LSI ER-237-10

INTEGRATION OF THE ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR WITH THE BOSCH CO_2 REDUCTION SUBSYSTEM

FINAL REPORT

by

F. H. Schubert, R. A. Wynveen
and T. M. Hallick

March, 1976

Prepared Under Contract No. NAS8-30891

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

GEORGE C. MARSHALL SPACE FLIGHT CENTER
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

ER-237-10

INTEGRATION OF THE ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR WITH THE BOSCH CO_2 REDUCTION SUBSYSTEM

FINAL REPORT

by

F. H. Schubert, R. A. Wynveen
and T. M. Hallick

March, 1976

Prepared Under Contract NAS8-30891

by

LIFE SYSTEMS, INC.
Cleveland, Ohio 44122

for

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812

FOREWORD

This report was prepared by Life Systems, Inc. for the National Aeronautics and Space Administration's (NASA) Marshall Space Flight Center in accordance with the requirements of Contract NAS8-30891, "Integration of the Electrochemical Depolarized CO_2 Concentrator (EDC) with the Bosch CO_2 Reduction Subsystem." The period of performance for the program was August 8, 1974 to March 22, 1976. The objective of the program was to generate the technology needed for integrating the EDC with the Bosch CO_2 Reduction Subsystem (BRS) and to demonstrate the maturity of the hardware's development for future multi-crew space missions.

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

Mr. Franz H. Schubert was Program Manager. The personnel contributing to the program and their areas of responsibility are indicated below.

Personnel	Area(s) of Responsibility
Tim M. Hallick	Program testing and data reduction
M. L. Kruszynski	Hardware fabrication, refurbishment and assembly
C. A. Lucas	Documentation
S. Mazzola	Electronics fabrication
J. J. Palagyi	Module assembly and test support
J. D. Powell	Interface and test system instrumentation design
F. H. Schubert	Integration concept definition and test results analysis
R. A. Wynveen, PhD	Subsystems integration and control concept analyses

Appreciation is expressed to Mr. David C. Clark, Technical Monitor for the NASA George C. Marshall Space Flight Center, AL 35810. Appreciation is also expressed to the NASA Ames Research Center, Moffett Field, CA 94035, for contributing the four-man EDC and its associated Ground Support Accessories and to Mr. P. D. Quattrone, Technical Monitor of the NASA Contract NAS2-6478 under which the EDC hardware was developed.

ACRONYMS

ARS	Air Revitalization System
BRS	Bosch CO_2 Reduction Subsystem
EC/LSS	Environmental Control/Life Support System
EDC	Electrochemical Depolarized Carbon Dioxide Concentrator
GSA	Ground Support Accessories
OGS	Oxygen Generation Subsystem
ORS	Oxygen Recovery System
PROM	Programmable Read Only Memory
SSP	Space Station Prototype
WES	Water Electrolysis Subsystem

TABLE OF CONTENTS

continued-

Table of Contents - continued

PAGE

continued-

Table of Contents - continued

PAGE

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Regenerative processes for the revitalization of spacecraft atmospheres are essential toward making long-term, manned space missions a reality. A major step in this revitalization process is the Oxygen Reclamation System (ORS); i.e., the collection of carbon dioxide (CO_2) and water vapor and the recovery of the oxygen (O_2) from these metabolic products.

Three life support subsystems uniquely qualified to form such an ORS are an Electrochemical CO_2 Depolarized Concentrator (EDC), a Bosch CO_2 Reduction Subsystem (BRS) and a Water Electrolysis Subsystem (WES). Various programs to develop these subsystems and their integration have been sponsored by the National Aeronautics and Space Administration (NASA). The work reported herein is on integrating the EDC with the BRS and is a portion of this overall development.

A program to develop and test the interface hardware and control concepts necessary for integrated operation of a four-man capacity EDC with a four-man capacity BRS was successfully completed. During the integrated testing, the function of the WES was simulated with Ground Support Accessories (GSA).

The control concept implemented proved successful in operating the EDC with the BRS for both constant CO_2 loading as well as variable CO_2 loading, based on a repetitive (24-hour) mission profile of the Space Station Prototype (SSP).

Existing EDC and BRS prototypes were refurbished and modified to allow for the integrated operation and the required interface hardware was developed. The latter was designed to supply a constant volumetric ratio of 2:1 of hydrogen (H_2) to CO_2 to the recirculation loop of the BRS in spite of variations in (1) crew's simulated CO_2 generation rate, (2) CO_2 removal rate by the EDC and (3) H_2 generation rates by the WES. The fixed 2:1 feed gas ratio is required to meet the stoichiometry of the chemical reaction of the Bosch CO_2 reduction process.

An extensive test program was completed consisting of:

- Subsystem familiarization and checkout tests
- A 30-day integrated system endurance test with constant CO_2 loading
- A subsystem maximum capacity test
- A 45-day integrated system endurance test with variable CO_2 loading

The 2,071 hours (86.3 days) of integrated system testing was accompanied by an additional 72 hours of nonintegrated operation on the EDC and 279 hours on the BRS.

During the integrated testing, carbon collection cartridge changeover techniques, relocation of EDC anode exhaust gas feed point in the BRS, and BRS

reactor purging techniques were modified and refined. A record total of 41 carbon collection cartridges were used with an average operating time of 57.3 hours per cartridge.

Ground Support Accessories were developed to provide for individual subsystem, as well as integrated system, operation.

No degradation in CO_2 removal efficiency or cell voltage for the EDC was observed during the testing, even though the EDC was operated at 25% above its design current density.

No reaction initiation or startup problems for any of the 41 carbon collection cartridges for the BRS were observed. At the completion of program testing a visual inspection of the interior of the copper-clad BRS reactors showed negligible signs of carbon formation on the cladding.

It is concluded the control and integration concept used to operate the EDC with a BRS is a viable solution to closure of the O_2 loop aboard manned spacecrafts.

It is recommended that ORS development be continued with the addition of a WES to the EDC and BRS used. Zero gravity compatible, water collection and distribution hardware should be developed to allow for total closure of the O_2 loop. Also, a flight-qualifiable BRS loop gas composition sensor should be developed. Successful completion of this recommended development will produce technology necessary to selecting an optimum Environmental Control and Life Support System (EC/LSS) for future manned missions in a timely manner.

PROGRAM ACCOMPLISHMENTS

Key program accomplishments were:

- EDC/BRS integration and control concepts demonstrated
- 2,071 hours (86.3 days) of integrated operation accumulated
- 2,143 hours of EDC operation at current density levels 25% above baseline demonstrated
- 41 carbon collection cartridge startups without reaction startup problems
- A programmable CO_2 partial pressure (pCO_2) controller to simulate mission profiles developed and tested
- Optimized cartridge changeover technique developed
- Automatic water collection incorporated and flight version designed
- Two computer software programs developed to calculate:
  - cabin pCO_2 levels and subsystem performance characteristics
  - gas properties in BRS recirculation loop

INTRODUCTION

Revitalization of the cabin atmosphere of a manned spacecraft is an important function of a regenerative Environmental Control/Life Support System (EC/LSS). Within an EC/LSS, various subsystems of the Air Revitalization System (ARS) are responsible for the regeneration of metabolically consumed oxygen (O_2) and the concentration and removal of the metabolically generated carbon dioxide (CO_2) from the atmosphere. For long duration manned space missions, launch and supply requirements can be materially reduced and simplified by in-flight reclamation of O_2 from the concentrated CO_2.

Three life support subsystems uniquely qualify to perform the function of reclaiming O_2 within an ARS. They are an Electrochemical Depolarized Carbon Dioxide Concentrator (EDC), a Bosch CO_2 Reduction Subsystem (BRS) and an Oxygen Generation Subsystem (OGS). Figure 1 is a block diagram of a closed O_2 loop, integrating these three subsystems with the spacecraft's atmosphere. Oxygen and hydrogen (H_2) are generated through electrolysis of water by the OGS. Carbon dioxide is stripped from the cabin atmosphere by the EDC and is sent premixed with H_2 to the BRS. The BRS reduces the CO_2 to form carbon and water. The water is returned to the OGS for subsequent regeneration of the O_2 and H_2.

Grouping these three subsystems into an integrated Oxygen Recovery System (ORS) results in total recovery of the O_2 from metabolically generated CO_2, i.e., permitting closure of the metabolic O_2 loop. This factor offers a significant advantage over the Sabatier-based CO_2 reduction concept where O_2, in the form of unreacted CO_2, is vented overboard. This means a net loss in O_2, hence an increase in spacecraft launch weight.(1)

Background

Under National Aeronautics and Space Administration (NASA) sponsored developed programs, EDC,(2-8) BRS(9-12) and OGS(13-20) technology has been developed and evaluated for application to a spacecraft's ARS. Various subsystem integration considerations have also been included as part of these activities. Such considerations must be included sufficiently early in each development to identify potential problems and to guide future subsystem design and testing.

Integration of an EDC with an OGS and/or Sabatier CO_2 reduction hardware has been investigated previously.(3,21-28) However, integration technology for an ORS based on the EDC, BRS and Water Electrolysis Subsystem (WES) processes had only been established at an analytical level.(29)

Representative state-of-the-art technology and hardware for the EDC and BRS subsystems have been advanced primarily under two separate NASA efforts. A one-man(3) and two six-man,(5,6) self-contained EDCs have been developed and experimentally characterized for NASA. Four-man capacity BRS prototype hardware has also been fabricated and tested under NASA sponsorship.(11,30)

---

(1) Numbers in parentheses are references cited at the end of this report.

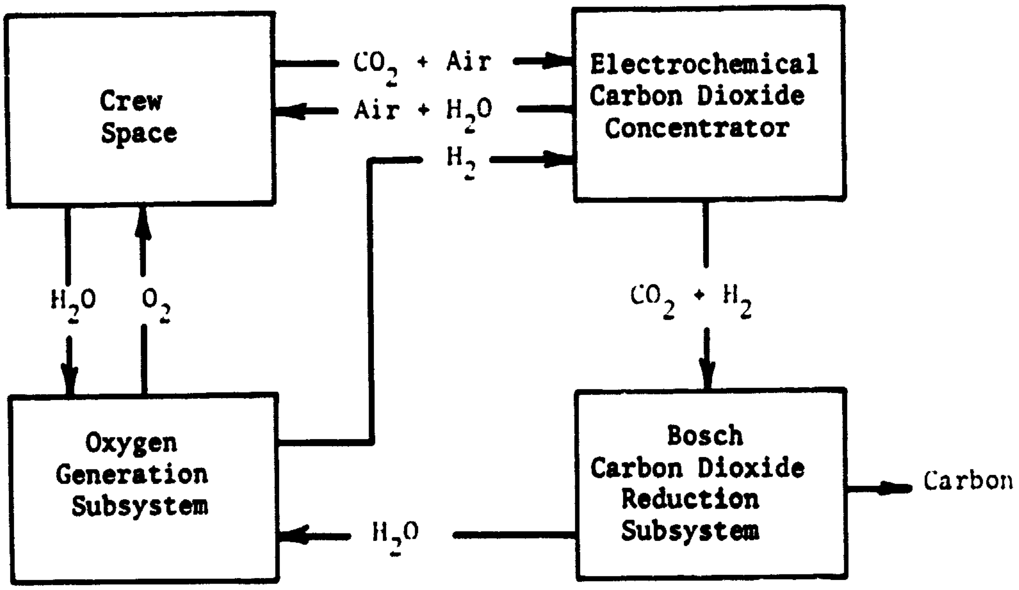


FIGURE 1 CLOSED OXYGEN LOOP WITH INTEGRATED EDC/BRS/OGS

Program Objectives

The program's primary objective was to demonstrate, through actual testing, a portion of the integration concept and controls previously derived.(29) These integration and control concepts had been established on an analytical basis for an ORS consisting of an EDC, BRS and OGS. The portion demonstrated under this program was integration of an EDC with the BRS while simulating the OGS function with Ground Support Accessories (GSA) hardware. As part of the program, refinement of the integration and control techniques were identified and demonstrated wherever possible. Demonstration of the remaining portions are recommended follow-on activities.

The integrated operation of an EDC with a BRS was performed at or near a four-man capacity level using previously developed subsystem hardware modified and refurbished to meet the integration requirements. Interface hardware and controls, as well as GSA needed to perform the program's testing, were designed, fabricated and assembled. The nature of the test program was to demonstrate the concept over a sufficiently long duration (75 days) to prove technology and operating conditions that closely simulated projected spacecraft requirements.

The objectives of the program were met.

Program Organization

To meet the above objectives, the program was divided into five tasks plus the documentation and program management functions. These five tasks were:

1. Refurbish and modify existing four-man capacity EDC and BRS subsystem hardware and design, fabricate and assemble required interface components and electronic control instrumentation to allow for fail-safe operation of the integrated system for both constant and variable CO_2 loading.

2. Design, fabricate, assemble, calibrate and functionally check out the GSA required for individual subsystem as well as integrated system operation.

3. Establish, implement and maintain a mini-Product Assurance Program through all phases of contractual performance, including design, fabrication, purchasing, assembly and testing consistent with a program in its early stages of development.

4. Complete program testing, including individual subsystem familiarization tests, subsystem maximum capacity tests, and 30- and 45-day duration endurance tests with constant and variable CO_2 loading, respectively.

5. Incorporate supporting technology studies associated with EDC/BRS integration technology advancement, including checkout of BRS startup problems, investigation of cartridge changeover techniques and consideration of improved control concepts.

The following six sections summarize the work completed and are organized to describe the subsystem hardware and operation, system integration, the GSA, product assurance activities, program testing and support activities. These six sections are followed by conclusions and recommendations based on the work performed.

SUBSYSTEM HARDWARE AND OPERATION

Electrochemical CO_2 Depolarized Concentrator

Detailed descriptions of the EDC, its theory of operation, specific hardware and performance have been discussed previously.(2-8) The following summarizes the EDC reactions, process, hardware and operation.

Reactions and Process Description

The EDC is an electrochemical method for continuously removing CO_2 from a flowing air stream. The removal takes place in an electrochemical module consisting of a series of cells. Each cell consists of two electrodes separated by a matrix containing an aqueous carbonate solution. Plates adjacent to the electrodes provide passageways for distribution of gases and electrical current.

The specific electrochemical and chemical reactions are detailed in Figure 2. The overall reaction is

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{Electrical Energy} + \text{Heat} \qquad (1)$$

Two moles of CO_2 are theoretically transferred for one mole of O_2 consumed.

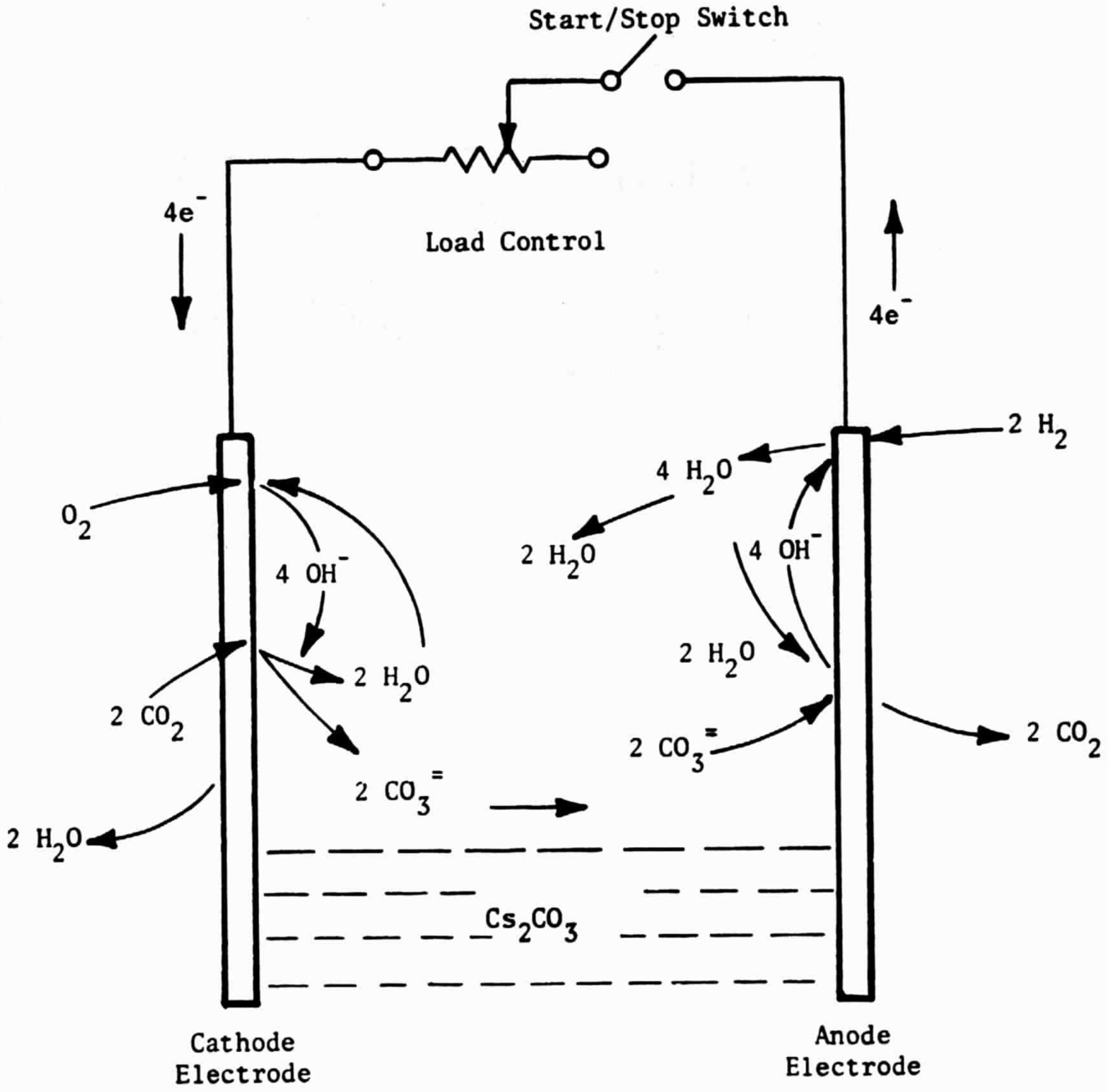
The observed ratio of CO_2 transferred to O_2 consumed represents the process removal efficiency, 100% efficiency occurs when 2.75 kg (2.75 lb) of CO_2 is removed for each kg (lb) of O_2 consumed.

Schematic and Operation

A simplified flow schematic of the EDC identifying the major components is shown in Figure 3. A blower draws air to be processed through the individual cells of the electrochemical module. The CO_2 is removed from the air while in the module and is transferred to a flowing H_2 stream.

The H_2 required by the reaction is supplied from an ARS OGS. The CO_2 is transferred from the air stream to the H_2 side of the cell and then flows, together with the excess H_2, through a backpressure regulator to the BRS.

A fan circulates cooling air over the cell's external fins to remove the waste heat from the electrochemical reaction. Subsequent modules have been developed with internal air cooling and liquid cooling.(8,27)



Cathode Reactions:

$O_2 + 2\,H_2O + 4e^- = 4\,OH^-$

$4\,OH^- + 2\,CO_2 = 2\,H_2O + 2\,CO_3^=$

Anode Reactions:

$2\,H_2 + 4\,OH^- = 4\,H_2O + 4e^-$

$2\,CO_3^= + 2\,H_2O = 4\,OH^- + 2\,CO_2$

Overall Reactions:

$O_2 + 2\,CO_2 + 2\,H_2 = 2\,CO_2 + 2\,H_2O$ + Electrical Energy + Heat

FIGURE 2 EDC FUNCTIONAL SCHEMATIC WITH REACTIONS

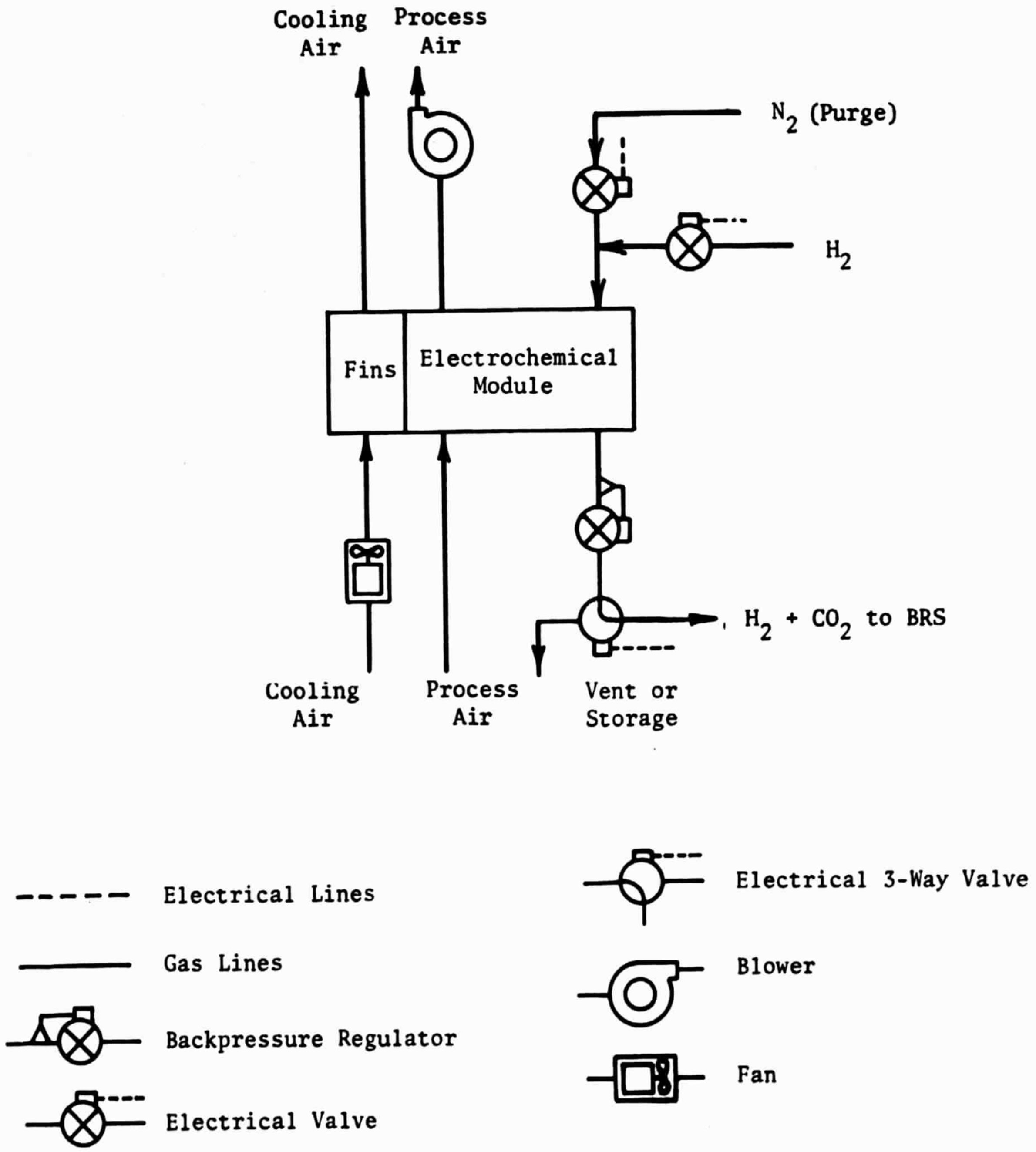


FIGURE 3 EDC FLOW SCHEMATIC

Electrochemical Module

A typical electrochemical module is shown in Figure 4.

The EDC and Its GSA Hardware

The six-man subsystem shown in Figures 5 and 6 was refurbished. In the process, 50% of the modules were removed. The remaining three modules were increased in output from a nominal three-man to a four-man capacity by operating at an increased current density.

A photograph of the EDC and its associated GSA is shown in Figure 7.

Major Subsystem Parameters

The five major EDC operating parameters affecting the CO_2 and electrical efficiencies (e.g., cell voltage) are:

1. Partial pressure of CO_2 (pCO_2) in the air supplied to the cell
2. Current density at which the cell operates
3. Air flow rate through the cathode compartment
4. Hydrogen pressure in and flow rate through the anode compartment
5. Temperature level at which the cell operates

Combining electrochemical theory with empirical data indicates these five parameters are related in the following manner:

1. Increasing the pCO_2 level in the inlet air increases the CO_2 removal efficiency, but has only a slight effect on the electrical efficiency.

2. Increasing the current density decreases both CO_2 removal and electrical efficiencies.

3. Increasing the air flow rate increases CO_2 removal efficiency and has a negligible effect on electrical efficiency.

4. Increasing the H_2 pressure and flow rate has a negligible effect on CO_2 removal efficiency and slightly increases the electrical efficiency.

5. Increasing the cell temperature has minimal effect on CO_2 removal efficiency and increases the electrical efficiency.

Preferred Operating Conditions and Interfaces

The preferred operating conditions and interfaces for the EDC are listed in Table 1. The values are shown for a four-man capacity subsystem and were considered baseline for the program.

