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Advanced CO_2 Removal Process Control and Monitor Instrumentation Development

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Life Systems, Inc.

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Space Administration

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FOREWORD

This report summarizes the development work of Advanced CO_2 Removal Process Control and Monitor Instrumentation conducted by Life Systems, Inc., during the period of June, 1980 to January, 1982, under NASA Contract NAS2-10674. The Program Manager was Dr. Dennis B. Heppner. Technical Support was provided by R. Klimas, M. J. Dahlhausen, D. W. Johnson, F. H. Schubert and Dr. R. A. Wynveen. Administrative and documentation support was provided by D. A. Jones, C. P. Mayo and M. Prokopcak.

The authors wish to acknowledge the technical contributions, support and program guidance offered by the program Technical Monitor, P. D. Quattrone, Chief, Advanced Life Support Office, NASA, Ames Research Center.

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LIST OF ACRONYMS

A/D	Analog/Digital
ALSS	Advanced Life Support Systems
ARS	Air Revitalization System
ARX-1	Air Revitalization System, One-Person Experimental
BID	Built-in Diagnostic
CCA	Coolant Control Assembly
C/M I	Control/Monitor Instrumentation
CPU	Central Processing Unit
CRT	Cathode-Ray Tube
CS-1	One-Person CO_2 Concentrator Subsystem
D/A	Digital/Analog
DARS	Data Acquisition and Reduction System
EDC	Electrochemical Depolarized CO_2 Concentrator
EDCM	EDC Module
EPROM	Erasable Programmable Read-Only Memory
FCA	Fluid Control Assembly
IC	Integrated Circuit
I/O	Input/Output
ISCM	In Situ Cell Maintenance
LED	Light Emitting Diode
LVDT	Linear Variable Differential Transformer
MDS	Microcomputer Development System
MDT	Mean-Down-Time
M/E A	Mechanical/Electrochemical Assembly
MTBF	Mean-Time-Between-Failure
MTBM	Mean-Time-Between-Maintenance
MTTR	Mean-Time-To-Repair
NASA	National Aeronautics and Space Administration
μP	Microprocessor
PL/M	Programming Language for Microprocessors
POR	Power On Reset
RAM	Random Access Memory
R&D	Research and Development
RH	Relative Humidity
RLSE	Regenerative Life Support Evaluation
S/C	Signal Conditioning
S/D	Shutdown
SOC	Space Operations Center
SRAM	Static Random Access Memory
TSA	Test Support Accessories
VPI	Valve Position Indicator
WWMS	Waste Water Management System

SUMMARY

Development of regenerative Advanced Life Support Systems requires instrumentation characteristics which evolve with successive development phases. As the development phase moves toward flight hardware, the system availability becomes an important design aspect which requires high reliability and maintainability. As part of a continuing development effort, a program to evaluate, design and demonstrate major advances in control and monitor instrumentation was undertaken by Life Systems. This program was directed toward a specific subsystem, a carbon dioxide removal process, one whose maturity level makes it a prime candidate for early flight demonstration. As such, the instrumentation design incorporates features which are compatible with anticipated flight requirements.

An important benefit of the program is the demonstration that the instrumentation is reaching its maturity at the same rate as the mechanical/electrochemical components for regenerative processes development for the spacecraft atmosphere revitalization. Current electronics technology and projected advances are included. In addition, The program established commonality of components for all Advanced Life Support Subsystems. In addition, it reduced the instrumentation development effort and the risks for individual subsystems as well as the integrated systems. The program provided a focal point for the instrumentation development effort and resulted in a coordinated program to ensure the instrumentation readiness for long-term manned space missions.

It was concluded from the studies and design activities conducted under this program that the next generation of instrumentation will be greatly "smaller" than the prior one. Not only physical size but weight, power and heat rejection requirements have been reduced in the range of 80-85% from the former level of research and development instrumentation. Using a microprocessor-based computer, a standard computer bus structure and non-volatile memory, improved fabrication techniques and aerospace packaging this instrumentation will greatly enhance overall reliability and total system availability.

INTRODUCTION

Under previous contracts NAS2-9251 and NAS2-10050, Research and Development (R&D) type Control/Monitor Instrumentation (C/M I) had been developed.[(1-3)] This type of C/M I, referred to as Series 100 C/M I, was designed specifically for the development and testing of laboratory breadboard Advanced Life Support Systems (ALSS) hardware. The capability of the Series 100 was focused primarily on providing testing flexibility for those subsystems or systems in the early stages of development.

As flight application of ALSS's and, in particular, regenerative air revitalization comes closer, the "push" for reducing C/M I size, including weight and power, becomes greater. The C/M I must become more dedicated to only needed capabilities. Efforts must be directed toward the development of flight qualifiable C/M I concepts in keeping, however, with the electronic hardware to be available during the flight application time period. This is needed to

(1-3) References cited at the end of this report.

ensure a development status comparable to and compatible with the ALSS chemical process hardware.

The subject program takes the next logical step in the evaluation of ALSS flight C/M I. This step is called the Series 200 C/M I. In order to focus on a point design, the program utilized the Electrochemical Carbon Dioxide (CO_2) Concentrator (EDC) removal process as a demonstrator of the flight qualifiable C/M I concepts and capabilities. The program was directed toward the definition, quantification and detailed design of the C/M I for a regenerative chemical process for CO_2 control aboard an enhanced Shuttle Orbiter and/or a Space Operations Center (SOC).

Background

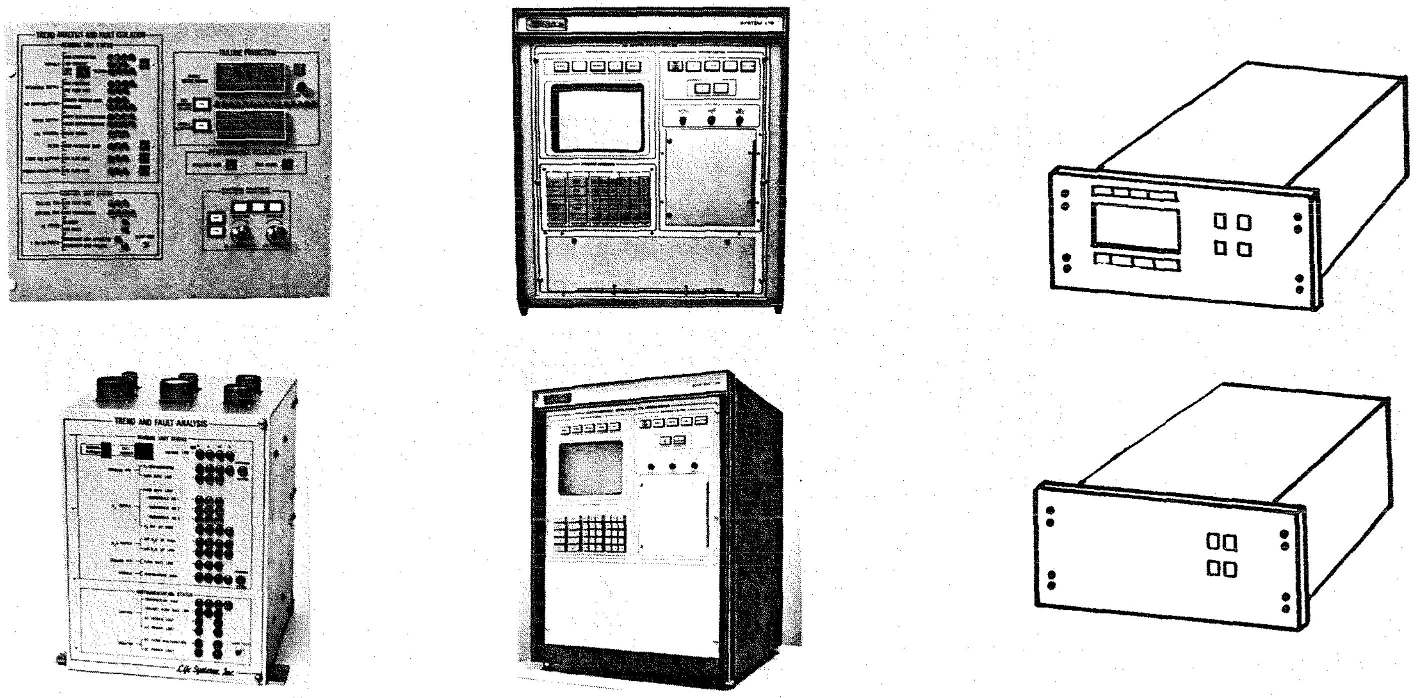
Regenerative ALSS processes have been under development for many years. The ALSS consists of two major systems: the regenerative Air Revitalization System (ARS) and the Waste Water Management System (WWMS). Life Systems, Inc. (LSI) has been involved in the design, development and testing of ARS subsystems to remove excess moisture from the air, concentrate CO_2 from the air, reduce CO_2 to water and methane or carbon, generate oxygen (O_2) from water, resupply nitrogen (N_2) and provide N_2 and hydrogen (H_2) separation. In addition, LSI has also developed a separate Independent Air Revitalization System (IARS) and a water reclamation subsystem using Vapor Compression Distillation (VCD) technology.

Because the applications of the National Aeronautics and Space Administration (NASA) requires low launch weight and long operating life based on in-flight maintenance, it is essential that the C/M I development is in pace with the electrochemical and mechanical process development. This is especially important because the actual flight of the ALSS hardware can be several years in the future. Because the technology associated with components of the electronic engineering field is expanding rapidly, the advancements projected for the electronics industry must be taken into consideration now when designing the C/M I for the advanced ALSS processes.

The ALSS instrumentation has advanced through a series of subsystem development programs including CO_2 removal, CO_2 reduction, O_2 generation and N_2 generation.[4-8] The instrumentation trend is depicted in Figure 1. In the past, the C/M I was typically designed with hard-wired logic circuits with fault detection, built-in checkout and limited fault avoidance/prediction capability. Instrumentation adjustments were made through potentiometers and switches. Displays typically used multiple level indicators and panel meters.

The current generation of C/M I is designed around a minicomputer.[9] Flexibility and operator/system interface are emphasized because it is primarily designed for the development and testing of ALSS process hardware under a laboratory R&D environment. The present R&D type C/M I features a cathode-ray tube (CRT) message display, advanced operator command keyboard, fault avoidance, fault prediction, fault detection, R&D flexibility and interface to a hard-copier/Data Acquisition and Reduction System (DARS). Based on this technology, a series of minicomputer-based, dedicated instrumentation hardware was developed for controlling and monitoring a

Past (1970-1976) | **Current (1976-1981)** | **Future (Post 1981)**



Past (1970-1976)

- Hardwired
- Four-level indicator
- Adjustment potentiometers/ switches
- Limited fault avoidance/ prediction
- Fault detection
- Built-in Checkout

Current (1976-1981)

- Minicomputer-based
- CRT display
- Advanced operator command keyboard
- Fault avoidance/prediction
- Fault detection
- R&D flexibility
- Interface to hard-copier
- Interface to DARS

Future (Post 1981)

- Microprocessor-based
- Flight-oriented design
- Interface to central computer
- Fault avoidance/prediction
- Fault detection
- Maintenance aids
- Fault tolerance
- Built-in Diagnostic/ Checkout
- Advanced control techniques
- Smaller size
- Availability vs. weight penalty optimized

FIGURE 1 TREND OF ALSS INSTRUMENTATION

variety of experimental ALSS hardware including an experimental, integrated one-person Air Revitalization System (ARX-1) and four subsystems for the three-person Regenerative Life Support Evaluation (RLSE) program. The RLSE subsystems involved were:

a. Electrochemical Depolarized CO_2 Concentrating Subsystem (CS-3)
b. Independent Air Revitalization Subsystem (IARS)
c. Vapor Compression Distillation Subsystem (VCDS)
d. Sabatier CO_2 Reduction Subsystem (S-CRS)

Figure 2 shows the four RLSE subsystem C/M I's. For communication and documentation purposes, these C/M I enclosures were designated Series 100 Laboratory R&D C/M I.

Program Objectives

The overall ALSS instrumentation development program objectives are to reduce size and to increase system availability (reliability and maintainability). The goal is to ready the C/M I for the space flight mission several years from now. Figure 3 shows the two dimensions of the advanced C/M I R&D thrust. One is the development thrust toward the flight hardware C/M I. It is projected that this development will go through perhaps three generations with the present Series 100 being the first for laboratory breadboard ALSS hardware development and testing. The next generation, Series 200, the subject of this program, will be dedicated to prototype hardware. Finally, Series 300 will be used for flight hardware applications. It is envisioned that Series 200 hardware could become Series 300 flight hardware with a minimum of upgrade to satisfy qualification rigor requirements. Examples would include packaging for vibration and use of high-reliability, mil-spec components.

The other dimension of the R&D effort is the engineering thrust within each of the three C/M I generations. These strive to improve quality, eliminate weak links and increase capability but not change the overall instrumentation architecture and configuration. The space thrust is the major driving force to push development toward increasing capability per unit size, incorporating new components and concepts and increasing the availability per unit size.

