process air requirements. These latter requirements are further amplified in Figure 7 which shows that the relative humidity (RH) requirements for flight hardware must cover a fairly large range from approximately 50% RH to almost fully saturated air.

The nominal CO_2 removal requirement is 0.67 kg (1.48 lb) of CO_2 over seven hours. Actual CO_2 generation rates are variable over time. A typical CO_2 profile having peak generation rates of approximately 0.16 kg/h (0.35 lb/h) is shown in Figure 8.[15] The importance of this curve is that the ERC Absorber, as well as the CCC, must have capacity to accommodate the higher generation rates both at the beginning of the EVA mission and at the end. The CO_2 removal requirements of the PLSS differ from those of the primary space vehicle Air Revitalization System (ARS). Nominal PLSS CO_2 removal requirements of 0.095 kg/h (0.21 lb/h) per person is 2.5 times the nominal ARS CO_2 removal requirement of 0.042 kg/h (0.092 lb/h) per person. The low PLSS process air flow rate and the small total suit volume requires that the CO_2 be removed at the same rate it is produced since there is no large volume to damp out sudden increases in CO_2 production as there is in the space vehicle. The high nominal CO_2 removal requirements and the need to handle sudden peak loads in CO_2 removal rate (up to 1.7 times nominal to match increased metabolic generation rate) limits the type of CO_2 absorption process that can be used. In general, the high and variable CO_2 removal requirements and the limited time of an EVA mission imply the use of a capacity-limited process for CO_2 absorption. The capacity limited ERC Absorber must be sized to ensure that the peak removal requirements can be met at the end of an EVA mission.

The EVA volume is of primary importance for backpack application. The present CCC is approximately 5.1 dm^3 (0.18 ft^3). Since most EVAs are performed in zero gravity only secondary importance is placed on EVA component mass although consideration for momentum and center of gravity is still required.

The envelope configuration selected for the ERC Absorber design and addressed under this program is the external dimensions of the current CCC while the CO_2 removal capacity (or mission time) was allowed to vary. Interface locations for process air and coolant connections were retained. Additional interface connections for absorbent removal/replacement are required and would be located at noninterference and acceptable locations.

In addition to the technical requirements, several guidelines were established as an aid in the present design effort. Shown in Table 2, these were adopted to ensure future design success, eliminate high risk developments and minimize subsequent development costs. The goal was to avoid pursuing a design approach which would later lead to design or operational limitations. Cognizance of materials availability and compatibility and selection of fabrication techniques at this early stage were emphasized in addition to performance parameters.

TABLE 1 ERC ABSORBER END-ITEM APPLICATION SPECIFICATIONS

Crew Size	1
CO_2 Absorption Capacity, kg (lb)	0.67 (1.48)
EVA Time, h	7
External Housing	CCC Configuration
Dimensions, cm (in)	
Body	33.5 x 23.6 x 6.4 (13.2 x 9.3 x 2.5)
Incl. Interface Envelope	34.3 x 29.2 x 6.4 (13.5 x 11.5 x 2.5)
Volume (Body), dm^3 (ft^3)	5.01 (0.177)
Process Air Temperature, K (F)	
Nominal	301 (83)
Range	289 to 305 (60 to 90)
Process Air Relative Humidity, %	
Nominal	64
Range	50 to 100 (Goal)
System Pressure, kPa (psia)	27.6 (4.0)
Inlet CO_2 Partial Pressure, Pa (mm Hg)	
Nominal	1,010 (7.6)
Range	0 to 2,000 (0 to 15)
CO_2 Absorption Rate, kg/h (lb/h)	
Nominal	0.10 (0.21)
Maximum	0.16 (0.35)
Process Air Composition	O_2/CO_2/Water Vapor
Process Air Flow Rate, dm^3/min (scfm)	53.5 (1.89)
Process Air Pressure Drop, Pa (in H_2O)	112 (0.45)
Coolant Type	H_2O
Temperature, K (F)	296 (74)
Flow Rate, kg/h (lb/h)	9.1 (20) Maximum

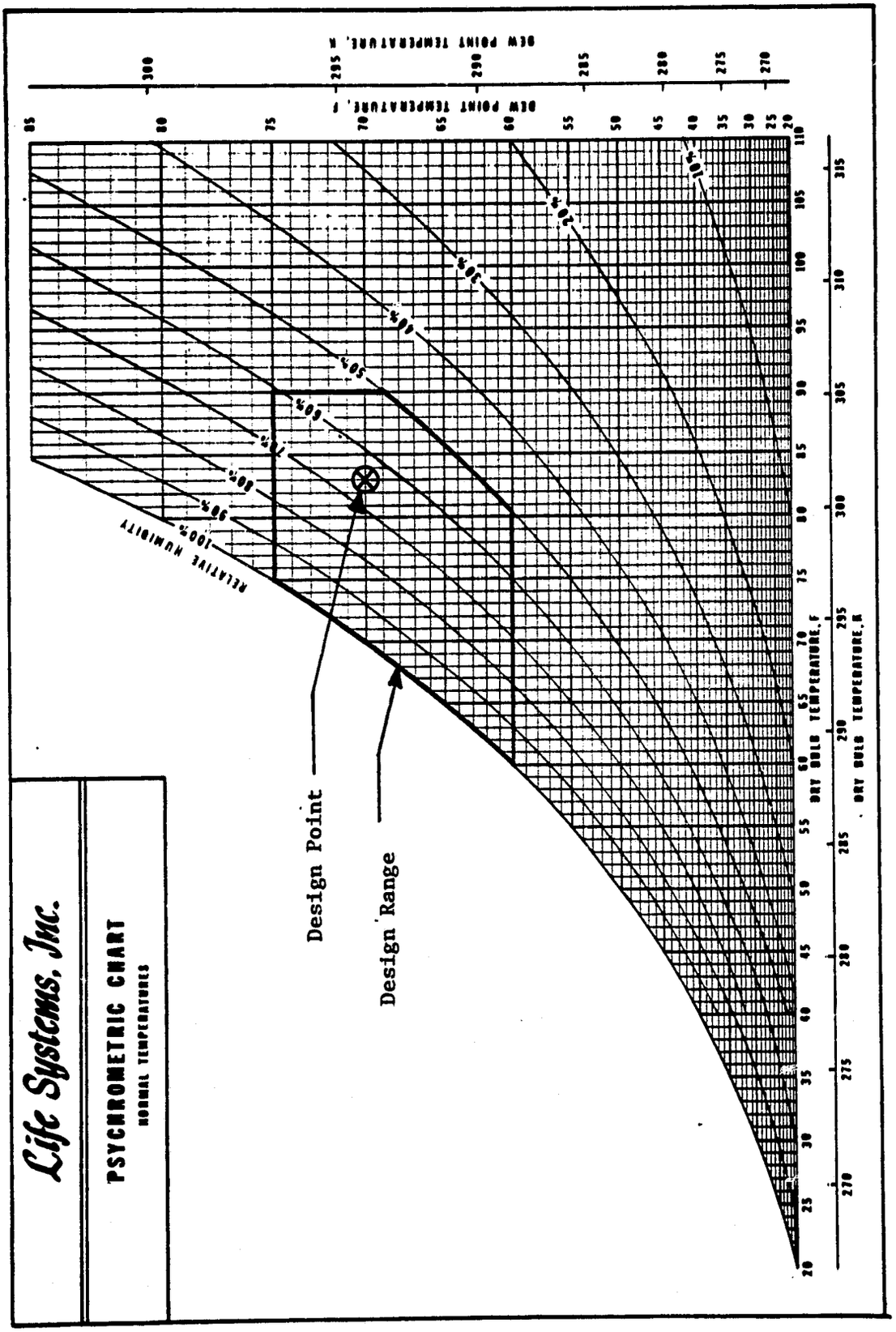


FIGURE 7 PROCESS AIR INLET CONDITIONS

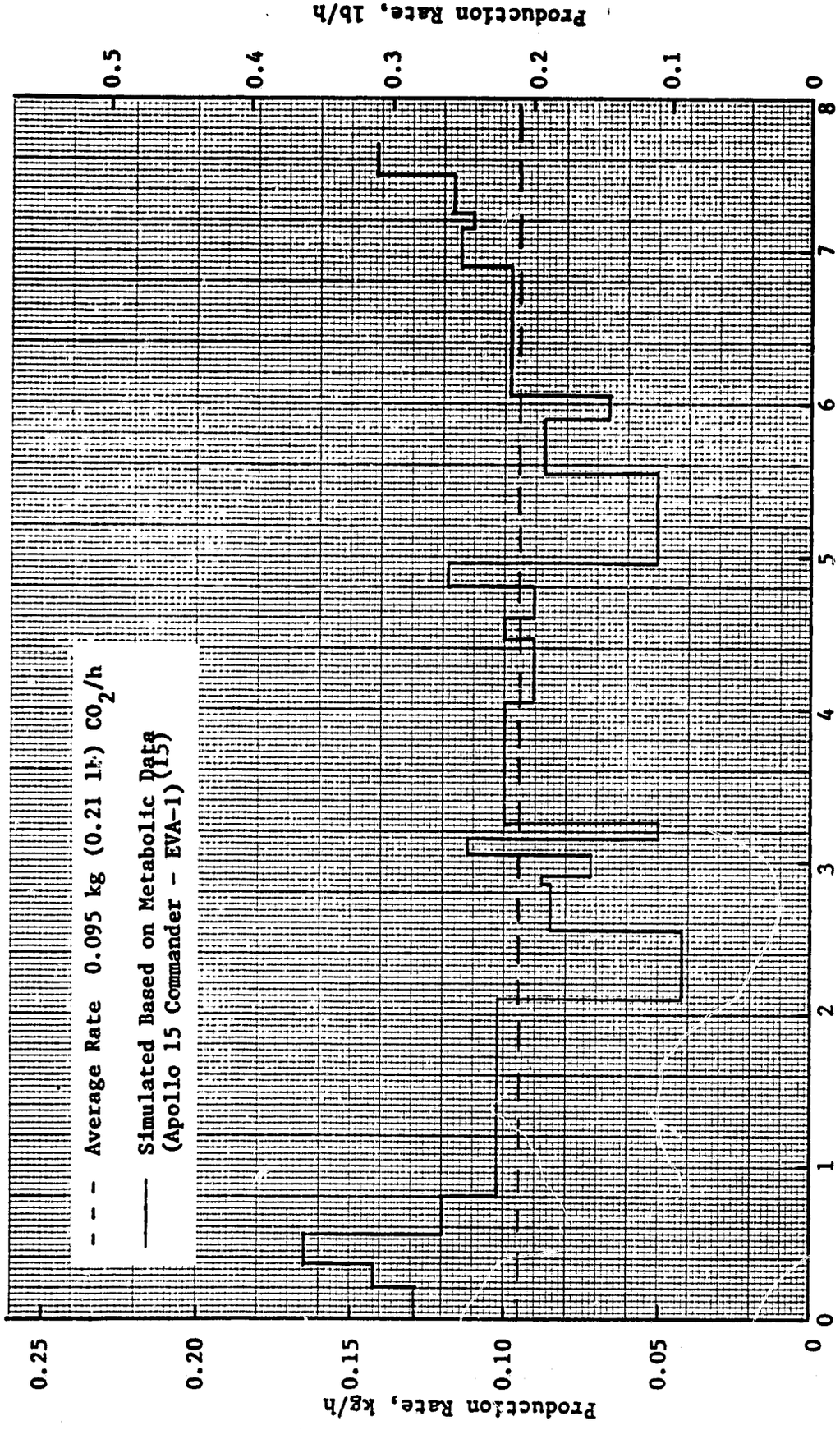


FIGURE 8 SIMULATED CO_2 PRODUCTION RATES DURING EVA

TABLE 2 MAJOR ERC ABSORBER DESIGN GUIDELINES

1. Gas/liquid separator must be available within existing technology.
2. Gas/liquid separator must be reliable.
3. Absorber fabrication technique must be within existing technology.
4. All materials must be spacecraft compatible and qualifiable.
5. High surface area to absorbent volume ratios ($\geq$1,400 ft^2/ft^3) are desirable for high absorbent utilization efficiencies
6. Capability to extract and replace absorbent must exceed 80% extraction efficiency.
7. Seals which separate liquid and gas passages must be reliable.
8. Sealing areas should be minimized so that active areas and volumes are maximized.

Concept Selection

The PLSS application dictates the criteria for evaluation of totally regenerable absorption concepts. The highest priority for comparison of potential concepts was placed on total equivalent launch weight and EVA volume. Secondary criteria included EVA time, 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 aboard the primary space vehicle during regeneration.

In a prior study several different concepts for the ERC Absorber were evaluated.[12] Some of these combined the absorption and regeneration functions within the same hardware. These concepts increased the size and mass of the EVA backpack due to the dual purpose hardware. A comparison of the projected volume goals of a combined ERCA hardware approach and the present concept is shown in Figure 9. The present ERC Absorber design (shown as crosshatched area) approaches the equivalent nonregenerative (LiOH) volume. When the launch weight savings due to reuse of the absorbent are included, the ERC Absorber concept with externally regenerable absorbent shows a decided advantage.