Bosch CO_2 Reduction Subsystem

Detailed descriptions of the BRS, its theory of operation, specific hardware

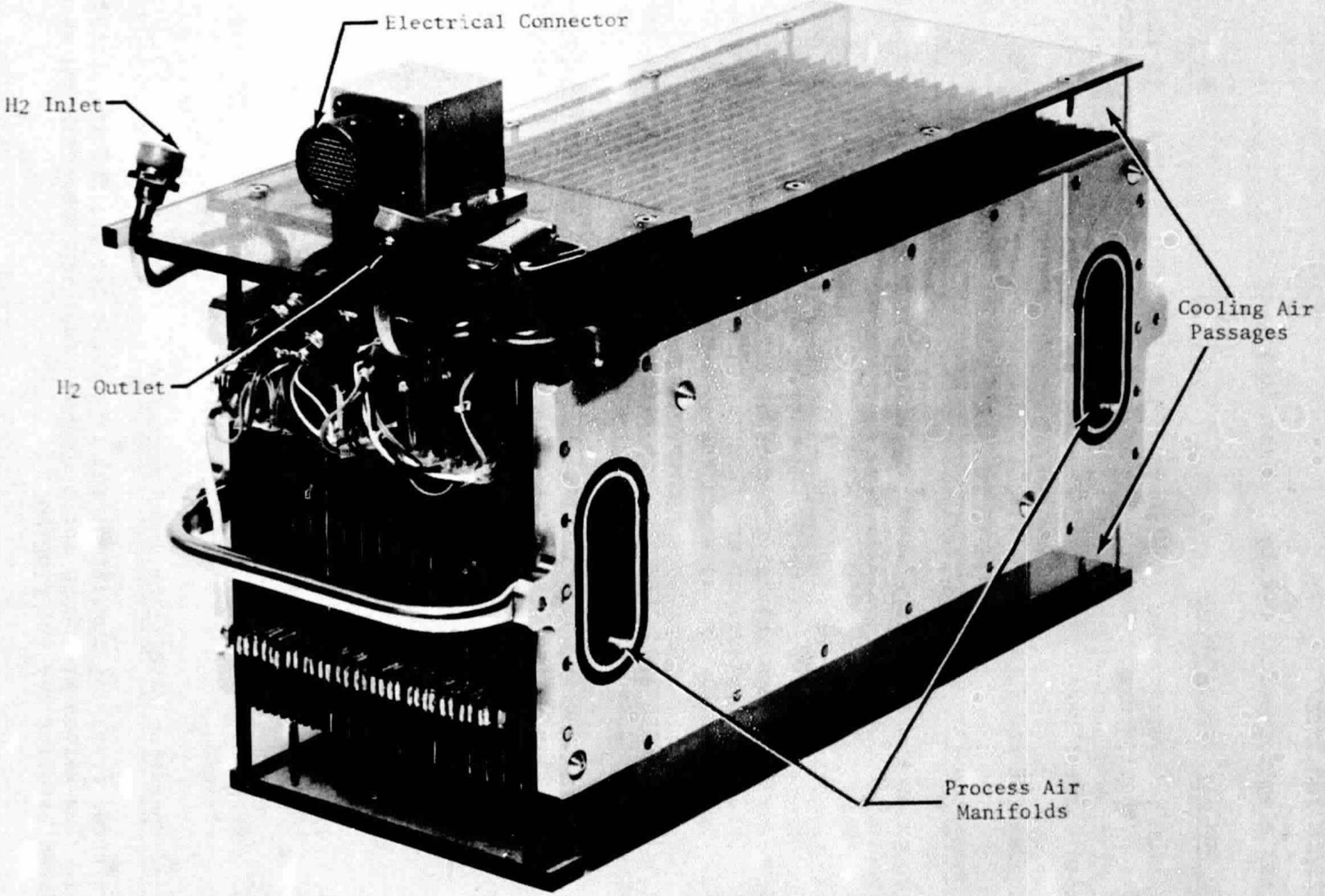


FIGURE 4 MULTI-CELL ELECTROCHEMICAL MODULE

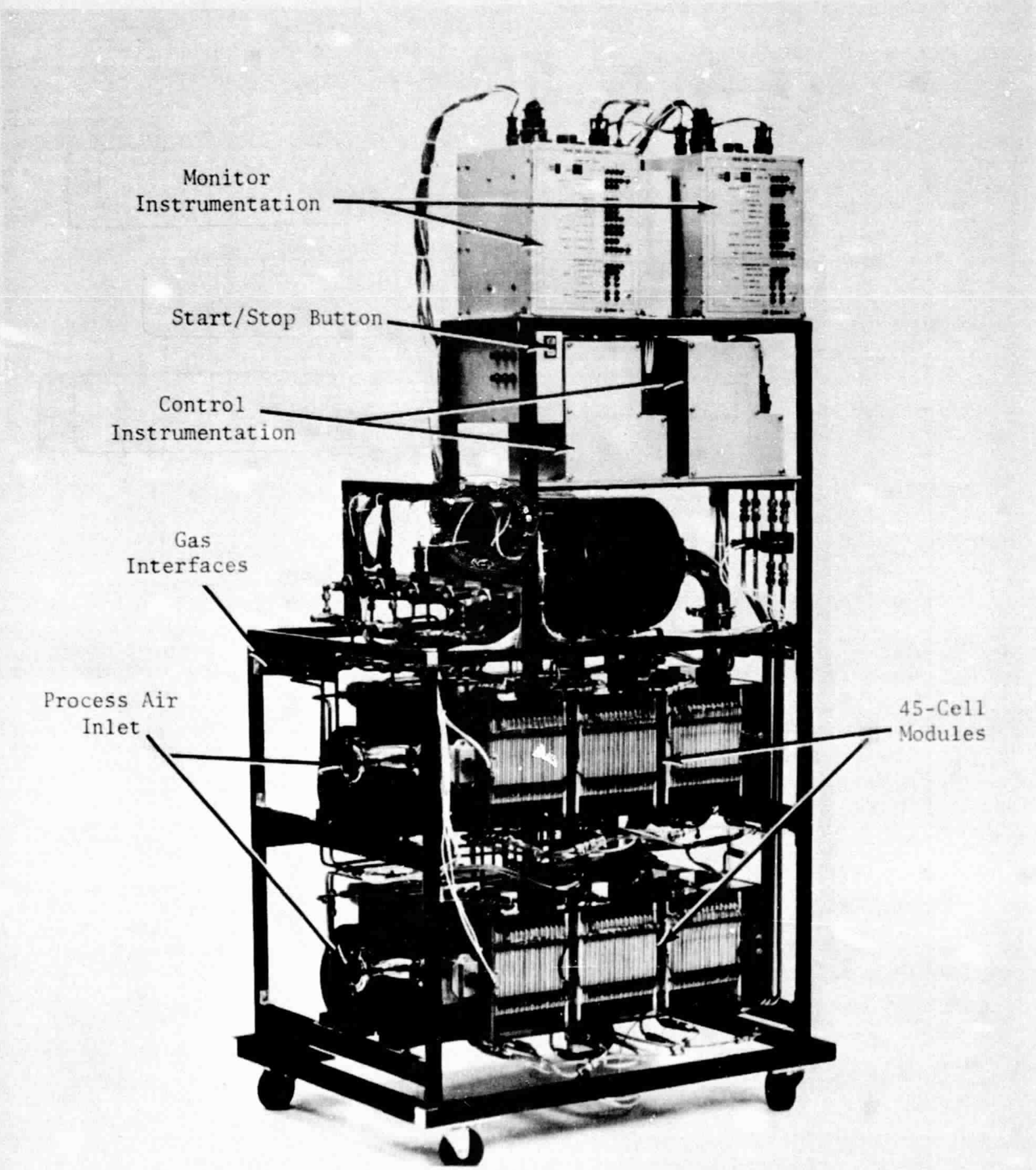


FIGURE 5 SELF-CONTAINED ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR, FRONT VIEW

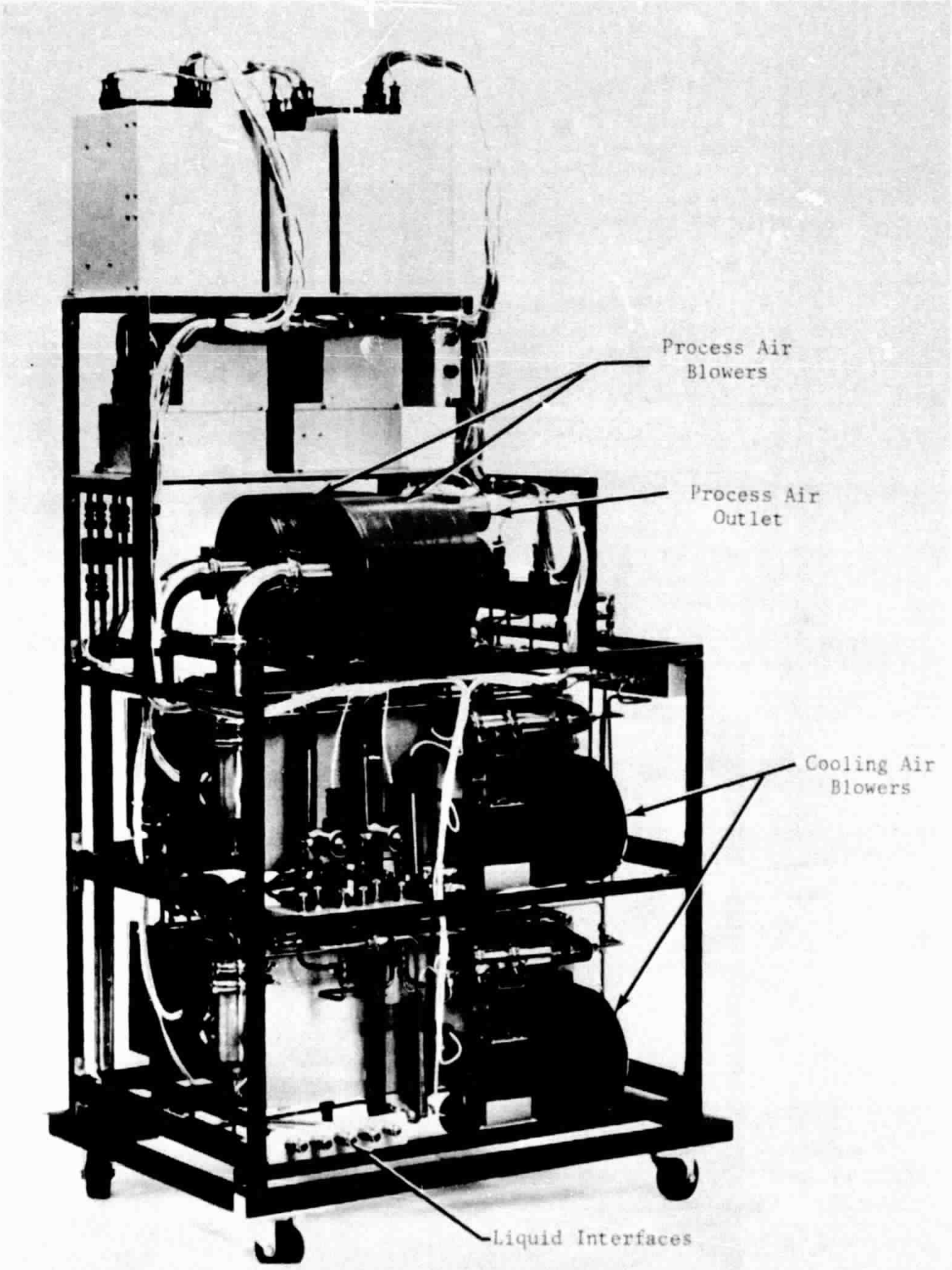


FIGURE 6 SELF-CONTAINED ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR, REAR VIEW

ORIGINAL PAGE IS OF POOR QUALITY

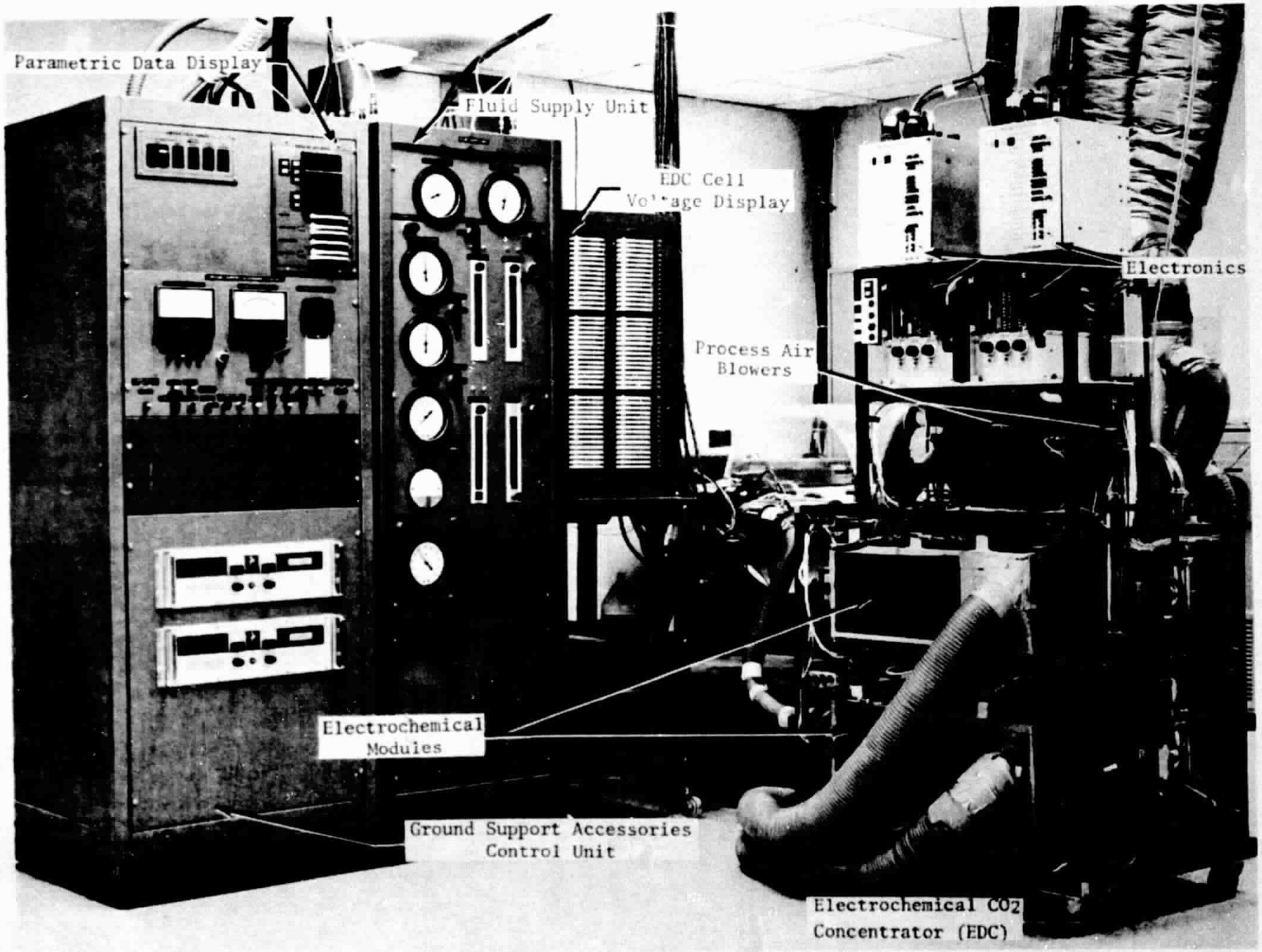


FIGURE 7 ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR WITH ASSOCIATED GSA

TABLE 1 PREFERRED OPERATING CONDITIONS AND INTERFACES FOR THE FOUR-MAN EDC

Process Air	
Inlet to EDC	
Dry Bulb Temperature, K (F)	
Design Point	Dew Pt + 3.3 (6)
Design Range	Dew Pt + 1.7 - 4.4 (3 - 8)
Humidity (Dew Point Temperature), K (F)	
Design Point	286 (55)
Design Range	284 - 287 (52 - 58)
Flow Rate	
Design Point	
kg/h (Lb/Hr)	73 (161)
l/min (Scfm)	1019 (36)
Design Range, l/min (Scfm)	755 - 1360 (27 - 48)
Pressure, kN/m^2 (Psia)	101 - 108 (14.6 - 15.7)
Gas Composition	Air
pCO_2, N/m^2 (mm Hg)	
Design Point	381 (2.86)
Design Range	240 - 400 (1.8 - 3.0)
Operating Range	0 - 2000 (0 - 15)
Exhaust from EDC	
Dry Bulb Temperature, K (F)	
Design Point, Module Exit	297 (75)
Design Point, Blower Exit	309 (96)
Control Tolerance	±0.3 (±0.5)
Humidity	
Design Point, K (F)	288 (58)
Relative Humidity, Module Out %	55
Relative Humidity, Blower Out %	28
Flow Rate	
Design Point	
kg/h (Lb/Hr)	72.9 (160.5)
l/min (Scfm)	1018 (35.9)
Design Range, l/min (Scfm)	736 - 1341 (26 - 47)

continued-

Table 1 - continued

Pressure, kN/m^2 (Psia)	101 - 108 (14.6 - 15.7)
Gas Composition	Air
pCO$_2$ at Exit, Nominal, N/m^2 (mm Hg)	200 (1.50)
Anode Gas	
Inlet to EDC (H$_2$)	
Dry Bulb Temperature, K (F)	294 (70)
Dew Point, K (F)	262 (13)
H$_2$ Flow Rate, kg/d (Lb/Day)	
Nominal	0.035 (0.077)
Minimum	0.031 (0.069)
Maximum	0.039 (0.086)
Pressure, kN/m^2 (Psia)	152 (22)
Gas Composition	H$_2$ + Water
Water Content, kg/d (Lb/Day)	
Nominal	6.05×10^{-4} (0.0013)
Minimum	5.44×10^{-4} (0.0012)
Maximum	6.65×10^{-4} (0.0015)
Exhaust from EDC	
Dry Bulb Temperature, K (F)	297 (75)
Dew Point, K (F)	285 (54)
H$_2$ Flow Rate, kg/d (Lb/Day)	
Nominal	0.024 (0.053)
Minimum	0.020 (0.045)
Maximum	0.028 (0.061)
H$_2$ Flow Rate, l/min	
Nominal	4.77
Minimum	4.05
Maximum	5.50
CO$_2$ Flow Rate, kg/d (Lb/Day)	
Nominal	0.166 (0.37)
Minimum	0.133 (0.29)
Maximum	0.186 (0.41)
CO$_2$ Flow Rate, l/min	
Nominal	1.52
Minimum	1.22
Maximum	1.69

continued-

Table 1 - continued

Water Flow Rate, kg/d (Lb/Day)	
Nominal	0.00291 (0.0064)
Minimum	0.00241 (0.0053)
Maximum	0.00331 (0.0073)
Water Flow Rate, l/min	
Nominal	0.065
Minimum	0.055
Maximum	0.074
Pressure, kN/m^2 (Psia)	138 (20)
Gas Composition	H_2 + CO_2 + Water
H_2/CO_2 Mole Ratio	
Nominal	3.14
Minimum	2.40
Maximum	4.51
CO_2/H_2 Mass Ratio	
Nominal	6.96
Minimum	4.84
Maximum	9.10

and performance have been discussed previously.(9-12) The following summarizes the BRS reactions, process, hardware and operation.

Reactions and Process Description

The Bosch reaction occurs at 800 to 1000K (980 to 1340F) in the presence of an iron catalyst. Carbon dioxide combines with H_2 and produces carbon and water vapor as indicated in the overall reaction

$$CO_2 + 2H_2 = C + 2H_2O \tag{2}$$

One mole of CO_2 combines with two moles of H_2 to form one mole of carbon and two moles of water vapor. In practice single pass efficiencies through the Bosch reactor are less than 100%. Complete conversion is obtained only by recycling the process gases with continuous deposition of carbon and removal of water vapor. The recycled gas mixture contains CO_2, H_2, carbon monoxide (CO) and methane (CH_4). The latter components are formed by intermediate reactions such as

$$CO_2 + C = 2CO \tag{3}$$

and

$$2H_2 + C = CH_4 \tag{4}$$

An equilibrium condition for the gas mixture is reached based on the specific operating temperatures, pressures and relative proportions of the primary reactants, CO_2 and H_2.

Schematic and Operation

Figure 8 is a simplified flow schematic of a BRS identifying the major subsystem components.

The BRS operates as follows. Gases are continually circulated through the recycle loop by a compressor. The gases leaving the compressor are diverted by two ganged valves to either of the two regenerative heat exchanger/reactor combinations. The gases are then preheated in the respective regenerative heat exchanger prior to entering a Bosch reactor. Within the reactor CO_2 and H_2 react over an iron catalyst in the volumetric ratio of 2:1 (H_2:CO_2) to form carbon and water vapor. The recycle gases, partially depleted in CO_2 and H_2, leave the reactor at a temperature near 922K (1200F) to exchange heat with the incoming gases in the regenerative heat exchanger. The mixture then flows through the valves to a condenser/separator where water vapor is condensed, separated and collected. The recycle loop gas mixture then returns to the compressor.

The feed gas from the EDC is added to the loop upstream of the compressor. This allows the feed gas pressure to remain at a minimum. Process rate control required due to changes in the amounts of feed gases entering the recycle loop

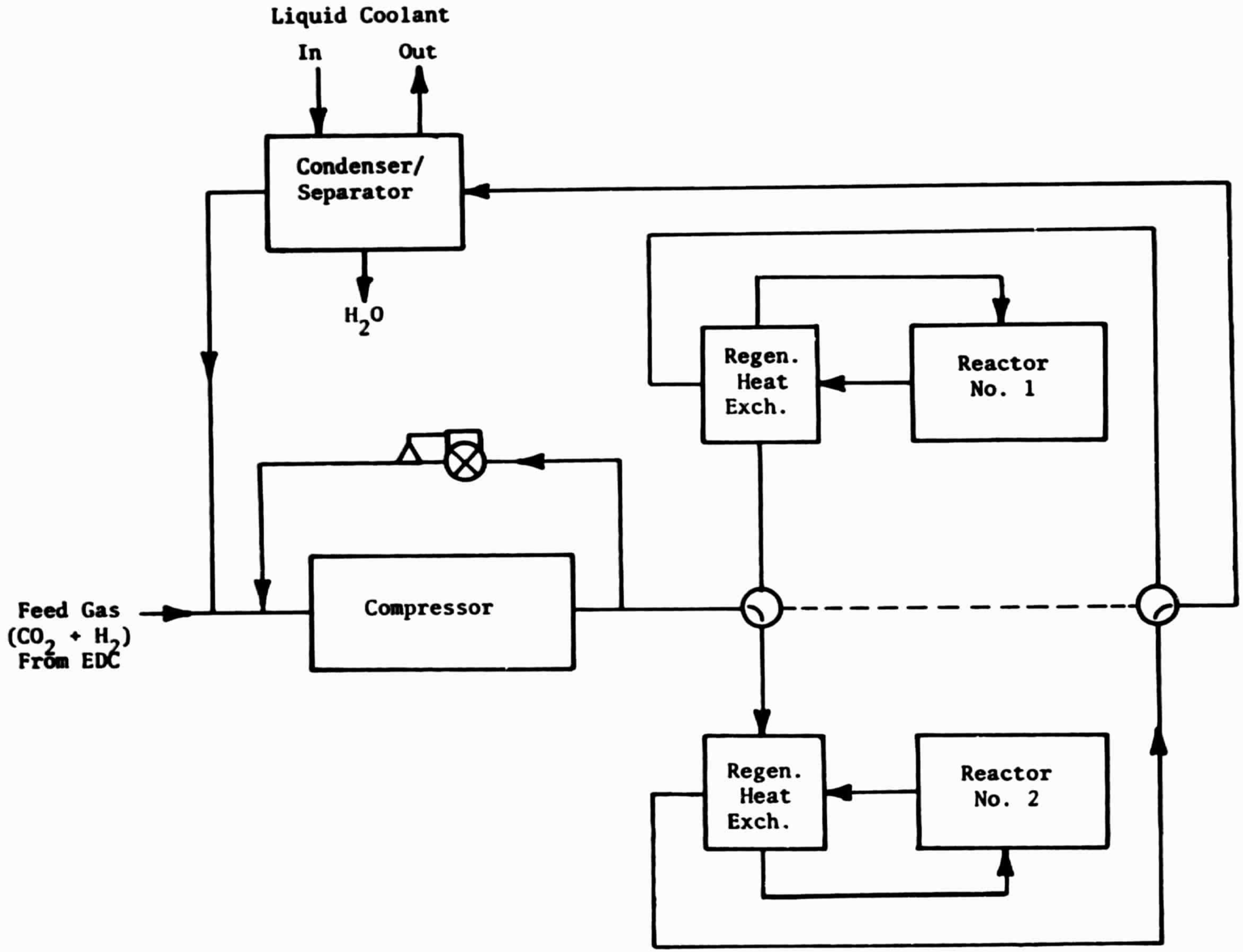


FIGURE 8 BRS SIMPLIFIED BLOCK DIAGRAM

and/or due to process rate efficiency changes within the reactor is achieved by use of the pressure regulator across the compressor.

As conversion efficiency drops or feed gas rate increases, the overall pressure level in the recycle loop tends to rise. This is resisted by the closing of the pressure regulator, thus increasing the recycle loop flow through the reactor. Conversely, a decrease in recycle loop flow will result from a decrease in feed gas flow rate and/or an increase in process reaction efficiency.

Using present-day technology, the carbon is collected in replaceable cartridges. The dual reactor system is used to enable continuous operation. It allows collection of carbon in one reactor while the other remains dormant until the first reactor is filled with carbon.

Carbon Collection Cartridge

A typical carbon collection cartridge is shown in Figure 9.

The BRS and Its GSA Hardware

The four-man subsystem shown in Figure 10 was refurbished and its gas feed control concept modified for integrated operation.

A photograph of the BRS and its associated GSA used during the integrated testing is shown in Figure 11.

Major Subsystem Parameters

The five major BRS parameters affecting process rates and CO_2 reduction efficiencies are:

1. Flow rate of the recycle gases through the reactor
2. Physical and chemical characteristics of the catalyst
3. Operating temperature of the reactor
4. Operating pressure
5. Composition of the recycle loop gases

Combining thermodynamic and chemical theory with empirical data indicates these five parameters are related in the following manner:

1. Increasing the recycle flow rate increases the process rate (conversion of CO_2 and H_2 into carbon and water).

2. Increasing catalyst surface area increases reaction rates and decreases startup time. Pretreatment of the catalyst such as degreasing and acid etch also increase reaction rate and decrease reaction startup times.

3. Operating at the higher end of the desired temperature range of 800 to 1000K (980 to 1340F) increases the process rate and vice versa.