Program Organization

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

1. Define the Series 200 C/M I to provide ALSS hardware with flight oriented reliability and maintainability.

2. Conduct trade studies of C/M I capabilities versus system penalties for adding the capabilities.

3. Design the advanced C/M I Series 200 in detail for operating a one-person CO_2 removal subsystem, designated CS-1.

4. Fabricate a mock-up of the projected Series 200 C/M I showing major components in detail.

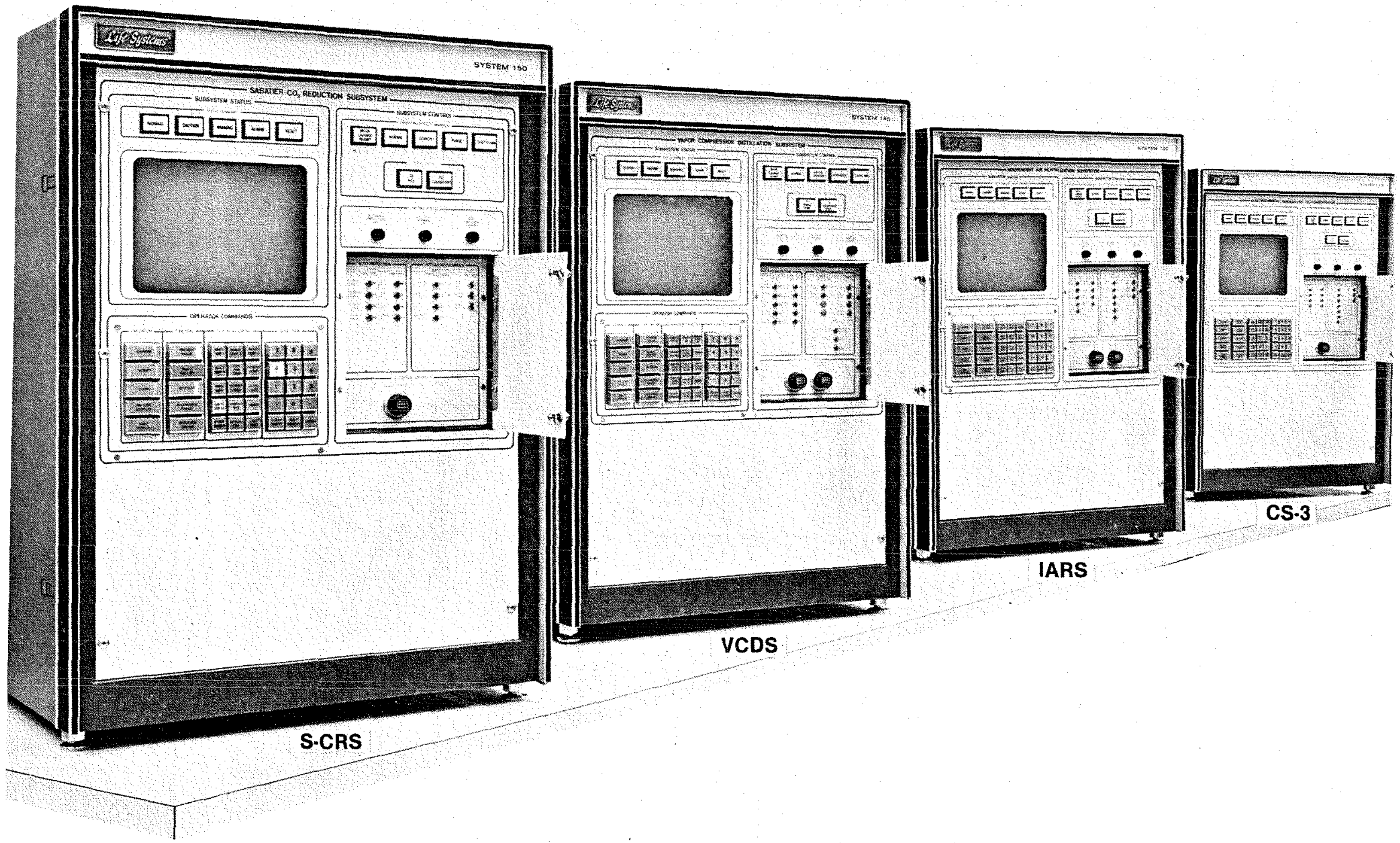
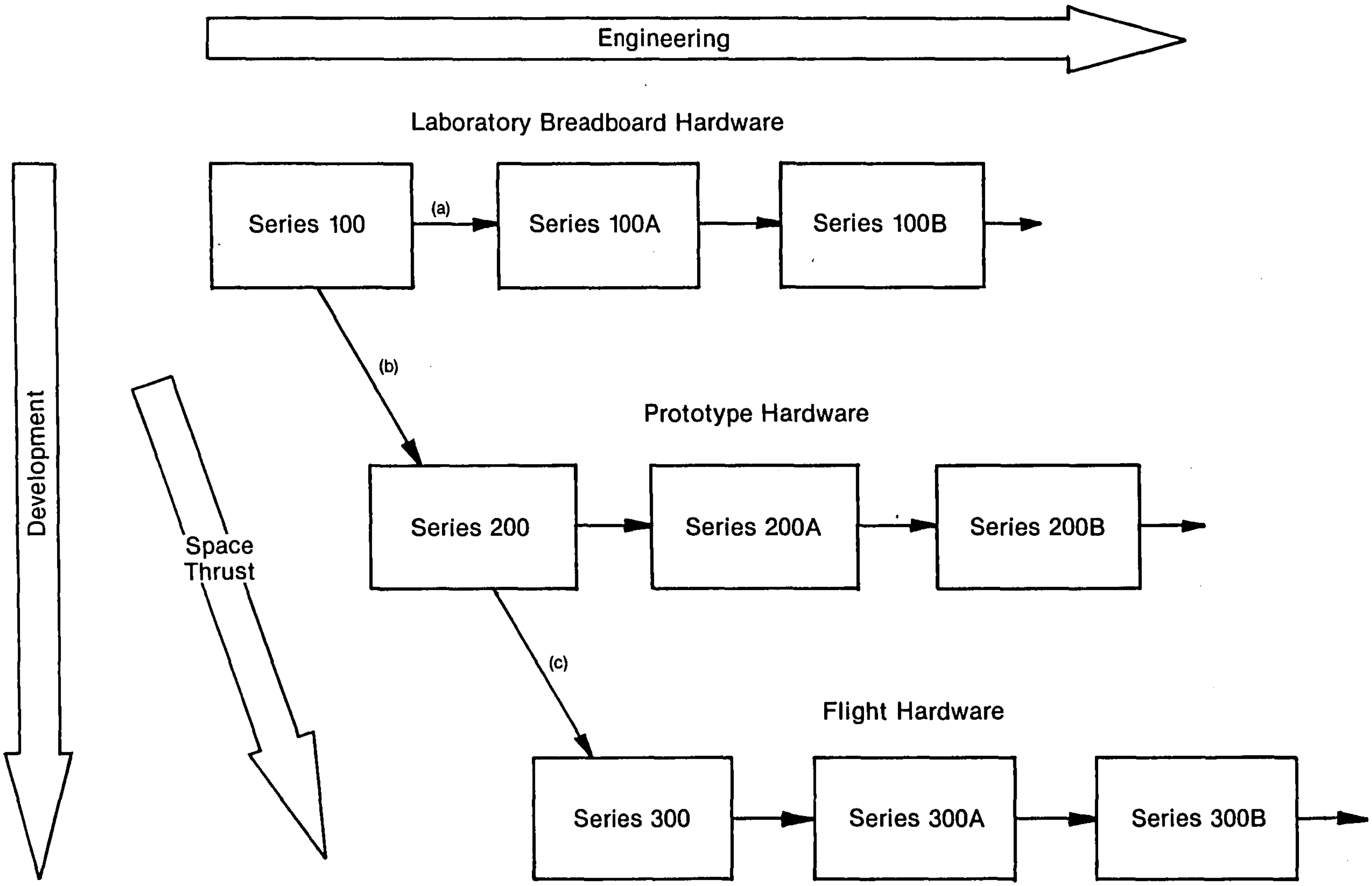


FIGURE 2 SERIES 100 C/M I FOR NASA'S RLSE PROGRAM



(a) Improve quality, eliminate weak links and increase capability.
(b) Increase capability per unit size, reduce flexibility and incorporate new components and concepts. Increase availability per unit size.
(c) Satisfy flight qualification requirements.

FIGURE 3 ADVANCED ALSS C/M I DEVELOPMENT

Report Organization

This Final Report covers the work performed during the period June, 1980 through December, 1981. The following three sections present the technical results grouped according to (1) Series 200 C/M I Definition, (2) CS-1 Description and Requirements and (3) Model 220 C/M I Design. These sections are followed by Conclusions based on the work performed.

SERIES 200 C/M I DEFINITION

Instrumentation is required to control ALSS processes. The basic C/M I process block diagram is shown in Figure 4. The interface with an ALSS mechanical/electrochemical assembly (M/EA) consists of monitoring sensor signals and providing power and control signals to sensors and actuators. Interfaces with the host spacecraft consists of: (a) power, (b) shutdown signals from and to other systems, (c) coolant (air or liquid), (d) a communication link with higher level computers for data logging, supervisoral control or downlink, and (e) physical mounting.

An "ideal" ALSS instrumentation is one that never fails and provides the essential functions to control the chemical, physical and electrochemical processes such as CO_2 removal, water electrolysis, CO_2 reduction and nitrogen N_2 generation. As these complex processes are integrated into the ALSS for flight missions, safety functions to protect personnel, ensure equipment integrity and generate ALSS availability are needed.

If one can assume "ideal" components, i.e., those that never fail nor require service during the mission period, the "ideal" C/M I will be the minimum C/M I that provides nothing but the essential control functions. Such a minimum C/M I can be described as shown in Figure 5. By assuming such hardware components (both C/M I and M/EA), no fault diagnostic functions are required in the minimum C/M I. The hardware and software are configured merely to read in sensor data and mode change requests, to properly sequence the actuators for mode transitions, and to accurately control process parameters at all times. Typical ALSS processes require complex and precise mode transition controls. An example is shown in Figure 6. The transition from shutdown to normal operation may require several minutes and a large number of steps or sequences to effect.

The assumption that "ideal" components exist is, probably, not realistic. Moreover, ALSS utilize sophisticated processes which, if not properly controlled and monitored, could cause safety hazards to the personnel and equipment. Because of these reasons, the requirements for fault diagnostic functions and for meeting strict availability rules are imposed upon the designers for long duration mission C/M I.

Reliability, Availability and Maintainability Groundrules

Some discussion on the definitions of reliability, availability and maintainability is in order before setting the groundrules for Series 200 C/M I. These terms are usually defined as follows:[10]