A major aspect of the ERC Absorber design is the contact mechanism of the CO_2 and the absorbent. Several concepts for providing the gas/liquid interface required between the process air and the liquid absorbent were evaluated. One initial concept which permitted excellent liquid/gas interchange was to aerosol the absorbent and spray it into the process air stream. However, problems of liquid/gas separation lessen its applicability. The use of membranes was the logical choice. Tubular membranes in particular were found to have a high surface area for minimum envelope volume. Additionally, they are readily available with many off-the-shelf selections. The ERC Absorber design presented herein is based on the use of hollow fiber membranes (HFM) which are currently available. The design, therefore, concentrated on selecting the HFM (type and size) which would provide the most capacity for the allowable volume. The availability of HFMs that meet the required size characteristics was researched.[16] Figure 10 indicates the size characteristics of the HFM tube technology that is currently available. The solid area shows the range which provides the desired HFM tube characteristics, i.e., low outside to inside diameter (OD/ID) ratios and wall thicknesses.

Absorber Design

Following concept selection (i.e., the use of HFM), surface area requirements and absorbent solution volume relationships were addressed. These were characterized in terms of specific absorption rate and capacity to meet the CO_2 removal requirements. Rate refers to the instantaneous amount of CO_2 removed per unit time, whereas capacity is the total amount of CO_2 that can be absorbed for a given bed size. These two parameters are related through the common parameter of surface area, as shown in Figure 11. The nominal CO_2 removal requirement of 0.095 kg/h (0.21 lb/h) over seven hours is superimposed upon the curve. The experimental data shown is from preliminary HFM tests performed under this program and prior ERCA performance.[25] To meet the nominal requirement (straight line) any ERC Absorber design must have performance above the straight line. Once the performance drops off to a point below the straight

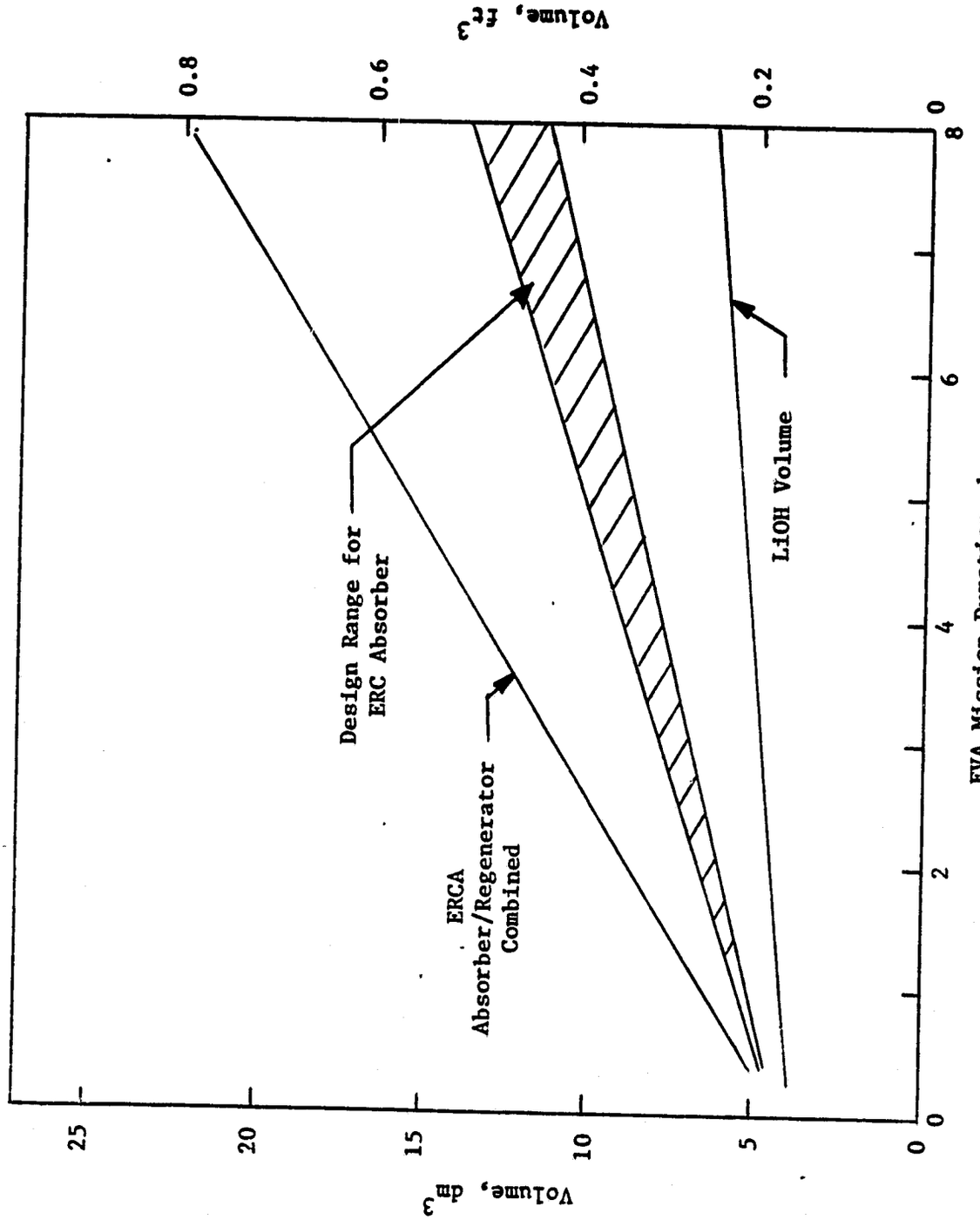


FIGURE 9 ERC ABSORBER VOLUME GOALS

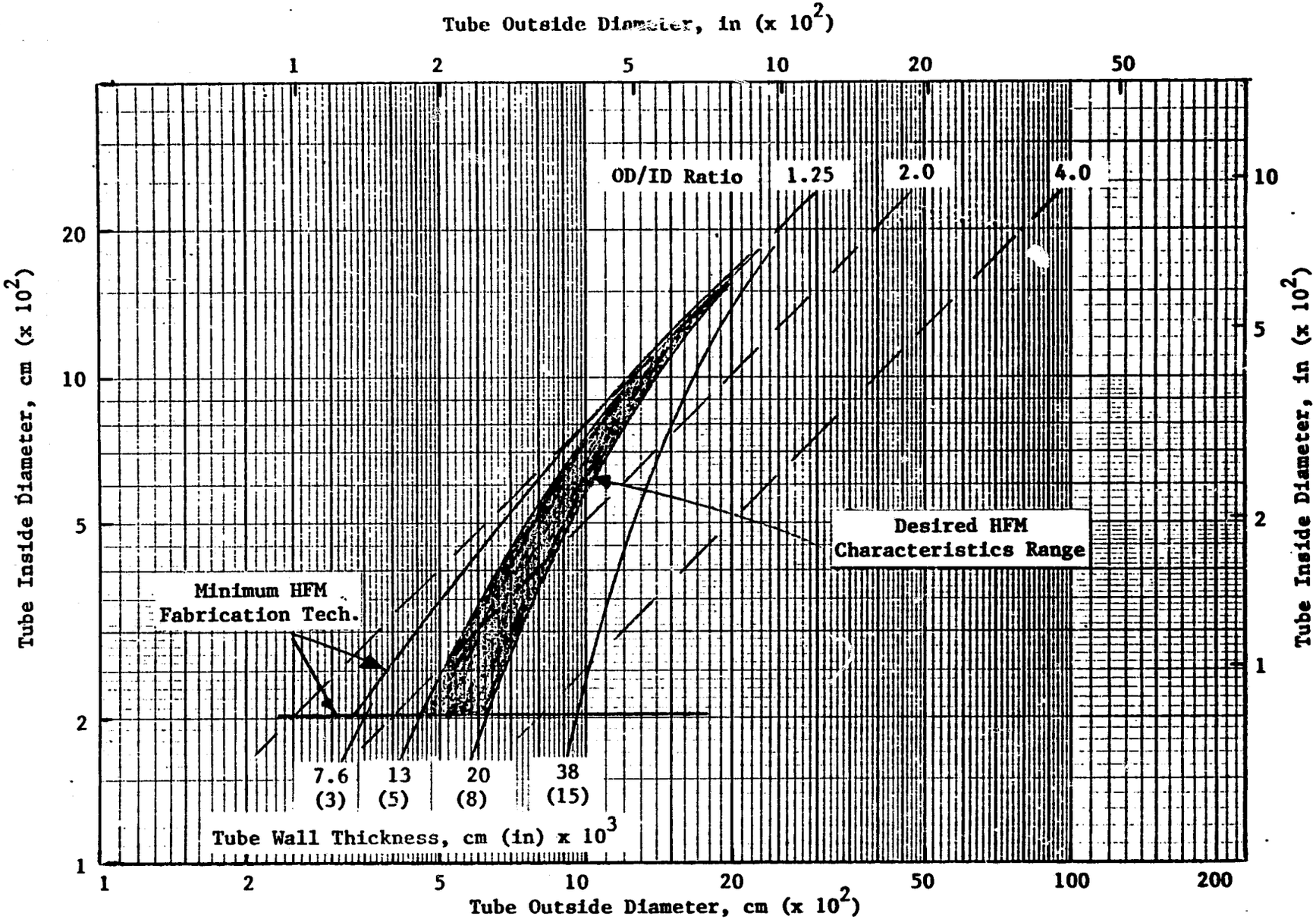


FIGURE 10 HFM TUBE TECHNOLOGY

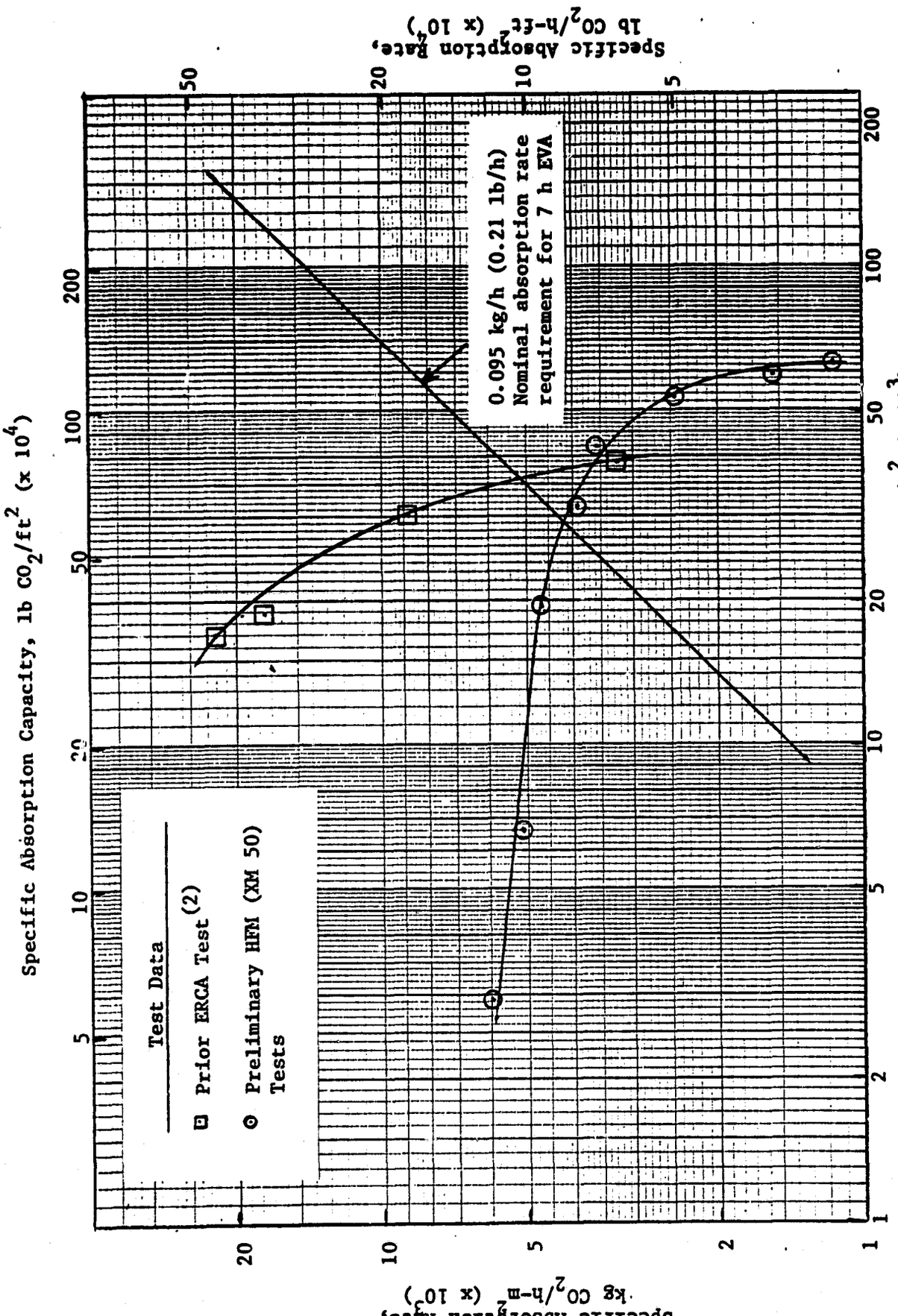


FIGURE 11 SPECIFIC ABSORPTION RATE VERSUS CAPACITY

line, the outlet pCO_2 will increase and the absorbent would be considered used. The absorbent would then have to be replaced with fresh absorbent.