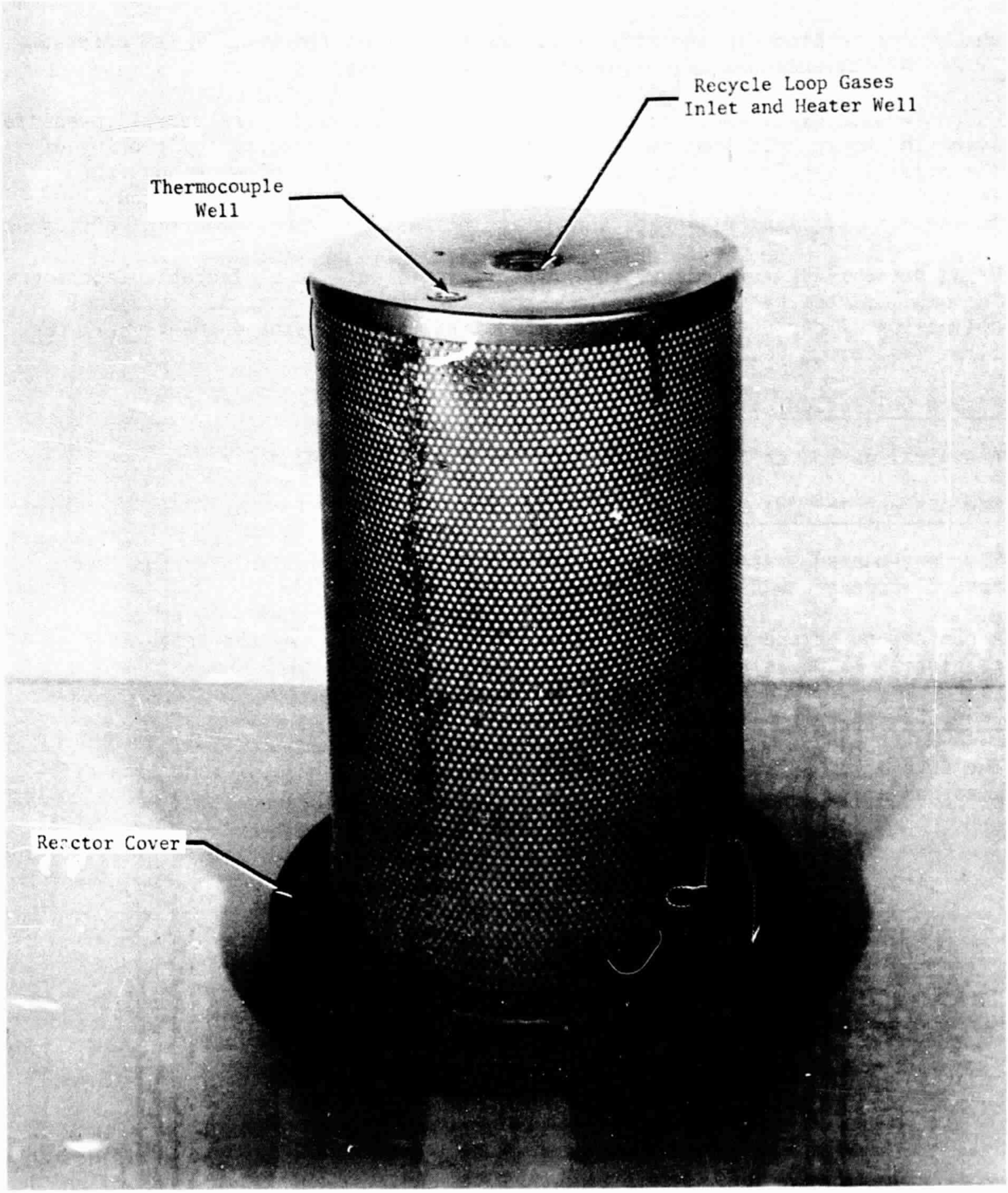


FIGURE 9 CARBON COLLECTION CARTRIDGE

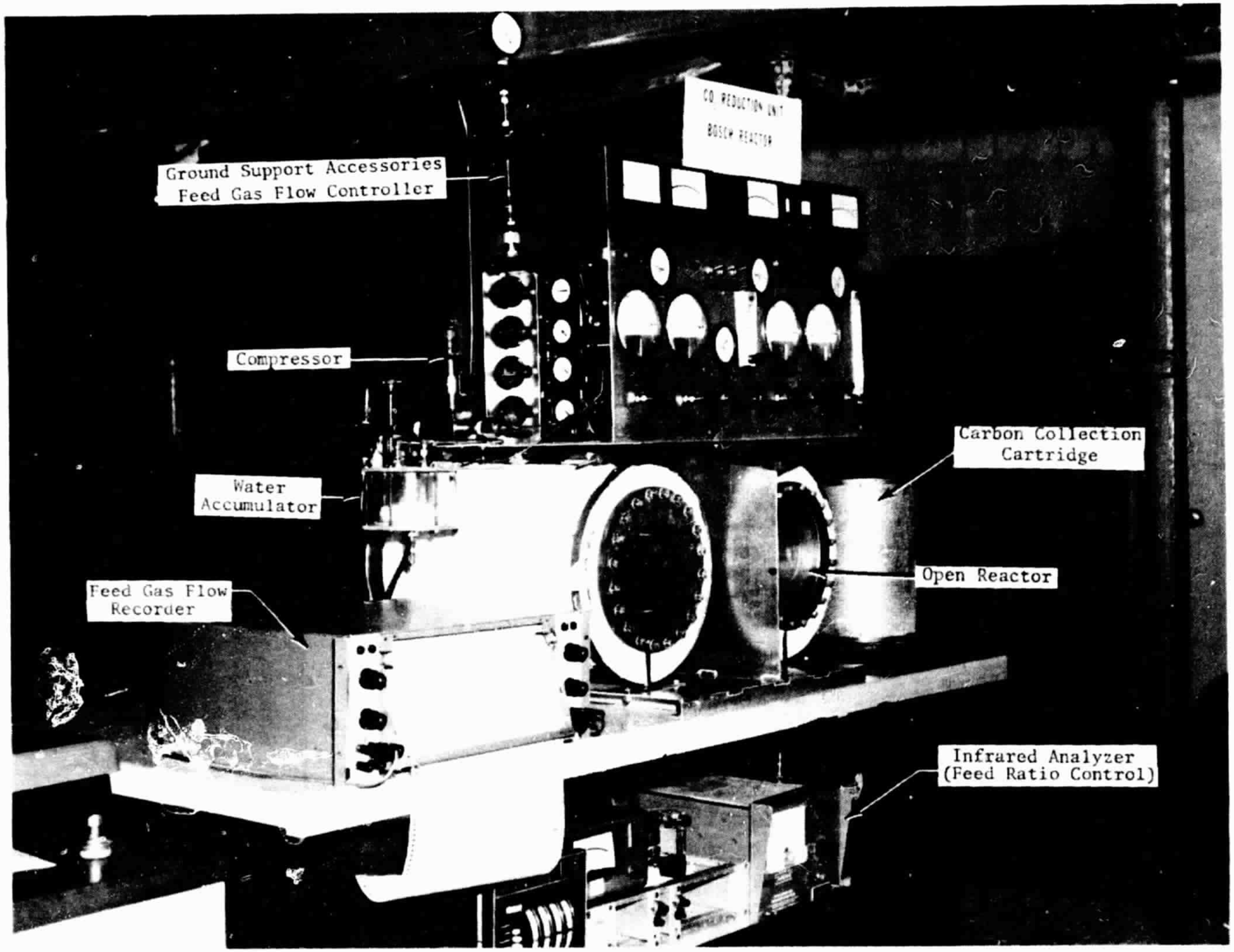


FIGURE 10 FOUR-MAN CAPACITY BOSCH CO_2 REDUCTION SUBSYSTEM

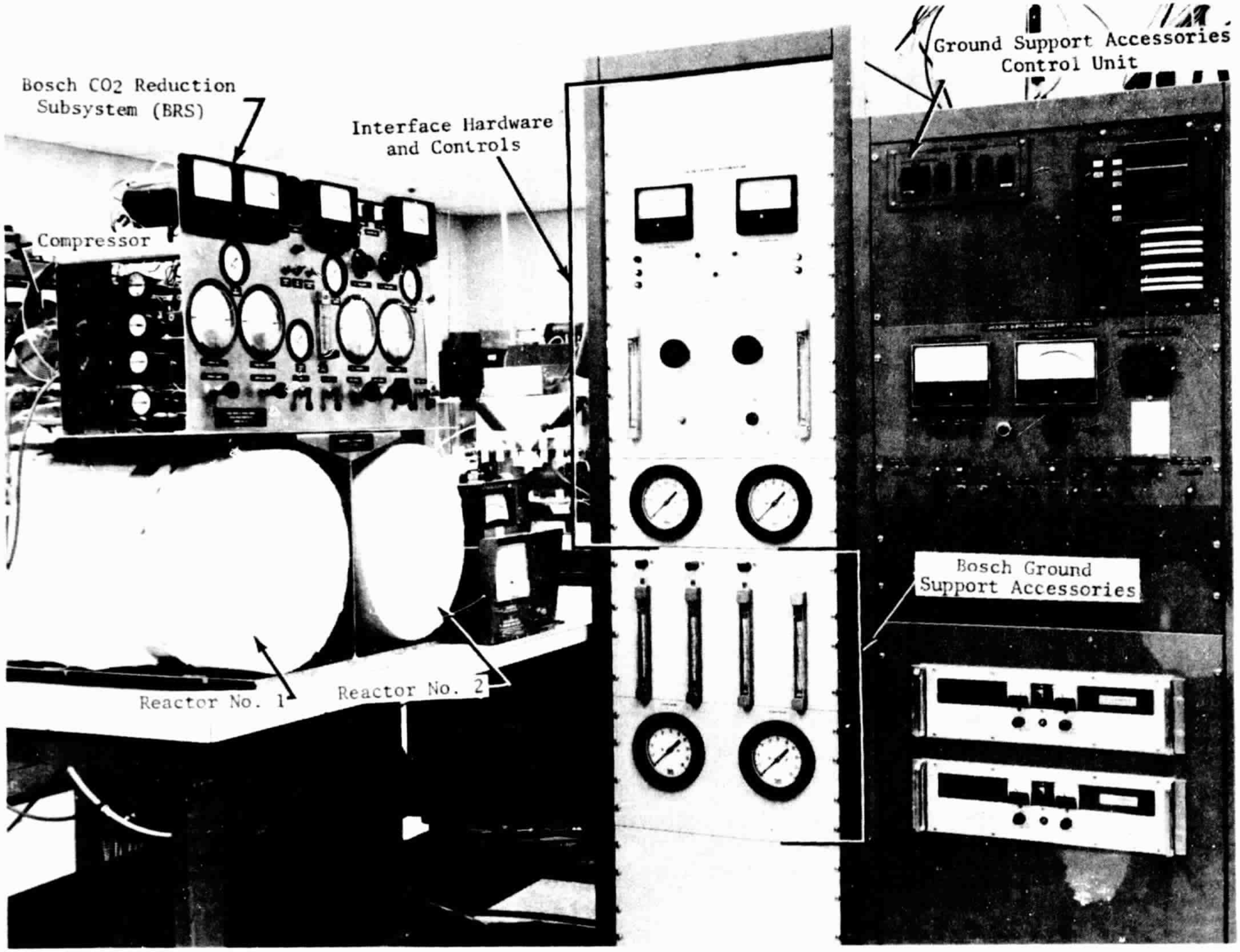


FIGURE 11 BOSCH CO_2 REDUCTION SUBSYSTEM WITH ASSOCIATED GSA

4. Reaction rate is relatively insensitive to gas pressures. Increased system pressure improves condenser performance and results in a lower content of water vapor in the recycle loop. Increased pressure, however, complicates component design, especially in high temperature components, and complicates interfacing with the EDC.

5. The composition of the recycle loop gases affect process rate; for example, increased water vapor partial pressure in the recycle loop will decrease the reaction rate. The composition reaches equilibrium corresponding to system temperatures, pressures, catalyst and flow rates.

Preferred Operating Conditions and Interfaces

The preferred operating conditions and interfaces for the BRS are listed in Table 2. The values are shown for a four-man capacity subsystem and were considered baseline for the program.

SYSTEM INTEGRATION

A major objective of the program was to operationally verify the integration philosophies and concepts developed previously.(29) The following summarizes the integration philosophies and concepts implemented and describes the resulting system schematic, operating modes, allowable mode transitions, quantified interface ranges and the integrated system's mass balance.

Guideline Integration Philosophies

- Maintain integrated system simplicity
- Maintain high system efficiencies
- Allow each subsystem to operate independent of the other subsystem
- Minimize restrictions on allowable interfaces
- Prevent interfering with a subsystem's primary function
- Avoid unproven concepts or operating conditons

Integration Concept

Variations in the composition (i.e., the ratio of H_2 to CO_2) and in the absolute flow rate of the EDC anode exhaust necessitates the addition of interface controls and hardware to allow proper integrated operation of the EDC with the BRS. These controls and hardware were sized and fabricated based on the projected variations in operating parameters and on the known stoichiometries of the subsystems.

TABLE 2 PREFERRED OPERATING CONDITIONS AND INTERFACES FOR THE FOUR-MAN BRS

Feed Gas	
CO_2 Flow Rate	
kg/h (Lb/Hr)	0.17 (0.37)
l/min (Scfm)	1.50 (0.053)
H_2 Flow Rate	
kg/h (Lb/Hr)	0.02 (0.03)
l/min (Scfm)	3.00 (0.106)
Water Vapor Flow Rate	
kg/h (Lb/Hr)	0.002 (0.006)
l/min (Scfm)	0.065 (0.0023)
Mixture Ratios	
H_2 to CO_2 by Volume	2
CO_2 to H_2 by Weight	11
Recycle Loop	
Flow Rate, kg/h (Lb/Hr)	3.08 (6.78)
Composition, Reactor Inlet, % Mole	
H_2	32
CO	27
CH_4	23
CO_2	16
Water	2
Composition, Reactor Exhaust, % Mole	
H_2	28
CO	28
CH_4	23
CO_2	14
Water	7
Feed Point Pressure, kN/m^2 (Psig)	6.9 (1.0)

continued-

Table 2 - continued

Gas Temperature, K (F)	
Reactor Out	920 (1196)
Condenser Out	290 (62)
Compressor Out	320 (116)
Reactor Pressure, kN/m^2 (Psig)	
Minimum	6.9 (1.0)
Maximum	69 (10.0)
Condenser/Separator	
Coolant	
Flow Rate, kg/h (Lb/Hr)	246 (541)
Supply Temperature, K (F)	277 (40)
Condensate, kg/h (Lb/Hr)	
Metabolic	0.14 (0.30)
EDC	0.069 (0.153)
Carbon Produced, kg/h (Lb/Hr)	0.05 (0.1)

Hydrogen/Carbon Dioxide Ratio and Flow Rate Variations

The composition and flow rate of the EDC anode exhaust are primarily determined by the O_2 consumption and CO_2 generation profiles of the crew, the operating modes adopted for the OGS and the EDC and the variations in EDC CO_2 removal efficiency with variations in cabin pCO_2.

The profiles and operating modes adopted for this program were those projected for the Space Station Prototype (SSP).(25) For this application cabin O_2 partial pressure (pO_2) was controlled by operating the OGS at ±10% of its nominal design point. This type of operation results in a repetitive cycle between minimum and maximum O_2 and H_2 generation with each cycle lasting in excess of several days.

Cabin pCO_2 was controlled by operating the EDC at a constant current level although CO_2 generation was varied as a function of time. A variation in cabin pCO_2 resulted with the maximum specified pCO_2 level maintained to less than 400 N/m^2 (3 mm Hg).

The variations in H_2 to CO_2 volumetric flow ratio and the variations in absolute CO_2 flow rate using the SSP concepts are shown in Figure 12. The lower portion of the figure shows (1) a typical CO_2 generation profile based on the sleep/work cycle for a six-man crew and (2) the CO_2 removal rate projected using a computerized solution of a math model based on the characteristics of Life Systems' EDC.(4)

The upper portion of Figure 12 shows the resulting H_2 to CO_2 volumetric ratios over the range in SSP OGS operation (either +10% or -10% of nominal O_2 requirements). The dotted line below the variable mixture ratios indicates the 2:1 volumetric ratio required by the Bosch stoichiometry. As shown, an excess of H_2 exists.

Oxygen/Hydrogen/Carbon Dioxide Mass Balance

Table 3 summarizes the $O_2/H_2/CO_2$ mass balance based on man's metabolic requirements for a regenerative life support system using a BRS, OGS and EDC. The table again shows that H_2 in excess of that required by the Bosch will always be generated. Metabolically this amounts to 0.01 kg/man-day (0.02 lb/man-day). Actually, the excess of H_2 is even larger (see Figure 12) due to the added O_2 needed to offset cabin leakage and other on-board needs for O_2.

BRS Feed Gas Composition Control

A control concept had been previously derived allowing integrated OGS, EDC and BRS operation under projected varying H_2 generation and CO_2 removal rates.(29) Figure 13 is a block diagram and flow schematic showing the major components required to implement it.

Pressure regulator PR-1 maintains a constant upstream H_2 pressure from the OGS resulting in a constant H_2 flow rate to the EDC as controlled by flow restrictor

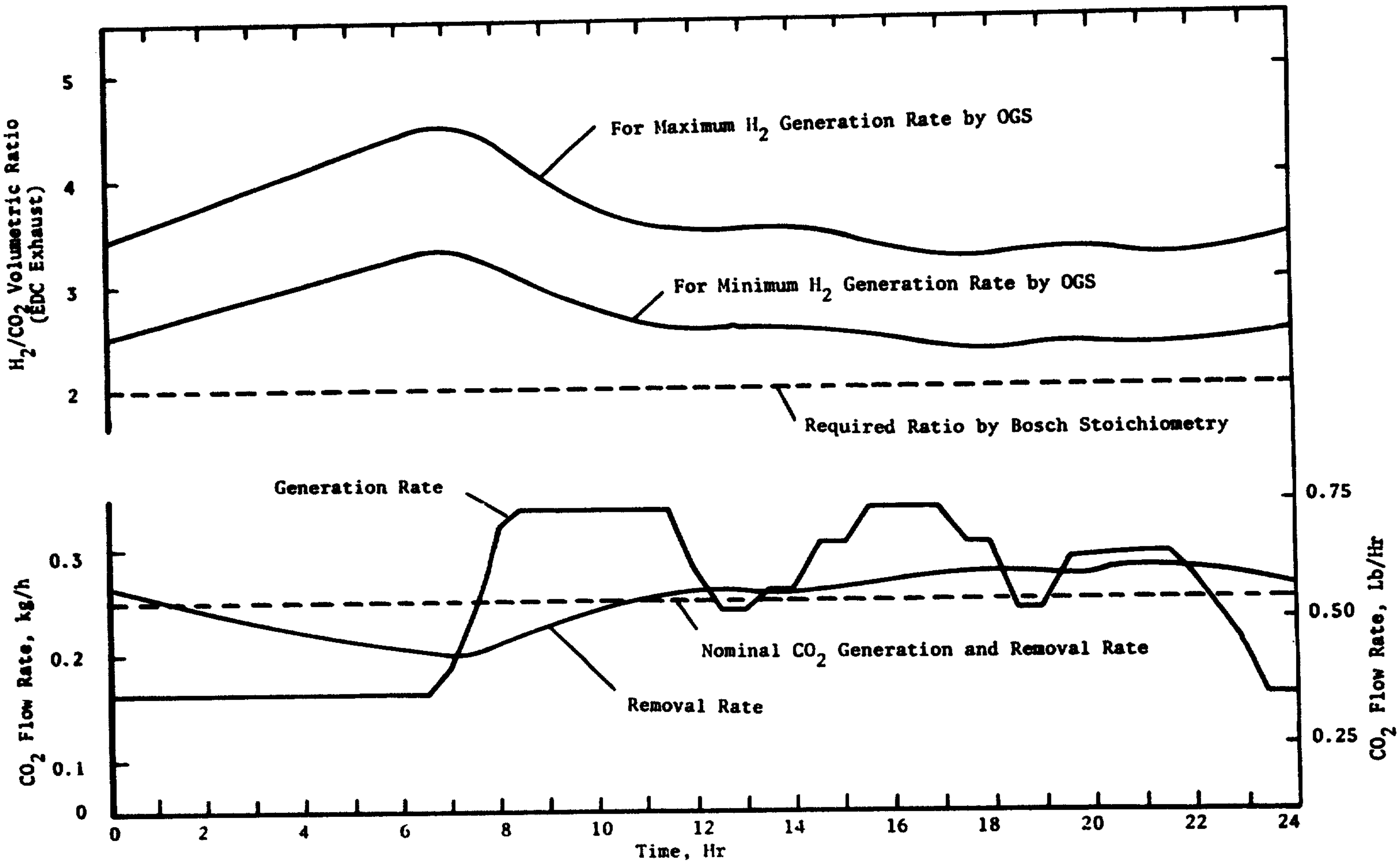


FIGURE 12 VARIATIONS IN H_2 TO CO_2 RATIOS AND CO_2 GENERATION AND REMOVAL RATES FOR A 24-HOUR PERIOD

TABLE 3 $O_2/H_2/CO_2$ METABOLIC MASS BALANCE

For an O_2 generation rate through water electrolysis of 0.84 kg/man-day (1.84 lb/man-day):

$$2H_2O = 2H_2 + O_2$$

36 = 4 + 32 mass ratio
0.94 = 0.10 + 0.84 kg/man-day
(2.06 = 0.22 + 1.84 lb/man-day)

For a CO_2 generation rate of 1 kg/man-day (2.20 lb/man-day) and using the Bosch reduction process:

$$CO_2 + 2H_2 = C + 2H_2O$$

44 + 4 = 12 + 36 mass ratio
1.00 + 0.09 = 0.27 + 0.82 kg/man-day
(2.20 + 0.20 = 0.60 + 1.80 lb/man-day)

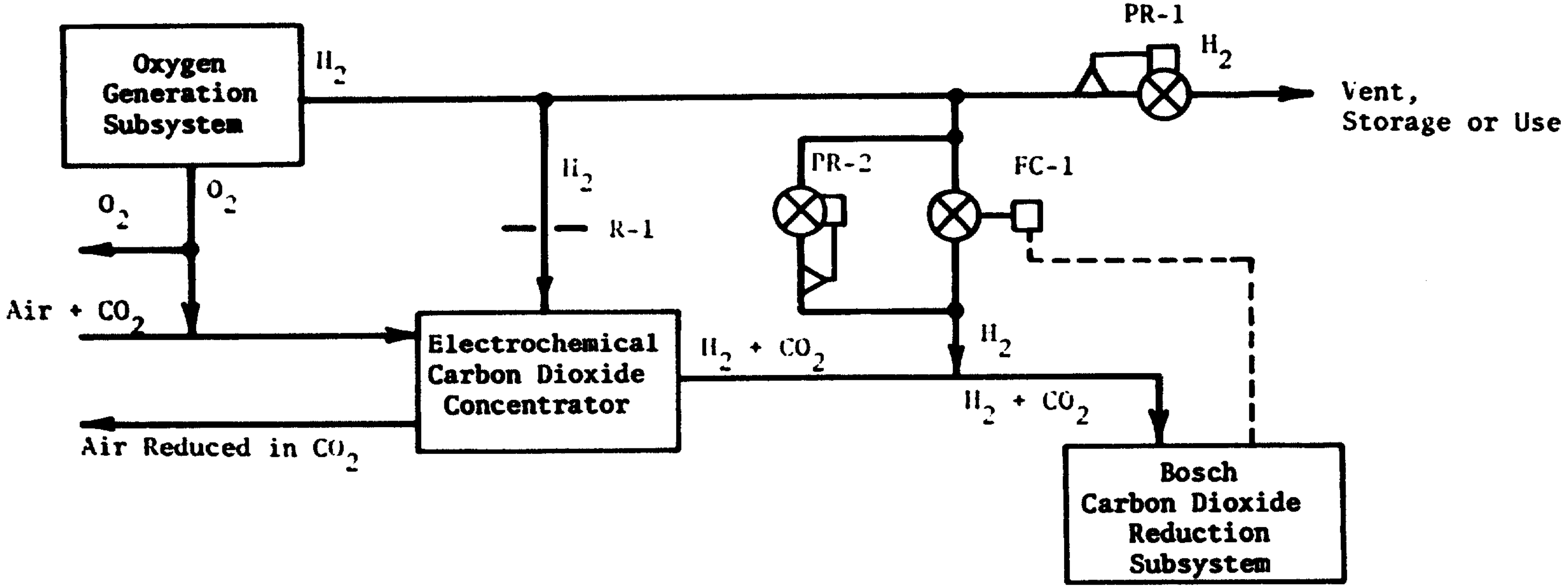


FIGURE 13 INTEGRATION SCHEMATIC FOR AN EDC, BRS AND OGS

R-1. This flow restrictor is fixed in size and has a capacity to supply a constant flow of H_2 to the EDC sufficient to satisfy the stoichiometric requirements of the EDC but always less than that required for the H_2 to CO_2 ratio of the EDC anode exhaust gas to reach a level of 2:1. Thus, H_2 must always be added to the BRS feed gas through FC1 as sensed by a BRS recycle loop gas composition sensor.

Pressure regulator PR-2 prevents the BRS recycle loop pressure from going subatmospheric by adding H_2 to the loop to throttle CO_2 and H_2 conversion efficiencies at low CO_2 feed rates and/or when minimum recycle loop flow rates have been reached.

Pressure regulator PR-1 is sized to maintain a critical pressure ratio across flow restrictor R-1. By maintaining this ratio above the critical level, choked flow, insensitive to changes in the EDC H_2 + CO_2 pressure drop through the modules, will result and will keep the flow through R1 essentially constant.

Bosch Feed Gas Source Definition

The BRS receives feed gas directly from the exhaust of the EDC and additional H_2 from the interface hardware as controlled by a loop composition signal from the BRS. A general expression for the EDC anode gas in terms of pertinent operating parameters can be derived independent of system size. Table 4 summarizes this expression and defines the source of the additional H_2 needed. Note that the value for N must always be selected such that $(N-1)/\eta$ is equal to or less than two for all anticipated values for η.

Based on past operating experiences with EDCs, a minimum value for N of 1.2 is required for satisfactory EDC operation. Substituting this value of 1.2 for N in the expression shown in Table 4 results in a minimum allowable EDC CO_2 removal efficiency of $\eta = 0.1$. This value for CO_2 removal efficiency is well below the expected ranges for the EDC.

Projected EDC/BRS Interface Ranges

The expected ranges in flow rate and gas composition of the EDC anode exhaust and the H_2 makeup flow can be calculated based on the expression derived for quantifying the EDC/BRS interface (see Table 4). Table 5 presents the results of the calculation and the performance characteristics used to derive these results. The operating conditions in Table 5 were used for both the 30- and 45-day tests.

Integrated System Mass Balance

The mass balance shown in Figure 14 and Table 6 was prepared for the integrated EDC/BRS. These values were used in sizing of the interface and GSA components and in preparation of operating conditions for the subsystems.