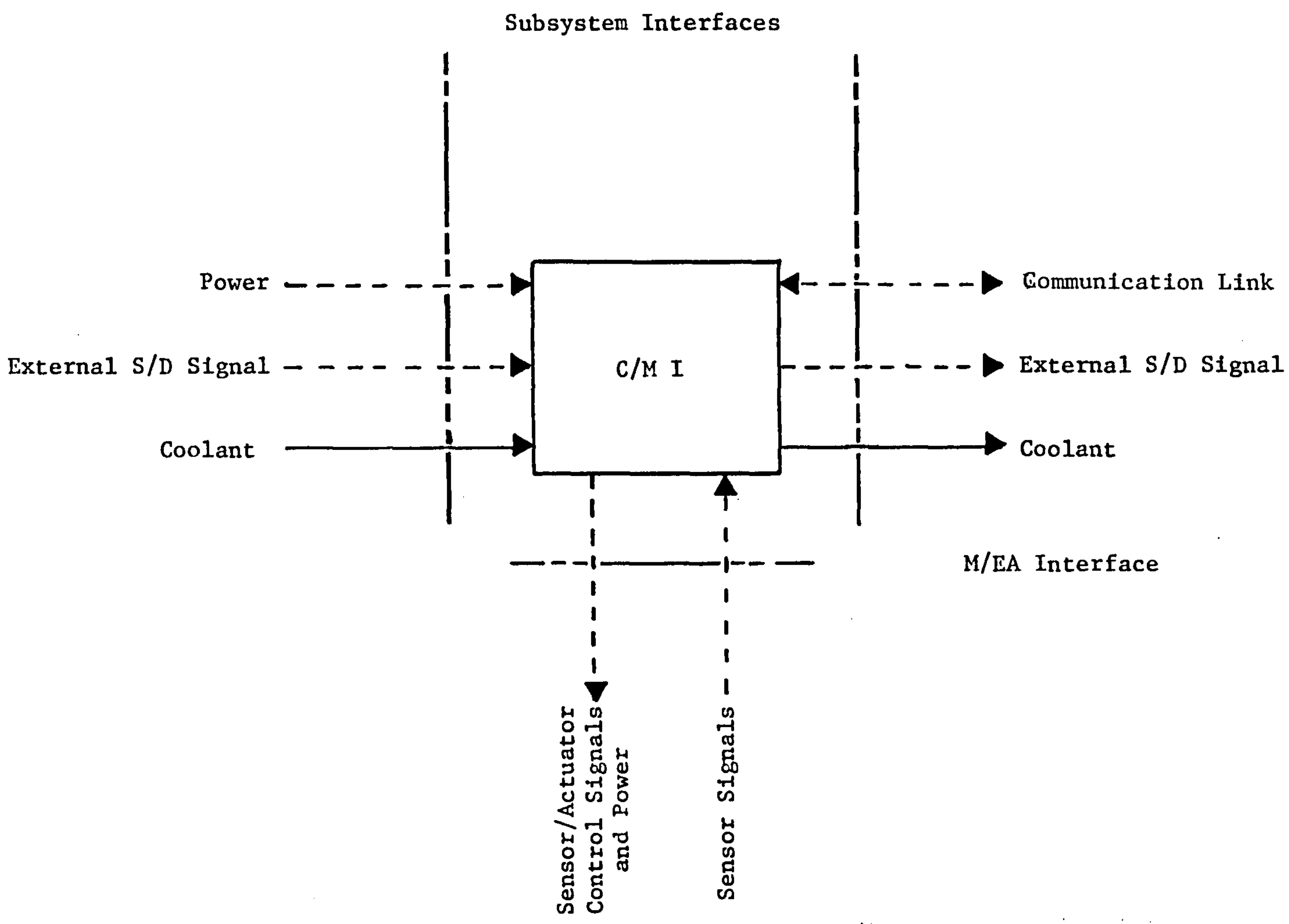


FIGURE 4 BASIC C/M I PROCESS BLOCK DIAGRAM

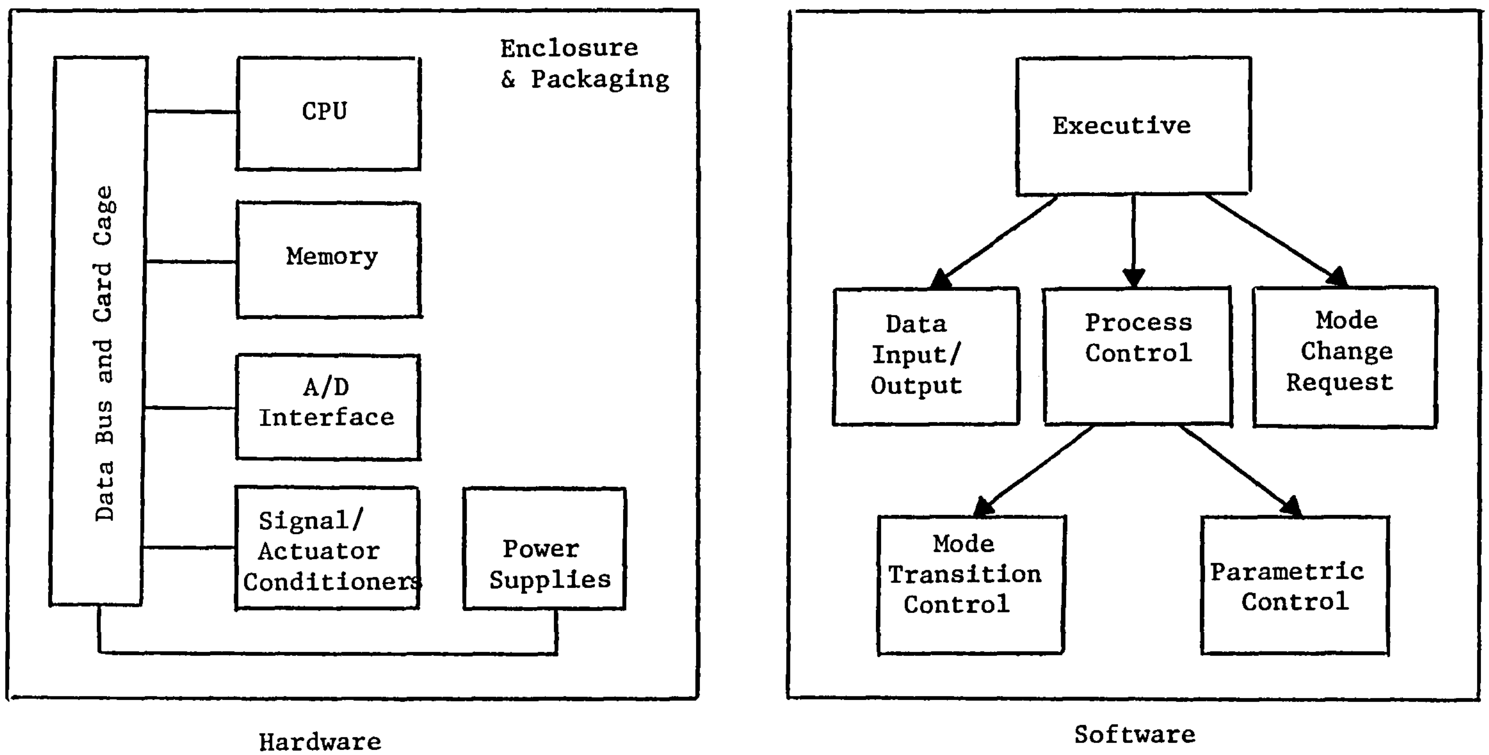
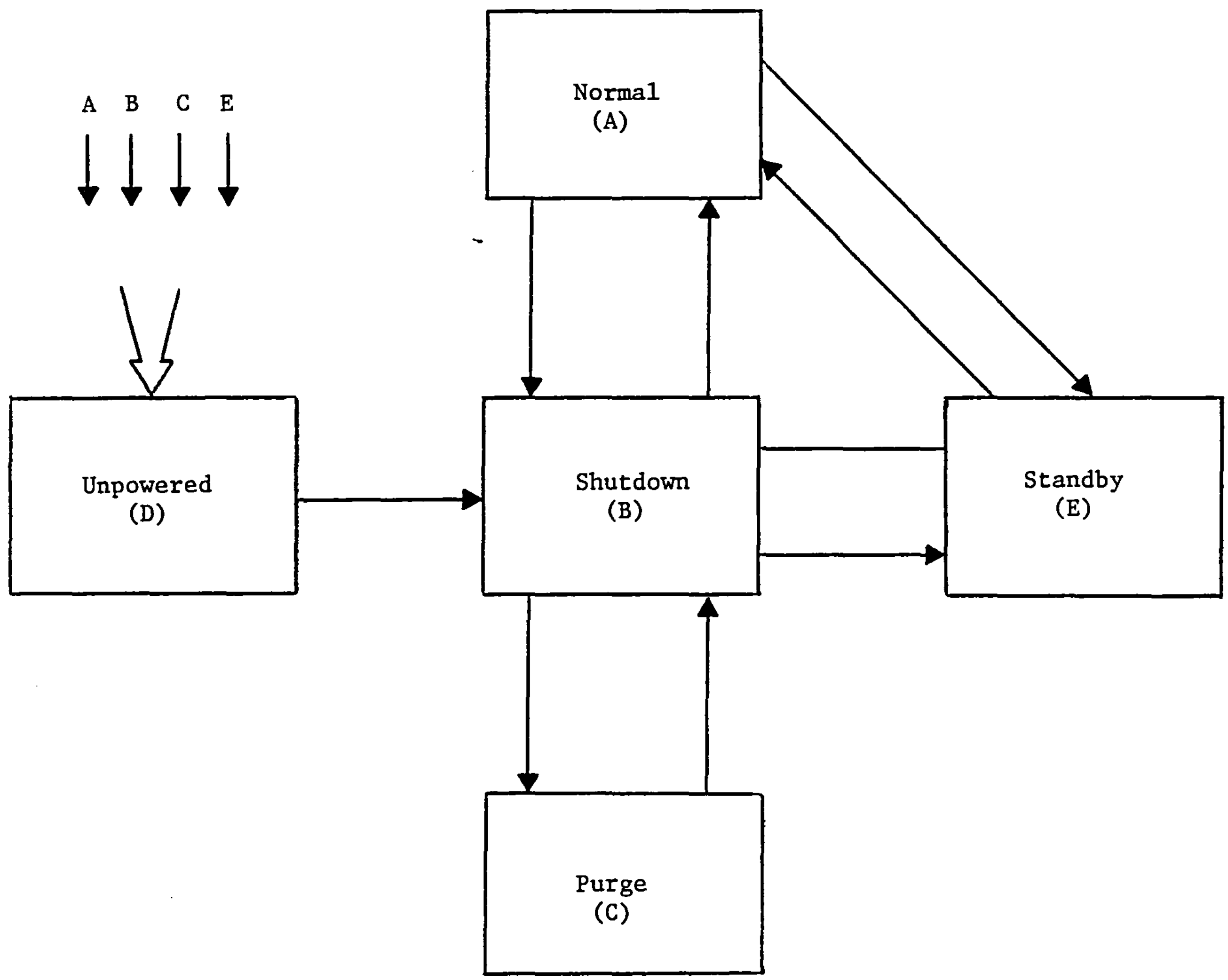


FIGURE 5 IDEAL, MINIMUM C/M I



- 5 Modes
- 4 Operating Modes
- 13 Mode Transitions
- 9 Programmable, Allowed Mode Transitions

FIGURE 6 TYPICAL ALSS MODES AND ALLOWED MODE TRANSITIONS

- Reliability: The probability that equipment will perform its intended function for a specified period, under stated conditions.

- Availability: The fraction of the total desired operating time that equipment actually is operable.

- Maintainability: A characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time when corrective or preventive action is performed in accordance with prescribed procedures and resources.

Further elaborated, reliability can be expressed by the mission duration and the equipment mean-time-between-failure (MTBF). For example, if the C/M I had a MTBF of 10,000 hours and the flight mission was for 90 days, then the reliability would be 1-(2,160/10,000) or 0.784. The failure rate is 1/MTBF or, in this example, 100×10^{-6} failures per hour.

Availability, a very important concept in Series 200 C/M I definition, is expressed by the formula:

$$A_i = \frac{MTBF}{MTBF + MTTR} \qquad (1)$$

where MTTR is mean-time-to-repair

This is also known as the "inherent availability" -- and is a quantitative measure of equipment availability under ideal support environment. In other words, A_i excludes whatever preparation, preventive maintenance, supply lead-time and logistics may require.

A slightly different concept is the operational availability which includes the effects of repair delay as well as the repair itself. Mathematically, it may be expressed as:

$$A_o = \frac{MTBM}{MTBM + MDT} \qquad (2)$$

where MTBM is mean-time-between-maintenance

MDT is mean-down-time

The term MTBM is the statistical mean of the time during which the subsystem is operational between shutdowns for maintenance and MDT is the statistical mean of the time during which the subsystem is out of service for any reason at each shutdown.

From these formulas, the required ALSS availability can be calculated. Figures 7 through 9 show the effects of O_2, CO_2 and water partial pressures when the respective ALSS subsystem is down. Among O_2 generation, CO_2 removal and water removal, O_2 generation is the least critical one as far as availability is concerned. Figure 7 shows that O_2 generation can be lost for 0.5 to 1.5 days for the Shuttle and up to four days for the SOC without reaching