The total absorbent volume required in the ERC Absorber is determined by the initial charge concentration and the total absorbent utilization (TAU) factor discussed previously. The relationship between these two parameters for the removal of 0.67 kg (1.48 lb) CO_2 is shown in Figure 12. The charge concentration is represented by the RH equilibrium of the absorbent solution. The nominal design point indicates that a volume of 6.0 dm^3 (0.21 ft^3) of absorbent solution is needed to meet the CO_2 removal requirements for a seven hour mission, at a projected TAU of 61% and 64% RH. However, because of the envelope constraint imposed on the design, the absorbent volume that was utilized for the design was 2.1 dm^3 (0.074 ft^3). Therefore, the anticipated EVA time for this design was proportionately reduced.

Figure 13 shows the assembly of the HFM ERC Absorber design while Table 3 lists the major component parts of the design. The process air enters the ERC Absorber and flows around the outside of the HFM tubes. The HFM tubes are manufactured, assembled and sealed within the canister in twelve bundles. The liquid absorbent resides statically on the inside of the tubes. The actual gas/liquid interface contact is within the tube wall itself. Coolant flows in series through two separate assemblies and is returned to the PLSS coolant control system. The major interfaces are shown in Table 4. Process air and coolant interfaces are the same as for the CCC. Only two additional interfaces are required to remove and replace the absorbent.

Table 5 shows the characteristics of the ERC Absorber design including anticipated performance. Some of the parameters are preliminary and will be further defined in the recommended follow-on activities. Figure 14 shows the stream operating parameters determined from a mass and energy balance performed on the design.

The total equivalent weight and volume comparison of this ERC Absorber design, as compared to the existing LiOH system, is shown in Figure 15. The value of the ERC Absorber is in the advantage it offers in terms of decreasing nonregenerable expendables represented by the throwaway LiOH, including canisters. Total equivalent volume includes the penalty paid for reserving extra space on the space vehicle (Space Shuttle) for LiOH canisters compared to a projected need of one ERC Absorber per crew member that would be on-board.

ERCA REGENERATION SYSTEM

The ERCAR System consists of all the components required to regenerate the absorbent from the the ERC Absorber. It interfaces with the resources of the primary space vehicle. The principal component of the ERCAR is the electrochemical module which contains the necessary electrodes and cell hardware to accomplish the regeneration process. The requirements of such a system and therefore the size of the system are dependent on the frequency of EVA use, the amount of used absorbent to be regenerated and system power and weight goals. The electrochemical module design described below will produce, at the design operating conditions, a specified regenerated absorbent flow rate. Table 6 lists the specifications for an ERCAR system based on an absorbent regeneration rate of 1.2 cm^3/min assumed for this study. This rate corresponds

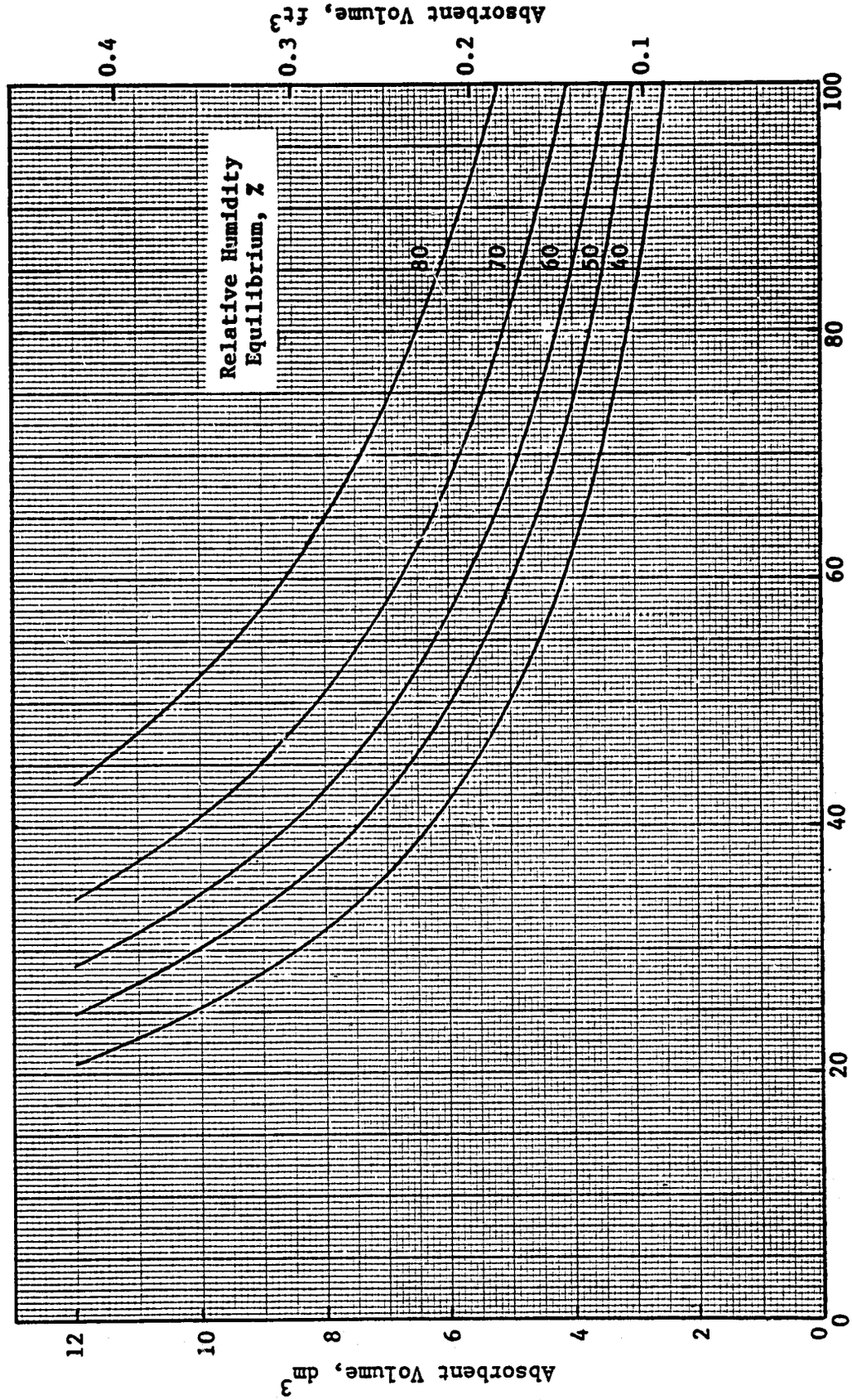


FIGURE 12 ABSORBENT VOLUME VERSUS ABSORBENT UTILIZATION

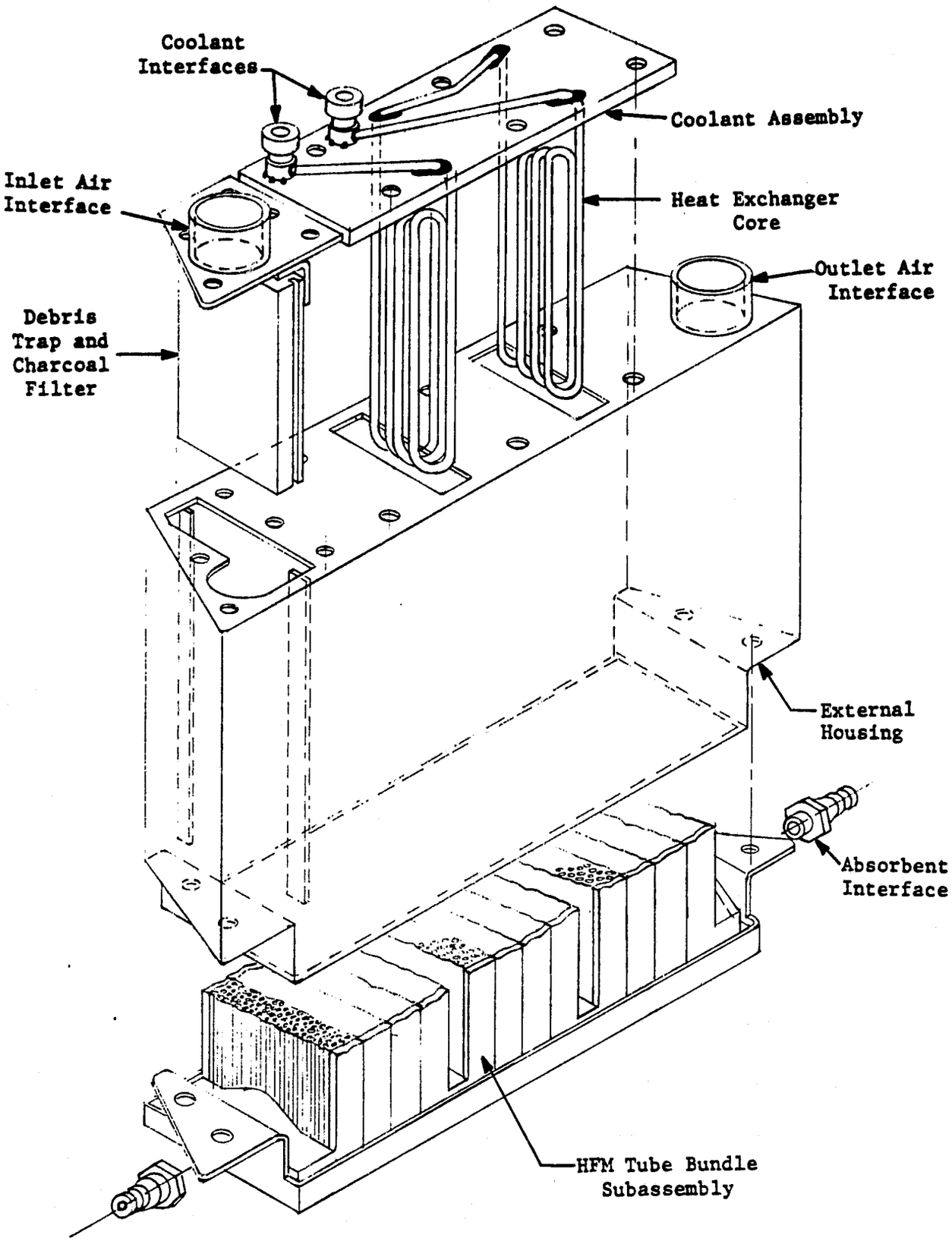


FIGURE 13 ERC ABSORBER ASSEMBLY

TABLE 3 ERC ABSORBER COMPONENT PARTS LIST

Housing

- External Shell
- Outlet Air Interface

Charcoal Bed Assembly

- Inlet Air Interface
- Debris Trap
- Contaminant Filter

Coolant Assembly

- Coolant Tubes
- Coolant Tube Interfaces

Absorbent Tube Fluid Assembly

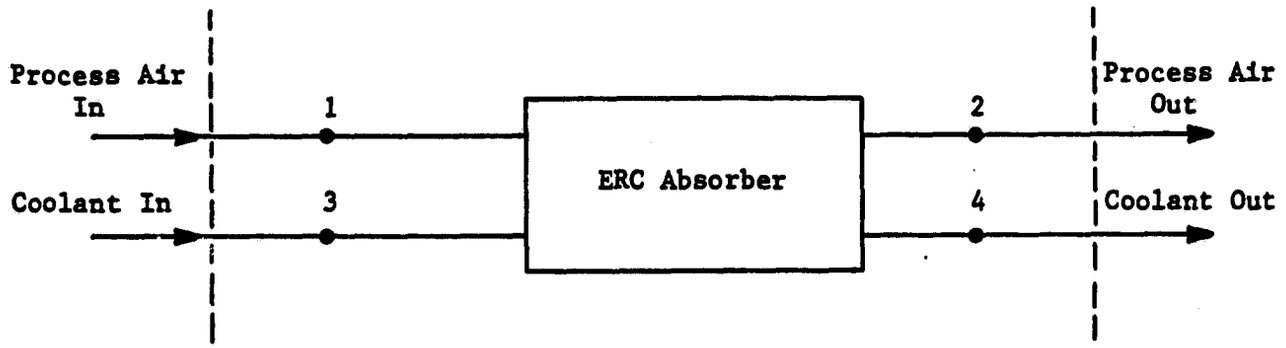
- HFM Absorber Tube Bundles (12)
- Absorbent Positive Isolation Disconnects (2)

TABLE 4 ERC ABSORBER INTERFACES

PLSS System	
Air Interface	
Process Air Flow Rate,	
sdm^3/min (scfm)	54 (1.9)
dm^3/min (cfm) at 28 kPa (4.0 psia)	201 (7.1)
Coolant Interface	
Coolant Water Flow Rate, kg/h (lb/h)	9.1 (20.0)
Heat Load, W-h/kg CO_2 (Btu/lb CO_2)	450 (700)
Absorbent Interfaces	Sealed and Capped During EVA
Power	None
ERCAR System	
Air Interface	
N_2 Purge	
Flow, sdm^3/min (scfm)	3.0 (0.1)
Pressure, kPa (psia)	124 (18)
Coolant Interface	Capped
Absorbent Interface	
Extraction Flow Rate, cm^3/min	175
Extraction Pressure Drop, kPa (psid)	10.3 (1.5)
Heat Load	None
Power	None