Integrated System Schematic

Figure 15 is a simplified integrated system schematic emphasizing the interface

TABLE 4 BOSCH FEED GAS SOURCES

Bosch/EDC Interface

$$\frac{H_2 \text{ to Bosch}}{CO_2 \text{ to Bosch}} = \frac{(H_2 \text{ to EDC}) - (H_2 \text{ used in EDC})}{CO_2 \text{ Transferred}} = \frac{NS-1S}{\eta S} = \frac{N-1}{\eta}$$

where:

N = Number of times stoichiometric flow of H_2 to EDC

S = Stoichiometric flow of H_2 to EDC

η = EDC CO_2 removal efficiency

and

$\frac{N-1}{\eta}$ must be <2 for all η values

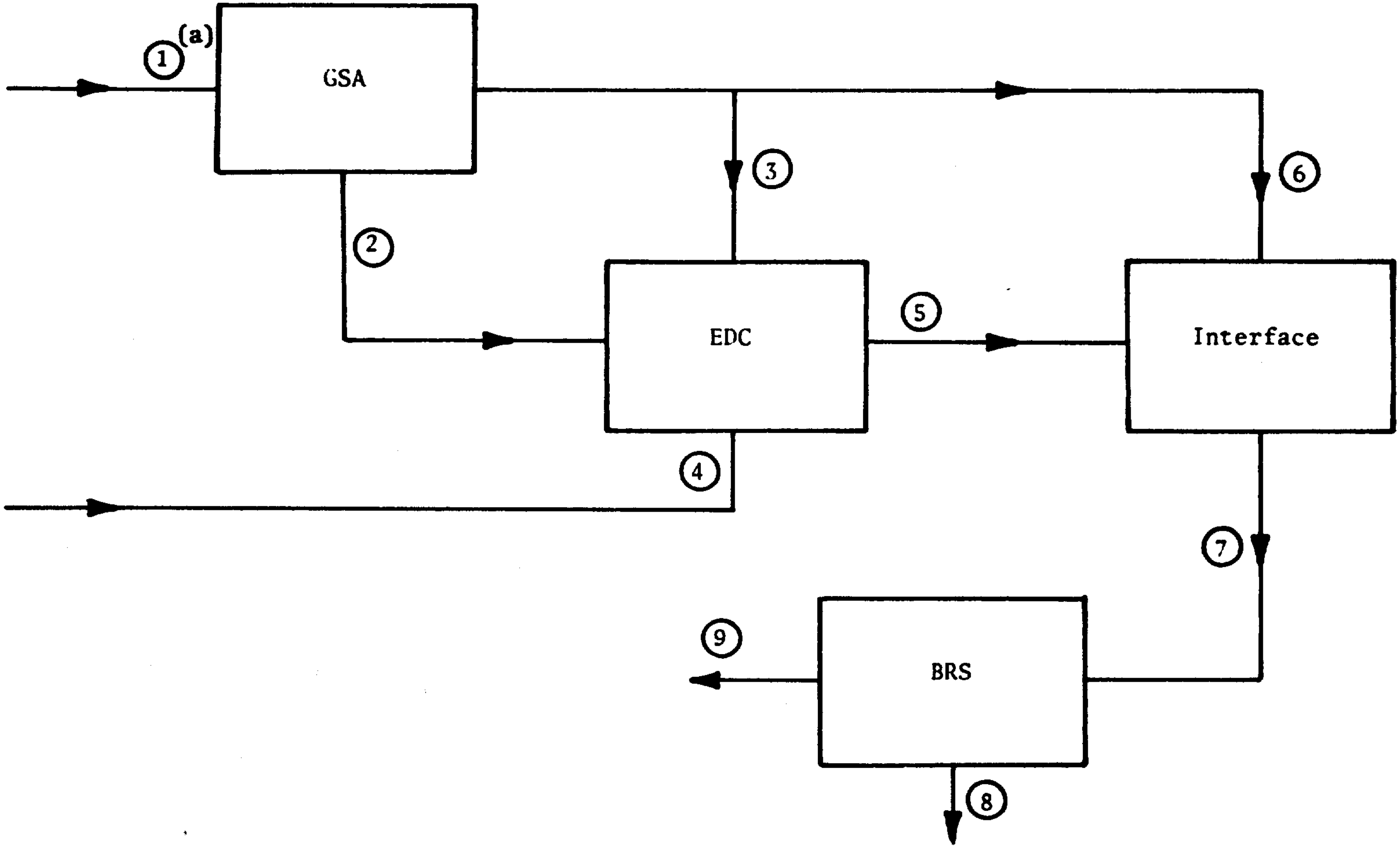
Bosch/Hydrogen Interface

Variable H_2 flow controlled by sensor in Bosch recirculation loop to maintain required gas composition

TABLE 5 PROJECTED EDC/BRS INTERFACE RANGES

	CO_2 Removal	
	Nominal[a]	Variable[b]
Feed Point Pressure, kN/m^2 (Psia)	110 (16)	110 (16)
Pressure Upstream of PR-1, kN/m^2 (Psia)	210 (30.4)	210 (30.4)
R-1 Critical Pressure Ratio	1.9	1.9
Cabin pCO_2, N/m^2 (mm Hg)[c]	400 (3.0)	239-397 (1.79-2.98)
EDC Current Density, mA/cm^2 (ASF)	30 (28)	30 (28)
Range in EDC CO_2 Removal Efficiency		
Percent	65.4	47.0-65.4
TI, kg CO_2/kg O_2 (Lb CO_2/Lb O_2)	1.8	1.3-1.8
Max. Stoichiometric H_2 Flow to EDC (N)	2.31	1.94
Stoichiometric Flow Selected	1.8	1.8
Volumetric Ratio of H_2:CO_2 in EDC Exhaust	1.22	1.22-1.70
CO_2 Flow Rate from EDC, cm^3/min	1517	1089-1517
H_2 Flow Rate from EDC, cm^3/min	1854	1854
H_2 Flow through FC-1, cm^3/min	1180	324-1180

(a) For constant CO_2 loading of 4.0 kg/Day (8.8 Lb/Day) - used in 30-day test.
(b) For variable CO_2 loading based on SSP mission profile - used in 45-day test.
(c) Based on data presented in Figure 12.



(a) See Table 6 for values.

FIGURE 14 INTEGRATED EDC/BRS MASS BALANCE

TABLE 6 INTEGRATED EDC/BRS MASS BALANCE

1.	Air	
	kg/h (lb/Hr)	55 (121.5)
	Slpm	764.5
2.	Air + CO_2 + Water	
	pCO_2, N/m^2 (mm Hg)	240 - 400 (1.8 - 3.0)
	pH_2O, N/m^2 (mm Hg)	2067 (15.5)
	pAir	Balance
3.	H_2	
	kg/h (Lb/Hr)	0.021 (0.046)
	Slpm	4.172
4.	Air + CO_2 + Water	
	pCO_2, N/m^2 (mm Hg)	200 (1.5)
	pH_2O, N/m^2 (mm Hg)	1400 (10.5)
	pAir	Balance
5.	H_2 + CO_2 + Water	
	H_2	
	kg/h (Lb/Hr)	0.0095 (0.021)
	Slpm	1.854
	CO_2	
	kg/h (Lb/Hr)	0.119 - 0.166 (0.262 - 0.365)
	Slpm	1.089 - 1.517
	Water	
	kg/h (Lb/Hr)	0.0029 (0.0064)
	Slpm	0.065
6.	H_2	
	kg/h (Lb/Hr)	0.0016 - 0.0063 (0.0036 - 0.0138)
	Slpm	0.324 - 1.180
7.	H_2 + CO_2 + Water	
	H_2	
	kg/h (Lb/Hr)	0.0104 - 0.0150 (0.023 - 0.033)
	Slpm	2.178 - 3.034

continued-

Table 6 - continued

CO_2	
kg/h (Lb/Hr)	0.119 - 0.166 (0.262 - 0.365)
Slpm	1.089 - 1.517
Water	
kg/h (Lb/Hr)	0.0029 (0.0064)
Slpm	0.065
8. Carbon, kg/h (Lb/Hr)	0.045 (0.1)
9. Water	
kg/h (Lb/Hr)	0.139 (0.307)
Slpm	0.0023

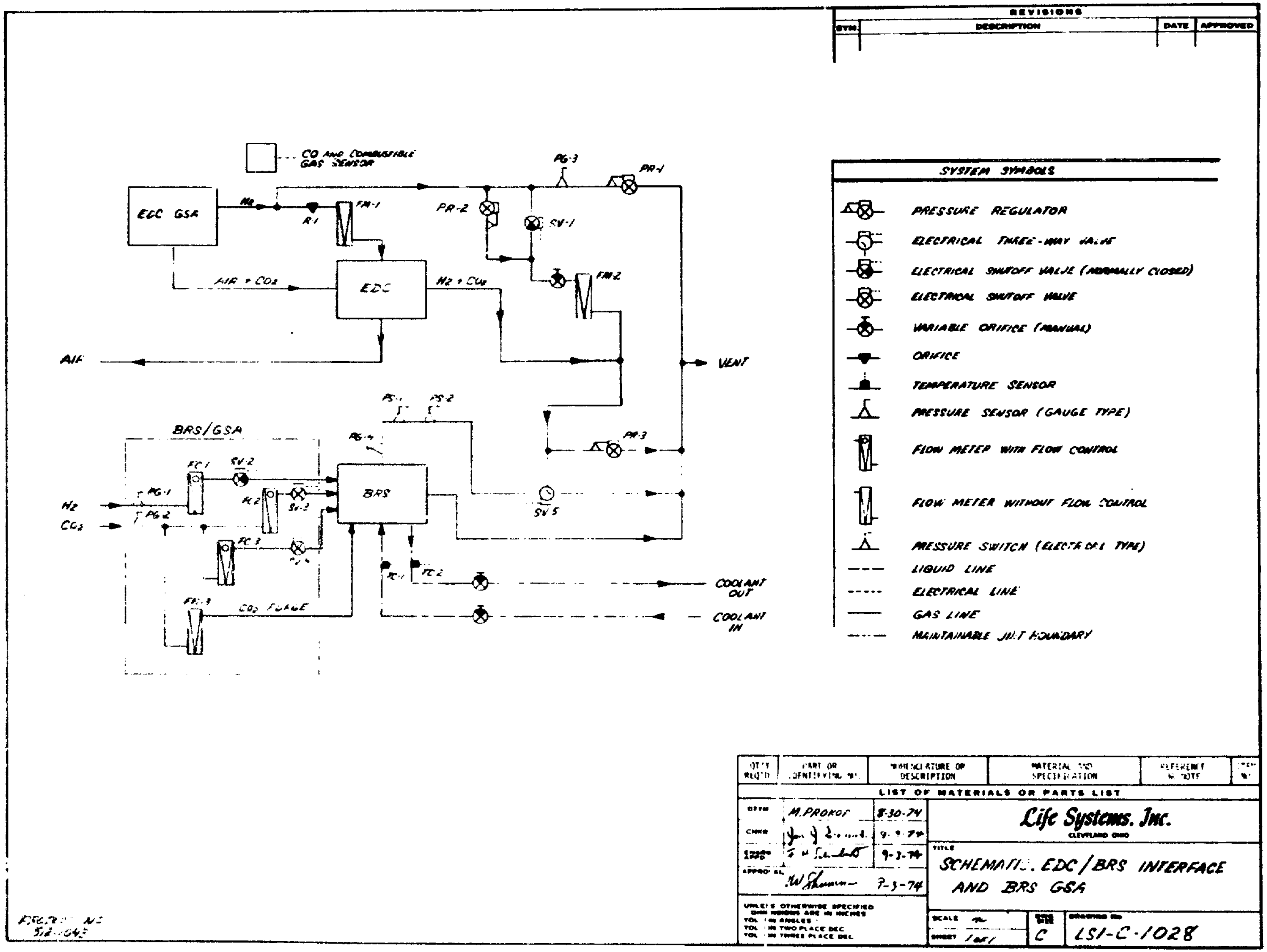


FIGURE 15 EDC/BRS INTERFACE AND BRS GSA SCHEMATIC

ORIGINAL PAGE IS
OF POOR QUALITY

hardware fabricated for the testing. Additional interface components added to the basic interface hardware include sensors for flow, pressure and temperature measurements as well as hand valves for flow controls and pressure relief valves for system protection.

The basic configuration shown in Figure 15 was maintained throughout total program testing. Changes, however, in the BRS configuration were incorporated between the 30- and 45-day endurance tests. Figures 16 and 17 are the detailed schematics of the setups for the 30- and 45-day tests, respectively.

The changes incorporated were

1. Provisions for automatic water collection
2. Replacement of recirculation loop composition sensor
3. Provisions for mixed gas purging
4. Relocation of feed gas point
5. Additional low level pressure relief valve
6. Change to solid state temperature controllers
7. Addition of recycle loop pressure transducer

Automatic Water Collection

The automatic water collection system incorporated removed the BRS-generated water from the condenser/separator accumulator. A high and low level switch within a secondary accumulator triggered the water discharge for external collection and use in mass balance and efficiency calculations.

The secondary accumulator had a volume of approximately 4000 cm^3 during the 30-day test and 600 cm^3 during the 45-day test. The larger accumulator allowed long-term unattended operation but the added volume in the BRS recirculation loop resulted in unrealistic pressure responses.

The automatic water collection system also minimized test operator hours by providing for limitless unattended operation.

Loop Composition Sensor/Controller

During the 30-day test the BRS used an infrared analyzer to maintain desired recirculation loop gas composition. The analyzer controlled the amount of H_2 added to the BRS by sensing and maintaining the pCO_2 of the recirculation gases at a selected value. While the technique was effective, the infrared analyzer available was not of a flight-type nature.

Following the 30-day test a thermal conductivity type sensor/controller directly measuring and controlling the partial pressure of H_2 (pH_2) was installed in the recirculation loop of the BRS. This sensor approached a flight type configuration, but was found to be position sensitive. A further refinement in gas composition sensing is required and recommended for the follow-on effort.

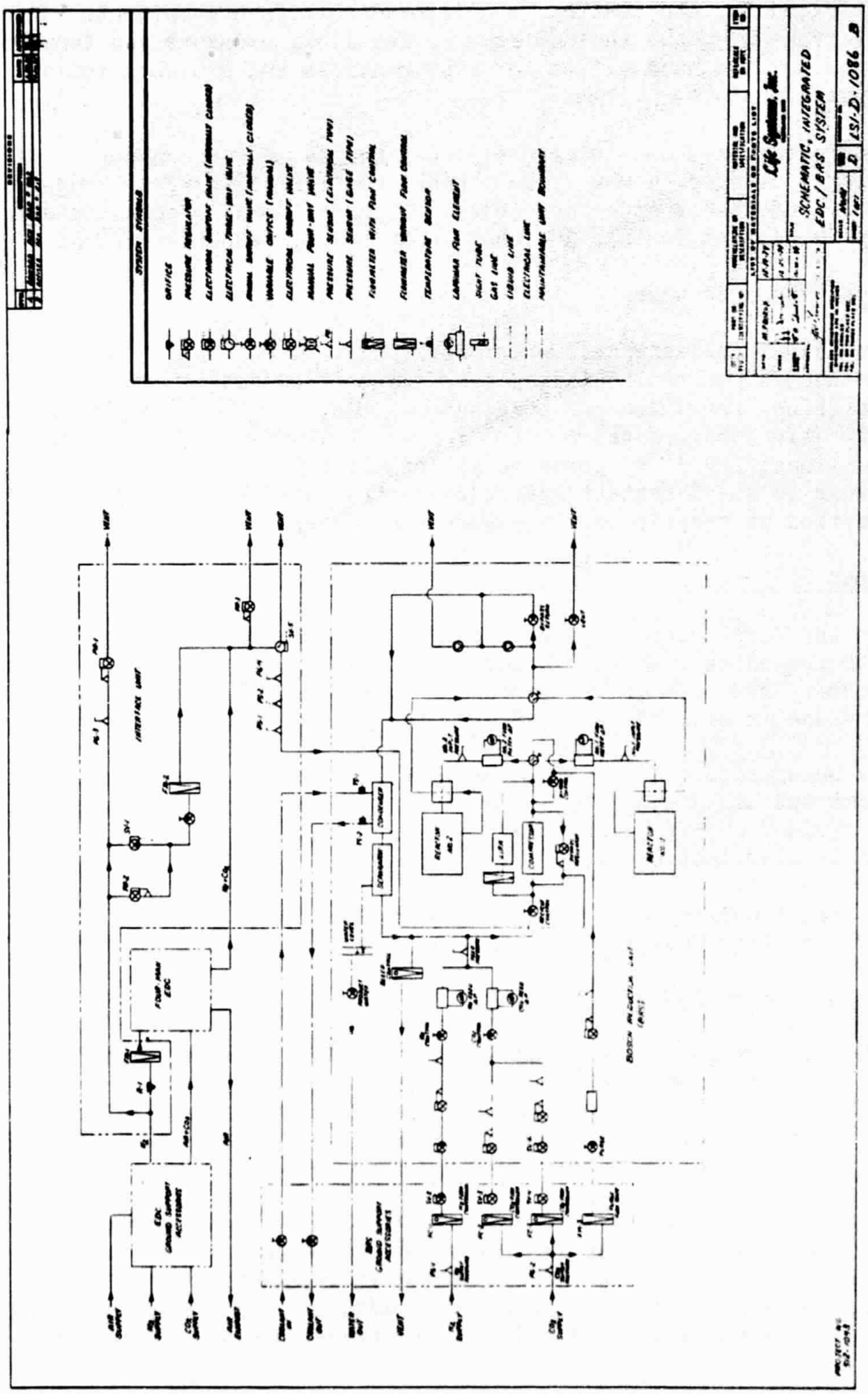


FIGURE 16 SCHEMATIC OF INTEGRATED EDC/BRS WITH INTERFACE UNIT AND BRS GSA - 30-DAY TEST

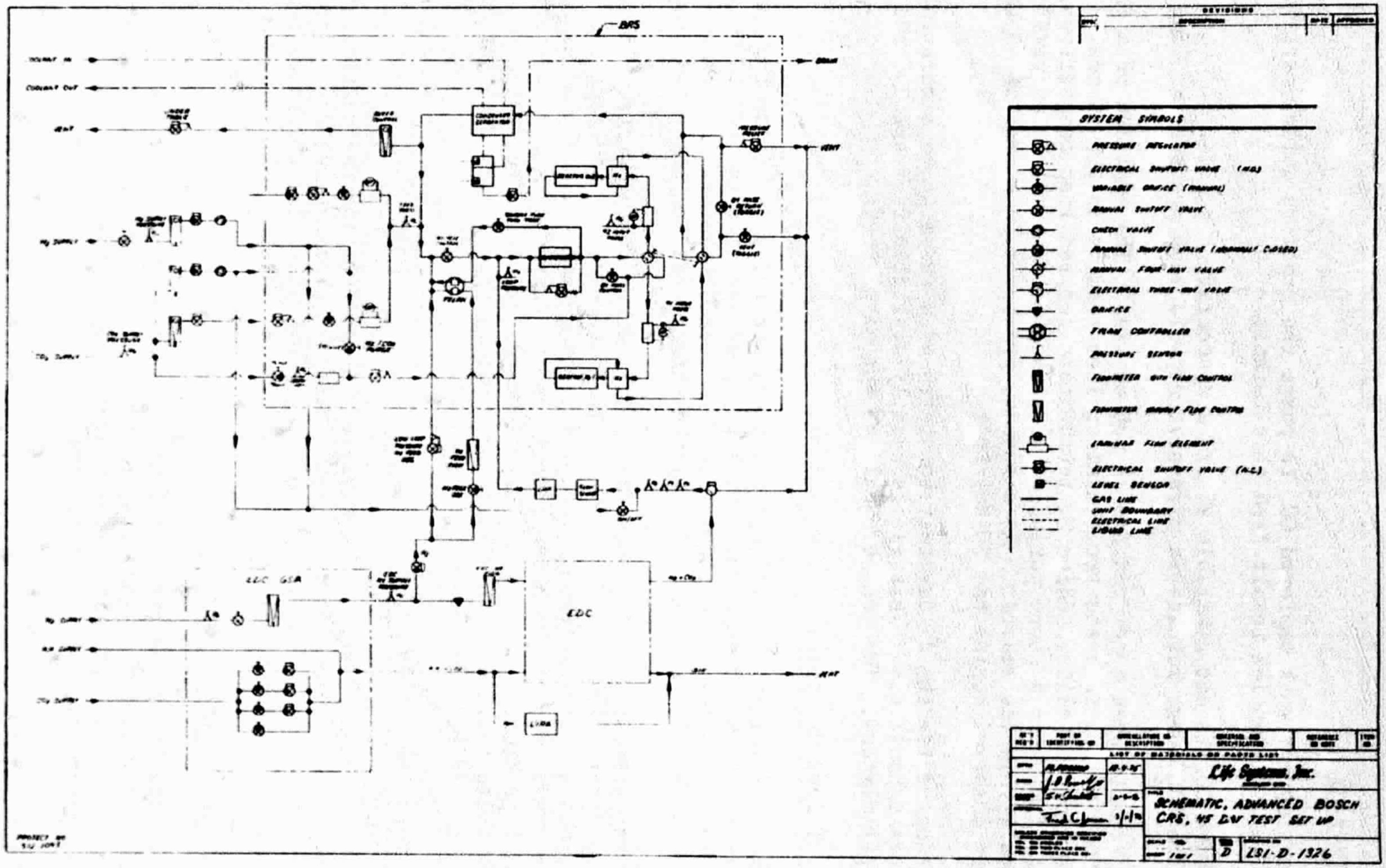


FIGURE 17 SCHEMATIC OF INTEGRATED EDC/BRS WITH INTERFACE UNIT AND BRS GSA - 45-DAY TEST

ORIGINAL PAGE IS
OF POOR QUALITY

Mixed Gas Purging

Past BRS development work employed CO_2 to purge the reactors during cartridge changes. Two deficiencies result from this technique:

1. Pure CO_2 is not available aboard a spacecraft
2. The CO_2 purge results in excessive recycle loop pressure buildup

The latter results when a new reactor is put on line. The addition of a large surge (volume) of CO_2 into the recirculating loop results in the automatic loop composition controller adding H_2 to maintain desired loop composition. This influx of H_2 over a short period of time exceeds that which can readily be converted within the reactor. As a result, pressures in excess of 55 kN/m^2 (8 psi) were observed during the 30-day test.

The purge adopted for the 45-day test consisted of a gas mixture simulating the EDC anode exhaust gas. This gas is readily available from the EDC and is of the proper mixture. The pressure buildup was eliminated.

Relocation of Feed Gas Point

Prior to the 30-day test the feed gas point was located upstream of the condenser/separator to remove water introduced with the feed gas from the EDC to maximize BRS efficiency. The location of this feed gas point, however, introduced excessive pressure fluctuations which proved detrimental to integrated operation.

For the 30-day test, the feed gas point was introduced just downstream of the pressure regulator. Results of the 30-day test, however, showed that the variable bypass gas stream through the pressure regulator also produced variable pressure drops through the plumbing which caused excessive variations in feed point pressure. As a result, the feed gas point was relocated to a stagnant pressure tap line. This kept the pressure essentially constant even with variations in recycle loop gas flow rates.

Additional Pressure Relief Valve

For the 45-day test a pressure relief valve was added to the BRS recirculation loop as a secondary protection to prevent excessive pressure buildup. The additional pressure relief valve proved unnecessary since the new purge technique eliminated pressure buildups.

Solid-State Temperature Controller

Experience during the 30-day test indicated that the mechanical ON/OFF relay type controllers used to regulate reactor temperatures were inadequate for endurance testing. Significant contact damage was observed. As a result a solid-state, time-proportioning, automatic reset unit was used.

Recycle Loop Pressure Transducer

For the 45-day test a recycle loop pressure transducer was added to the BRS to provide analog readouts for continuous recording of loop pressure. This pressure level is a key parameter in analyzing BRS performance characteristics.

Operating Modes and Allowable Mode Transitions

The five operating modes listed in Table 7 were defined for the integrated system operation. Changing from one operating mode to another is termed a mode transition. Figure 18 illustrates the allowable mode transitions for both the 30- and 45-day test configurations. The desire to operate one subsystem while the other was shut down to provide for additional BRS operating experience, was no longer needed for the 45-day test.

Electrical Controls and Instrumentation

Since the BRS requires from 1.5 to 3.0 hours for initial reactor heatup time the capability for individual subsystem operation was retained in the integration instrumentation design. The integration unit logic required that both subsystems be in normal operating modes before the interface control valve, SV-5 (see Figure 15) could be energized. The controls also allowed for either subsystem to be operating while the other was shut down.

Shutdown protections were incorporated to provide for fail-safe operation to protect personnel and equipment.

The EDC contained shutdown provisions for low voltage, high H_2 to air pressure differentials, high module temperature, high instrumentation temperature and facility power failure.

The BRS originally contained only a high reactor temperature shutdown circuit. To this was added shutdown provisions for high temperature in the inlet and outlet of the condenser/separator coolant flow lines and for the prevention of restart of the BRS without manual intervention when failed facility power was restored.

Since high and low interface pressures in the interface plumbing could cause damage to either unit, high and low pressure protection was added to the interface components (PS-1 and PS-2, see Figure 15).

During the 30-day test, interface pressure levels drifting outside the allowable limits caused the subsystems automatically to go to individual operation. For the 45-day testing, a total system shutdown would have resulted if interface pressure levels had drifted outside allowable limits.

GROUND SUPPORT ACCESSORIES

Ground Support Accessories were needed during testing of the individual subsystems and the integrated system. Their function was to supply the required fluids, electrical inputs, controls, instrumentation displays and shutdown protections.

The GSA developed allowed for independent operation of the EDC and BRS at a four-man level and integrated operation with constant and variable CO_2 loading.

TABLE 7 INTEGRATED EDC/BRS OPERATING MODES

- System Shutdown/System Power Loss - Neither subsystem operational (30-day test) or either or both subsystems non-operational (45-day test)
- Independent Operation/Startup - Subsystems independent but both operational, BRS GSA operating, EDC venting
- BRS Shutdown/BRS Off - BRS not operational, EDC operational and venting
- EDC Shutdown/EDC Off - EDC not operational, BRS operational, BRS GSA operating
- Normal - Both subsystems integrated, BRS GSA off, EDC venting to BRS

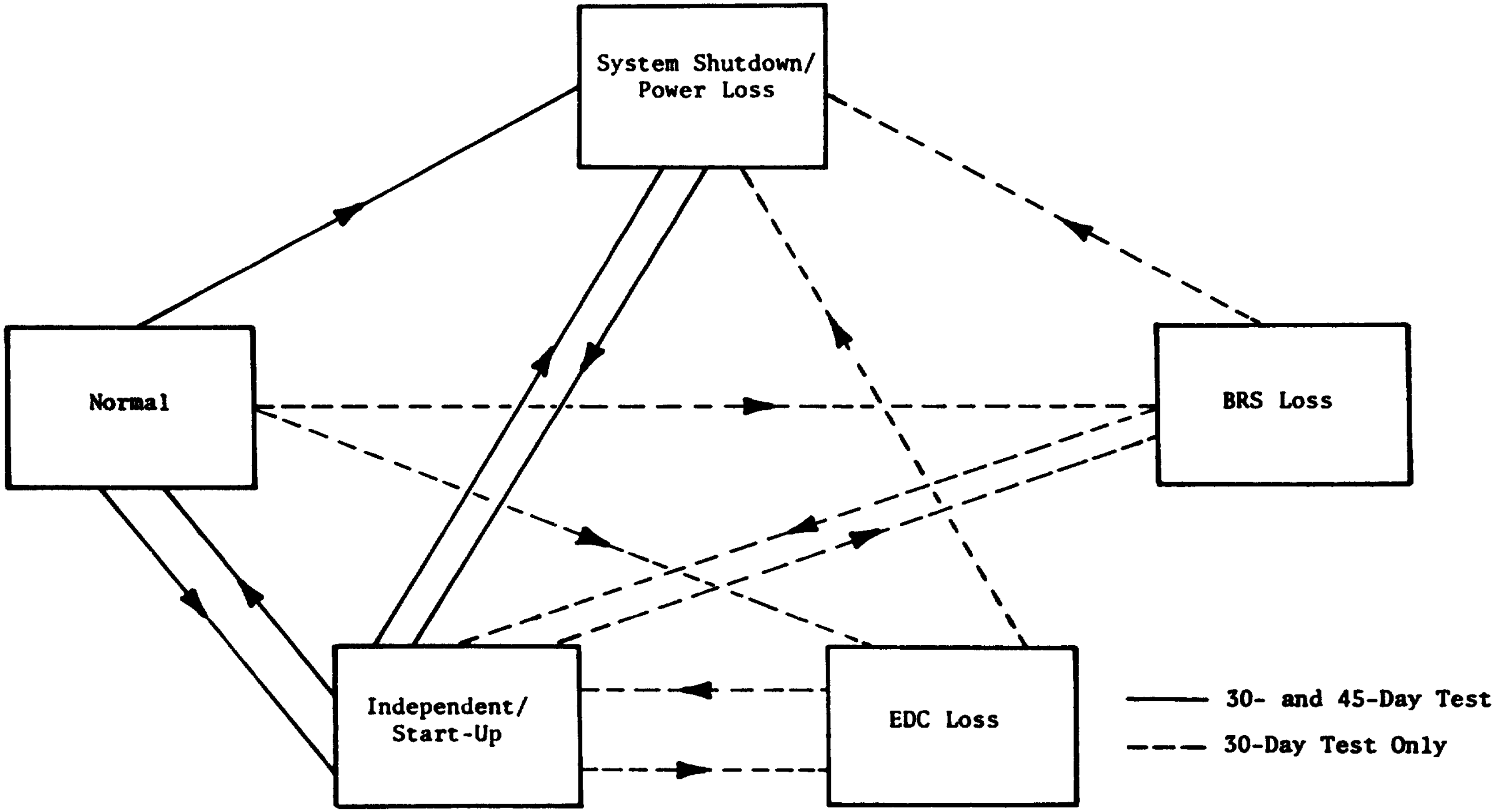


FIGURE 18 EDC/BRS OPERATING MODES AND ALLOWABLE TRANSITIONS

In addition, the GSA provided for refurbishment of the carbon collection cartridges.