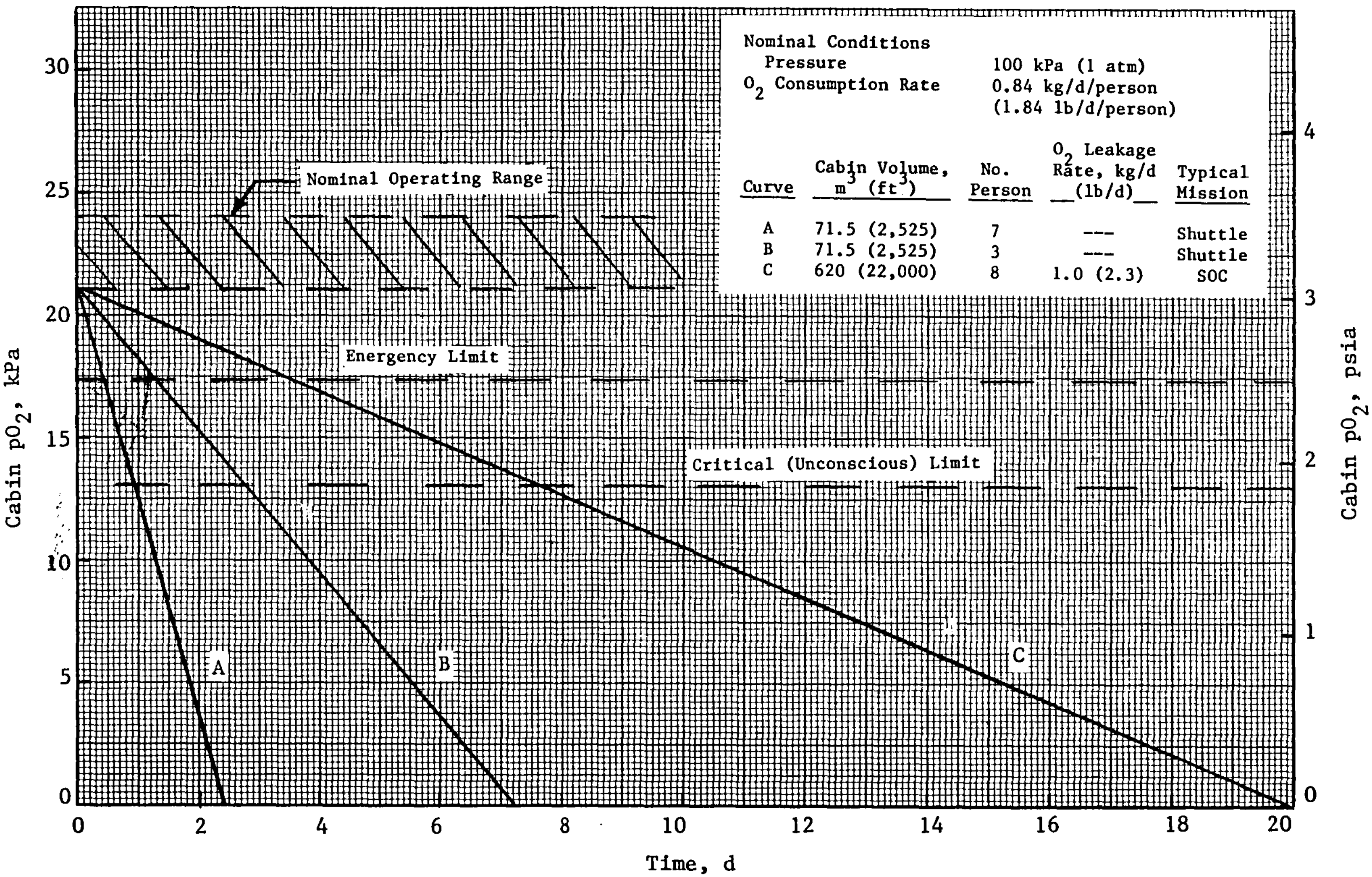


FIGURE 7 CHANGE IN CABIN pO_2 WITHOUT O_2 GENERATION

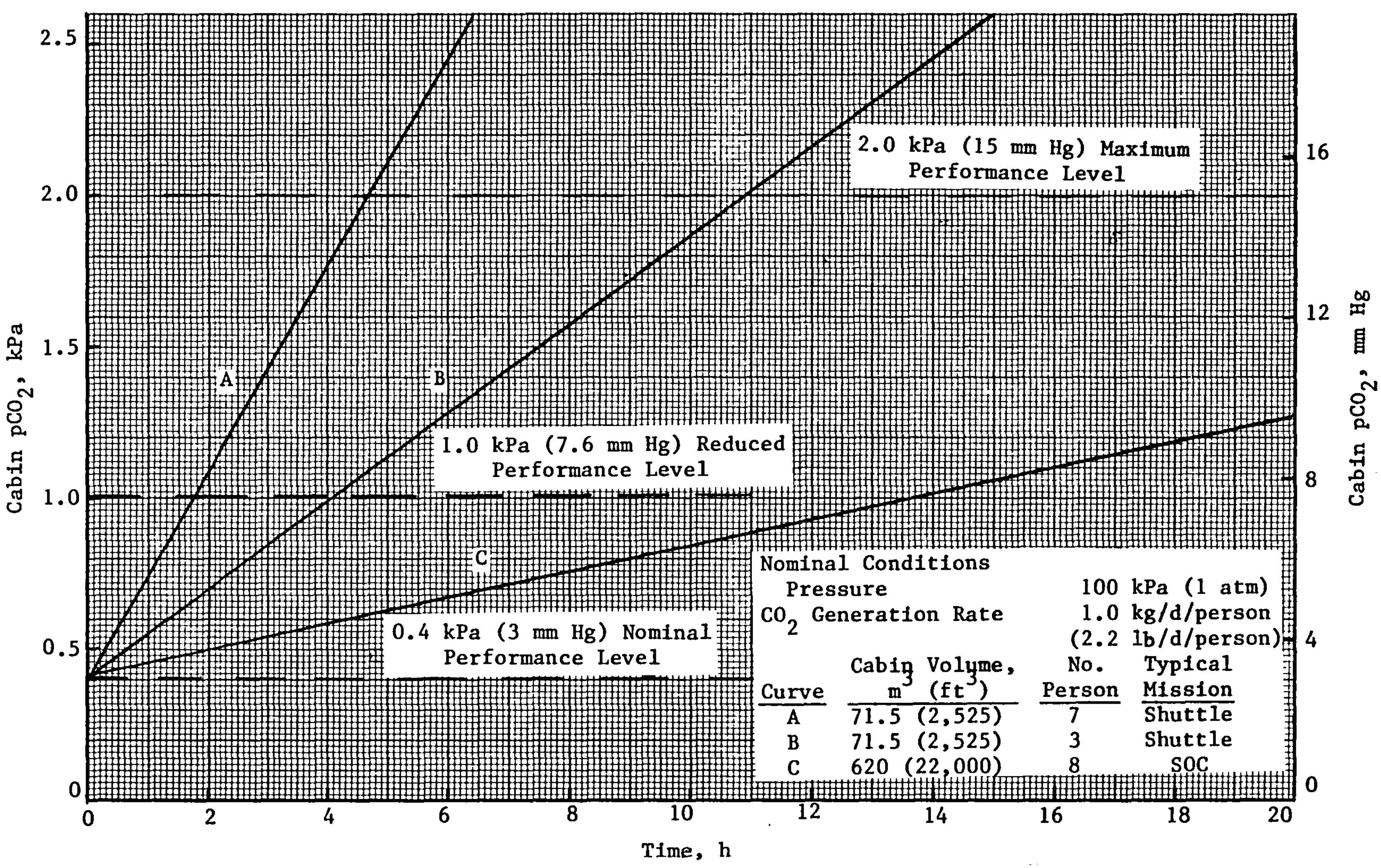


FIGURE 8 CHANGE IN CABIN pCO_2 WITHOUT CO_2 REMOVAL

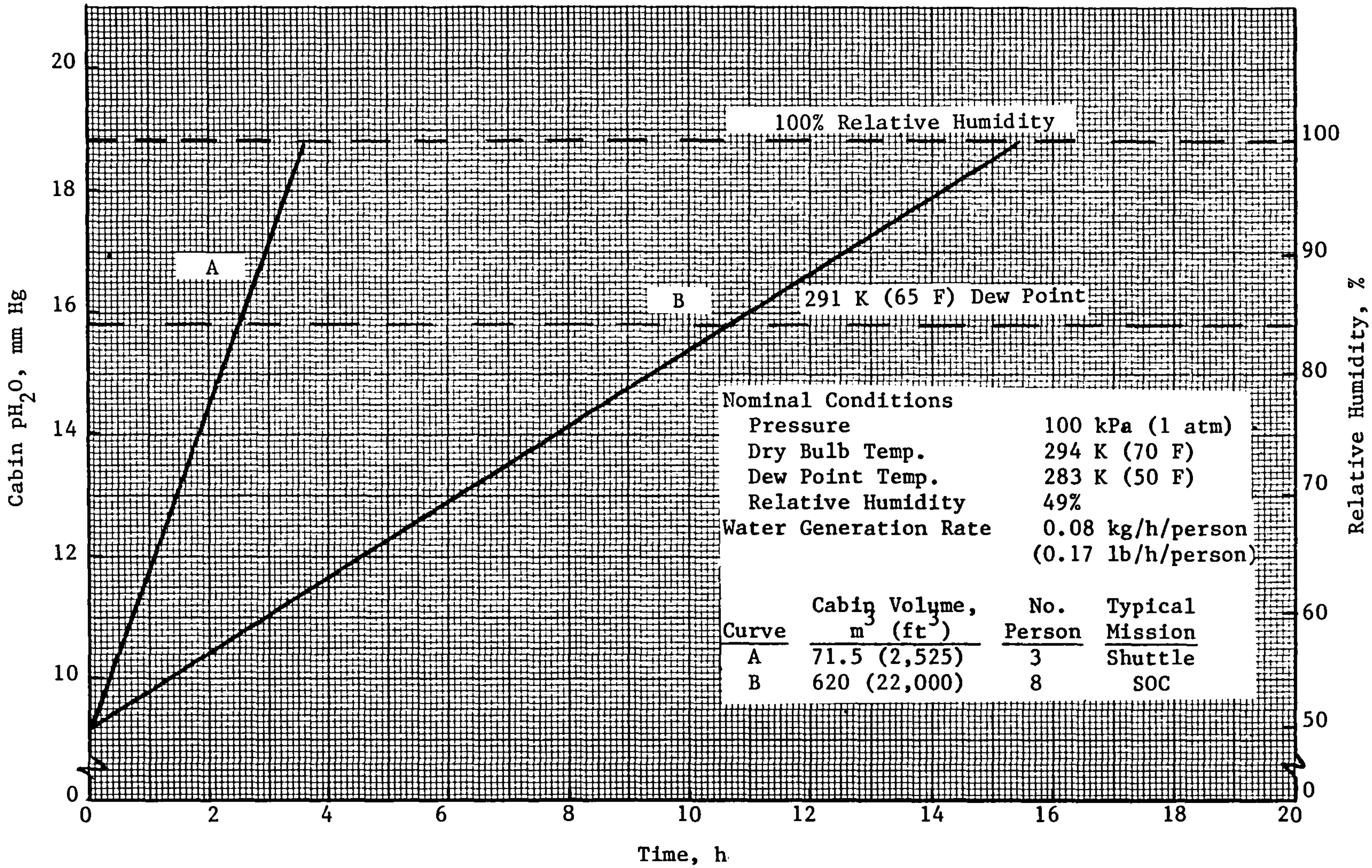


FIGURE 9 CHANGE IN CABIN HUMIDITY WITHOUT WATER REMOVAL

the emergency limit. For CO_2 removal, as shown in Figure 8, the CO_2 removal subsystem can be down for 4.5 to 11 hours for the Shuttle and over 36 hours for the SOC before it reaches the emergency limit. The cabin humidity, however, will reach 100% relative humidity after 3.5 hours or 15.5 hours without water removal for the Shuttle or SOC, respectively. From these data, availability requirements can be calculated and reliability/maintainability requirements extrapolated. The following is an example using the CO_2 Removal Subsystem.

CO_2 Removal Subsystem Availability

The CO_2 Removal Subsystem is designed to run 100% of the time during a mission and maintain the cabin atmosphere CO_2 level at a partial pressure of 400 Pa (3 mm Hg) or less. To achieve this goal all supplies (H_2, electrical power and coolant) must be present and the subsystem must be operational. Any time the subsystem is not performing its function, regardless of the cause, detracts from the subsystem's availability.

Since repair delay time is not a subsystem design parameter, the inherent availability A_i is used for design purposes. The inherent availability A_i assumes that all shutdowns are caused by malfunctions, i.e., no preventative maintenance is performed. Thus, the MTBM equals the MTBF.

If it is assumed that there is a backup system for CO_2 removal (either lithium hydroxide (LiOH) or a second identical subsystem depending on the application) the availabilities can be calculated based on the following assumptions:

a. a 90-day mission
b. up to three shutdowns in the mission are allowed
c. repair can be accomplished in two hours
d. up to eight hours is allowed before repair is started

Since there are three shutdowns and the total mission time is 90 days or 2,160 h,

$$3 \times (\text{MTBM} + \text{MDT}) = 2{,}160 \text{ h}$$

Therefore $$\text{MTBM} + \text{MDT} = 720 \text{ h}$$

or $$\text{MTBM} = 720 \text{ h} - \text{MDT}$$

The MDT can be between 2 h and 10 h from (c) and (d) above.

Therefore, from equation (2) the operational availability will be

$$\frac{710}{720} \leq A_o \leq \frac{718}{720}$$

or $$0.9861 \leq A_o \leq 0.9972$$

The inherent availability will be $A_i = \frac{720}{722} = 0.9972$

Thus, the operational availability for the CO_2 removal subsystem will be between 98.61% and 99.72% and the inherent availability will be 99.72% under the assumed conditions.

Failure rate is the reciprocal of the MTBF. Therefore, the overall subsystem failure rate will be 1,389 x 10^{-6} failures per hour.

The conclusions from these calculations are that the desired reliability, availability and maintainability for the CO_2 removal subsystem are expressed as follows:

a. MTBF = 720 hours (three shutdowns in 90 days of operation)
b. MTTR = 2 hours
c. MDT = MTTR + eight hours delay = ten hours or less
d. Inherent Availability = MTBF/(MTBF + MTTR) = 0.9972
e. Operational Availability = MTBM/(MTBM + MDT) ≥ 0.9861
f. Failure Rate = 1,389 x 10^{-6} failures/h

Equivalent Weight Penalties

Weight, size and power consumption considerations are critical for flight mission oriented C/M I. For evaluation purposes, the equivalent weight penalties associated with the spacecraft power and heat rejection are to be assumed as shown in Table 1.

Fault Diagnostics and Maintainability

To achieve the availability goals defined previously, fault diagnostic functions are needed to meet the MTBM and MDT requirements. A general definition of fault diagnostics is "any function designed to avoid, detect, predict, isolate or correct a component or system failure." More specific functions are as follows:

- Fault Avoidance
- Fault Prediction
- Fault Detection
- Fault Isolation
- Fault Correction Instructions
- Fault Tolerance

The scope of each of these functions is described in Table 2. During the design of C/M I 200, these functions are evaluated and quantified from a size viewpoint. Only those capabilities which can be justified in terms of increased hardware availability are incorporated.

In order to quantify the impact of selecting certain fault diagnostic functions, an analysis of features and benefits was performed. The CO_2 removal process and CS-1 were selected as the "target" subsystem. The results are presented in Table 3 with the major assumptions given in Table 4.

As can be seen in Table 4, almost all features that can be considered add to C/M I hardware or software. Those that add software have to add some hardware

TABLE 1 TYPICAL EQUIVALENT WEIGHT PENALTIES

Service	Equivalent Weight Penalties	
	Shuttle	SOC
AC Power	0.047 kg/W + 0.023 kg/W-d[a] (0.104 lb/W + 0.051 lb/W-d)	0.32 kg/W (0.710 lb/W)
DC Power	0.036 kg/W + 0.017 kg/W-d[a] (0.079 lb/W + 0.038 lb/W-d)	0.27 kg/W (0.590 lb/W)
Heat Rejection to Liquid	0[b]	0.84 kg/W (0.184 lb/W)
Heat Rejection to Air	0[b]	0.20 kg/W (0.436 lb/W)

(a) Nonrecurring penalty plus that for daily consumption
(b) No penalty because the water used in flash evaporator is not considered an expendable

TABLE 2 SCOPE OF FAULT DIAGNOSTICS

1. Fault Avoidance

Definition. Prevents faults from occurring by (1) eliminating human errors, (2) monitoring major interfaces, (3) product assurance controls, and (4) system design features and adaptive controls.