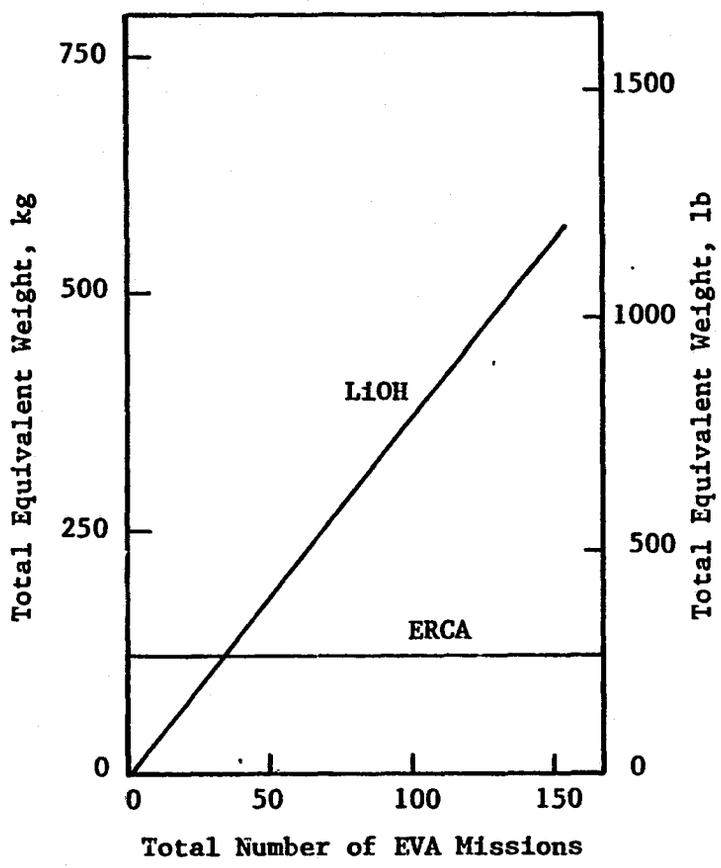
TABLE 5 ERC ABSORBER PROJECTED CHARACTERISTICS

Absorbent Tube Assembly	
CO_2 Absorption Capacity, kg (lb)	
Nominal	0.11 (0.25)
Maximum	0.19 (0.42)
CO_2 Absorption Rate, kg/h (lb/h)	
Nominal	0.095 (0.21)
Maximum	0.16 (0.35)
Number Subassemblies/Assembly	12
Number Tubes/Subassembly	1,000
Absorbent Volume, dm^3 (ft^3)	2.1 (0.074)
Total Surface Area, m^2 (ft^2)	14 to 17 (150 to 180)
Tube Packing Open Area, %	30
Volume, dm^3 (ft^3)	3.1 (0.11)
Weight, kg (lb)	8.2 (18)
Dimensions, cm (in)	23.4 x 5.8 x 21.8 (9.2 x 2.3 x 8.6)
Cooling Tube Assemblies	
Surface Area, cm^2 (in^2)	450 (69)
Flow Rate, kg/h (lb/h)	9.1 (20)
Volume, cm^3 (in^3)	150 (9.2)
Dimensions, cm (in)	20.3 x 1.3 x 5.8 (8.0 x 0.5 x 2.3)
Charcoal Bed Filter	
Operating Time/Unit, h	7
Weight of Charcoal, kg (lb)	0.054 (0.12)
Weight, kg (lb)	0.15 (0.33)
Volume, cm^3 (in^3)	174 (10.6)
Dimensions, cm (in)	19.3 x 5.1 x 1.8 (7.6 x 2.0 x 0.7)
Overall	
Dimensions (Body), cm (in)	33.5 x 23.6 x 6.4 (13.2 x 9.3 x 2.5)
Volume, dm^3 (ft^3)	5.03 (0.177)
Weight, kg (lb)	18 (40)



Parameter	Location 1	2	3	4
Temperature, K (F)	301 (83)	304 (88)	296 (74)	301 (83)
Pressure, kPa (psia)	27.6 (4.0)	27.4 (3.98)	41.4 (6.0)	34.5 (5.0)
Volumetric Flow, dm^3/min (cfm)	202 (7.12)	201 (7.09)	-	-
Volumetric Flow, sdm^3/min (scfm)	53.5 (1.89)	52.7 (1.86)	-	-
Total Mass Flow, kg/h (lb/h)	4.13 (9.08)	4.03 (8.87)	9.1 (20)	-
O_2 Mass Flow, kg/h (lb/h)	3.82 (8.40)	3.82 (8.40)	-	-
CO_2 Mass Flow, kg/h (lb/h)	0.096 (0.211)	0	-	-
Water Mass Flow, kg/h (lb/h)	0.214 (0.471)	0.214 (0.471)	9.1 (20)	9.1 (20)
O_2 Partial Pressure, kPa (mm Hg)	24.6 (185)	24.9 (187)	-	-
CO_2 Partial Pressure, kPa (mm Hg)	0.451 (3.39)	0	-	-
Water Partial Pressure, kPa (mm Hg)	2.43 (18.5)	2.49 (18.7)	-	-
Dew Point Temperature, K (F)	294 (70)	294 (70)	-	-
Relative Humidity, %	64	55	-	-

FIGURE 14 ERC ABSORBER STREAM OPERATING PARAMETERS



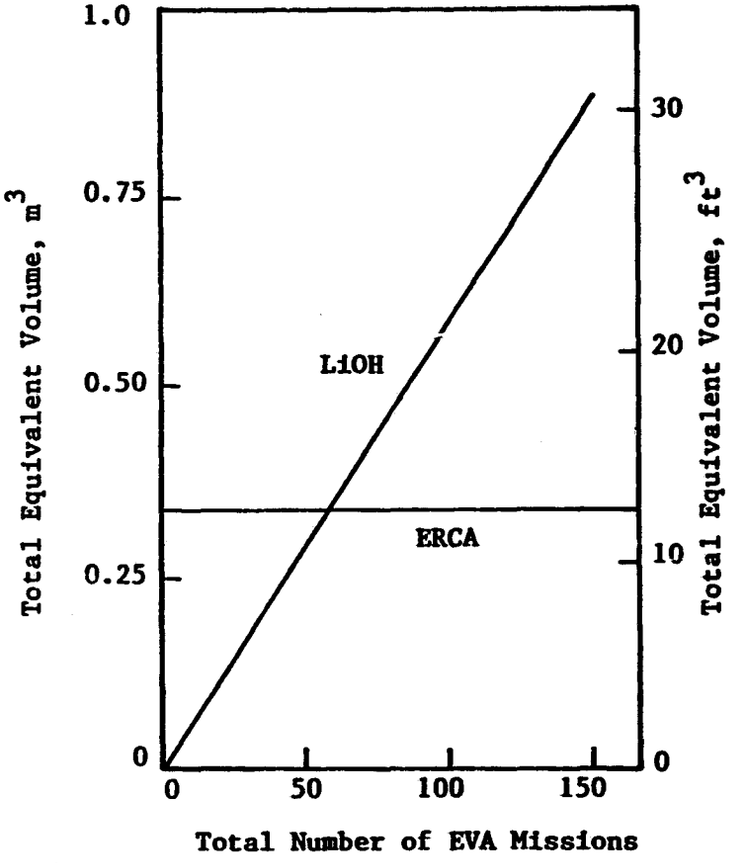


FIGURE 15 ERCA VERSUS LiOH WEIGHT AND VOLUME COMPARISONS

TABLE 6 ERCAR SYSTEM DESIGN SPECIFICATIONS

Crew Size	1
Absorbent Regeneration Rate, cm^3/min	1.2
CO_2 Evolution Rate, kg/h (lb/h)	0.029 (0.063)
H_2 Supply Flow Rate, kg/h (lb/h)	2.7×10^{-3} (6.0×10^{-3})
H_2 Relative Humidity, %	95 Max.
Coolant	
Type	Water
Temperature, K (F)	300 - 322 (80 - 120)
Flow Rate, kg/h (lb/h)	32 (70)
Purge Gas	
Type	N_2
Pressure, kPa (psia)	310 (45)
Electrical Power, VAC	115/200, 400 Hz, 3Ø
Gravity	0 to 1

to the absorbent of the ERC Absorber being regenerated within 45 hours. Designing a module to regenerate the required amount (2.1 dm^3 (0.084 ft^3)) over a shorter time period would require a larger number of electrochemical cells and an increase in the total power needed to operate these cells. The other parameters, including the interfaces with the vehicle, were based on this absorbent flow rate.

System Description

The regeneration hardware design consists of the ERCAR module, five assemblies and associated C/M I. A block diagram of the ERCAR System is given in Figure 16. The function of the ERCAR module is to remove the metabolic CO_2 from the expended absorbent solution in order to reestablish its CO_2 absorbing capability. The Fluid Control Assembly provides H_2 and nitrogen (N_2) interfaces with the module, maintains module pressure levels and provides CRS or vacuum vent interfaces. The Coolant Control Assembly provides thermal control for the module to maintain the module at desired operating temperature. The absorption 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. Table 7 lists the required components of the ERCAR System. Except for the module and the C/M I, these mechanical or electromechanical components are available off-the-shelf.

Electrochemical Module

The heart of the ERCAR is the electrochemical module. It consists of several electrochemical cells packaged as a single unit and operates with other components in the manner described above to produce regenerated absorbent of a quality acceptable for reuse in the ERC Absorber. The design of the ERCAR electrochemical cell is based on Life Systems' prior experience with electrochemical cells such as those associated with the Electrochemical Depolarized Concentrator (EDC) and Water Electrolysis Subsystem (WES) hardware.

Figure 17 is a functional schematic of a cell designed for the ERCAR module. Expended absorbent is supplied to a feed plate/matrix assembly and flows through the cell matrix from anode to cathode due to a small pressure differential. Hydrogen flows adjacent to the anode. Some of the H_2 is consumed in the anode reaction while the remainder, along with the evolved CO_2, exits the cell at the H_2/CO_2 outlet. Regenerated absorbent and evolved H_2 is removed from the cavity adjacent to the cathode which is initially purged with N_2. Finally, coolant is circulated through the cell to maintain operating temperature. For a multi-cell module, the flow paths for liquids and gases of individual cells are in parallel. Electrically, the cells are connected in series.

The operating characteristics for a six-cell module of a full-scale ERCAR system are listed in Table 8. Interfaces with the spacecraft to operate this module are listed in Table 9. These include the fluid supplies (N_2 and H_2), coolant, power and the heat load imposed upon the spacecraft. Table 10 is a detailed list of the parts required for the module.

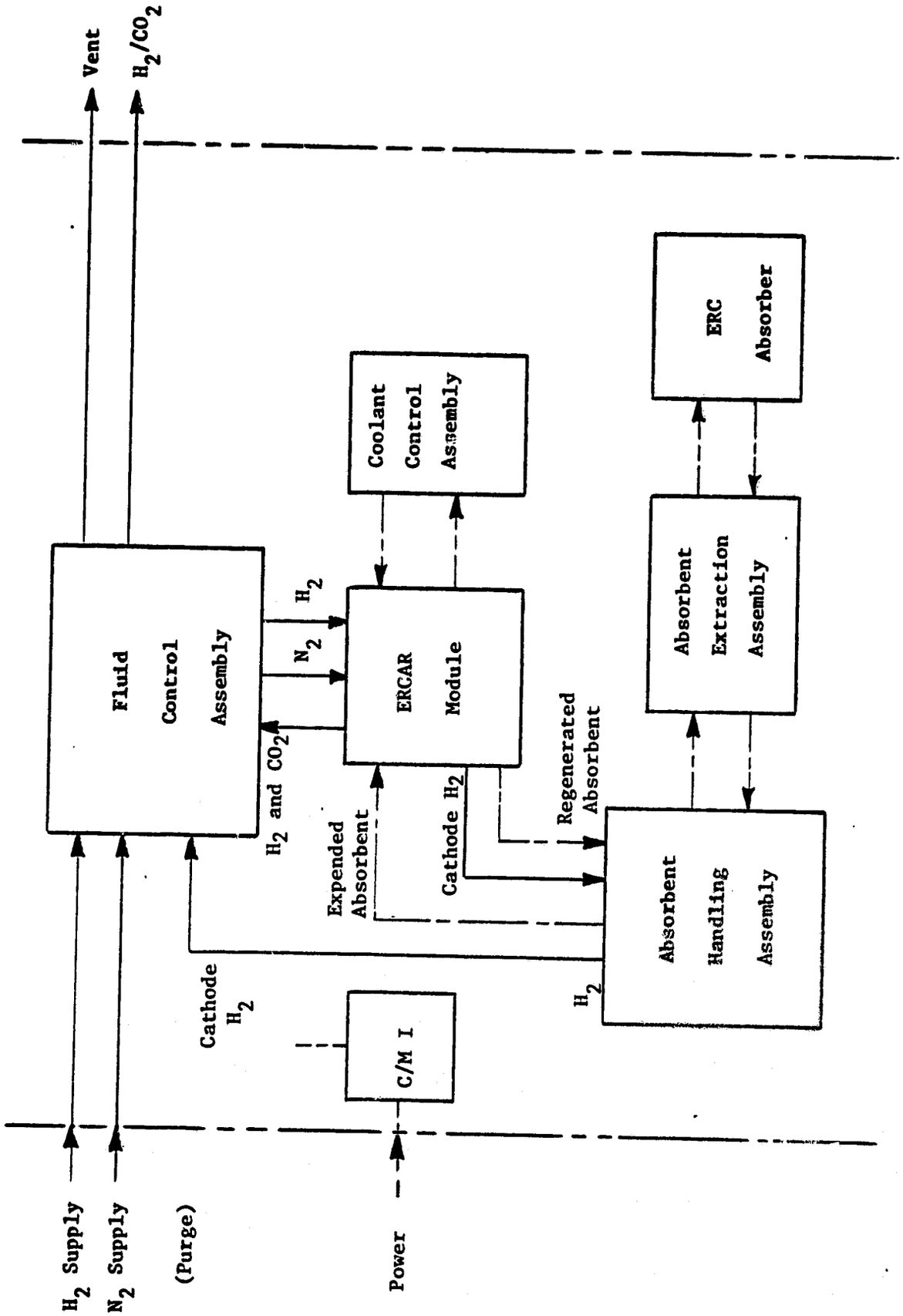


FIGURE 16 ERCAR SYSTEM BLOCK DIAGRAM

TABLE 7 ERCAR SUBASSEMBLIES/COMPONENTS

Item	No. Req'd	Description
1	1	Electrochemical Module
2	3	Pumps
3	3	Pressure Regulators
4	2	Liquid/Gas Separators
5	8	Valves
6	2	Accumulators
7	2	Storage Tanks
8	9	Sensors (Temperature, Pressure, Level, Flow)
9	1	Control/Monitor Instrumentation
10	Misc.	Mechanical (Checkvalves, Orifices, Tubing, Fittings)