Electrochemical CO_2 Depolarized Concentrator Ground Support Accessories

The EDC GSA previously developed(5) was refurbished and modified for the program. It consisted of units to supply H_2 and CO_2 to the EDC, process and cooling air at proper dry bulb and dew point temperature levels, liquid coolant for the electronic controllers, electrical power and parametric data readouts in engineering units.

The modifications to the EDC GSA consisted of

1. Increasing the H_2 supply pressure from a previous maximum level of 207 to 310 kN/m^2 (30 to 45 psia) to enable meeting the requirements of the integration concept
2. Provisions to supply a predetermined, variable CO_2 flow to the EDC process air to simulate the variable CO_2 loading

Figure 7 presented a photograph of the EDC with its associated GSA.

Bosch CO_2 Reduction Subsystem Ground Support Accessories

The GSA required to allow independent and integrated operation of the four-man capacity BRS were designed, fabricated, assembled and checked out. It consisted of the H_2 and CO_2 for independent BRS operation, CO_2 or CO_2 premixed with H_2 at a H_2 to CO_2 ratio of 2:1 purge gas, liquid coolant for the BRS condenser/separator, automatic water collection hardware for collection and quantification of the water generated by the BRS, ground checkout instrumentation for readout of engineering parameters not displayed on the BRS front panel and carbon collection cartridge refurbishment.

A schematic of the BRS GSA was contained in Figure 15. Figure 19 is a photograph of program GSA with the BRS GSA located in its lower portion.

Interface Ground Support Accessories

Interface GSA was designed, fabricated, assembled and checked out. It enabled control and monitoring of the interface components and consisted of flow, pressure and temperature indicators, mode selection switches, operating mode indicators, and feed mode control indicators. It is shown in the upper portion of Figure 19. The mode selection switches provide for system startup, independent subsystem operation and integrated system operation. Lights indicate the operating mode initiated. Figure 20 is a layout of the interface GSA instrumentation panel shown in the upper portion of Figure 19.

Variable pCO_2 Controller

Since the 45-day endurance test required operation of the integrated system with variable CO_2 generation rates based on a SSP mission profile, a variable

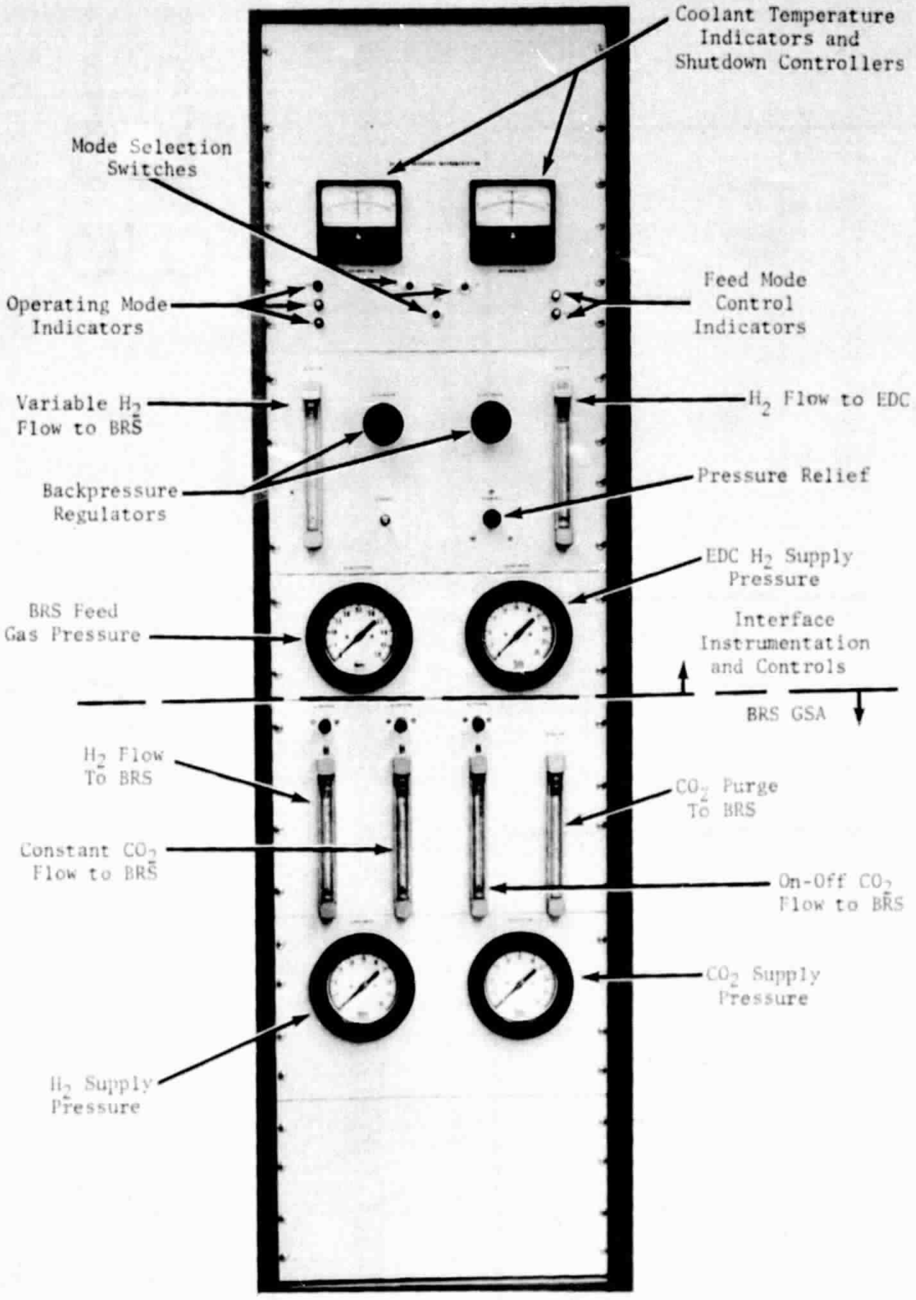


FIGURE 19 EDC/BRS GROUND SUPPORT ACCESSORIES AND INTERFACE INSTRUMENTATION CONTROLS

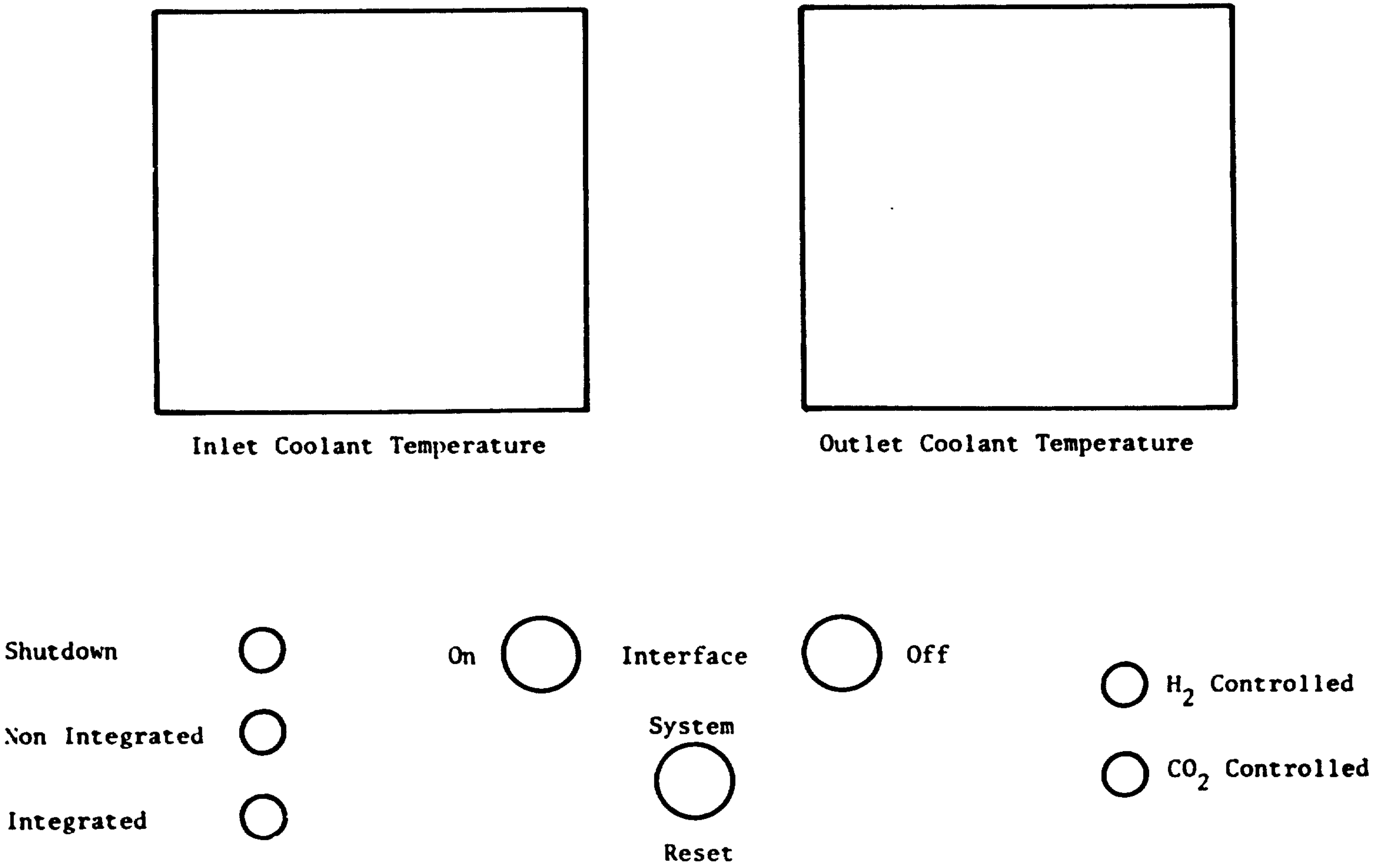


FIGURE 20 EDC/BRS INTERFACE CONTROL PANEL DETAILS

pCO_2 controller had to be developed. Two requirements were established for the controller:

1. The capability to simulate the pCO_2 variations in the EDC anode exhaust
2. The capability to simulate the cabin pCO_2 profile based on a sleep/work cycle of the SSP crew.

Controller Concept

Figure 21 is an overall block diagram of the variable pCO_2 controller developed. The controller operated as follows. A modulated CO_2 flow was added to a primary fluid stream. The latter could either be the process air stream to the EDC or a H_2 stream simulating BRS feed gas from the EDC. This was accomplished with a group of solenoid valves and fixed orifices arranged in four parallel flow paths. One path contained a single orifice, and the others each contained a solenoid valve and a fixed orifice in series. Different CO_2 flow rates were obtained by opening and closing various combinations of flow paths.

Automatic electronic control circuits were developed to operate the solenoid valves. Figure 22 is a block diagram of the electronics. Two signals were compared by an error amplifier:

1. A feedback signal from an infrared CO_2 analyzer sampling the main gas stream
2. A variable reference signal generated electronically

By comparing the feedback signal with the variable reference signal and actuating respective solenoid valves, variable amounts of CO_2 were added to the main gas stream. The variable reference signal generator within the electronic circuits used a Programmable Read Only Memory (PROM) to generate the desired CO_2 percentage versus time signal.

The inherent flexibility of using a PROM in the reference signal generator circuits allowed for programming the BRS feed gas and the cabin pCO_2 simulations using only one set of hardware. Only reprogramming of the PROM was required to allow for the different modes of operation.

The variable reference generator circuits were built with a capability of subdividing any repetitive time period into 256 distinct steps. In this manner, any pCO_2 analog curve of a repetitive nature could be simulated by up to 256 different levels of CO_2 flow. A photograph of the variable pCO_2 controller is shown in Figure 23.

Cabin pCO_2 Simulation

Figure 24 shows cabin pCO_2 and CO_2 generation rates based on a 24-hour SSP work cycle. The cabin pCO_2 levels are shown for an EDC operating with 45 and

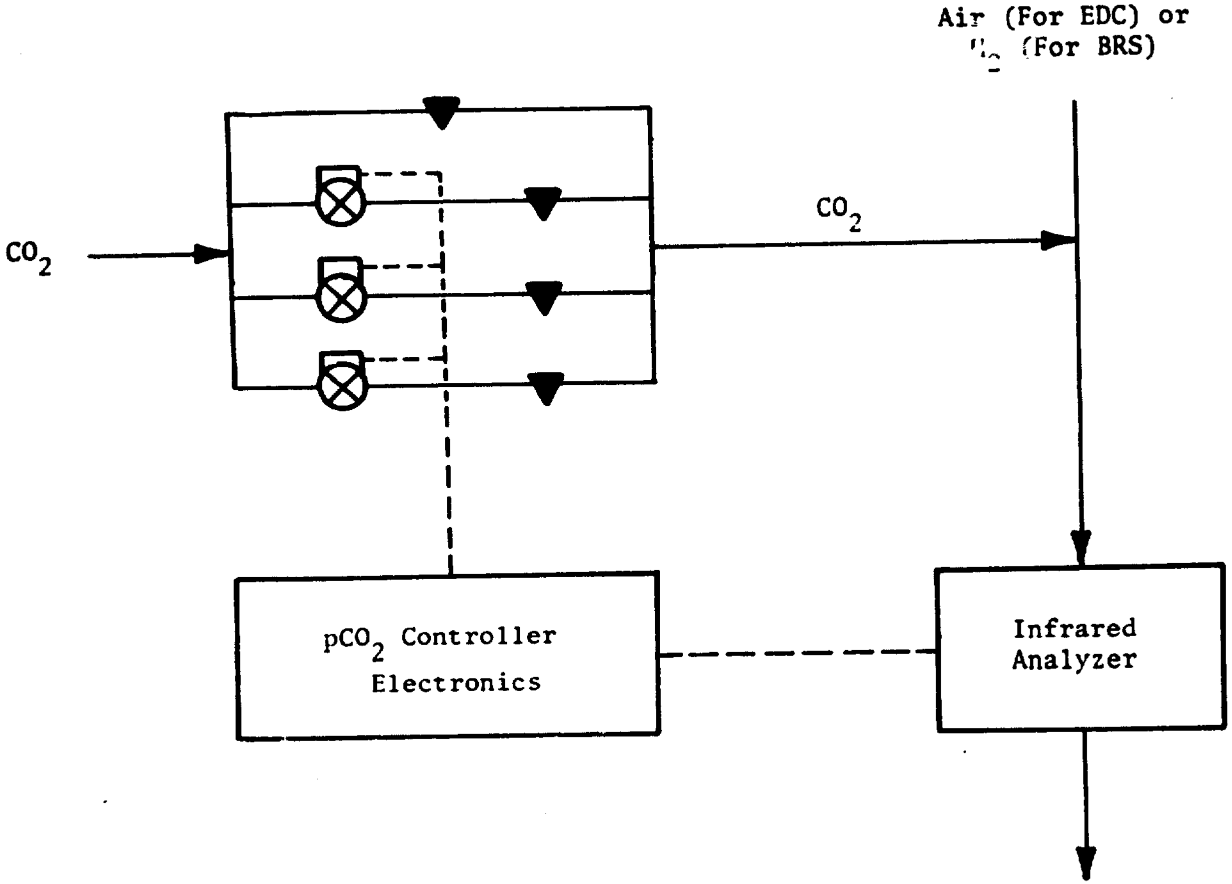
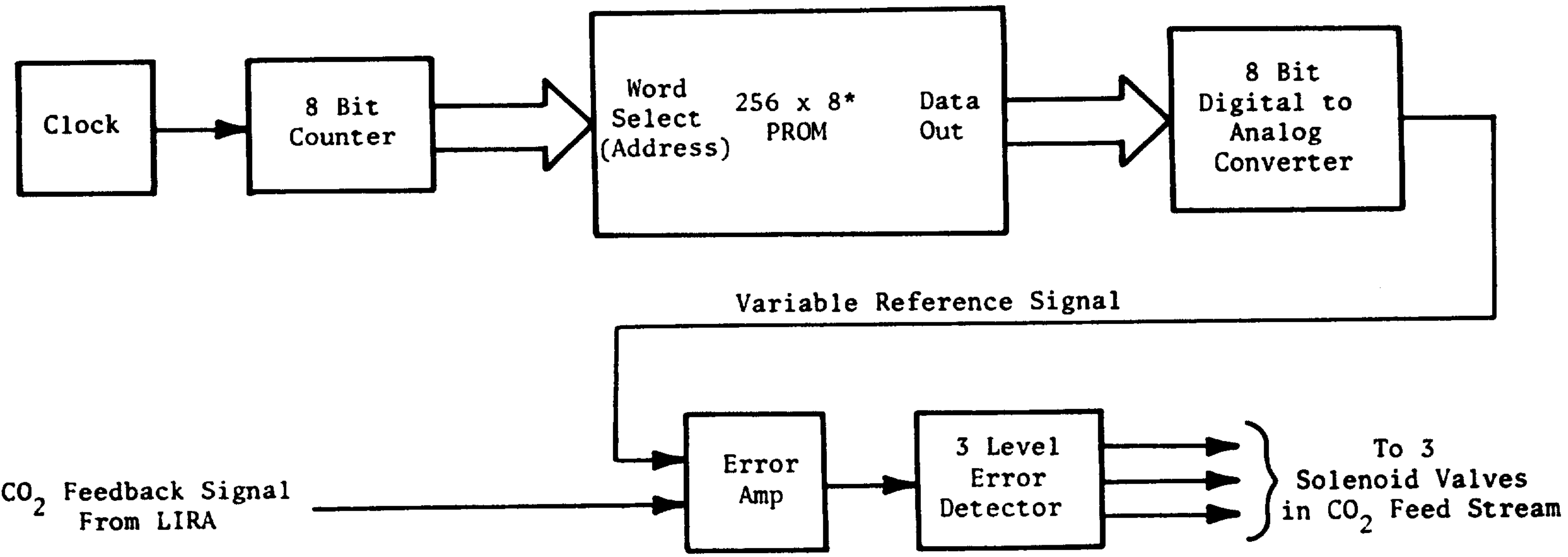


FIGURE 21 pCO_2 CONTROLLER OVERALL BLOCK DIAGRAM



*256 x 8 = 256 words each with 8 bits PROM
can be erased and reprogrammed for desired profile

FIGURE 22 BLOCK DIAGRAM, VARIABLE pCO_2 CONTROLLER ELECTRONICS

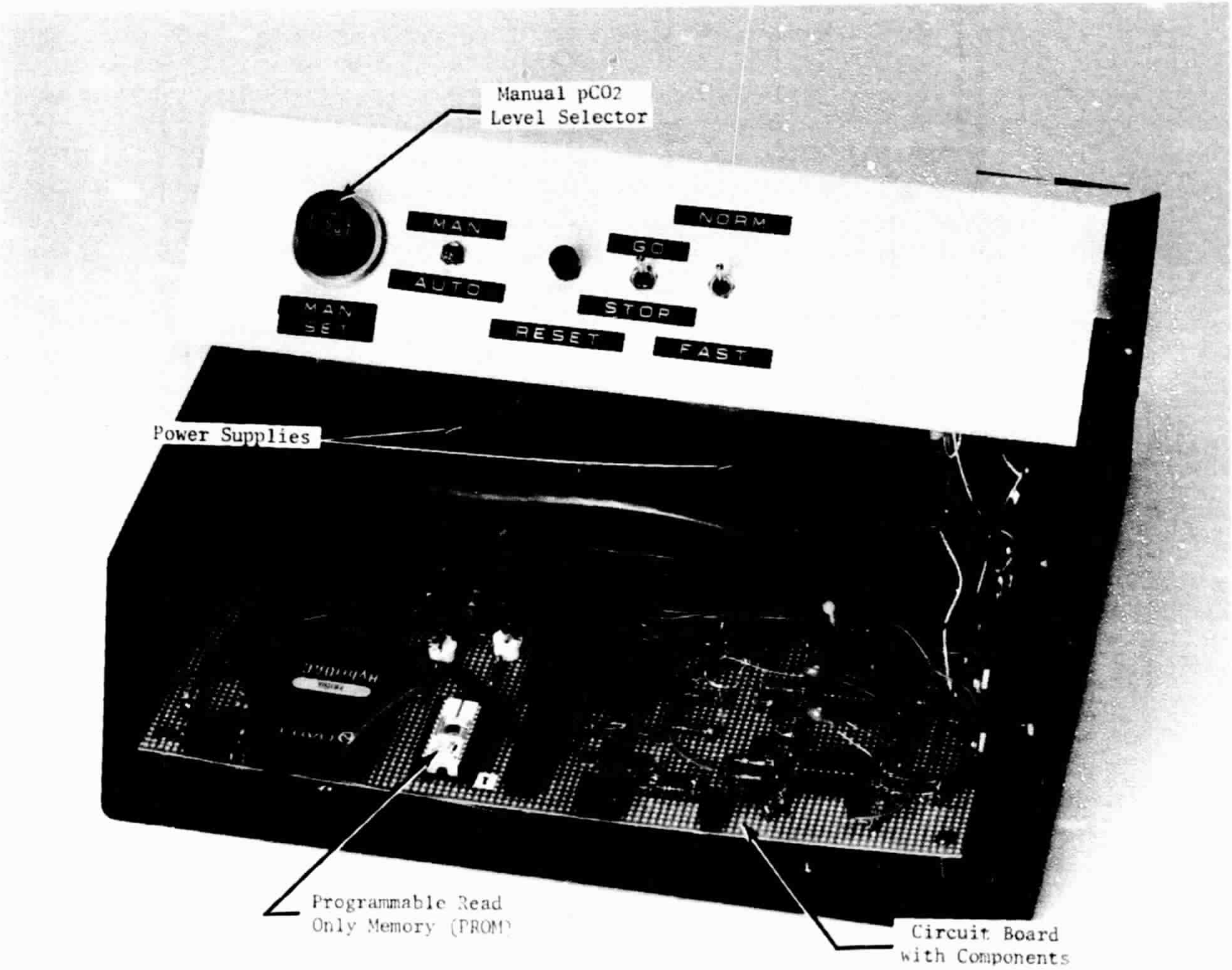


FIGURE 23 pCO_2 CONTROLLER HARDWARE

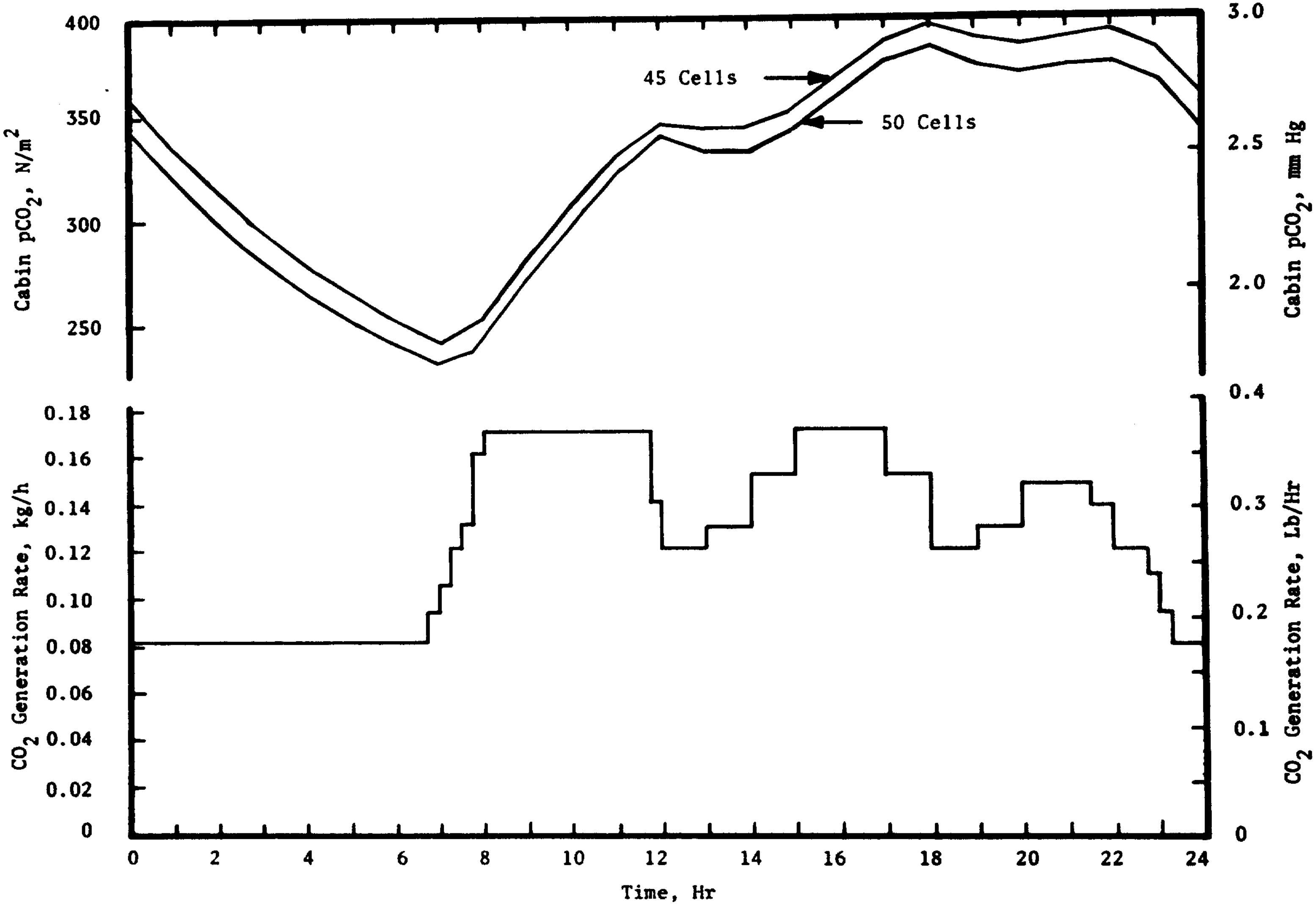


FIGURE 24 CALCULATED CABIN pCO$_2$ AND CO$_2$ GENERATION RATE FOR A 24-HOUR WORK PERIOD

50 cells. The cabin pCO_2 variations were calculated using the computer program for modeling of the EDC performance characteristics.(4) The variable pCO_2 controller was programmed to simulate the curve for the 45 cell EDC performance. Figure 25 shows the results obtained during the checkout testing of the controller. As seen, the CO_2 generated profile simulated, in a series of 256 steps, the analog curve of the projected cabin pCO_2 levels (taken from Figure 24).