Examples

1. Front panel human engineering
2. Operator authorization codes
3. Prior definition of all scheduled and unscheduled maintenance operations
4. Product Assurance program
5. Automatic sequence transition
6. Feedback control (e.g., outlet RH, current, temperature, and pressure)
7. Monitoring interface parameters for off design conditions
8. Derated operation for out-of-design conditions
9. Pre-maintenance procedures (such as N_2 purge or cell depolarization)
10. Detailed definition of out-of-design and off-design conditions
11. Design conditions (such as sensor placement, hardware selection, etc.)
12. In situ sensor calibration
13. Adaptive controls for nonoptimal environmental conditions
14. Capability for electrochemical cells to operate over wide ranges in current density, inlet RH, H_2 flow rates, etc.
15. Incorporation of components in the system design which modify nonoptimal operating conditions (e.g., the inlet air/liquid heat exchanger of the EDCM)
16. Over-capacity designs
17. Modify operational parameters after prediction of faults

2. Fault Prediction

Definition. Performs analysis which determine and define process or component failures prior to failure in order to (1) prevent the predicted failure by adapting operation, (2) prevent component damage by system shutdown, and (3) decrease maintenance time by scheduling maintenance prior to failure.

Examples

1. Static trend analysis (normal, caution, warning and/or alarm with setpoints)
2. Dynamic trend analysis (change in cell voltage, module temperatures, gas pressures, and other parameters as a function of time)
3. Vibration analysis (actuator signature analysis for such components as pumps, motors, valves, etc.)
4. Dynamic system modeling (e.g., water balance on a module during operation)

continued-

Table 2 - continued

3. Fault Detection

Definition. Detects component failures or symptoms of component failures not necessarily knowing the cause of the failure or of the symptom.

Examples

1. Monitoring subsystem parameters and displaying trend analysis (results as lights and/or messages)
2. Built-in checkout and/or built-in diagnostics functions
3. Detection of redundant sensor failures
4. Failure to complete transition sequence

4. Fault Isolation

Definition. Pinpoints the failed component and/or cause of the failure or symptom which was initially observed by fault detection.

Examples

1. Failure can be indicated by:
   a. Light on component
   b. Message display such as "Blower B1 failed"
2. Failure can be isolated by:
   a. Single parameter 9e.g., speed, voltage)
   b. Logical evaluation of static trend data at shutdown
   c. Logical evaluation of static and dynamic trend data at shutdown
3. Built-in checkout and/or built-in diagnostic circuits to isolate C/M I component failures

5. Fault Correction Instructions

Definition. Instructs the operating personnel on the isolation and/or maintenance actions after a fault is detected.

Examples

1. Display message (e.g., "Replace sensor C1"; "Pressure too high, check valves V3 and V5"; "check valve V1, if normal then check sensor P2").
2. Maintenance "handbook" information on paper or in memory which defines detailed procedures.

6. Fault Tolerance

Definition. Provides the built-in capability which allows the system to continue operation without external assistance in the presence of system or component failures.

continued-

Table 2 - continued

Examples

1. Triple redundant sensors
2. Redundant instrumentation such as parallel processors, installed but inactive until called, replacement circuits, two or three sensor (as opposed to triple redundant sensors) or spare cells installed in a module
3. Automatic In Situ Cell Maintenance (ISCM) with automatic current density adjustments
4. Automatic reconditioning of modules after failures
5. Central process systems which can take over the system C/M I at failures
6. Modifications of selected monitor setpoints with adaptive control logic for continued operation

TABLE 3 SIZE OF INSTRUMENTATION FEATURES/BENEFITS APPLIED TO CS-1 C/M I

Area	No.	Feature Description	Benefit Description	Est. Memory Size, bytes
Process Control	1	RH2 Control Optimization	Increased MTBF	200
Fault Diagnostics	2	RH1 Monitoring	Increased Module Life	-
Fault Avoidance	3	Insitu Cal for TRHS	Decreased Down Time	-
Fault Prediction	4	LoRH1 4 Level Trend Anal.	Reduced MTTR	60
	5	HiRH1 4 Level Trend Anal.	Reduced MTTR	60
	6	LoP1 4 Level Trend Anal.	Reduced MTTR	60
	7	HiP1 4 Level Trend Anal.	Reduced MTTR	60
	8	Dynam. Perform. Trend Anal.	Incr. Equip. Protect.	250
	9	Actuator Sign. Anal.	Incr. Equip. Protect.	16K
Fault Detection	10	Transmission Error Det.	Incr. Reliability	100
Fault Isolation	11	F2 H -CO Flow Out	Reduced MTTR	-
	12	F1 Inlet H_2 Flow	Reduced MTTR	-
	13	Shutdown Status Latch	Reduced MTTR	120
	14	Built-In-Checkout	Reduced MTTR	120
	15	Built-In-Diagnostics	Reduced MTTR	512
	16	Isolation Indicators	Reduced MTTR	50
	17	P2 Inlet H_2 Press Mon.	Decr. MTTR & Incr. Life	-
	18	M1 Speed Sensing	Decr. MTTR	-
Corrective Instruction	19	One-Line Instruction	Reduced MTTR	-
	20	Instruction Codes	Reduced MTTR	200
	21	Message Display on Diag. Unit	Reduced MTTR	-
	22	Message Sent to Central	Reduced MTTR	1K
Fault Tolerance	23	$TRRH_2$ with No. 27	Increased MTBF	-
	24	Transmission Error Recovery	Increased Reliability	10
	25	Redundant H_2CO_2 Pressure Mon.	Increased MTBF	-
	26	Triple Redun. H_2 Sens. w/No. 27	Increased MTBF	-
	27	Voting Logic	Increased MTBF	330
Equipment Protection	28	C/M I Enclosure	Equipment Protect	-
Maintainability	29	Quick Disconnect LRU's	Decreased MTTR	-
Power Utilization	30	EDC Power Use By C/M I	Reduced Power Consump.	-

Table 3 - continued

No.	Est. No. Elect. Parts	Weight, g (lb)	Power, W	Total Equiv. Weight, kg (lb)	Dimensions, cm (in)	Volume, cm^3 (in^3)
1	0.2	3.6 (0.008)	0.02	0.014 (0.032)	1.5x1.5x1.3 (0.6x0.6x0.5)	3.3 (0.2)
2	71	52.7 (0.116)	1.5	0.84 (1.849)	8.9x8.9x1.3 (3.5x3.5x0.5)	100 (6.1)
3	47	35 (0.077)	3.25	1.74 (3.831)	8.6x8.6x1.3 (3.4x3.4x0.5)	93 (5.7)
4	-	-	-	-	-	-
5	-	-	-	-	-	-
6	-	-	-	-	-	-
7	-	-	-	-	-	-
8	0.25	4.5 (0.010)	0.25	0.018 (0.039)	1.8x1.8x1.3 (0.7x0.7x0.5)	4.1
9	16	190 (0.640)	1.6	1.13 (2.488)	14x14x1.3 (5.7x5.7x0.5)	260 (16)
10	0.1	1.8 (0.004)	0.01	0.011 (0.024)	1.1x1.1x1.3 (0.45x0.45x0.5)	1.6 (0.1)
11	28	21 (0.046)	3.15	3.02 (6.639)	6.2x6.2x1.3 (2.45x2.45x0.5)	49 (3)
12	28	21 (0.046)	3.15	3.04 (6.685)	6.2x6.2x1.3 (2.45x2.45x0.5)	49 (3)
13	0.1	2.3 (0.005)	0.012	0.009 (0.019)	1.3x1.3x1.3 (0.5x0.5x0.5)	2.0 (0.12)
14	25	19 (0.041)	0.112	0.082 (0.181)	11x11.x1.3 (4.2x4.2x0.5)	150 (9)
15	55	41 (0.090)	2	1.1 (2.400)	11x11x1.3 (4.2x4.2x0.5)	150 (9)
16	200	230 (0.500)	0.500	0.49 (1.078)	8.9x8.9x1.3 (3.5x3.5x0.5)	98 (6)
17	20	15 (0.033)	0.150	0.094 (0.206)	4.8x4.8x1.3 (1.9x1.9x0.5)	29 (1.8)
18	30	22 (0.049)	0.300	0.18 (0.396)	6.2x6.2x1.3 (2.45x2.45x0.5)	4.9 (3)
19	2.5K	49 (0.108)	4.63	2.48 (5.456)	6.5x6.5x1.3 (2.55x2.55x0.5)	53 (3.25)
20	1	4.5 (0.010)	0.02	0.015 (0.033)	1.3x1.3x1.3 (0.5x0.5x0.5)	2.5 (0.15)
21	1	18 (0.040)	-	0.018 (0.040)	1.0x1.0x1.3 (0.4x0.4x0.5)	1.5 (0.09)
22	6	62 (0.135)	0.85	0.476 (1.047)	8.9x8.9x1.3 (3.5x3.5x0.5)	98 (6) 100
23	141	105 (0.231)	9.75	5.22 (11.493)	15x15x1.3 (6.05x6.05x0.5)	300 (18.3)
24	-	-	-	-	-	-
25	20	15 (0.033)	0.15	0.093 (0.206)	4.8x4.8x1.3 (1.9x1.9x0.5)	29 (1.8)
26	84	63 (0.138)	9.45	9.12 (20.055)	11x11x1.3 (4.2x4.2x0.5)	150 (9)
27	0.3	5.9 (0.013)	0.033	0.023 (0.051)	2.0x2.0x1.3 (0.8x0.8x0.5)	5.4 (0.33)
28	-	3,840 (8.46)	-	3.84 (8.46)	-	1,390 (84.6)
29	-	1,270 (2.8)	-	1.27 (2.8)	40-10x1.3x1.3 40-(4x0.5x0.5) +6-5x8.0x1.3 +6-(2x3.14x0.5)	810 (49.4)
30	205	11,500 (25.3)	45	-83 (-182.6)	23x10x13 (9x4x5)	2,950 (180)

TABLE 4 ASSUMPTIONS USED IN PREPARING FEATURES/BENEFITS VERSUS INSTRUMENTATION SIZE ANALYSIS

No.	Description of Assumption
1	Hardware shall be able to fly by 1985
2	100 nW power dissipation for each 1Kx8 memory
3	Sixteen cm^3 (1 in^3) for each 1Kx8 memory
4	One electronic part for each 1Kx8 memory
5	Each 1Kx8 memory weighs 18 g (0.04 lb)
6	Assembly language software development costs 0.5 h/byte
7	DC power penalty - 0.27 kg/W (0.59 lb/W) weight penalty. Cooling penalty - 0.20 kg/W (0.436 lb/W). With 80% efficiency DC-DC converter, total is 0.53 kg/W (1.17 lb/W).
8	All 1Kx8 memories cost $25/part
9	Linear circuits cost $10/part
10	Digital circuits (except microprocessor, memory and A/D or D/A) cost $2/part
11	Recurring labor is 15 min/part (includes build, debug, overhead, etc.)
12	Features are implemented with off-the-shelf parts
13	An 18 x 38 x 38 cm (7 x 15 x 15 in) enclosure of 0.13 cm (0.050 in) aluminum with 2.77 g/cm^3 (0.1 lb/in^3) density
14	Goal in size of C/M I

Series	Weight, kg (lb)	Volume, dm^3 (ft^3)	Power Consumption, W
200	18 (40)	42 (1.5)	80
300	11 (25)	28 (1.0)	50

in the form of additional RAM or ROM memory. This added hardware generally has minimal impact on total equivalent weight since the incremental weight, power and heat rejection are so small. Also, note that while Table 4 lists each feature individually, incorporating several features does not necessarily mean cumulative penalties. This is because memory elements (RAM or ROM) generally are added in units of 1 K (actually 1024) bytes. Also, if the memory unit is added to an existing memory card there would be no volume impact.

It is clear then, that additional desirable, but not essential, features have to be evaluated on a basis other than total equivalent weight. This would be how cost and overall system reliability is affected. Cost is straight-forward. Labor costs in designing, implementing and debugging software are the drivers. Hardware costs are low. System reliability impacts are harder to evaluate. Added software will generally mean a more complex overall software architecture. If the additional feature does not compromise system performance (measured by testing) and provides the indicated benefit to the mechanical subsystem to meet its function; then the feature is worthwhile and should be added.

CS-1 DESCRIPTION AND REQUIREMENTS

The function of the Electrochemical CO_2 Concentrator Subsystem (CS-1) is to remove the metobolically produced CO_2 of one person. It will eventually be integrated with other subsystems to form either a central ARS for a SOC or the Space Shuttle ARS. The heart of the CS-1 consists of an Electrochemical Depolarizied CO_2 Concentrator (EDC) module (EDCM) to remove CO_2 from the cabin air. Details of the EDC processing including reactions and prior hardware developments are amply described in the literature.[4,5] Under a prior program, NAS2-10204, the CS-1 went through a preliminary design.[5] It is intended to be fabricated and tested under a following program.

General Description

The overall CO_2 removal processing control scheme is described in Figure 10. The M/E A includes a six-cell EDCM and all components required to sense and control gaseous and liquid fluid flows to and from this module. The C/M I controls overall subsystem operation through the sensors and actuators of the M/E A. It monitors, interprets and displays subsystem operational parameters and it provides appropriate changes in operating modes in response to operator inputs or subsystem malfunctions.

Applications

Two applications considered at present for the CS-1 include use in the Shuttle Orbiter ARS and as part of a central ARS, such as NASA's proposed SOC.[11] The design focused primarily on the former application which makes much greater demands on subsystem operating range. These demands are apparent in the design specifications discussed below.