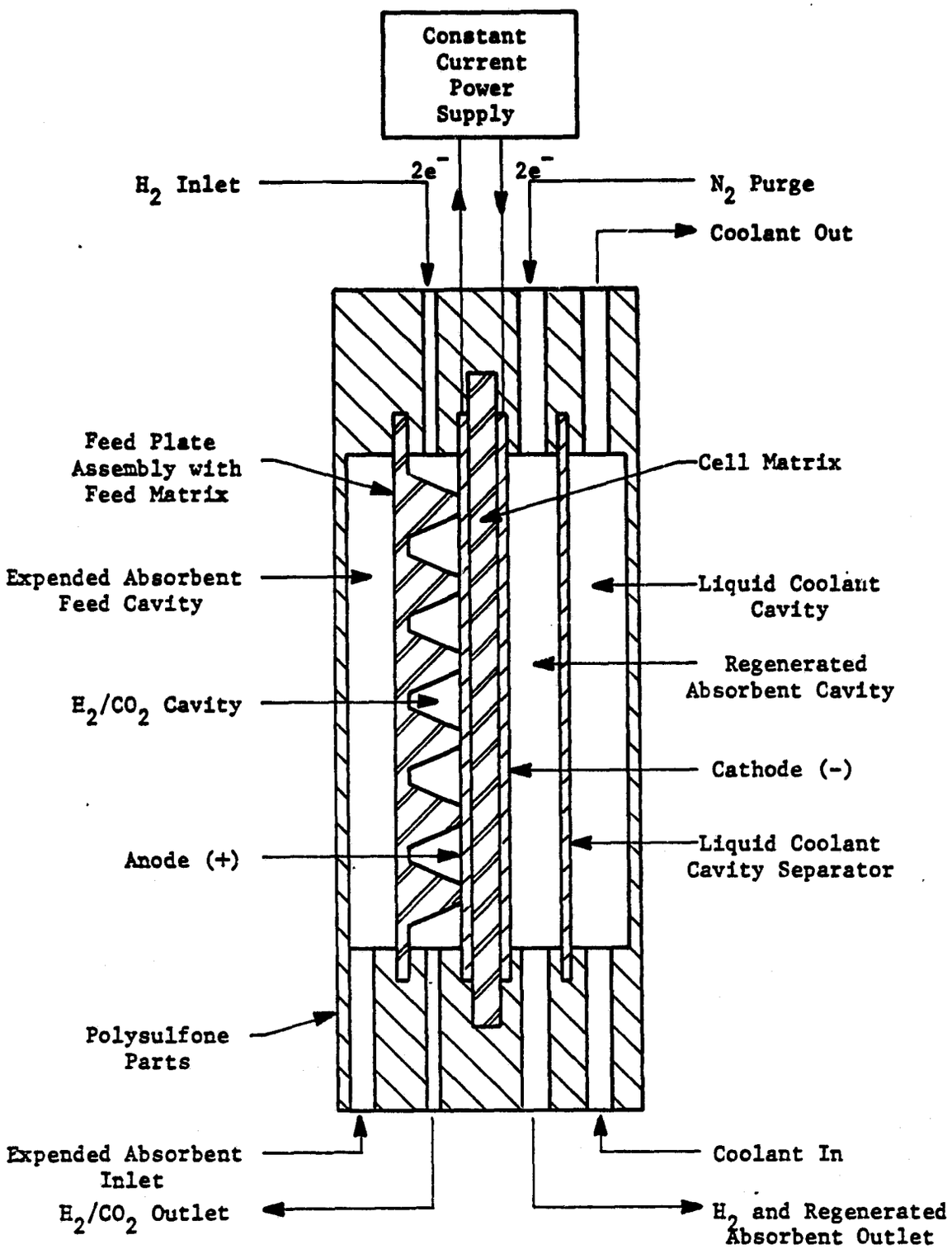


FIGURE 17 ERCAR CELL FUNCTIONAL SCHEMATIC

TABLE 8 ERCAR MODULE OPERATING CONDITIONS

Number of Cells	6
Active Area Per Cell, cm^2 (ft^2)	93 (0.1)
Current Density, mA/cm^2 (ASF)	65 (60)
Cell Voltage, V	0.7
Absorbent Production Rate, cm^3/min	1.2
Regeneration Efficiency, %	60 to 80
CO_2 Evolution Rate, kg/h (lb/h)	0.029 (0.063)
Power Consumed, W	25
Heat Generated, W	25 minus 450 W-h/kg times CO_2 Evolution Rate in kg/h

TABLE 9 ERCAR MODULE INTERFACES

Process Gas (H_2)	
Flow Rate, kg/h (lb/h)	2.7×10^{-3} (6.0×10^{-3})
Temperature, K (F)	294 to 322 (70 to 120)
Pressure, kPa (psia)	240 (35)
Anode Exhaust (H_2/CO_2)	
Flow Rate, kg/h (lb/h)	3.1×10^{-2} (6.9×10^{-2})
Temperature, K (F)	322 (120)
CO_2 Concentration, %	30
Pressure, kPa (psia)	210 (30)
Cathode Exhaust (H_2)	
Flow Rate, kg/h (lb/h)	1.3×10^{-3} (3.0×10^{-3})
Temperature, K (F)	322 (120)
Pressure, kPa (psia)	210 (30)
Nitrogen Purge Gas	
Temperature, K (F)	294 (70)
Pressure, kPa (psia)	310 (45)
Absorbent Solution	
Expended Absorbent Flow Rate, cm^3/min	1.2
Temperature, K (F)	294 (70)
Regenerated Absorbent Flow Rate, cm^3/min	1.2
Temperature, K (F)	322 (120)
Coolant Requirements	
Coolant Type	Water
Flow Rate, kg/h (lb/h)	32 (70)
Temperature, K (F)	322 (120)
Heat Load (Max), W	25
Power, W	
DC Nominal	25

TABLE 10 ERCAR MODULE PARTS LIST

Part	No. Req'd
Cell Frame	6
End Plate w/Fittings	2
Insulation Plate	2
Cathode Current Collectors w/Exmet	6
Cathode Current Collector w/o Exmet	1
Anode Current Collectors	6
Feed Plate Assembly	6
Feed Matrices	6
Anodes	6
Cell Matrices	6
Cathodes	6
O-Rings, Assorted Sizes	Misc.

MINI-PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout the contractual performance including design, purchasing, fabrication and testing. The Product Assurance program included Quality Assurance, Reliability, Safety and Materials Control activities.

Quality Assurance

Quality Assurance activities were included during the conceptual design studies, interface requirements definition and 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 as specified in the test article drawings and test setup schematics. Also a quality assurance effort was involved in the preparation of the Final Report with the objective of identifying and resolving deficiencies that could affect the quality of future equipment.

Reliability

Reliability activities consisted of (1) proper calibration of test equipment and test support instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. A survey of the component and test setup designs was performed to determine the calibration requirements for the testing. Applicable components were calibrated during assembly and after installation (e.g., CO_2 analyzers and mass flow meters).

A test procedure was established to insure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures. Test data and observations were appropriately recorded using standard laboratory procedures.

Safety

A Safety program was initiated to insure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of identifying possible adverse component and test setup characteristics, reviewing design and design changes for a potential safety hazard, reviewing NASA Alerts for safety information and incorporating the equipment's protective features.

A primary safety consideration concerned the use of H_2 in the ERCAR cells containing catalyzed electrodes. A combination of three factors eliminated this as a potential safety hazard: N_2 purge was used before introducing H_2 into the cell cavity, total gas void volume was kept at a minimum and operation at ambient pressure limited the mass of reactants present in the cavity. These provisions eliminated potential safety hazards from the operating procedure and will contribute to a future ERCAR system that is inherently safe.

Materials Control

Considering the developmental nature of the program, only the materials associated with the ERC Absorber and the ERCAR electrochemical cell projected for

application hardware were evaluated from a flight suitability standpoint. The evaluation was performed in two categories, metallic and nonmetallic. Acceptability for metallic materials was based on the SSP design criteria handbook.[17] The nonmetallic materials were also screened for flight acceptance.[18] All metallic and nonmetallic materials projected for the application hardware were evaluated as flight acceptable.

TEST PROGRAM ACTIVITIES

The testing activities of this program were directed toward demonstration of the ERC Absorber concept and operation of a single-cell ERCAR module to support the overall design activities. Additional objectives of the testing were to gain confidence in the selected approaches. Benchtop test setups were used to perform the two tests. Over 800 hours testing time was accumulated for all tests conducted under this program.

ERC Absorber Testing

Tests were conducted with a small scale HFM module in an experimental test setup. The objectives of these tests were to: (1) determine whether CO_2 removal capability is improved when absorbent is placed inside the tube instead of outside, (2) determine the best location for the electrolyte (inside or outside the tube) as it relates to extracting the absorbent solution from the ERC Absorber and (3) characterize the capability of the HFM module to remove CO_2 in terms of specific absorption rate and capacity. The following is a description of the test hardware and the test results.

Test Setup and Operation

A schematic of the experimental test setup is shown in Figure 18. Process air at the desired temperature, moisture and concentration of CO_2 (pCO_2) was supplied from a process air source. Because this source provided a fixed flow rate, a portion of the flow was bypassed using valve V1. In this way the desired flow rate through the module was established. The absorber module was contained in a housing with manifolds such that the process air could flow through either the inside or outside of the tubes depending on where the absorbent was located (outside or inside, respectively). The principal sensors were a flow meter (F1), inlet and outlet temperature sensors (T1 and T2) and a differential pressure sensor (P1). Gas sampling provisions allowed the measurement of the dew point and pCO_2 of the inlet and outlet flows. These provisions are indicated in the schematic as sampling ports A and B.

Table 11 shows the test operating conditions including nominal and range values for the principal control parameters. The control parameters were process air flow rate, dry bulb temperature, dew point temperature (or RH) and pCO_2. The tests were conducted by establishing the desired process air conditions and then diverting the given flow (valve not shown) to a freshly charged absorber module and monitoring the outlet pCO_2 level as a function of time. The resulting data was then reduced in terms of absorption rate and capacity as a function of time.