BRS Feed Gas Simulation

A computer program was written and implemented using one PROM to simulate the feed gas to the BRS. The CO_2 flow rates were based on a computer program characterizing the EDC's performance when exposed to the variable cabin pCO_2 of a SSP mission (lower portion of Figure 12).(31)

The printout of the pCO_2 monitored in the H_2/CO_2 mixture during the controller checkout testing is shown in Figure 26. The shape of the curve simulates the smooth analog curve shown for the CO_2 removal rate (taken from Figure 12).

Carbon Collection Cartridge Refurbishment

The BRS uses cyclically operated reactors to collect the carbon generated by the Bosch reaction. Refurbishment of a carbon collection cartridge is not anticipated in the spacecraft application. For the test program, however, refurbishment was required since only five cartridges were available and in excess of 40 cartridges were needed.

Figure 9 showed an assembled cartridge ready for insertion into a reactor while Figure 27 shows a disassembled cartridge indicating the various parts that make up a cartridge. The overall cartridge dimensions are 19.5 cm (7.7 in) in diameter by 30.0 cm (11.8 in) in length or a volume of 8,954 cm^3 (546 in^3).

Fiber blankets were used to contain the catalyst and to serve as a filter for retaining the carbon.

New fiber blankets were used with each refurbishment. Each cartridge used 150 gm (0.33 lb) of pretreated steel wool catalyst. An empty cartridge with catalyst weighed 1.3 kg (2.86 lb) and had a three to four day capacity at the four-man CO_2 generation level.

Although each of the five cartridges was reused about nine times, little wear was visible and no carbon formation was observed on the metallic parts.

MINI-PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance, including design, fabrication, purchasing, testing and shipping consistent with a program in the early stages of development.

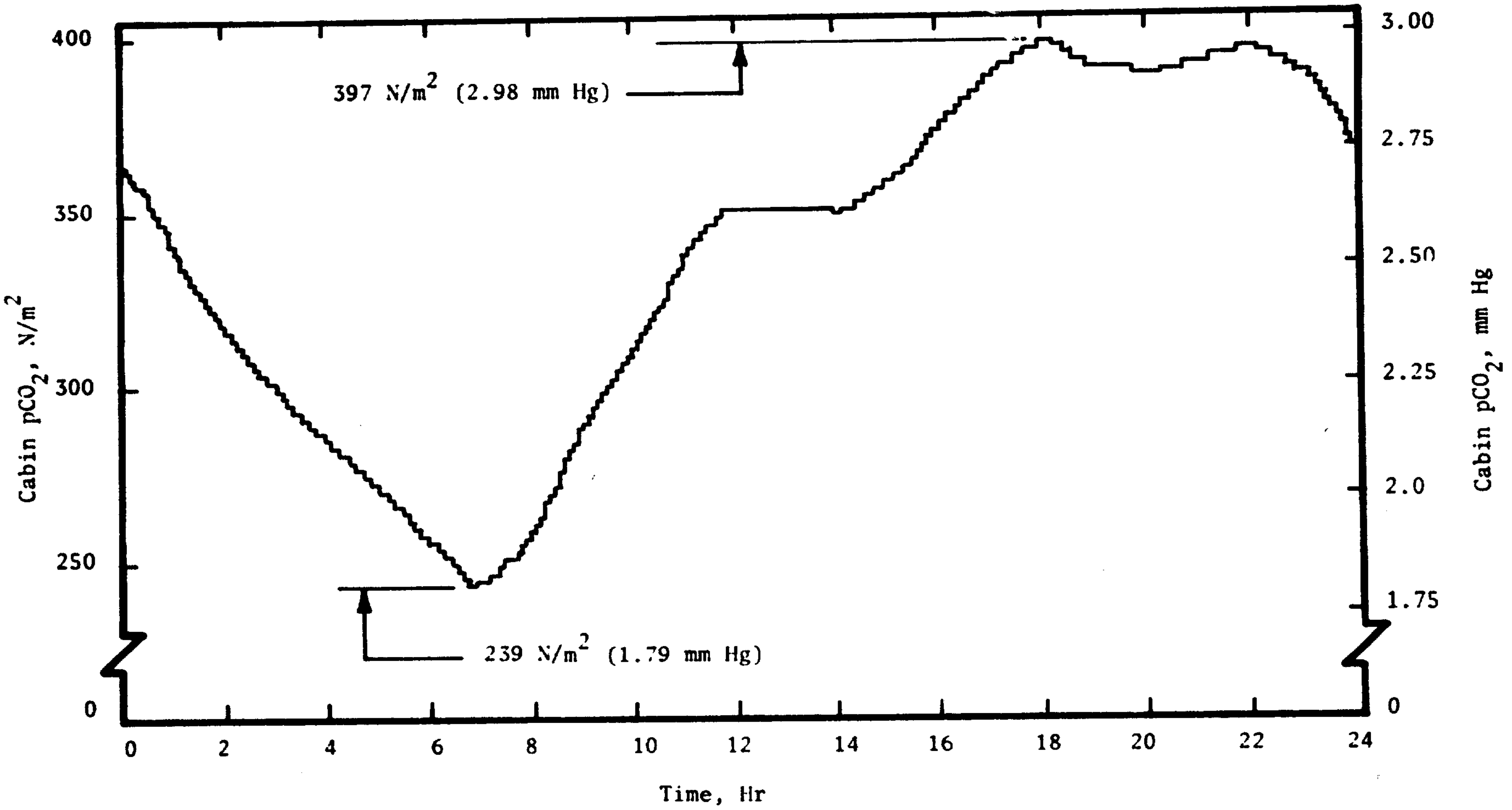


FIGURE 25 SIMULATED CABIN pCO$_2$ PROFILE USING VARIABLE pCO$_2$ CONTROLLER

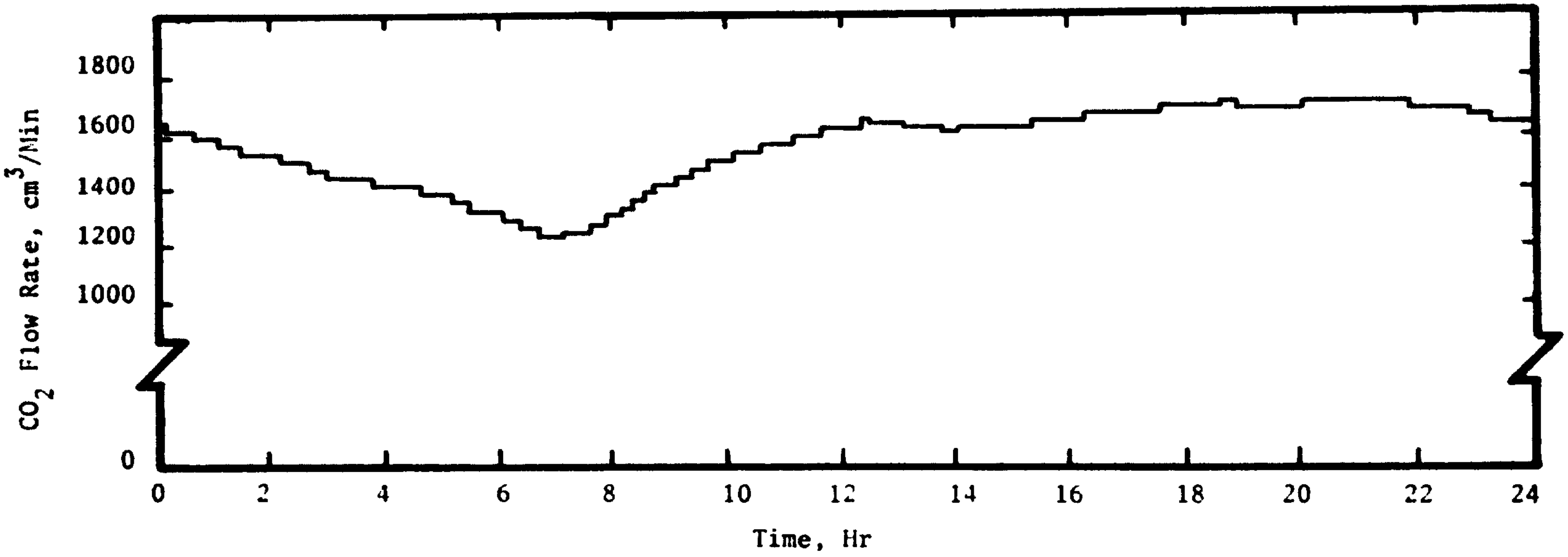


FIGURE 26 SIMULATED CO_2 CONTENT IN EDC ANODE EXHAUST USING VARIABLE pCO_2 CONTROLLER

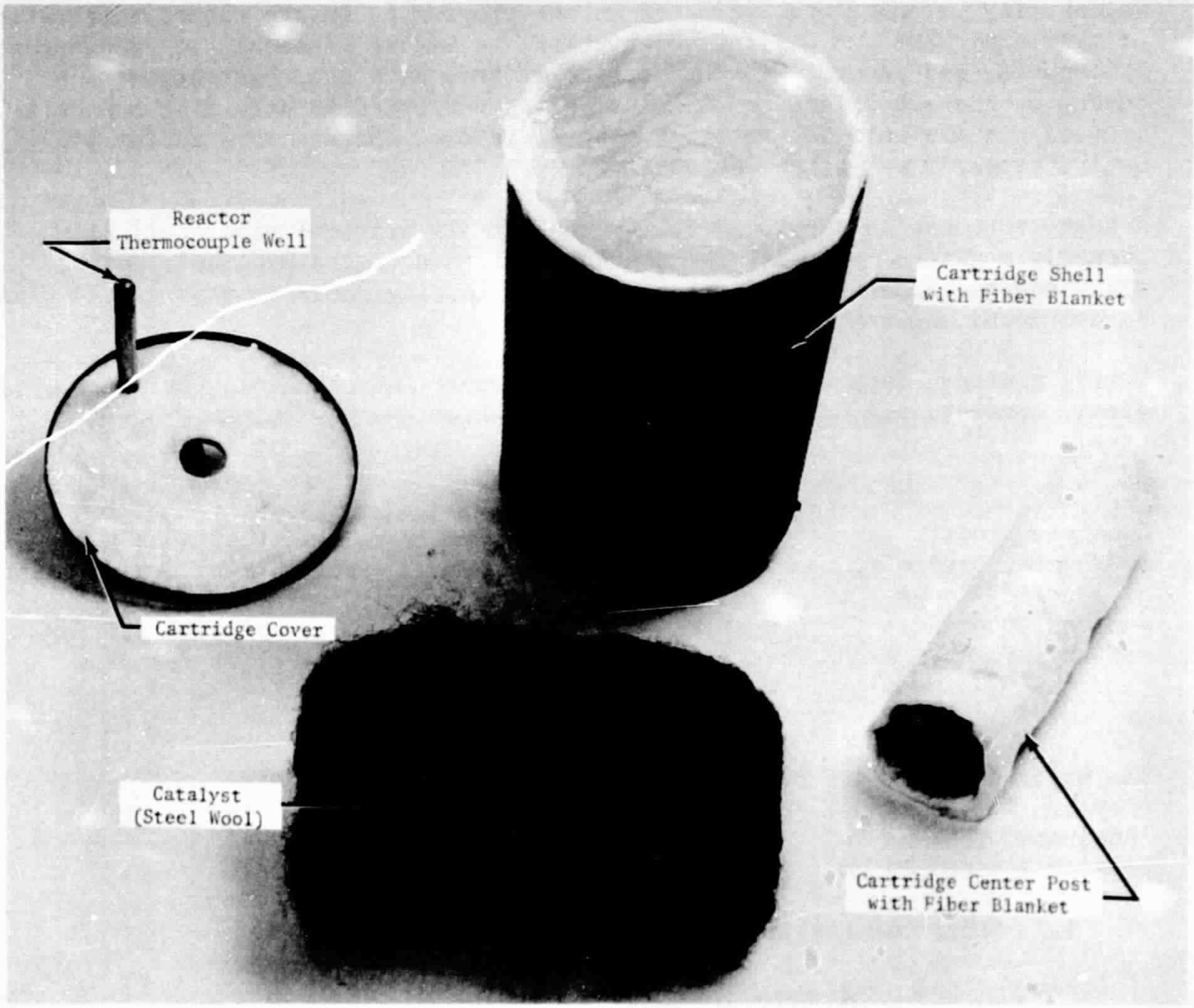


FIGURE 27 DISASSEMBLED CARBON COLLECTION CARTRIDGE

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. Also, quality assurance effort was involved in the preparation of the final report with the objective of identifying and resolving deficiencies that could impact the quality of future equipment.

Reliability

Reliability personnel participated in the program to insure proper calibration of test equipment and GSA instrumentation, to assure adherence to proper test procedures, and recording and reporting of test data and observations. A survey of the subsystems and GSA design was performed to determine the calibration requirements for testing. Appropriate components were calibrated during assembly and after installation.

A test procedure was followed to insure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures. All major testing required that a test plan be completed and reviewed.

During testing, data was recorded in a laboratory notebook along with observations, comments and operator-initiated parameter changes.

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 subsystem characteristics, reviewing designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features.

PROGRAM TESTING

The major objective of the test program was to experimentally verify the proposed integration concept and to characterize the performance of the integrated EDC and BRS. To accomplish this objective, a three-part test program was completed.

1. Subsystem Familiarization and Checkout Tests
    - 24-hour EDC test
    - 200-hour BRS test
2. Integrated Testing with constant CO_2 Loading
    - Sensor Calibration and Shakedown Test
    - Design Verification Test (DVT) - 100 Hours
    - 30-day Endurance Test

3. Integrated Testing with variable CO_2 Loading

   - Sensor Calibration and Shakedown Test
   - Maximum Capacity Test
   - 45-day Endurance Test

An overview of the total test program is shown in Figure 28.

Subsystem Familiarization and Checkout Tests

The objective of these tests was to obtain familiarity with hardware and associated GSA and to verify the capability of the refurbished and modified hardware to operate at the four-man capacity level.

EDC 24-Hour Test

Over 1,000,000 cell operating hours have been accumulated on the EDC and 1,200 hours on the EDC modules used for the integrated tests. Thus, only a 24-hour test of the EDC with its associated GSA was needed to successfully demonstrate design capability: removal of 4.0 kg/d (8.8 lb/day) of CO_2 with a constant inlet pCO_2 level of 400 ±13 N/m^2 (3.0 ±0.1 mm Hg).

BRS 200-Hour Test

A 200-hour checkout and familiarization test with the BRS and its associated GSA was successfully completed. The test constituted the first startup and operation of the BRS hardware following approximately three years of storage.

A total of four cartridges were expended during the testing. The first cartridge, partially filled with carbon from previous tests, was reused. The remaining three cartridges were totally refurbished prior to testing. No problems were encountered with any of the four cartridges and startup and reactor changeover procedures derived for the refurbished and modified BRS were verified.

No problems were experienced when operating the BRS at the projected four-man capacity level. Table 8 summarizes data on the four cartridges. All equalled or exceeded the four-man capacity CO_2 generation/removal rate of 0.045 kg/h (0.099 lb/hr). Figure 29 is a cartridge photograph with its end cover removed to expose the collected carbon.

Mass balances were performed based on the gas quantities delivered to the BRS from the GSA and on the carbon and the water collected. Table 9 summarizes a typical mass balance using the results of cartridge No. 2. The data shows a mass balance closure within 3.2% and within the expected experimental error.

During typical testing, reactor pressure differentials increased slightly over the first half of the cartridge life, then increased gradually with a sharper rise toward the end of cartridge life. After a reactor changeover and due to the fresh catalyst in the new cartridge, the pressure would initially decrease

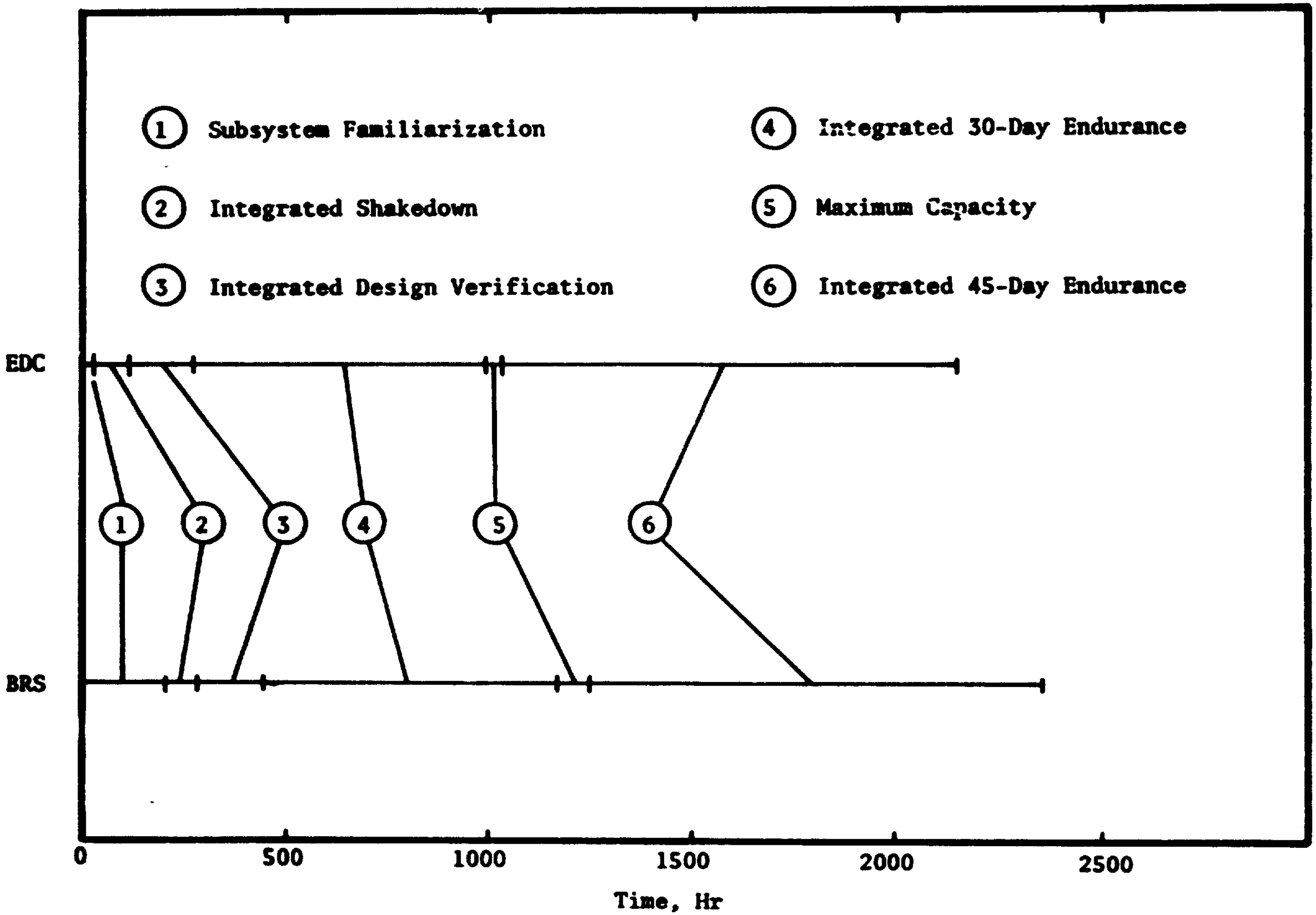


FIGURE 28 OVERVIEW OF PROGRAM TESTING

TABLE 8 BRS CARBON FORMATION RATE, BRS FAMILIARIZATION TEST

Reactor No.	Operating Time, Hr	Carbon Deposited, kg (Lb)	Production Rate, kg/h (Lb/Hr)[a]
1	49	2.36 (5.20)	0.048 (0.106)
2	75	3.52 (7.75)	0.047 (0.103)
1	52	2.66 (5.85)	0.051 (0.113)
2	24	1.08 (2.37)	0.045 (0.099)

(a) Average rate for four men is 0.045 kg/h (0.099 Lb/Hr).

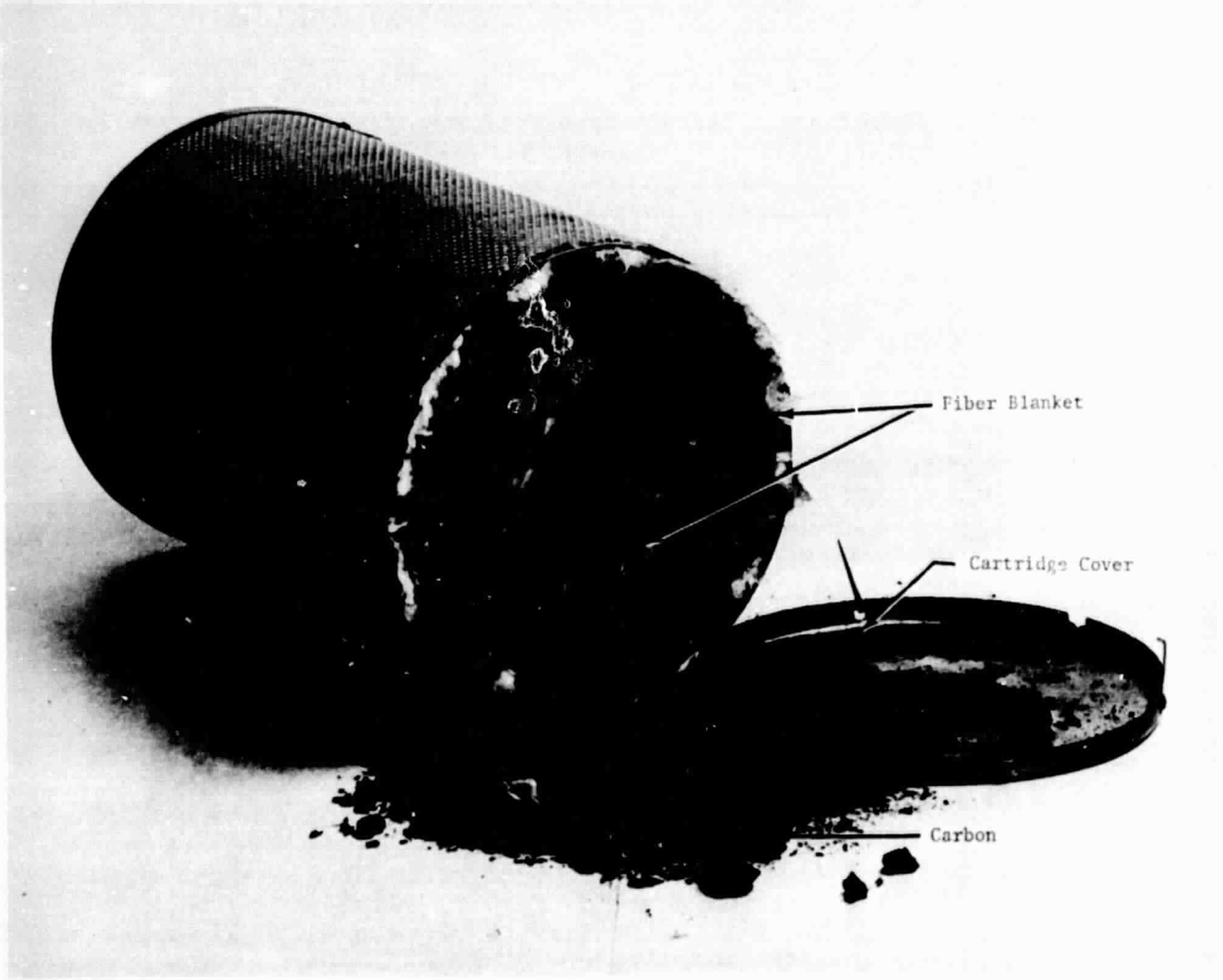


FIGURE 29 FILLED CARBON COLLECTION CARTRIDGE

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 9 CARTRIDGE NO. 2 MASS BALANCE, BRS FAMILIARIZATION TEST

Total Cartridge Time at Reaction Temperature, >755K (900F), Hr		75
Reaction	$2H_2 + CO_2 = C + 2H_2O$	
H_2 In, kg (Lb)[a]		1.198 (2.636)
CO_2 In, kg (Lb)[b]		13.167 (28.967)
Water Out, kg (Lb)		10.385 (22.847)
Carbon Out, kg (Lb)		3.523 (7.751)

Mass In = Mass Out

Mass Balance 1.198 kg + 13.167 kg = 10.385 kg + 3.520 kg

14.365 kg = 13.905 kg

(2.636 Lb + 28.967 Lb = 22.847 Lb + 7.751 Lb)

(31.603 Lb = 30.598 Lb)

Error, %	3.2

(a) Measurement accuracy based on Hastings mass flowmeter ±2%.
(b) Based on 2:1 H_2-to-CO_2 stoichiometric requirement as controlled by infrared analyzer (Lira).

over a relatively short period of time as reaction rate increased. The pressure would then decrease until a new equilibrium was reached. The pressure differential cycle would then repeat for the new cartridge.

During the 200-hour familiarization/checkout testing the No. 1 reactor pressure differential was less than that experienced with the No. 2 reactor. For comparison, loop No. 1 would average 27.6 kN/m^2 (4 psid) versus 41.3 kN/m^2 (6 psid) for reactor No. 2. Cause of this difference was traced to carbon formation in the regenerative heat exchanger of the BRS hardware. The difference was eliminated prior to the 45-day endurance test by replacement of the regenerative heat exchangers.

During the 200-hour test, gas chromatograph samples were taken from the recycle loops. Table 10 shows two typical compositions obtained during this testing. The data does not contain water found in the recycle gases since it is removed prior to the analyses. The numbers compare well with those listed in literature.(11)

TABLE 10 RECYCLE LOOP GAS CHROMATOGRAPH ANALYSIS, BRS FAMILIARIZATION TEST

H_2, %	CH_4, %	CO, %	CO_2, %	O_2, %	N_2, %
39.9	14.4	29.4	15.5	0.0	0.8
39.1	15.1	29.6	15.5	0.0	0.7

One automatic shutdown occurred during the 200-hour test due to building power failure.

Integrated Testing with Constant CO_2 Loading

The first integrated testing was performed with a constant CO_2 loading of the air processed by the EDC. The testing consisted of sensor calibration and shakedown tests, design verification tests and endurance tests. The operating time goals of 8 hours, 100 hours and 30 days (720 hours), respectively, were met or exceeded.