Specifications

General design specifications are listed in Table 5 and Figure 11. The relative humidity (RH) and temperature range projected for the Shuttle application

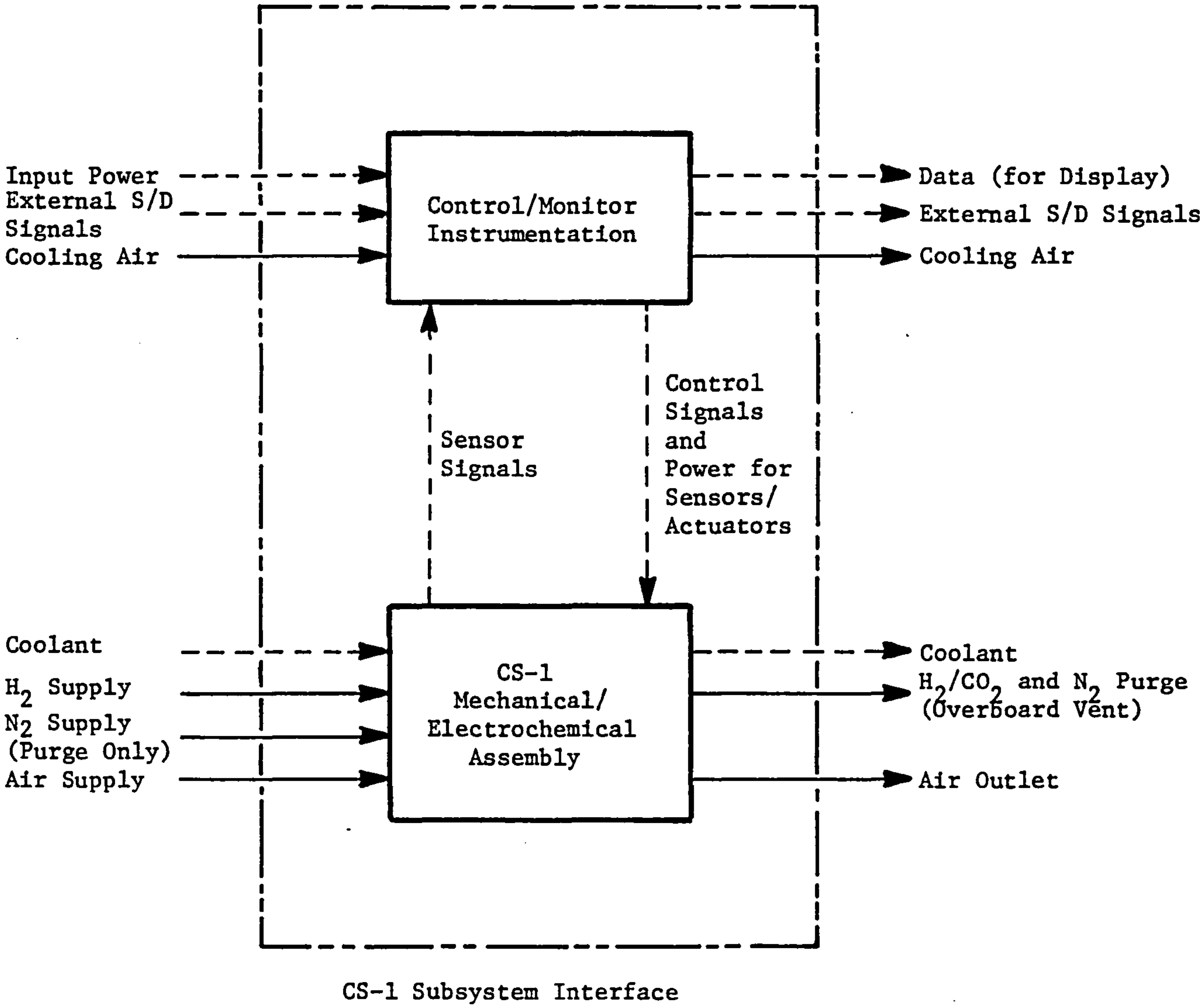


FIGURE 10 CS-1 PROCESS BLOCK DIAGRAM

TABLE 5 CS-1 DESIGN SPECIFICATIONS

	Application: Shuttle	Application: Central[a]
Crew Size	1	--
CO_2 Removal Rate, kg/h (lb/h)	0.040 (0.088)	--
Cabin pCO_2, Pa (mm Hg)		
Daily Average	667 (5.0)	400 (3.0)
Maximum	2,013 (7.6)	667 (5.0)
Cabin pO_2, kPa (psia)	22.1 (3.2)	--
Cabin Temperature, K (F)	291 to 302 (65 to 84)	295 to 300 (65 to 80)
Cabin Dew Point, K (F)	277 to 289 (39 to 61)	279 to 294 42.5 to 69)
Cabin Pressure, kPa (psia)	101 (14.7)	--
Process Air Humidity Range	See Figure 11	--
Liquid Coolant		
Temperature, K (F)	275 to 297 (35 to 71)	280.2 Max
Flow Rate, kg/h (lb/h)	432 (950)	--
H_2 Supply		
Flow Rate, kg/h (lb/h)	0.003 (0.006) 1.2 Stoichiometric (9.0 A)	0.007 (0.014) 2.9 Stoichiometric (9.9 A)
Pressure, Pa (psia)	173 (25)	--
Relative Humidity, %	0 to 5	0 to 75
Purge Gas		
Type	N_2	--
Pressure, kPa (psia)	173 (25)	--
Electrical Power, VAC	115, 400 Hz, 1Ø	--
Gravity	0 to 1	--
Noise Criteria, db	55[b]	--

(a) By exception only. Specifications not indicated are the same as for the Shuttle.
(b) Difficult to meet and will be met in flight hardware.

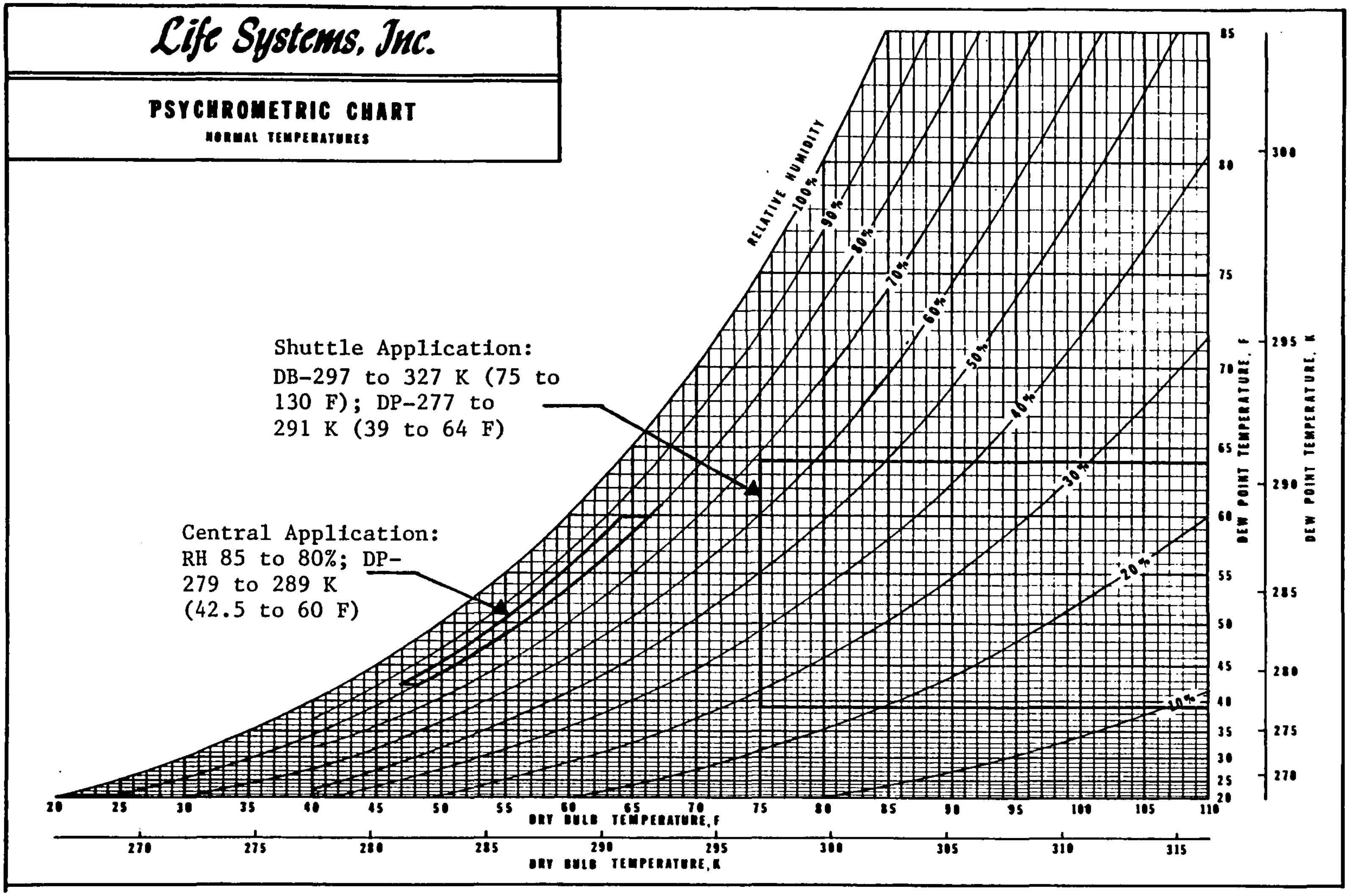


FIGURE 11 PROCESS AIR HUMIDITY RANGES TO CS-1 FOR BOTH CENTRAL AND SHUTTLE APPLICATIONS

is broad because the CS-1 could be located upstream of the spacecraft condensing heat exchanger and the RH and temperature of air entering the subsystem would be unregulated. In contrast, the CS-1 would be located downstream of the condensing heat exhanger in a central ARS application (i.e., SOC). Fluid, electrical and thermal inputs and outputs for the CS-1 are further illustrated in Figure 12.

Subsystem Operating Modes

The subsystem has been designed with four operating modes, as shown in Figure 13. Two separate normal modes are provided corresponding to the operating conditions of either the Shuttle or central application. Each mode is further defined in Table 6.

Subsystem Schematic and Description

The schematic of the CS-1 is shown in Figure 14. Process air is drawn from the source through a filter/isolation valve (FV1) and the EDCM. The process air is returned to the source through an outlet air filtration/isolation valve (FV2). The filter/isolation valves prevent the module from drying out during nonoperational periods. Internally, the process air is manifolded in parallel through the process air cavities of the six cells of the module, while H_2 flows through the cells in series. The cells are electrically connected in series. Each cell has an active electrode area of 460 cm^2 (0.5 ft^2). Part of the waste heat generated by the cell is removed through heatup of the module air stream passing through the cathode compartment. The remaining waste heat is conducted to the internal liquid cooling cavity of each cell which is adjacent to each cathode current collector. From there the cooling liquid goes to the Coolant Control Assembly (CCA).

The CCA removes EDCM generated heat and cools the inlet process air to the desired humidity conditions required for optimum operation. Depending on the inlet humidity conditions, the CCA may also allow the EDCM to heat up during transients in process air operating condition. The CCA consists of a pump (M1) with speed sensor (S1), an accumulator (WT1) and diverter valve (V1) with valve position indicator (W1). The CCA circulates a constant coolant flow through the EDCM and varies coolant temperature to provide temperature control. The latter is provided by the diverter valve position which controls the amount of coolant flowing through an external heat exchanger (HX1) or bypassing the heat exchanger. The external heat exchanger is a heat sink to remove process air heat. The remixed stream, at the desired temperature, is then circulated through the EDCM.

Two RH sensors (R1, R2) consisting of dewpoint temperature sensors (D1, D2) and dry bulb temperature sensors (T1, T2) monitor the inlet and outlet process air to protect the subsystem from out-of-tolerance conditions of temperature and RH. The RH is calculated from the dew point and dry bulb temperatures by the C/M I. The C/M I maintains the outlet RH by a feedback control loop which adjusts the position of the diverter valve in the CCA.