The absorber module selected was a commercially available HFM module containing 250 individual tubes. Although small in scale in terms of the final end

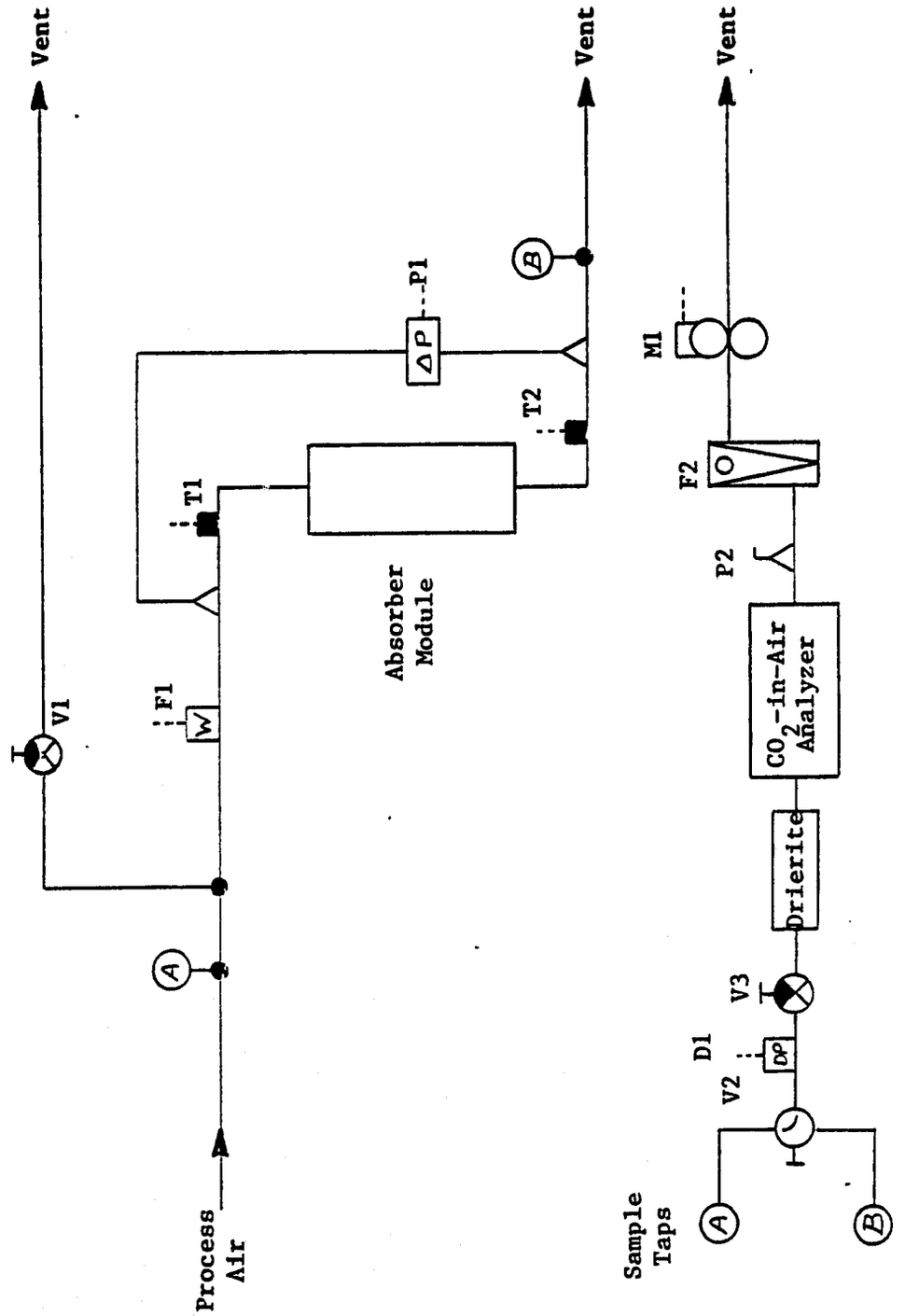


FIGURE 18 ERC ABSORBER TEST SETUP SCHEMATIC

TABLE 11 ERC ABSORBER TEST OPERATING CONDITIONS

Process Air Flow Rate, scm^3/min (scfm)	
Nominal	1100 (0.040)
Range	600 - 1500 (0.021 - 0.052)
Dry Bulb Temperature, K (F)	
Nominal	296 (73)
Range	294 - 297 (70 - 75)
Dew Point Temperature, K (F)	
Nominal	288 (59)
Range	286 - 291 (55 - 65)
pCO_2, Pa (mm Hg)	
Nominal	530 (4.0)
Range	270 - 800 (2.0 - 6.0)
Ambient Pressure, kPa (psia)	98.6 (14.3)
Ambient Temperature, K (F)	296 (74)

application, the flow rates and pCO_2 levels selected for the test were based on full-scale, end application requirements. Characteristics of the module used in the test are given in Table 12.

Test Results

Two groups of tests were conducted for the CO_2 absorption demonstration. One group tested the absorbent solution on the outside of the tubes and a second group tested the absorbent on the inside. For a given tube size initial calculations had indicated a higher surface area at the liquid/gas interface for the absorbent on the outside of the tubes. However, the capability to efficiently extract the absorbent under these conditions was compromised. Absorbent on the inside of the tube, on the other hand, while much easier to extract by simple flush-through methods, was anticipated to have reduced capacity. Therefore, the absorber module tests were conducted to compare the CO_2 removal ability of both electrolyte configurations.

Figure 19 shows the results of one test with the bulk absorbent solution on the outside of the tube and process air passing through the inside. For this test the inlet pCO_2 level was 350 Pa (2.65 mm Hg). It is seen that initially the module removed all of the CO_2. This removal capability gradually decreases as indicated by the increasing outlet pCO_2 level. The steep slope of the curve (from 60 to 140 min) is a result of the absorption process changing from the OH mechanism to the surface area limiting $CO_3^=$ mechanism and does not indicate a CO_2 capacity limiting factor. After about 150 min, the outlet pCO_2 flattened out and the module continued to absorb CO_2 until the test was terminated at about six hours. The steady absorption rate is an indication of the surface area limit of the liquid phase $CO_3^=$ transport of the test module.

The results of a similar test for the absorbent solution on the inside of the tubes and process air on the outside is shown in Figure 20. Similar behavior was observed although the surface area limitation effect occurred sooner. This was caused by two factors. The test conditions were run at higher pCO_2 and flow rate than the test of Figure 19; therefore, more CO_2 had to be removed. Second, the projected effective liquid/gas interface surface area for this case is smaller than for absorbent outside of the tubes. The apparent improved performance (drop in outlet pCO_2) which occurred at 125 min is an anomaly created by an inadvertant mixing of the absorbent in the test module. This result is another indication of the liquid phase transport limit of the $CO_3^=$ absorption process since the physical mixing effectively provided additional capacity.

When the data from the absorbent tests are compared in terms of specific absorption rate and capacity, the curves shown in Figure 21 result. The line for the nominal absorption rate requirement of 0.095 kg/h (0.21 lb/h) is shown. As discussed previously, any ERC Absorber performance would have to be above the line and the farther above the line the better the residual capacity of the design. It is seen that the "absorbent-inside" test indicates better performance when based on specific absorption rate and capacity. Based on these data the design of the ERC Absorber using the HFM has the absorbent solution on the inside of the tubes. In addition to improved CO_2 removal performance, the removal of the absorbent for regeneration is greatly simplified.

TABLE 12 TEST ABSORBER MODULE CHARACTERISTICS

Number of Tubes	250
Tube Characteristics	
Total Length, cm (in)	20 (8.0)
Active Length, cm (in)	15 (6.0)
Internal Diameter, cm (in)	0.051 (0.020)
External Diameter, cm (in)	0.091 (0.036)
Material	Polysulfone
Bundle Characteristics	
Active Surface Area, m^2 (ft^2)	0.061 (0.65)
Active Volume, cm^3 (in^3)	43.4 (2.65)
Fiber Active Volume, cm^3 (in^3)	25.0 (1.52)
Absorbent Charge Volume (Outside Tubes), cm^3 (in^3)	34.0 (2.07)