Sensor Calibration and Shakedown Test

A total of 82 hours of integrated operation, including one cartridge changeover, were achieved during this test on the integrated system. Initially all installed subsystem sensors were calibrated. A water leak in the condenser/separator of the BRS was noticed during the early portion of the shakedown test. The condenser/separator was repaired and simultaneously modified internally to allow more cooling flow at a substantially lower pressure drop. With a 278K (41F) coolant inlet temperature, the dew point downstream of the condenser/separator was measured to be 279.7K (44F).

The EDC anode exhaust feed point upstream of the condenser/separator, originally chosen to minimize water content within the BRS recycle loop, yielded excessively high and fluctuating backpressures for the EDC. This made control of integrated operation difficult. A more controllable feed point pressure level resulted when the feed point was moved to the downstream side of the recycle loop compressor bypass regulator. No adverse effects were noted on BRS performance.

The performance obtained during the 82 hours of integrated testing compared well with that of the individual subsystems.

Design Verification Test (100 Hours)

The DVT verified integrated system and associated GSA operability over a six-day time period. A total of 160.5 hours of integrated operation were accumulated and two reactor changeovers performed.

No cartridge startup time or reaction initiation problems were encountered. Reactor changeover procedures ran smoothly. A fresh reactor was first purged with five volumes of CO_2 followed by preheating to approximately 723K (842F) and recirculating approximately one-seventh of the recycle loop gases through the new reactor. Initiation of the reaction in the second reactor was signaled by a decrease in loop pressure. The four-way valves were then actuated to complete switchover to the new cartridge.

Thirty-Day Endurance Test

The 30-day endurance test characterized the performance as a function of operating time. It was performed with a constant pCO_2 level in the air processed by the EDC. The pCO_2 level was 400 N/m^2 (3.0 mm Hg) with a tolerance of ±13.3 N/m^2 (0.1 mm Hg).

Thirty days (720 hours) of integrated operation were successfully completed. Figure 30 shows some performance indicating operating parameters of the integrated system. The system operated at an average four-man CO_2 removal and reduction rate for the first 60% of the test time. During the last 40% the average BRS reactor temperature was decreased from 950K (1250F) to 866K (1100F) to slow down the rate of carbon buildup in the regenerative heat exchangers. The decrease in temperature enabled successful completion of the 30-day endurance test. The capacity decreased to approximately the 3.6-man level.

The EDC was operated at 27 mA/cm^2 (25 ASF) to allow the three one-man capacity (by design) modules to operate at a four-man CO_2 removal rate. The 30 days of testing marked the first time a multi-man EDC system had operated for extended periods at the elevated current density level although smaller modules and single cells had demonstrated the capability. As Figure 30 shows, the EDC performed above projected levels. Twelve reactor changeover operations were performed during the 30 days. This required 13 cartridges for an average operating time of 55.4 hours per cartridge. No reaction startup problems were encountered.

All testing was performed using the original set of reactor seals. At the end of the 30-day test a visual inspection of the inner copper-coated stainless steel(9) surfaces of the reactors showed no carbon buildup or surface damage.

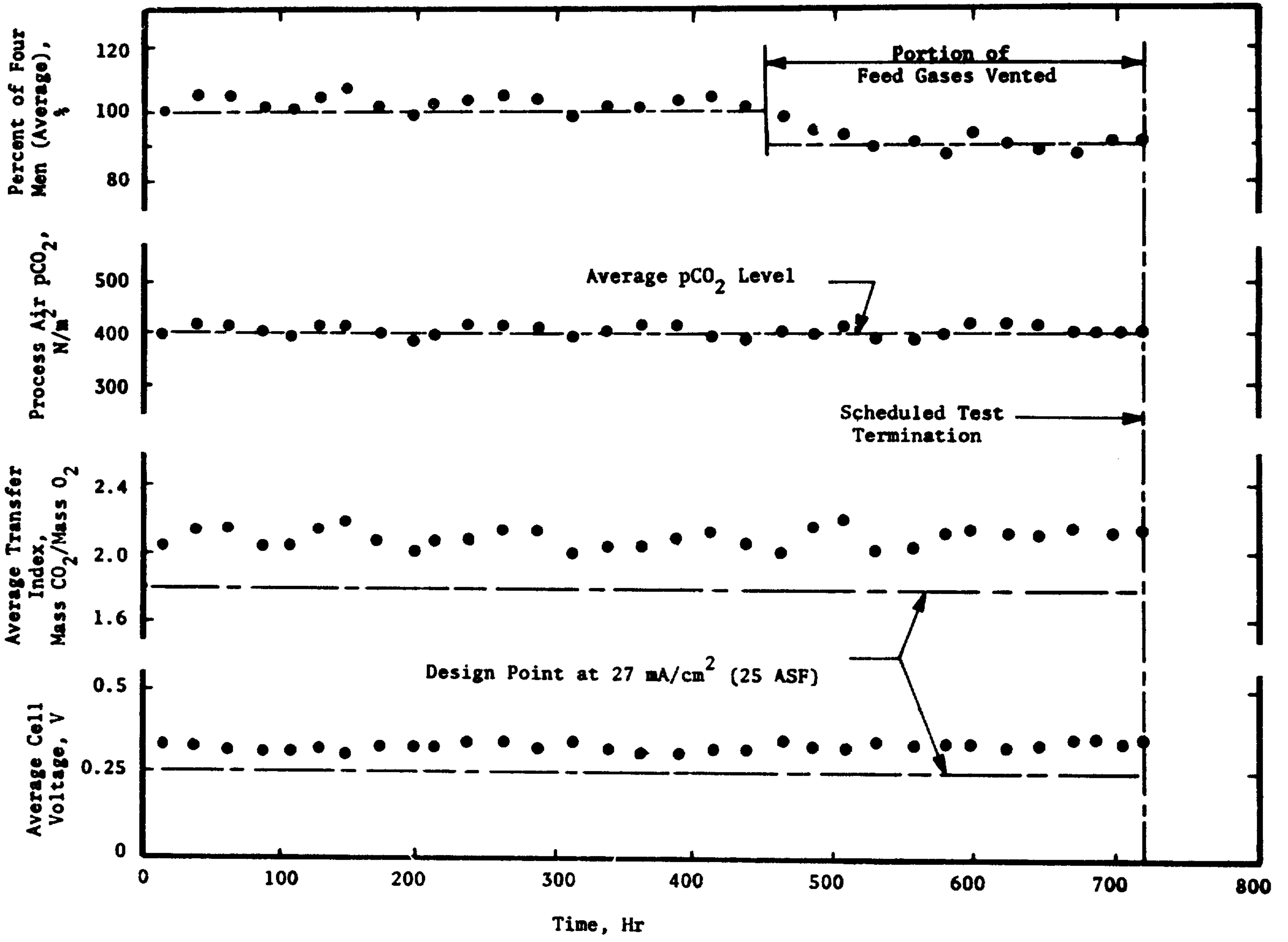


FIGURE 30 SYSTEM PERFORMANCE PARAMETERS AS A FUNCTION OF TIME, 30-DAY ENDURANCE TEST

A total of seven unscheduled shutdowns occurred, two due to loss in building power. Table 11 summarizes the causes.

Integrated Testing with Variable CO_2 Loading

Following completion of the hardware modifications to allow operation with variable CO_2 in the air processed by the EDC, additional tests were completed:

- Sensor calibration and shakedown test
- Maximum capacity test for both the EDC and the BRS at individual subsystem levels
- 45-day endurance test

BRS Sensor Calibration and Shakedown Tests

This testing was performed using GSA furnished gases. No problems were encountered. No shakedown testing was planned or required for the EDC.

Maximum Capacity Test

The objective of the maximum capacity tests was to determine whether the subsystems, on an individual basis, would have sufficient overcapacity to remove for the EDC and reduce for the BRS the amounts of CO_2 associated with the variable pCO_2 mission profile selected.

EDC Tests. The current density was maintained at the 27 mA/cm^2 (25 ASF) while the inlet process air pCO_2 was varied from 239 to 397 N/m^2 (1.79 to 2.98 mm Hg). At the reduced process air inlet pCO_2 levels the EDC had a CO_2 removal capacity equivalent to 3.5 ±0.1 man.

BRS Tests. The BRS was first tested with constant feed rate and composition to obtain an upper maximum limit of CO_2 reduction. It was found to be equivalent to a 4.7 man loading while maintaining recycle loop pressures constant.

The BRS was then operated with feed gases controlled by the variable pCO_2 controller simulating the anode exhaust gas of an EDC operating with variable pCO_2 levels. The CO_2 loading was varied from a 3.2 to a 4.5 man level. The BRS again operated successfully without showing a rise in recycle loop pressure.

During both the constant and variable CO_2 feed rate tests the reactor temperatures could be readily maintained at 923K (1202F). This verified that the regenerative heat exchangers incorporated were effective and could even maintain the higher level conversion capacities.

A total of 79 hours of operation were accumulated with the BRS during the maximum capacity tests.

Forty-Five Day Endurance Test

The objective of the 45-day endurance test was to verify that the integration

TABLE 11 30-DAY INTEGRATED TEST SHUTDOWN SUMMARY

1. BRS Recycle Loop High Pressure (Condenser/Heat Exchanger)
2. BRS Recycle Loop High Pressure (Condenser/Heat Exchanger)
3. Replacement of Condenser/Heat Exchanger
4. EDC Low Voltage Shutdown
5. Building Power Failure
6. EDC Low Voltage Shutdown
7. Building Power Failure

concept proven successful with constant CO_2 loading would also be successful with variable CO_2 loadings. Other objectives of the test included:

1. Characterizing performance under variable operating conditions
2. Developing optimum cartridge changeover procedure for improved purge technique
3. Obtaining dynamic response to variations in key operating parameters

Test System Configuration. To meet the test objectives required adding instrumentation and continuous recording equipment. Figure 31 is a block diagram of the 45-day test system. Five system parameters were selected for continuous recording:

1. Inlet process air to the EDC
2. BRS feed gas flow
3. pCO_2 of BRS feed gas
4. BRS recirculation loop pressure
5. BRS feed gas composition represented by the pH_2

A detailed schematic of the test setup was shown in Figure 17.

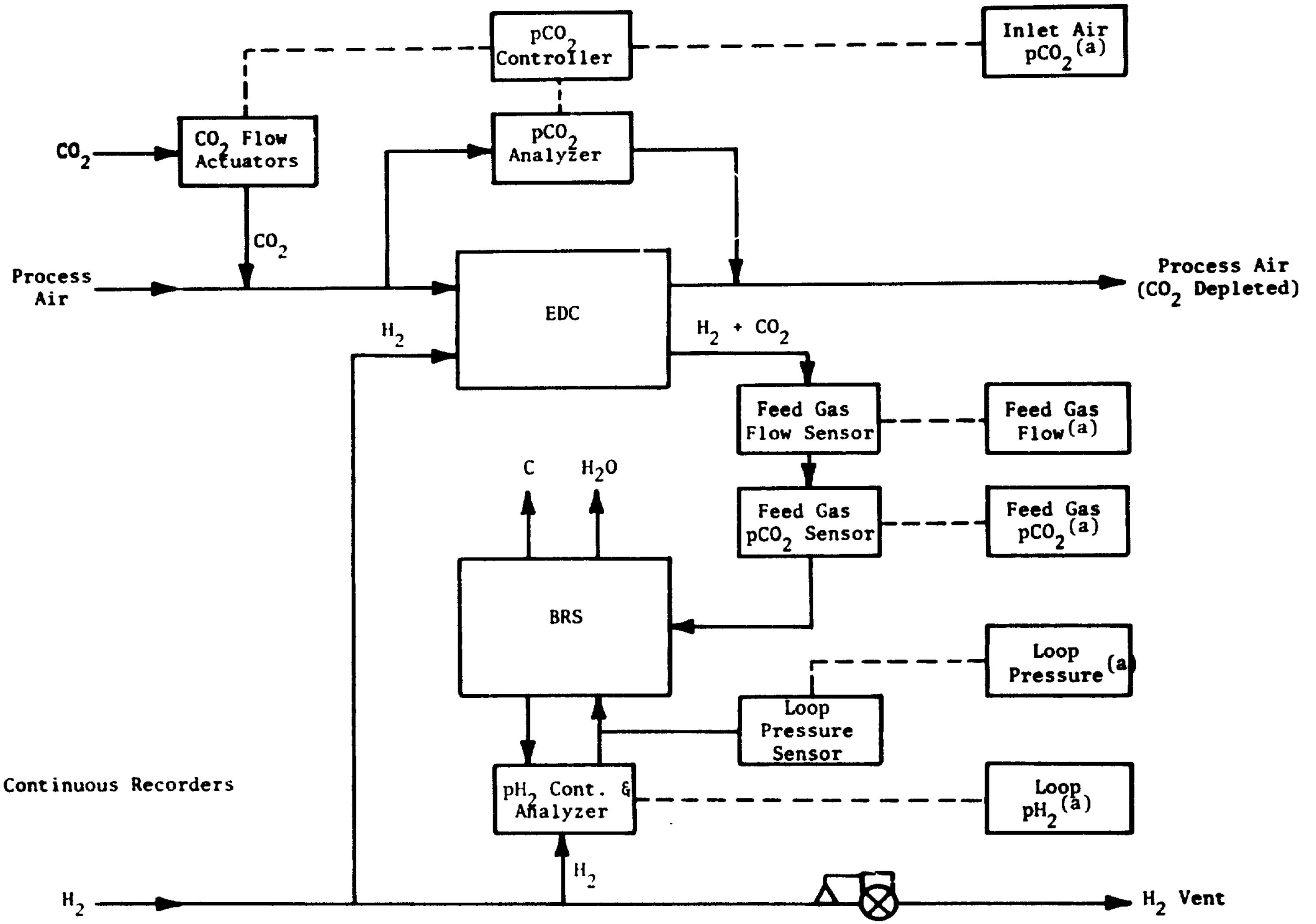
Performance as a Function of Time. Figure 32 shows pertinent system parameters as a function of the 1108 hours (46.2 days) of testing. The system capacity averaged 3.5 men based on the total amount of carbon collected. This compares well with the projected capacity based on the maximum capacity test results.

Seventeen cartridge changeovers were performed at an average of 65.2 hours per cartridge. Table 12 summarizes the related cartridge data. No problems were encountered with reaction startup times and reactor changeover for the 17 cartridges used.

Both subsystems performed at levels projected for the operating conditions. Tables 13 and 14 show the average operating conditions for the two subsystems during the test.

At various times the EDC was operated at the original baseline design level of 21.5 mA/cm^2 (20 ASF) and a pCO_2 level of 400 N/m^2 (3 mm Hg) to compare its CO_2 removal efficiency and electrical efficiency (cell voltage) with levels obtained at baseline operation during prior long-term testing. The values observed for the CO_2 removal and electrical efficiencies remained constant at levels previously obtained.(4-6) No degradation occurred as a function of time for the EDC, even when operated at 25% overdesign capacity. The results of the efficiency checks tests are shown on Figure 32.

Table 15 summarizes the performance of the EDC based on average and specific cartridges. The first column shows equivalent CO_2 removal efficiencies based on the total 17 cartridges. The second and fifth column were based on the average amount of carbon collected in cartridges 5 and 9, respectively. Columns 3 and 4 were based on water collection during pCO_2 step changes with



(a) Continuous Recorders

FIGURE 31 TEST SYSTEM BLOCK DIAGRAM, 45-DAY TEST

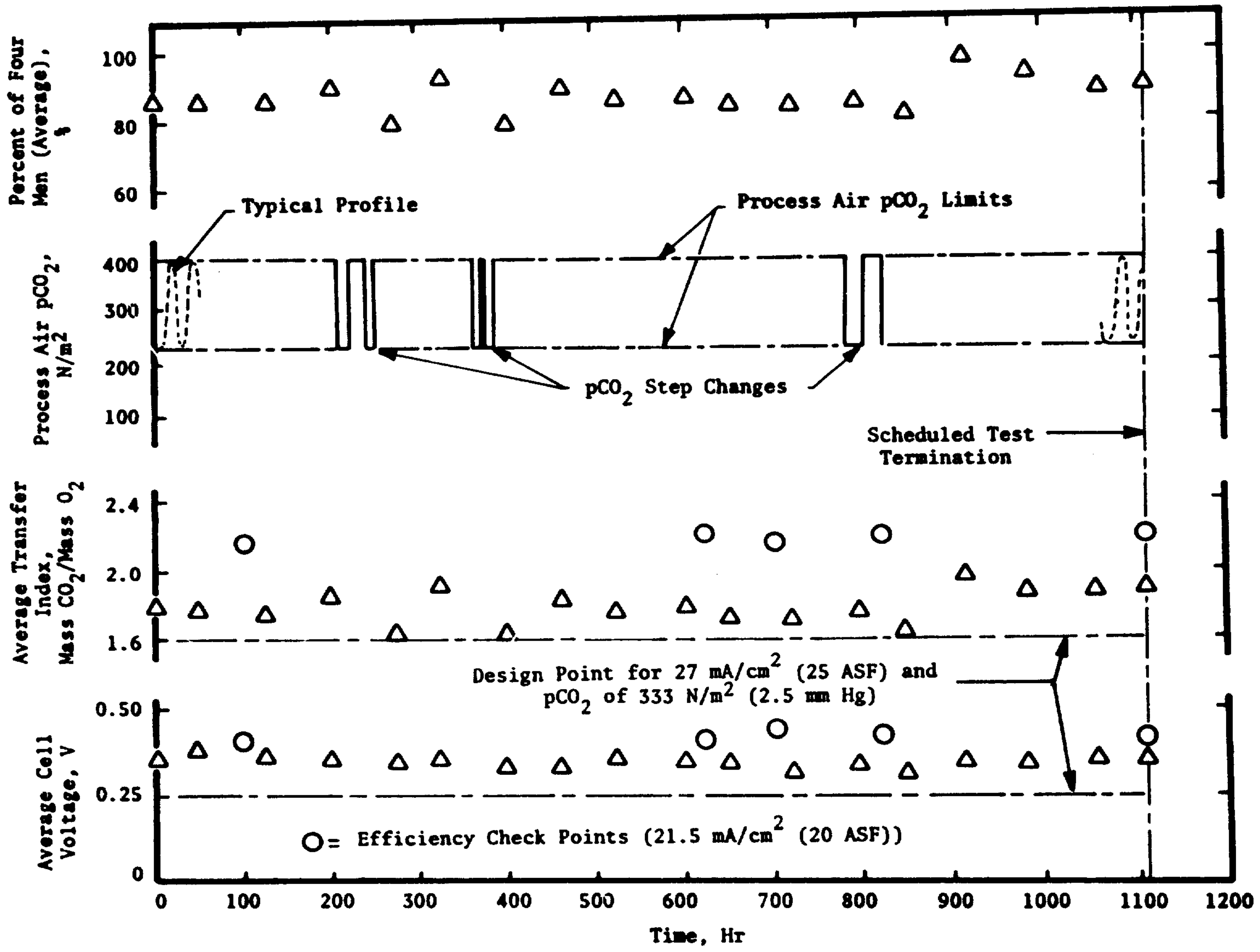


FIGURE 32 SYSTEM PERFORMANCE PARAMETERS AS A FUNCTION OF TIME, 45-DAY ENDURANCE TEST

TABLE 12 CARBON COLLECTION SUMMARY, 45-DAY ENDURANCE TEST

Cartridge Number	Reactor Number	Operating Time, Hr	Net Weight Gain in Carbon, kg (Lb)	Carbon Collection, kg/h (Lb/Hr)	Number of Equivalent Men(a)
1	1	51.0	2.01 (4.42)	0.0395 (0.0867)	3.47
2	1(b)	77.0	3.01 (6.62)	0.0391 (0.0860)	3.44
3	2	70.0	2.88 (6.34)	0.0411 (0.0906)	3.61
4	1	71.0	2.56 (5.63)	0.0361 (0.0793)	3.17(c)
5	2	56.0	2.34 (5.15)	0.0418 (0.0919)	3.67
6	1	77.5	2.79 (6.14)	0.0360 (0.0792)	3.16(c)
7	2	59.0	2.39 (5.26)	0.0406 (0.0891)	3.57
8	1	68.0	2.68 (5.90)	0.0394 (0.0867)	3.46
9	2	74.5	2.96 (6.51)	0.0397 (0.0874)	3.49
10	1	50.0	1.91 (4.20)	0.0382 (0.0840)	3.34
11	2	64.5	2.45 (5.39)	0.0380 (0.0836)	3.38
12	1	69.0	2.68 (5.89)	0.0388 (0.0854)	3.45
13	2	67.0	2.45 (5.39)	0.0366 (0.0804)	3.25(c)
14	1	54.0	2.36 (5.20)	0.0438 (0.0963)	3.89
15	2	76.5	3.19 (7.02)	0.0417 (0.0918)	3.71
16	1	75.0	3.01 (6.62)	0.0401 (0.0883)	3.57
17	2	48.0	1.93 (4.25)	0.0403 (0.0886)	3.58
Total:		1108.0	43.60 (95.92)	0.0394 (0.0866)	3.50

(a) Based on 1.0 kg (2.2 lb) CO_2 produced per man-day
(b) Only one reactor operational; No. 2 reactor heater sheath being repaired
(c) Low pCO_2 operation

TABLE 13 AVERAGE EDC OPERATING CONDITIONS, 45-DAY ENDURANCE TEST

Process Air	
Flow Rate, dm^3/min (Scfm)	991 (35)
Pressure, kN/m^2 (Psia)	97.8 (14.2)
Temperature, K (F)	290 (62)
Dew Point, K (F)	286 (55)
pCO_2 (Avg), N/m^2 (mm Hg)	339 (2.54)
H_2 Supply	
Flow Rate, dm^3/min (Scfm)	3.92 (0.138)
Pressure, kN/m^2 (Psia)	131 (19)
Temperature, K (F)	294 (70)
Dew Point, K (F)	289 (60)
EDC Module	
Current Density, mA/cm^2 (ASF)	27 (25)
Temperature, K (F)	295 (71)
H_2 Backpressure, kN/m^2 (Psia)	117 (17)
Cooling Air	
Flow Rate, m^3/min (Scfm)	5.1 (180)
Temperature, K (F)	283 (50)

TABLE 14 AVERAGE BRS OPERATING CONDITIONS, 45-DAY ENDURANCE TEST

Reactor Temperature, K (F)	923 (1202)
Heater Sheath Temperature, K (F)	1023 (1382)
Loop pH_2, %	40
Loop Pressure, kN/m^2 (Psig)[(a)]	
Reactor Inlet	24.1 (3.5)
Reactor Outlet	3.4 (0.5)
Feed Point	1.4 (0.2)
Recycle Loop Flow, dm^3/min (Scfm)	73.6 (2.6)
Feed Gas Flow, dm^3/min (Scfm)	
H_2 from EDC	1.85 (0.065)
CO_2 from EDC	1.34 (0.047)
H_2 from WES[(b)]	0.83 (0.029)
Feed Gas CO_2 from EDC, %	42
Feed Gas Ratio from EDC, H_2 to CO_2	1.38

(a) Above ambient
(b) Simulated with GSA

TABLE 15 EDC PERFORMANCE, 45-DAY ENDURANCE TEST

	Cartridge Number				
	1-17	5	4	4	9
pCO_2 Level, N/m^2 (mm Hg)					
Average	339 (2.54)	339 (2.54)	239 (1.79)[a]	397 (2.98)[a]	339 (2.54)
Minimum	239 (1.79)	239 (1.79)	-	-	239 (1.79)
Maximum	397 (2.98)	397 (2.98)	-	-	397 (2.98)
Carbon Collected, kg (Lb)	43.60 (95.92)	2.54 (5.59)	-	-	2.96 (6.51)
Operating Time, Hr	1108	56	-	-	74.5
Carbon Production Rate, kg/h (Lb/Hr)	0.039 (0.087)	0.042 (0.092)	-	-	0.040 (0.087)
Equivalent CO_2 Removal Rate, cm^3/Min	1338	1401	-	-	1372
Water Collected, kg (Lb)	-	-	0.77 (1.70)	2.42 (5.32)	-
Operating Time, Hr	-	-	7	18.8	-
Water Production Rate, kg/h (Lb/Hr)	-	-	0.110 (0.241)	0.129 (0.283)	-
Equivalent CO_2 Removal Rate, cm^3/Min	-	-	1239	1444	-
EDC Current, A	6.1	6.1	6.1	6.1	6.1
EDC Current Density, mA/cm^2 (ASF)	27 (25)	27 (25)	27 (25)	27 (25)	27 (25)
CO_2 Removal Efficiency					
Percent	64.6	67.7	60.0	70.0	66.3
TI(b)	1.78	1.86	1.65	1.92	1.82

(a) Constant pCO_2 levels

(b) Transfer Index, mass CO_2 removed per mass O_2 consumed column 3 showing a CO_2 removal efficiency of 60% for the lowest pCO_2 level and column 4 showing a CO_2 removal efficiency of 70% for the highest pCO_2 level.

All EDC operation shown in Table 15 is for a current density of 27 mA/cm^2 (25 ASF). The CO_2 removal efficiency obtained during the testing compared well with previous baseline data at the same conditions.(4)

The BRS performed within projected limits for the variable CO_2 loading as reflected by reactor temperature levels and recycle loop pressures. Reactor temperature could be maintained at 923K (1202F) while maintaing recycle loop pressures at less than 13.8 kN/m^2 (2 psig) above ambient.

Table 16 shows mass balances for three typical cartridges. They are based on total carbon and water produced and amount of CO_2 and H_2 fed from the EDC. Mass balance closure was achieved with a maximum percent error of 5.83, within the expected range.

During the test, only six unscheduled shutdowns occurred. Only the first was related to subsystem hardware failure. The control thermocouple on the heater sheath of reactor No. 2 failed closed causing heater failure. As shown in Table 17, the remaining five shutdowns were related to GSA or building power failures.

Cartridge Changeover Procedures. Prior to start of the 45-day test the GSA and test system hardware was modified to allow purging with a H_2 and CO_2 gas mixture from the GSA. This alternate technique was developed to eliminate BRS recycle loop pressure buildup during reactor changeover as discussed previously.

Various techniques for cartridge changeover were investigated and are discussed elswhere in this report. The procedure adopted consisted of:

1. Inserting new cartridge
2. Purging with five volumes of simulated EDC anode exhaust gas
3. Preheating reactor to 823K (1022F)
4. Actuating four-way reactor switchover valve.

Figure 33 is a tracing of the recorder printouts of the recirculation loop gas composition and pressure levels during a typical cartridge changeover. It shows that the pressure level rose only slightly from near zero to approximately 7 kN/m^2 (1 psig) at actuation of the reactor changeover valve. At the same time only a slight perturbation in recycle loop gas composition was noted. Within four to eight minutes gas composition was restabilized and recirculation loop pressure decreased as the newly charged reactor initiated feed gas conversion.

It should be noted that for the cartridge illustrated a step change from the minimum to the maximum pCO_2 level of the profile was performed approximately 1.5 hours after reactor changeover. The purpose was to check cartridge changeover under the most severe operating conditions. Even then, the changeover was successfully completed.