The functions of the Fluid Control Assembly (FCA) include: (a) controlling EDCM pressure with the backpressure regulator (PR1); (b) restricting maximum flow rates of H_2 and purge N_2 with the flow control orifices (RX1 and RX2);

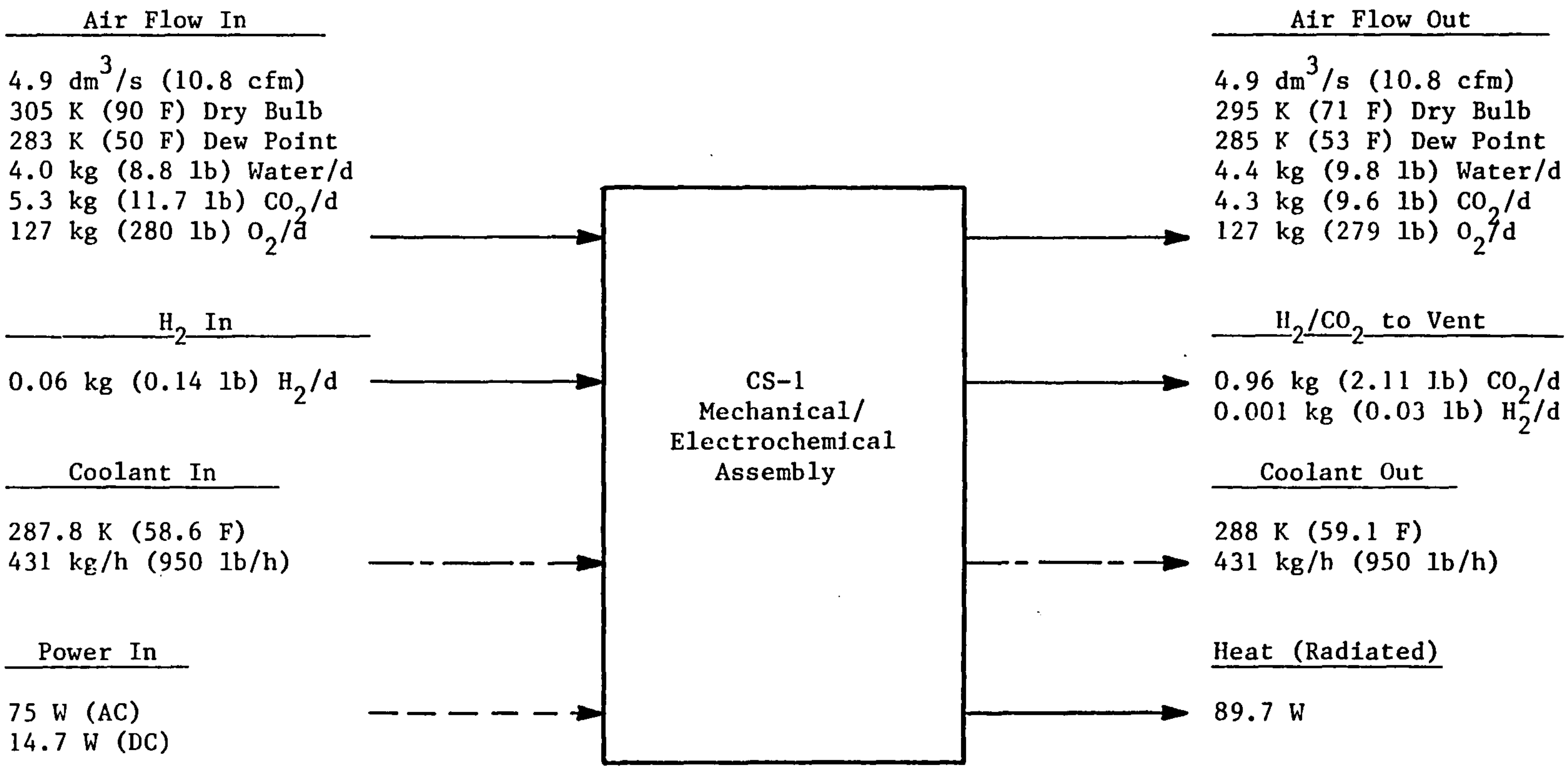
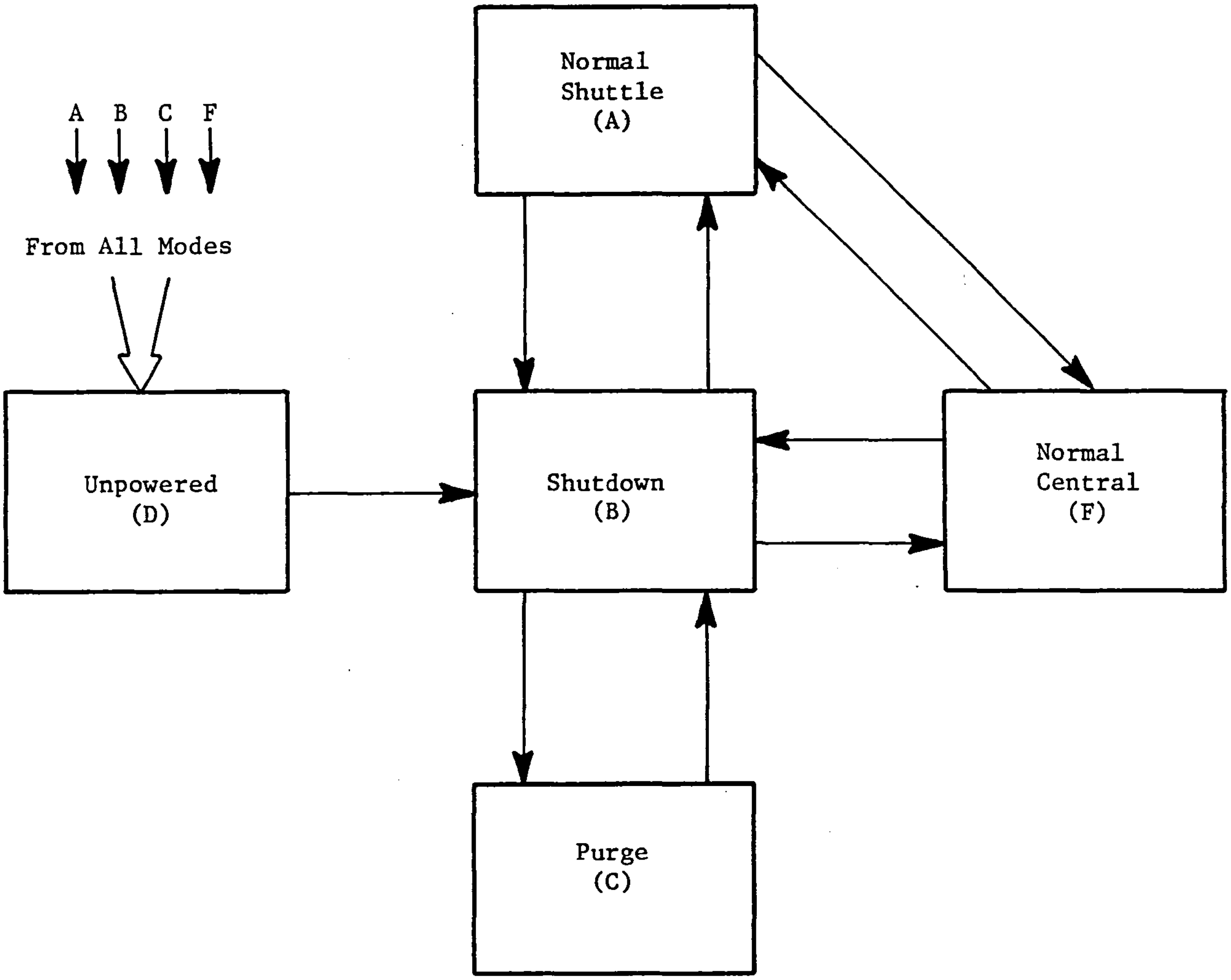


FIGURE 12 CS-1 MASS AND ENERGY BALANCE



- 5 Modes
- 4 Operating Modes
- 13 Mode Transitions
- 9 Programmable, Allowed Mode Transitions

FIGURE 13 CS-1 MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 6 CS-1 MODE DEFINITIONS

MODE (CODE)	DEFINITIONS
Shutdown (B)	The EDCM is not removing CO_2. Module current is zero, the coolant pump is off and all valves are closed. The system is powered and all sensors are working. The Shutdown Mode is called for by: • Manual actuation • Low EDCM individual cell voltage • Low H_2 pressure • High H_2 pressure • Low H_2/CO_2 pressure • High H_2/CO_2 pressure • Low outlet process air RH • High outlet process air RH • High outlet process air temperature • High combustible gas concentration • Second failure of triple redundant sensors for pressure, relative humidity, temperature and combustible gas concentration (capability only) • Power on reset (POR) from Unpowered Mode (D) • Mode transition from Shutdown Mode (B) to Normal Shuttle (A), Normal Central (F), or Purge (C) was not successful. All transitions to the Shutdown Mode except POR and Purge include a timed purge sequence as part of the mode transition sequence.
Normal Shuttle (A)	The EDCM is operating at the constant current density of 19.4 mA/cm^2 (18.0 ASF) sized to perform the CO_2 removal function for one-person assuming an inlet pCO_2 level of 667 Pa (5.0 mm Hg). The Normal Shuttle Mode is called for by: • Manual actuation
Normal Central (F)	The EDCM is operating at a constant current density of 21.3 mA/cm^2 (19.8 ASF) sized to perform the CO_2 removal function for one-person assuming an inlet pCO_2 level of 400 Pa (3.0 mm Hg). The Normal Central Mode is called for by: • Manual actuation

continued-

Table 6 - continued

MODE (CODE)	DEFINITIONS
Purge (C)	The EDC is being purged with N_2 through all H_2 carrying module cavities and out through the vent line. Module current and the coolant pump are off. This is a continuous purge until a new mode is called for or a preset time duration is reached. The Purge Mode is called for by: • Manual actuation
Unpowered (D)	No electrical power is applied to the EDC. Actuator positions can only be verified visually. There may or may not be process air flow. There could be N_2 purge or H_2 flow depending on when the EDC was unpowered. The Unpowered Mode is called for by: • Manual actuation (circuit breaker) • Electrical power failure • C/M I failure as detected by the Built-in Diagnostic (BID) circuit

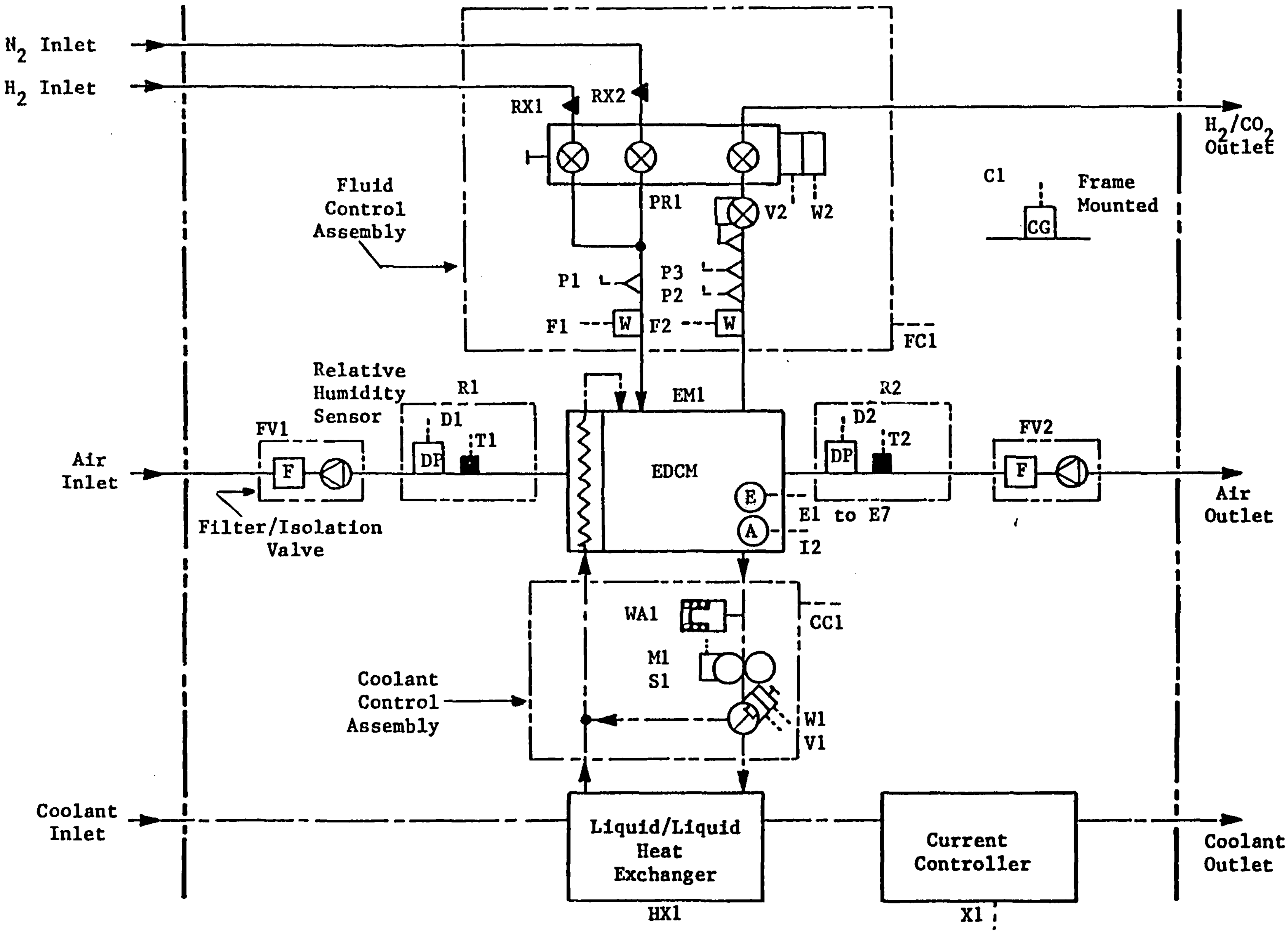


FIGURE 14 CS-1 MECHANICAL SCHEMATIC

(c) measurement of fluid flow rates (F1 and F2) both upstream and downstream of the EDCM; (d) measurement of pressures upstream and downstream (P1, P2 and P3), and (e) providing valve position indication (W2) of the FCA motor (M2) as a feedback to the control electronics. Hydrogen, supplied by an external source, passes through the FCA prior to entering the EDCM. The H_2 and CO_2 exhaust stream from EDCM returns to the FCA and then to an outlet or vent. The FCA controls and monitors subsystem H_2 flow and pressures. The N_2 purge is also supplied to the subsystem via the FCA. Pressure in the H_2 line is maintained at greater than or equal to 108 kPa (15.2 psia) during operation to ensure that any possible H_2 leakage would be external and be detected by the combustible gas sensor (C1) located on the subsystem frame.