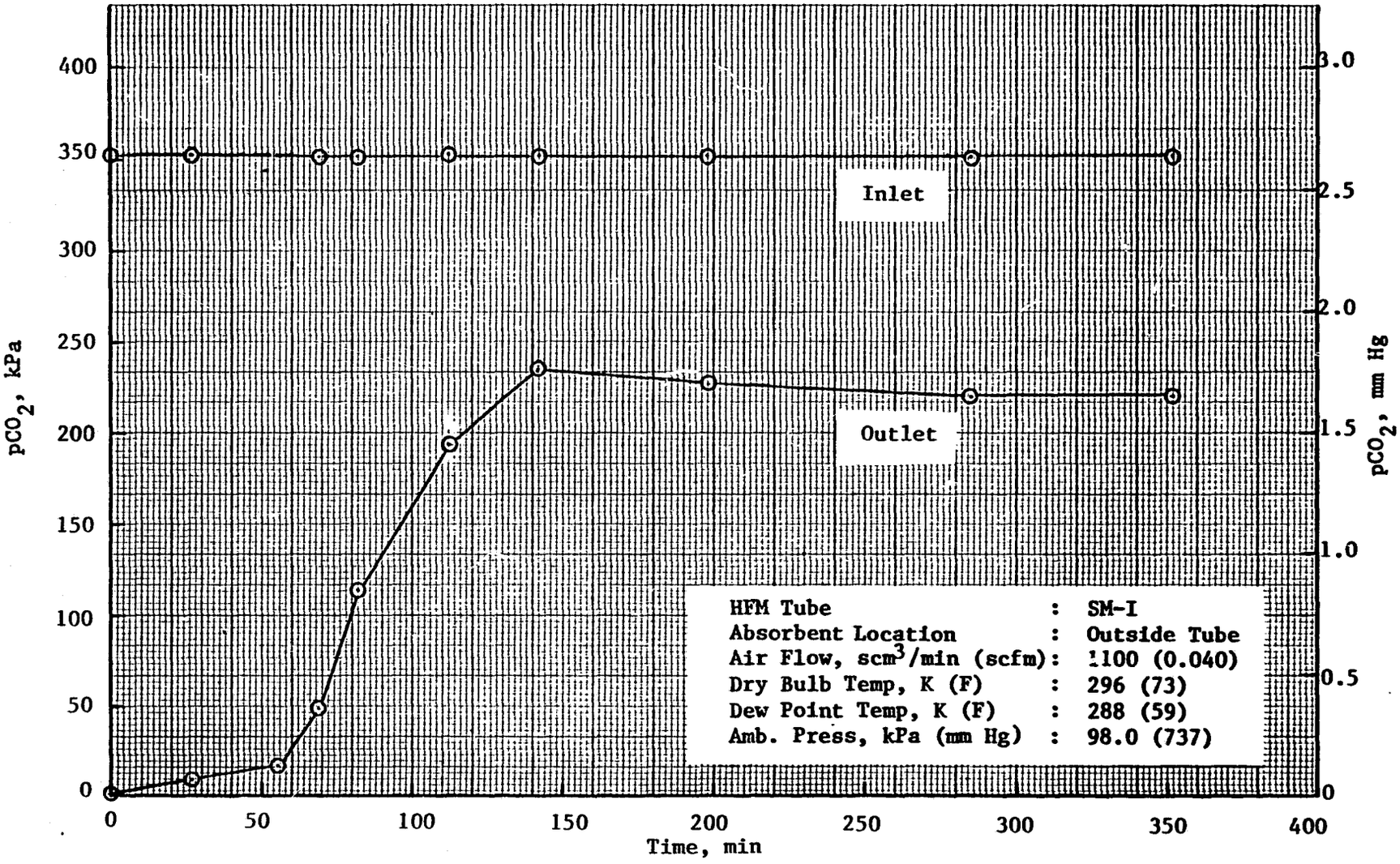


FIGURE 19 ABSORBER TEST PERFORMANCE - ABSORBENT EXTERIOR

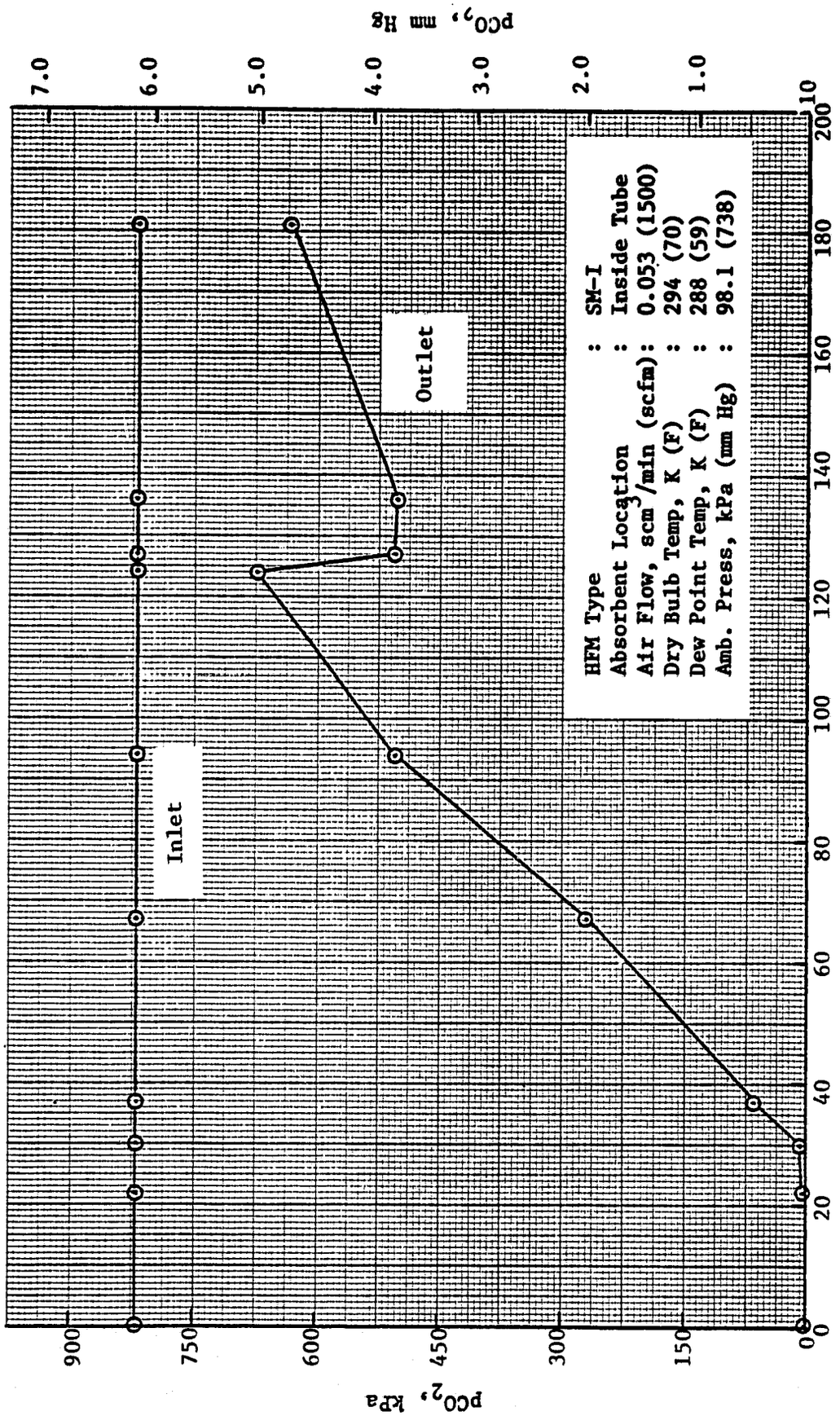


FIGURE 20 ABSORBER TEST PERFORMANCE - ABSORBENT INTERIOR

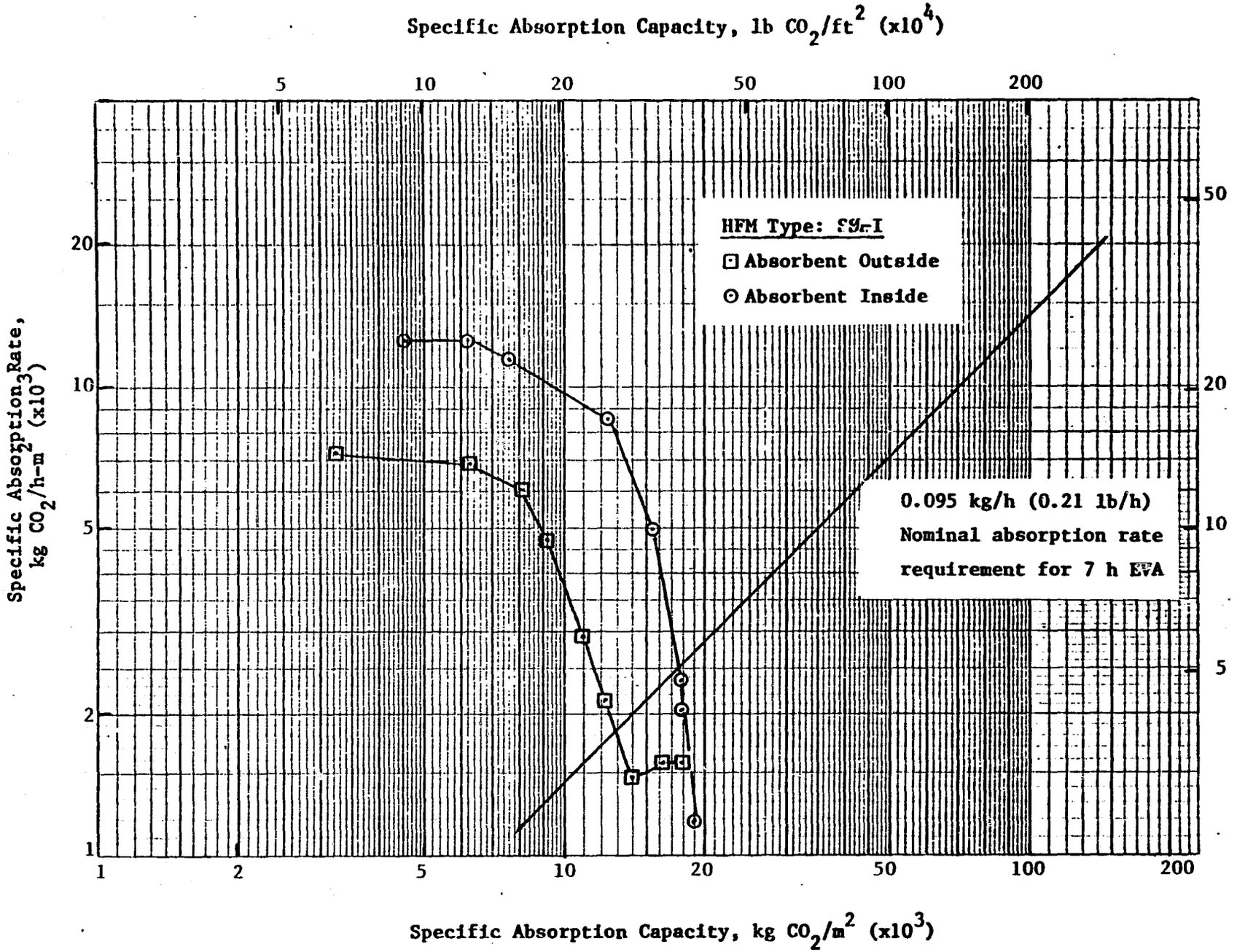


FIGURE 21 ABSORBER TEST PERFORMANCE COMPARISON

ERCAR Single Cell

A series of experimental tests were conducted with a single-cell ERCAR module to characterize the regeneration of the used absorbent in the continuous mode described above. The objective of these tests were to (1) characterize the cell in terms of its voltage versus current performance, (2) determine the effect of feed pressure and (3) characterize the regeneration efficiency and absorbent production rate as functions of time.

Test Setup and Operation

Figure 22 shows the ERCAR test setup schematic. Feed absorbent is supplied from a reservoir by feed pump (M1) to the feed plate cavity. Product absorbent is removed from the cathode side of the cell and returned to the product absorbent container. Hydrogen supplied by valve V2 to the anode passes over the anode electrode where some is consumed and the rest, with the evolved CO_2, passes to vent through a backpressure regulator (PR1). In these tests excess feed absorbent was removed from the anode cavity. Therefore, the anode exhaust line was returned to the feed absorbent container before the gas exhaust. The capability to purge the cell cavities with N_2 was provided by valve V1. Coolant was supplied to the cell from a constant temperature bath using pump M2. In this fashion the cell could be maintained at isothermal conditions. Valve V3 permitted excess feed solution to be returned to the feed absorbent vessel. Power was supplied from a constant current power supply.

The sensors for this test setup included H_2 source pressure (P1), anode-to-cathode differential pressure (P2), cell temperature (T1) and cell voltage (E1). The principal measured parameter was absorbent outlet concentration. This was determined analytically by taking samples of the cathode outlet solution at periodic intervals and chemically determining the OH^- concentration.

The baseline operating conditions for the single cell testing are shown in Table 13. These conditions were determined from prior analysis and anticipated performance levels. However during the actual testing several of these were varied over wide ranges. For instance, the current density was varied from 43 to 161 mA/cm^2 (40 to 150 ASF). Similarly, cell feed pressure difference and feed rate were also varied. Hydrogen feed flow was maintained at approximately 1.8 times the stoichiometric value. Coolant flow and cell temperature were maintained at the given values throughout the testing.

Test data was collected on basically two single cell designs, an initial baseline cell design and a modified cell design. The modified cell design had an improved feed matrix and other differences in internal cell construction. The single cell tests were conducted by setting up the appropriate conditions and operating the cell continuously over a long period of time. Because the analytical determination of the product absorbent OH^- concentration required several hours, the calculation of regeneration efficiency had to be done in a non-real time mode. Therefore samples were collected periodically and concentration measurements and regeneration efficiency calculations were made later.

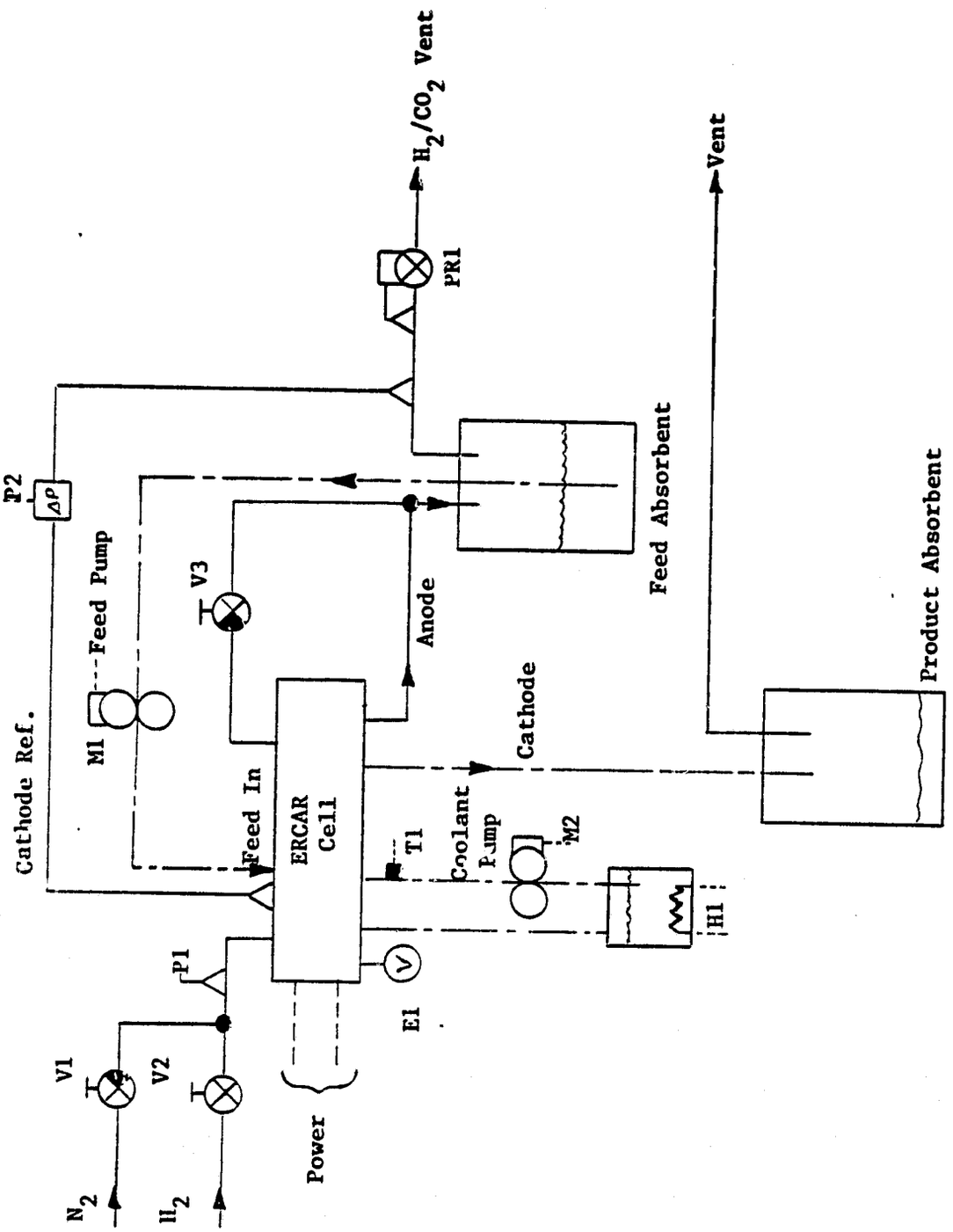


FIGURE 22 ERCAR SINGLE CELL TEST SETUP SCHEMATIC

TABLE 13 ERCAR SINGLE CELL BASELINE OPERATING CONDITIONS

Number of Cells	1
Cell Area, cm^2 (ft^2)	93 (0.1)
Current Density, mA/cm^2 (ASF)	6[illegible] (60)
Absorbent Feed Rate, cm^3/min	1.4
Anode to Cathode ΔP, kPa (psid)	21 (3.0)
H_2 Feed Flow, dm^3/min (ft^3/min)	0.09 (0.003)
Coolant Flow, cm^3/min (lb/h)	100 (13)
Cell Temperature, K (F)	322 (120)

Test Results

The principal single-cell test performance parameters were absorbent production rate, regeneration efficiency and cell voltage. The time variations of these parameters for the baseline cell is shown in Figure 23. Cell voltage, which is a measure of required power is primarily dependent on current. Higher cell voltages are generally associated with the higher current densities. However, as is shown, whenever there was a current density change the cell voltage initially increased but then fell off. The last data point (0.75 V) may be anomalous. Regeneration efficiency generally increased for increasing current densities. However, absorption production rate fell. It is actually the product of these two parameters, absorption production rate and regeneration efficiency, which signifies overall OH^- concentration in the product solution and is the important parameter. The baseline cell was operated for 530 h. Because it showed somewhat erratic performance over this time certain design alterations were incorporated into the modified cell.

The test results for the modified cell, which was run for approximately 210 h, showed much more consistent and steady behavior. A comparison of the performance of the two cells at various current densities is shown in Table 14. It is seen that at the design baseline current density of 65 mA/cm^2 (60 ASF) the product of absorption production rate and regeneration efficiency is higher for the modified cell as compared to the baseline cell. Further investigations of the ERCAR single cell technology would have the modified cell as the technology baseline.

In addition to performance over time, other parameters were investigated in the single cell testing. Figure 24 shows the cell voltage versus current density performance. The trend is typical for a power consuming electrochemical cell. Also shown is effect of cell temperature. Although the differences are not great, operation at the higher cell temperature (322 K (120 F)) showed better voltage performance. This was expected behavior. Figure 25 shows the variation of absorption production rate with anode-to-cathode pressure differential. Since the basic mechanism of operation is bulk flow through the cell matrix it would be expected that larger pressure differences would increase the bulk flow rate. This was found to be the case.