TABLE 16 SAMPLE MASS BALANCES, 45-DAY ENDURANCE TEST

	Cartridge Number		
	5	10	9
Time On Line, Hr	56	50	74.5
Carbon Collected, kg (Lb)	2.34 (5.15)	1.91 (4.20)	2.96 (6.51)
Average Carbon Collection Rate, kg/h (Lb/Hr)	0.042 (0.092)	0.038 (0.084)	0.040 (0.087)
Number of Equivalent Men (Carbon Base)(a)	3.67	3.34	3.49
Water Collected, kg (Lb)	6.78 (14.92)	5.75 (12.65)	8.94 (19.67)
Average Water Collection Rate, kg/h (Lb/Hr)	0.121 (0.266)	0.115 (0.253)	0.120 (0.264)
Number of Equivalent Men (Water Base)(a)	3.60	3.38	3.53
Average CO_2 Flow Rate, cm^3/Min	1455	1325	1372
Number of Equivalent Men (CO_2 Base)(a)	3.81	3.47	3.59
Error, Maximum, %	5.83	3.89	2.87

(a) Based on 1.0 kg (2.2 lb) CO_2 produced per man-day

TABLE 17 45-DAY INTEGRATED TEST SHUTDOWN SUMMARY

1. Heater sheath thermocouple electrical short (No. 2 Reactor)
2. EDC process air inlet dew point from GSA exceeded preset limit
3. Electrical relay (GSA) failure, total power loss to test system and all GSA
4. EDC process air inlet dew point from GSA dropped below preset limit
5. Building electrical power failure
6. Electrical relay (GSA) failure total power loss to test system and all GSA

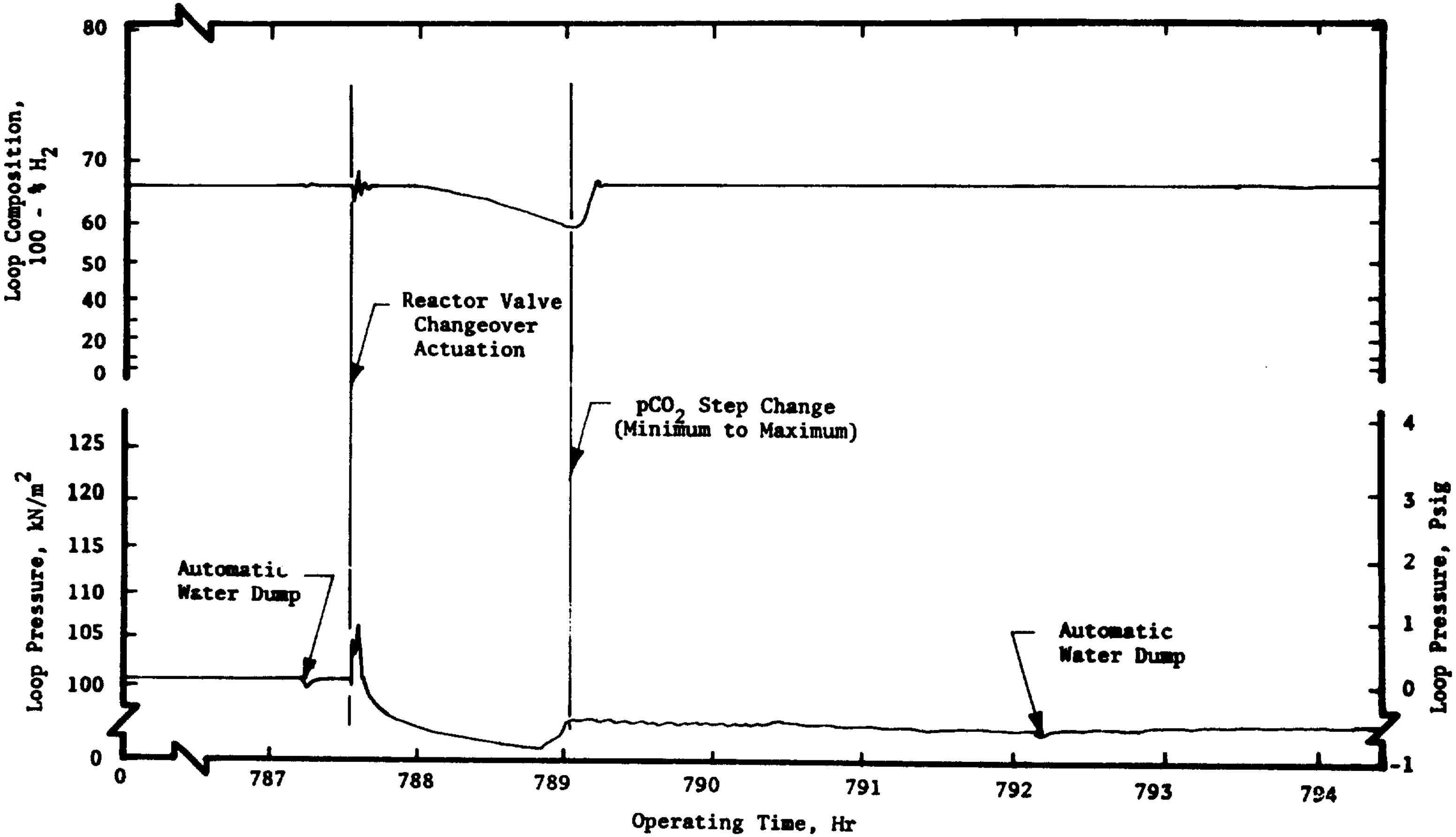


FIGURE 33 BRS LOOP COMPOSITION AND LOOP PRESSURE VARIATIONS AS A FUNCTION OF TIME DURING CARTRIDGE CHANGEOVER

pCO$_2$ Step Change Tests. At various times during the 45 day test the variable pCO$_2$ profile loading of the EDC process air was interrupted and the integrated system was operated at constant CO$_2$ levels. The levels chosen were the minimum and maximum of the profile (239 N/m^2 (1.79 mm Hg) and 397 N/m^2 (2.89 mm Hg, respectively)). Also, to obtain dynamic responses of the system for projected worst case conditions, the changes from minimum to maximum and maximum to minimum pCO$_2$ levels were accomplished in a step-wise fashion.

Figure 34 reproduces the recorder traces for the feed gas flow rate, feed gas composition, pCO$_2$ of the process air, recirculation loop gas composition and recirculation loop pressure.

The step changes reviewed in Figure 34 included constant operation at the maximum pCO$_2$ level followed by a step change to the minimum level and operation at that level for approximately 7.5 hours before returning to the cyclic profile.

Changes in feed gas flow rate and feed gas composition reacted quickly to the changes in EDC process air inlet conditions. A decrease of approximately 3.5 N/m^2 (0.5 psi) in operating loop pressure is noted when minimum pCO$_2$ levels were reached. No change in feed gas composition can be detected indicating that the feed gas loop composition control was capable of handling the step changes. The reduction in recirculation loop pressure levels is a direct result of the automatic decrease in recirculating gas flow rates within the BRS to accommodate the decrease in the total amount of CO$_2$ added to the loop.

Based on the data collected during the pCO$_2$ step change tests, the integration concept developed is readily capable of accommodating projected changes in spacecraft cabin pCO$_2$ levels.

SUPPORTING ACTIVITIES

Supporting activities completed on the program included:

1. Demonstrating BRS operation without startup problems
2. Evaluating carbon collection cartridge changeover techniques
3. Establishing that an interface accumulator is not required
4. Solving several hardware problems

No BRS Startup Problems

The catalyst preparation and loading techniques used avoided long-term BRS startup times previously reported.(11,12) Table 18 lists the startup times experienced on the first 15 cartridges after which time the data was no longer recorded. Startup times were normally a function of reactor temperatures, with the time to reach reaction initiation dependent on reactor heater power input.

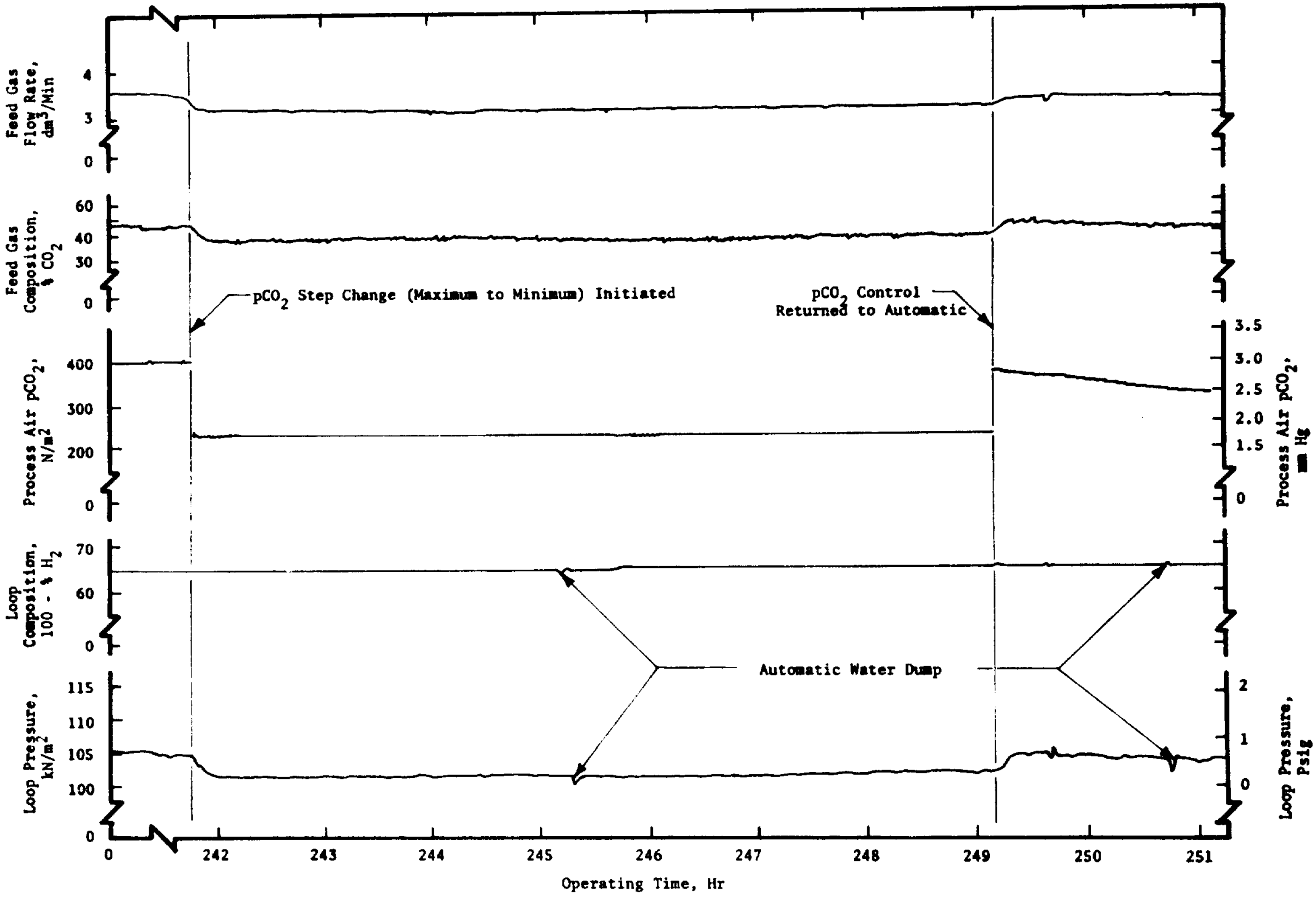


FIGURE 34 SYSTEM PERFORMANCE PARAMETERS DURING pCO_2 STEP CHANGE TEST

TABLE 18 BRS STARTUP TIMES

Cartridge No.	Time to Reaction Initiation, Hr	Temperature, K (F)
1	2.0	645 (705)
2	1.5	760 (910)
2(a)	3.0	845 (1060)
3	3.0	910 (1180)
4	3.0	775 (940)
5	2.0	775 (940)
5(a)	1.5	645 (700)
5(a)	2.0	690 (780)
6	2.0	700 (800)
6(a)	1.5	675 (750)
7	2.0	760 (910)
7(a)	1.0	705 (810)
8	2.0	815 (1010)
9	2.0	905 (1170)
10	1.5	855 (1080)
11	1.0	690 (780)
11(a)	1.5	675 (750)
12	1.5	765 (920)
13	2.0	700 (800)
14	1.5	665 (740)
15	2.0	761 (910)

(a) Signifies cartridge restarts after cool-down

Cartridge Changeover Considerations

A simplified cartridge changeover technique was evolved and verified. The new technique is useable for advanced BRS hardware.

Initial Procedure

Cartridge changeover required the cold reactor be purged with approximately ten volumes of CO_2. Reactor heating was then initiated. The gas had to be recirculated through the cold reactor to obtain short preheating times.

Since the BRS used was a one-compressor unit, the gases present in the recirculation loops and the two reactors were mixed during the recirculation phase of preheating. This resulted in an increase in the pCO_2 level which the infrared analyzer sensed and initiated additional H_2 flow to dilute the mixture. The added H_2 increased the reactor loop pressure above tolerable limits unless loop venting was used. Manual manipulation of the valves and automatic pressure relief were needed to maintain pressures.

Procedures Developed for Advanced BRS

A cartridge changeover technique for an advanced BRS was proposed in a previous study.(29) This technique would utilize reactor evacuation followed by refilling with recycle loop gas from the operating reactor. A pressure decrease would result within the recycle loop of the active reactor to approximately half its initial operating pressure until the feed gases from the EDC flowed sufficiently into the recycle loop of the new reactor to bring its pressure to nominal operating point. The reactor containing the spent cartridge at one-half of its original operating pressure could then be evacuated with loss of only one half of a recycle loop volume of gases.

The above technique, while considered most applicable for a flight-type system, was not used since the present BRS hardware could not tolerate the needed vacuum. As a result, alternative techniques had to be studied.

Technique Selection Criteria

The preferred cartridge changeover procedure was established to be one:

1. causing minimum loop pressure and/or gas composition perturbations,
2. that was simple and could be automated, and
3. that was flight qualifiable.

Techniques Identified

Four changeover techniques were investigated:

1. Purge with CO_2, preheat, circulate portion of loop gas through new cartridge, actuate changeover valve

2. Purge with CO_2, preheat, actuate changeover valve

3. Purge with CO_2 + H_2, preheat, circulate portion of loop gas through new cartridge, actuate changeover valve

4. Purge with CO_2 + H_2, preheat, actuate changeover valve

The last technique was the simplest and satisfied the selection criteria. The technique was first verified during cartridge changeover No. 12 (see Figure 33) and used during the remaining 45-day test changeovers.

No Interface Accumulator Required

Initially, there was concern whether an accumulator was needed to lessen pressure spikes during reactor changeover operations. When a cartridge is replaced the interior of the reactor is exposed to air and subsequently purged before reheating. On heating, the gas inside increases in pressure. When placed "on line" it comes into equilibrium with the recycle loop gases causing an increase in total subsystem pressure.

If the BRS is operated only with its GSA the above increase in pressure is controlled by a corresponding decrease in flow through the feed gas regulators. In an integrated mode, however, the supply gas is constantly fed from the EDC and cannot simply be decreased to compensate for the pressure increases.

A refurbished reactor will increase the BRS pressure from 100 kN/m^2 (1 psig) to 140 kN/m^2 (5.5 psig), assuming the unspent volume equals the recycle loop and spent reactor volumes. For BRS operation with gases supplied by GSA, a decrease in feed rate would occur until a sufficient amount of H_2 and CO_2 is consumed to decrease loop pressure below the H_2 feed regulator's 125 kN/m^2 (3.5 psig) setting.

In the integrated mode, the added volume of the interface hardware reduces the subsystem pressure increase to less than 132 kN/m^2 (4.5 psig). Since the EDC is operated with a 136 kN/m^2 (5 psig) anode exhaust backpressure, the interface hardware acts as a surge tank and absorbs fluctuations caused by reactor changeovers without affecting EDC anode exhaust flow. The need for a separate interface accumulator was not required.

Problems Solved

During the course of the program three hardware failures required modifications and repair.

- Failure of the regenerative heat exchangers
- Failure of the condenser/separators
- Failure of one heater sheath thermocouple

Two regenerative heat exchangers used previously on a more advanced BRS(11) were adapted to the existing BRS hardware. The original unit's heat exchanger failed due to carbon buildup. No carbon buildup was noted during the 45 days of testing with the new hardware.

Leaks and high coolant loop pressure drop in the BRS condenser/separator were experienced at various times during testing. The unit was repaired and modified and functioned satisfactorily for the remainder of testing.

The control thermocouple located on the inside of the No. 2 reactor heater sheath shorted causing heater and heater sheath cladding (copper) failures. A new heater was installed and a new copper cladding was fabricated.

CONCLUSIONS

Based on the activities performed under this contract, the following conclusions are drawn:

1. The control and interfacing concept derived allows for integrated operation of an Electrochemical Depolarized CO_2 Concentrator (EDC) and a Bosch CO_2 Reduction Subsystem (BRS) as part of an overall Air Revitalization System (ARS) for manned missions having variable CO_2 loading profiles.

2. The carbon collection cartridge changeover procedure developed allows for smooth transition between reactors without adverse pressure or gas composition perturbations, is adaptable to the advanced BRS configuration having two individual recirculation loops and is flight qualifiable.

3. The catalyst and its loading technique used avoid BRS reaction startup problems, as demonstrated for all 41 carbon collection cartridges used.

4. An interface accumulator is not required to act as a surge tank for dampening pressure fluctuations during carbon collection cartridge changeover.

5. The copper cladding used to prevent carbon formation within the BRS reactors showed negligible signs of carbon reaction after the additional 2,350 hours of testing on the hardware.

6. The reactor seals operating in a heated zone (922K (1200F)) successfully passed through the 2,350 hours of BRS testing which included 41 reactor openings and closings, half on each reactor seal. Additional testing would, however, require seal replacement.

7. The EDC successfully operated at 27 mA/cm^2 (25 ASF) or 25% above design current density for the 2,140 hours of testing without degradation in CO_2 removal or voltage efficiencies.

8. Operation with cyclic SSP mission metabolic CO_2 loading reduced the capacity of the integrated system by approximately 12%, i.e., crew of 4.0 instead of 3.5, compared to operating at a constant pCO_2 level of 400 N/m^2 (3.0 mm Hg).

RECOMMENDATIONS

Based on the program results the following recommendations are made:

1. Convert the existing integrated EDC/BRS hardware into a total Oxygen Reclamation System (ORS) by including an Oxygen Generating Subsystem (OGS) and zero gravity compatible Water Collection and Distribution Hardware (WCDH).
2. Incorporate the advanced, four-man capacity EDC module characterized by higher CO_2 removal and electrical efficiencies and 64% reduction in weight and 57% reduction in volume.(8)
3. Incorporate the advanced BRS reactors to allow simulation of vacuum purging projected for spacecraft application.
4. Incorporate advanced instrumentation at the subsystem as well as at the integrated system level to allow for increased performance trend and fault detection and isolation analyses and to provide maintenance aids to decrease operator time during system testing.
5. Incorporate an alternate catalyst configuration(32) shown to reduce recycle loop power requirements by decreasing pressure drops through the reactors. This configuration would consist of a sheet metal (iron) convolute having a star-shaped cross section.

REFERENCES

1. Davenport, R. J., Schubert, F. H., Shumar, J. W. and Steenson, T. S., "Evaluation and Characterization of the Methane-Carbon Dioxide Decomposition Reaction," Final Report, Contract NAS8-30748, ER-207-3, Life Systems, Inc., Cleveland, OH, June, 1975.

2. Wynveen, R. A. and Quattrone, P. D., "Electrochemical Carbon Dioxide Concentrating System" ASME Paper No. 71-AV-21, San Francisco, CA, July 12-14, 1971.

3. Wynveen, R. A., Schubert, F. H. and Powell, J. D., "One-Man, Self-Contained Carbon Dioxide Concentrating System," Final Report, Contract NAS2-6118, CR-114426, Life Systems, Inc., Cleveland, OH, March, 1972.

4. Marshall, R. D., Schubert, F. H. and Carlson, J. N., "Electrochemical Carbon Dioxide Concentrator: Math Model," Final Report, Contract NAS2-6478, CR-114639, Life Systems, Inc., Cleveland, OH, August, 1973.

5. Powell, J. D., Schubert, F. H., Marshall, R. D. and Shumar, J. W., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem," Final Report, Contract NAS2-6478, CR-114743, Life Systems, Inc., Cleveland, OH, June, 1974.

6. Kostell, G. D., Schubert, F. H., Shumar, J. W., Hallick, T. M. and Jensen, F. C., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem for Space Station Prototype (SSP) Application," Final Report, Contract NAS2-6478, CR-114742, Life Systems, Inc., Cleveland, OH, May, 1974.

7. Wynveen, R. A., Schubert, F. H., Kostell, G. D., Hallick, T. M. and Quattrone, P. D., "Electrochemical Concentration of Carbon Dioxide Aboard Spacecraft," Paper No. 74-109, International Astronautical Federation Congress, Amsterdam, The Netherlands, September 30 to October 5, 1974.

8. Schneider, J. J., Schubert, F. H., Hallick, T. M. and Woods, R. R., "Electrochemical Carbon Dioxide Concentrator Advanced Technology Tasks," Final Report, Contract NAS2-6478, CR-137732, Life Systems, Inc., Cleveland, OH, October, 1975.

9. Holmes, R. F., Keller, E. E. and King, C. D., "A Carbon Dioxide Reduction Unit Using Bosch Reaction and Expendable Catalyst Cartridges," CR-1682, Convair Division of General Dynamics, San Diego, CA, November, 1970.

10. King, C. D., Holmes, R. F. and Keller, E. E., "Design Optimization Studies for CO_2 Reduction by the Bosch Process," Report No. GDC-ERR-1658, Convair Division of General Dynamics, San Diego, CA, December, 1971.

11. Holmes, R. F., King, C. D. and Keller, E. E., "Bosch CO_2 Reduction System Development," Interim Report, GDCA-DBD73-001, Contract NAS8-27276, Convair Division of General Dynamics, San Diego, CA, January, 1973.

12. Manning, M. P. and Reid, R. C., "Carbon Dioxide Reduction by the Bosch Process," ASME Paper No. 75-ENAs-22, San Francisco, CA, July 21-24, 1975.

13. Schubert, F. H., "Long-Term Operation of a Water Electrolysis Module," SAE Paper No. 690643, Los Angeles, CA, October, 1969.

14. Gillen, R. J., Greenough, B. M., Mills, E. S., Sanderson, W. G. and Schubert, F. H., "Six-Month Test Program of Two Water Electrolysis Systems for Spacecraft Cabin Oxygen Generation," ASME Paper No. 72-ENAv-5, San Francisco, CA, August 14-16, 1972.

15. Schubert, F. H., "Status of the Life Systems' Static Feed Water Electrolysis System," ASME Paper No. 71-AV-25, San Francisco, CA, July 12-14, 1971.

16. Greenough, B. M., "Status of the LMSC Circulating Electrolyte Water Electrolysis System," ASME Paper No. 71-AV-20, San Francisco, CA, July 12-14, 1971.

17. Greenough, B. M., "The Development of a Noncryogenic Nitrogen/Oxygen Supply Technique," CR-114912, Lockheed Missiles and Space Co., Sunnyvale, CA, 1971.

18. Porter, Jr., F. J., "Development of a Solid Polymer Electrolyte Electrolysis Cell Module and Ancillary Components for a Breadboard Water Electrolysis System," Final Report, Contract NAS1-9750, CR-112183, General Electric Co., Lynn, MA, August, 1972.

19. Nuttall, L. J. and Titterington, W. A., "Development Status of Solid Polymer Electrolyte Water Electrolysis for Manned Spacecraft Life Support Systems," ASME Paper No. 74-ENAs-2, Seattle, WA, July 29 - August 1, 1974.

20. Powell, J. D., Schubert, F. H. and Jensen, F. C., " Static Feed Water Electrolysis Module," Final Report, Contract NAS2-7470, CR-137577, Life Systems, Inc., Cleveland, OH, November, 1974.

21. Quattrone, P. D., Babinsky, A. D. and Wynveen, R. A., "Carbon Dioxide Control and Oxygen Generation," ASME Paper No. 70-AV/SpT-8, Los Angeles, CA, June 21-24, 1970.

22. Kiraly, R. J., Powell, J. D., Huebscher, R. G. and Babinsky, A. D., "Aircrew Oxygen System Development, Laboratory Breadboard System Test Report," Contract NAS2-4444, CR-73396, TRW, Inc., Cleveland, OH, July, 1970.

23. Huddleston, J. C. and Aylward, Dr. J. R., "Development of an Integrated Water Vapor Electrolysis Oxygen Generator and Hydrogen Depolarized Carbon Dioxide Concentrator," Contract NAS9-11830, CR-115575, Hamilton Standard, Windsor Locks, CT, May, 1972.

24. Samonski, F. G. and Neel, J. M., "Atmosphere Revitalization for Manned Spacecraft - An Assessment of Tehcnology Readiness," 24th IAF Congress, Baku USSR, October, 1973.

25. "Space Station Prototype Environmental Control/Life Support System," Final Report, Contract NAS9-10273, Document No. 165, Hamilton Standard, Windsor Locks, CT, October, 1973.

26. Quattrone, P. D., "Spacecraft Oxygen Recovery System," Astronautica Acta, Vol. 18, pp 261-271, 1973.

27. Woods, R. R., Schubert, F. H. and Hallick, T. M., "Electrochemical Air Revitalization System Optimization Investigation," Final Report, Contract NAS9-14301, ER-247-3, Life Systems, Inc., Cleveland, OH, October, 1975.

28. Mills, E. S., Linzey, T. J. and Harkee, J. F., "Oxygen Recovery for the 90-Day Space Station Simulator Test," ASME Paper No. 71-AV-18, San Francisco, CA, July 12-14, 1971.

29. Schubert, F. H., "A Study of the Integration of the Electrochemical Depolarized Carbon Dioxide Concentrator and Bosch Carbon Dioxide Reduction Subsystem," Final Report, Contract NAS8-29623, ER-185-4, Life Systems, Inc., Cleveland, OH, June, 1974.

30. North, B. F., "NASA/Langley Integrated Life Support System Program Summary for the Period February 1966 Through August 1967," Report No. GDC-DBD67-003, Convair Division of General Dynamics, San Diego, CA, November, 1967.

31. Schubert, F. H. and Marshall, R. D., "Integrated Water Vapor Electrolysis and Electrochemical Depolarized Concentrator," Annual Status Report, IRAD 1523 Program, ER-192, Life Systems, Inc., Cleveland, OH, April, 1973.

32. Shumar, J. W., See, G. G., Schubert, F. H., and Powell, J. D., "Solid Electrolyte Oxygen Regeneration System," Final Report, ER-190-12, Life Systems, Inc., Cleveland, OH, March, 1976.