CONCLUSIONS

The following conclusions were reached as a result of the program activities:

1. Both the ERC Absorber and ERCAR module concepts are feasible for the PLSS regenerable CO_2 scrubber application based on the results of partial-scale testing.

2. A flight-level ERC Absorber configured to the current PLSS volume requirement will have an EVA stay time less than seven hours. Alternatively, a seven-hour capacity absorber would be somewhat larger than the present CCC.

3. The HFM absorber bed is the best approach to the design of an ERC Absorber based on projected sizing, performance and minimization of development risk.

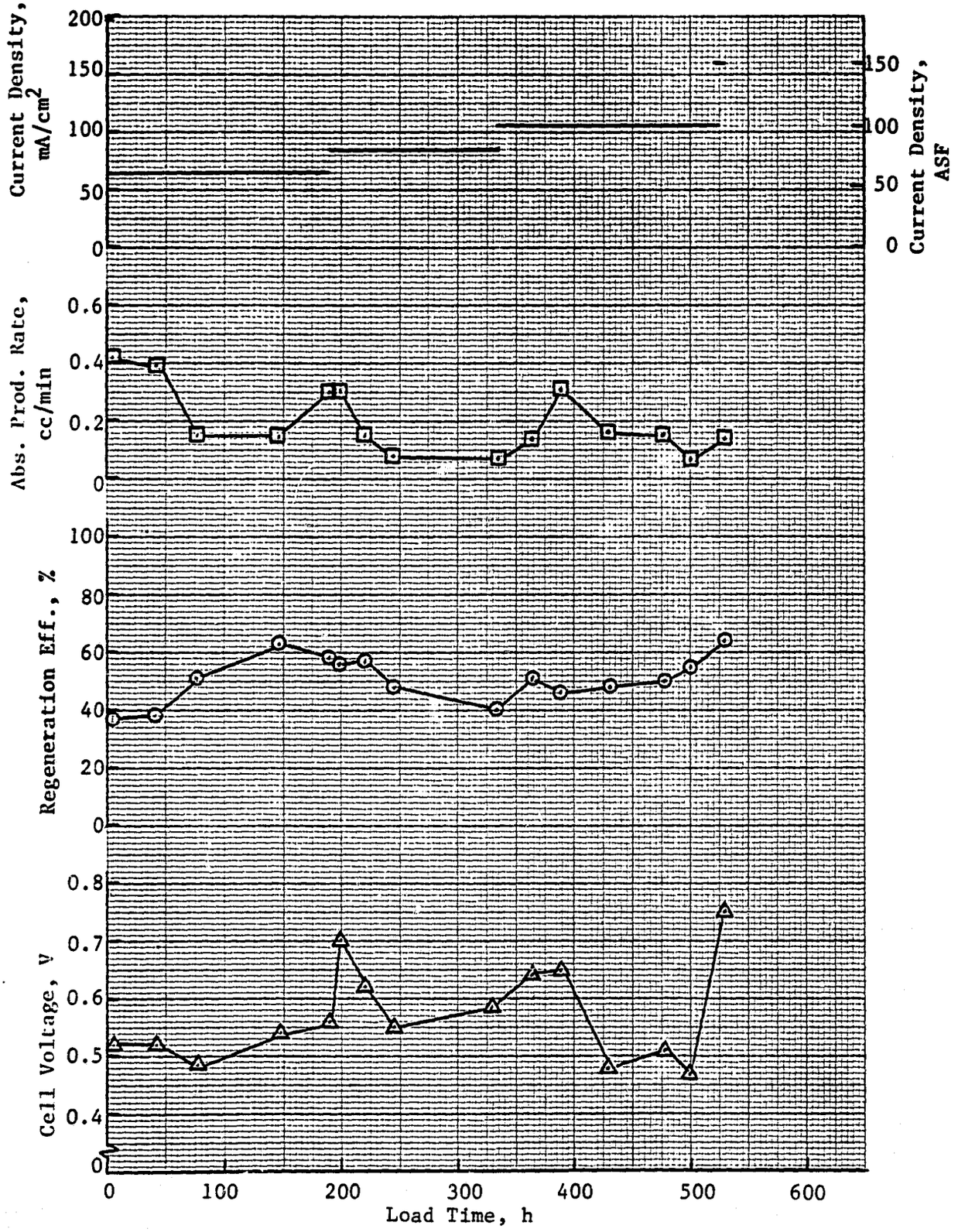


FIGURE 23 SINGLE CELL (BASELINE) TEST RESULTS

TABLE 14 SINGLE CELL ERCAR TEST SUMMARY

Current Density mA/cm^2 (ASF)	Baseline Cell			Modified Cell		
	Operating Time, h	Abs. Prod. Rate, cm^3/min	Reg. Eff., %	Operating Time, h	Abs. Prod. Rate, cm^3/min	Reg. Eff., %
43 (40)	---	---	---	83	0.20	43
65 (60)	189	0.30	40	110	0.30	63
86 (80)	146	0.18	49	6	0.18	39
108 (100)	191	0.15	52	8	0.05	91
161 (150)	4	0.14	64	---	---	---
	530			207		

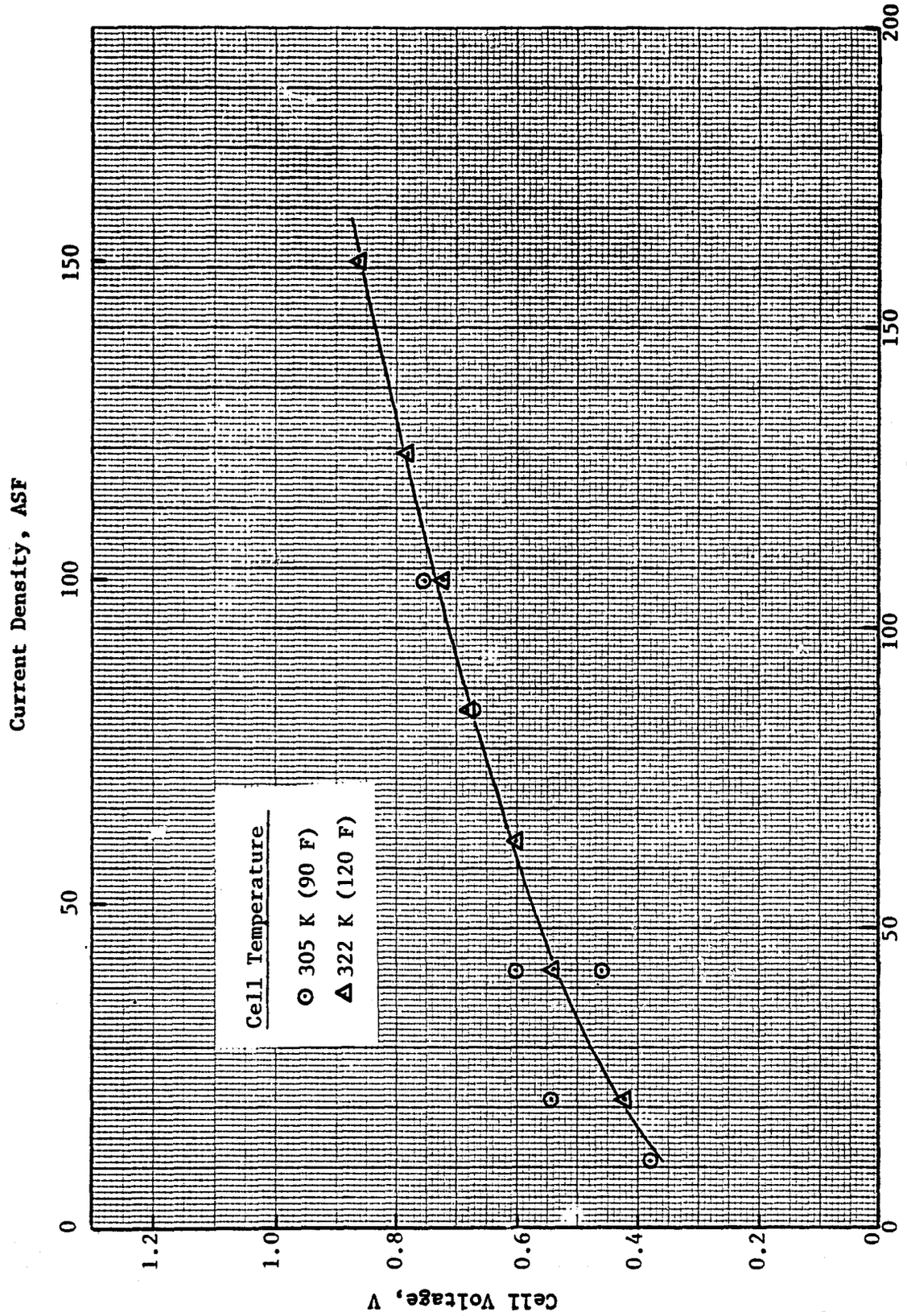


FIGURE 24 CURRENT DENSITY PERFORMANCE

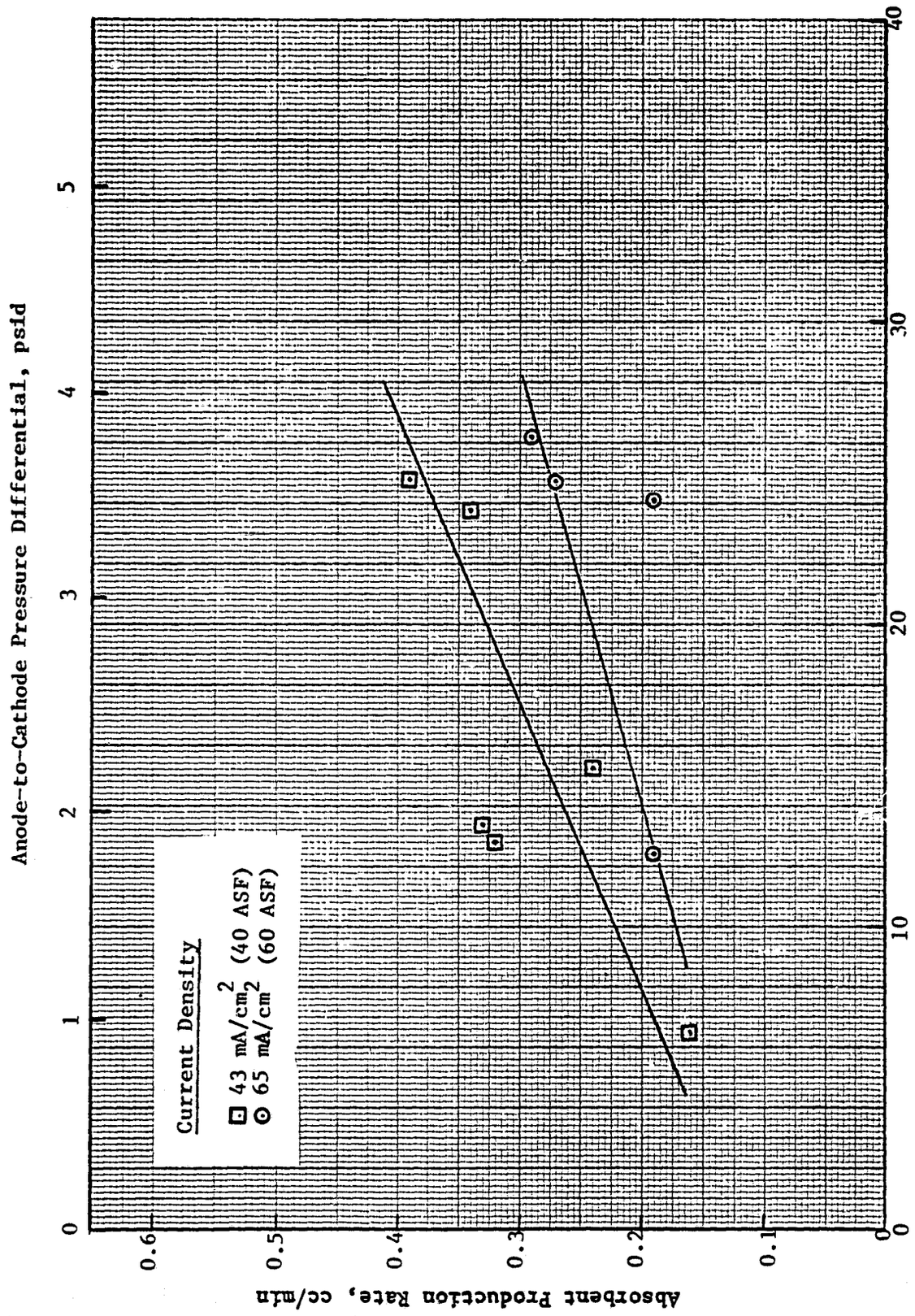


FIGURE 25 ABSORBENT PRODUCTION VERSUS DELTA P

4. Regeneration of used absorbent can be achieved with an ERCAR System based on the electrochemical cell used in the testing. Implications of scale-up and total system design must be addressed.

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 ERC Absorber at the full-scale level. This breadboard absorber would be used to acquire engineering data to fully evaluate the ERC Absorber concept.

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

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