The voltages of the six individual cells (E1 to E6) of the EDCM are monitored along with the total module voltage (E7). The current controller houses a programmable constant current supply for the EDCM. It accepts an analog current setpoint voltage (X1) from the C/M I and maintains the electrical current (I1) through the EDCM cells. The current controller is supplied with liquid coolant and is packaged as part of the M/EA.

Figure 15 describes the projected dimensional configuration of the CS-1. The subsystem is constructed so that the EDCM (end plates and cell stack) form a mounting structure for the other components. The height dimension, therefore, is a function of capacity. The figure shows that the total height would only double for increasing capacity sevenfold. Table 7 summarizes projected weight, power and heat rejection requirements for the CS-1.

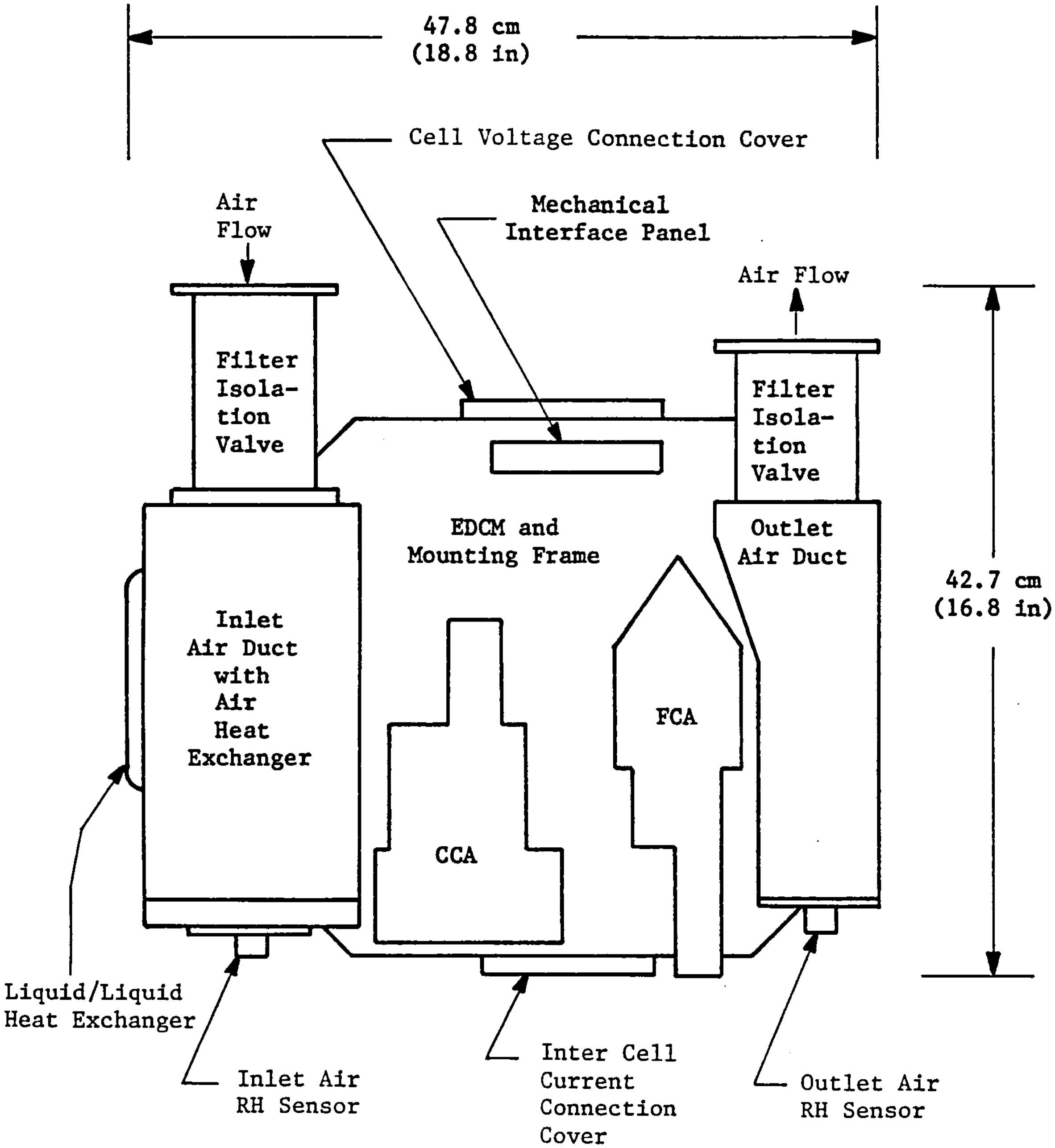
MODEL 220 C/M I DESIGN

It was stated previously that the Series 200 C/M I will approach as close as possible flight configuration hardware without the constraints of qualification rigor imposed on the physical design. As such, efforts have been made to include provisions for spacecraft type interfaces specifically power and packaging. Figure 16 shows the first level Series 200 C/M I hardware functional block diagram. The hardware consists of the following major sections:

- a. System Input/Output (I/O)
- b. Computer
- c. Operator/System Interface
- d. Power Supply
- e. Enclosure

The C/M I interfaces with outside DC power sources, ambient cooling air and the system or subsystem sensor/actuator signals and power. In some applications, e.g., CS-1, special external electronic packages might be required. The C/M I also interfaces with these packages.

The following describes the Series 200 C/M I and specifically Model 220, the designation Life Systems has assigned to the CS-1 C/M I. The description is organized according to hardware, software and packaging.



Front Dimensions/Volume

Height, cm (in)	Volume, dm^3 (ft^3)
30.5 cm (12.0 in)	62 (2.2)

FIGURE 15 CS-1 PACKAGING ILLUSTRATION (TOP VIEW)

TABLE 7 CS-1 MECHANICAL COMPONENT WEIGHT, POWER AND HEAT REJECTION SUMMARY

Item No.	Component	No. Req'd	Unit Weight,[a] kg (lb)	Total Weight, kg (lb)	Total AC Power, W	Total DC Power, W	Heat Rejection, W
1	EDCM[b]	1	18.2 (40.0)	18.2 (40.0)	---	---[c]	39
2	Assembly, Fluids Control	1	2.8 (6.1)	2.8 (6.1)	---	1.9[d]	1.9
3	Assembly, Coolant Control	1	3.7 (8.1)	3.7 (8.1)	75	11.4[e]	86.4
4	Heat Exchanger, Liq/Liq	1	0.8 (1.8)	0.8 (1.8)	---	---	---
5	Filter/Isolation Valve	2	0.7 (1.5)	1.4 (3.0)	---	---	---
6	Sensor, RH	2	0.9 (2.0)	1.8 (4.0)	---	---	---
7	Sensor, Combustible Gas	1	0.2 (0.4)	0.2 (0.4)	---	0.4	0.4
8	Interface, Inlet Air (W/Heat Exchanger), 1.50 kg (3.29 lb) for Hx	1	2.3 (5.0)	2.3 (5.0)	---	---	---
9	Interface, Outlet Air	1	0.5 (1.0)	0.5 (1.0)	---	---	---
10	Frame, Mounting	1	0.5 (1.0)	0.5 (1.0)	---	---	---
11	Assembly, Current Controller	1	3.2 (7.0)	3.2 (7.0)	---	1	28[c]
			---	35.2 (77.4)	75	14.7	155.7

(a) Wet weight.
(b) Does not have honeycomb end plates.
(c) The 27 W of EDCM power is converted to heat for CS-1 application.
(d) Steady-state operation.
(e) Assumes Diverter Valve controlling continuously.

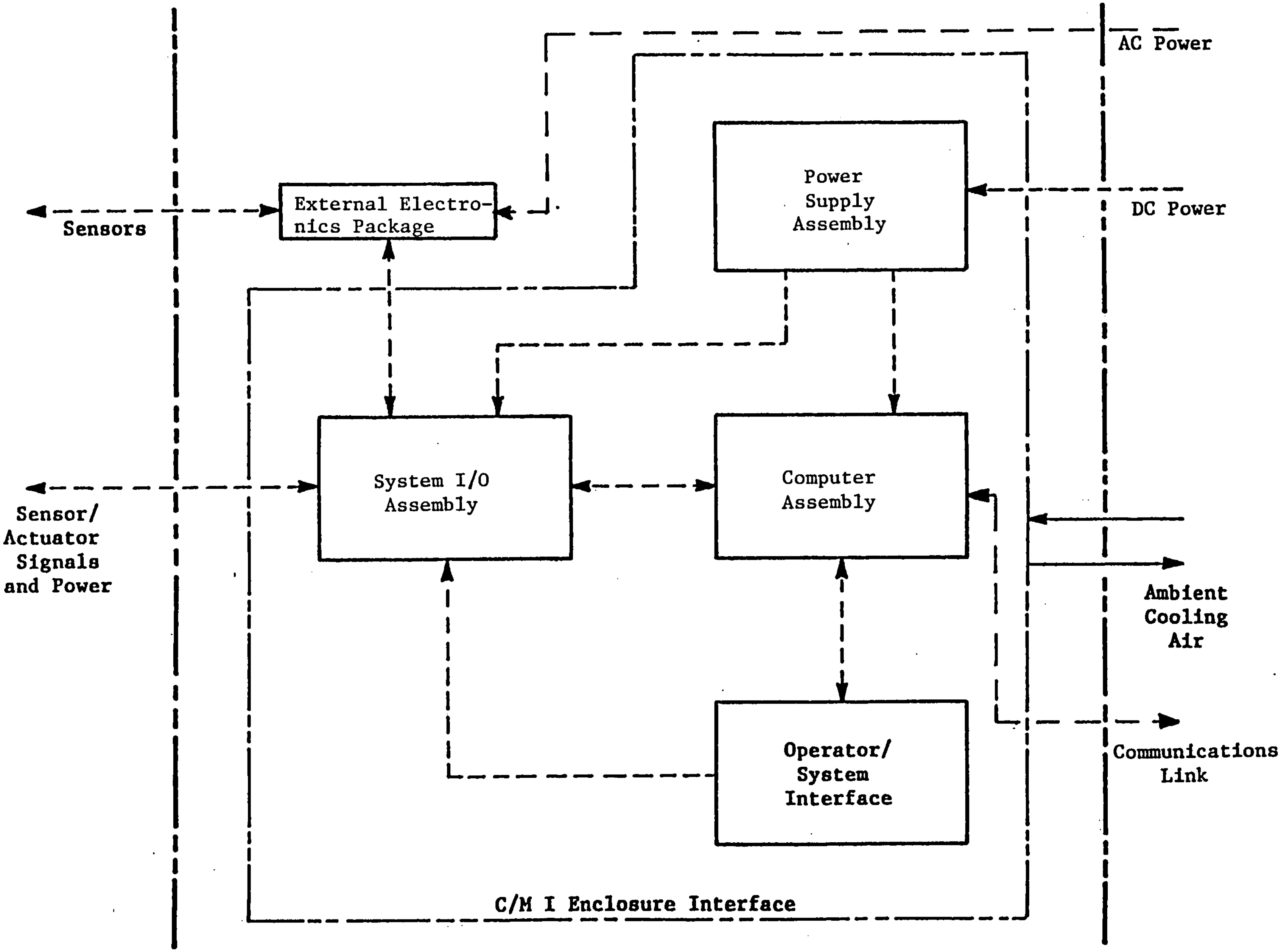


FIGURE 16 C/M I HARDWARE FUNCTIONAL BLOCK DIAGRAM (LEVEL 1)

Hardware Description

Figure 17 shows the hardware functional block diagram in more detail. Each of the four major assemblies is discussed below.

Computer Assembly

The computer assembly consists of a cardcage and motherboard which houses the nine individual cards identified in Figure 17. The major computer card is the central processor unit (CPU). The Series 200 C/M I uses a microprocessor based computer as well as integrated circuit (IC) memory. Once this decision was made the next step involved selecting the processor type, card size and bus structure. The last two choices were tied together. In general, once a bus specification is chosen, the card size is also determined. Some of the bus systems are available for several microprocessor types so that after the bus and card size were chosen the specific microprocessor was also selected.

Most microprocessor-based computer system cards are fairly large. Table 8 lists several bus systems, their developer and the card size associated with each. Most of these bus systems use large cards. Each card can contain many functions. As the various functions become more and more integrated into single chips (large scale integration) the cards have room for other functions. Unused card space can lead to problems when designing a system such as the Series 200 C/M I which needs many different functions but not much of each. The more modular the system can be the more flexible it is. Since each module is so specialized, the unneeded functions and subsequent higher costs and waste of space of large multi-purpose boards are eliminated. This leads toward smaller units that eliminate waste.

A further advantage to using the smallest available cards is the flexibility in packaging. If a card has, for instance, a 30 cm (12 in) dimension the package will have to be over 30 cm (12 in) to accommodate even one board. This puts a lower limit on the computer card cage size.

The smallest cards examined were the STD bus cards which are 11 x 17 cm (4.5 x 6.5 in). These cards are available from over 20 manufacturers and there are new cards constantly being developed. The STD bus has found applications in many different areas including industrial control, R&D type developments and flight systems. They are usually used in small systems where no more than 12 to 16 cards are used. However, there is no limit to the size of the system that can be built with them. Because of the wide availability of the cards and their small size the standard bus was selected as the basic architectural bus structure for the Series 200. As indicated in Figure 17 nine cards are required to perform the function. These nine cards can be packaged in a rack which is 16 x 11 x 13 cm (6.5 x 4.5 x 5 in).

A great many microprocessor chips are available today. An examination of those that are available reveals that as far as hardware is concerned any chip from a leading manufacturer (Intel, Zilog, TI, Motorola, etc.) is as good as another. A major difference in microprocessors is the software necessary to use them.

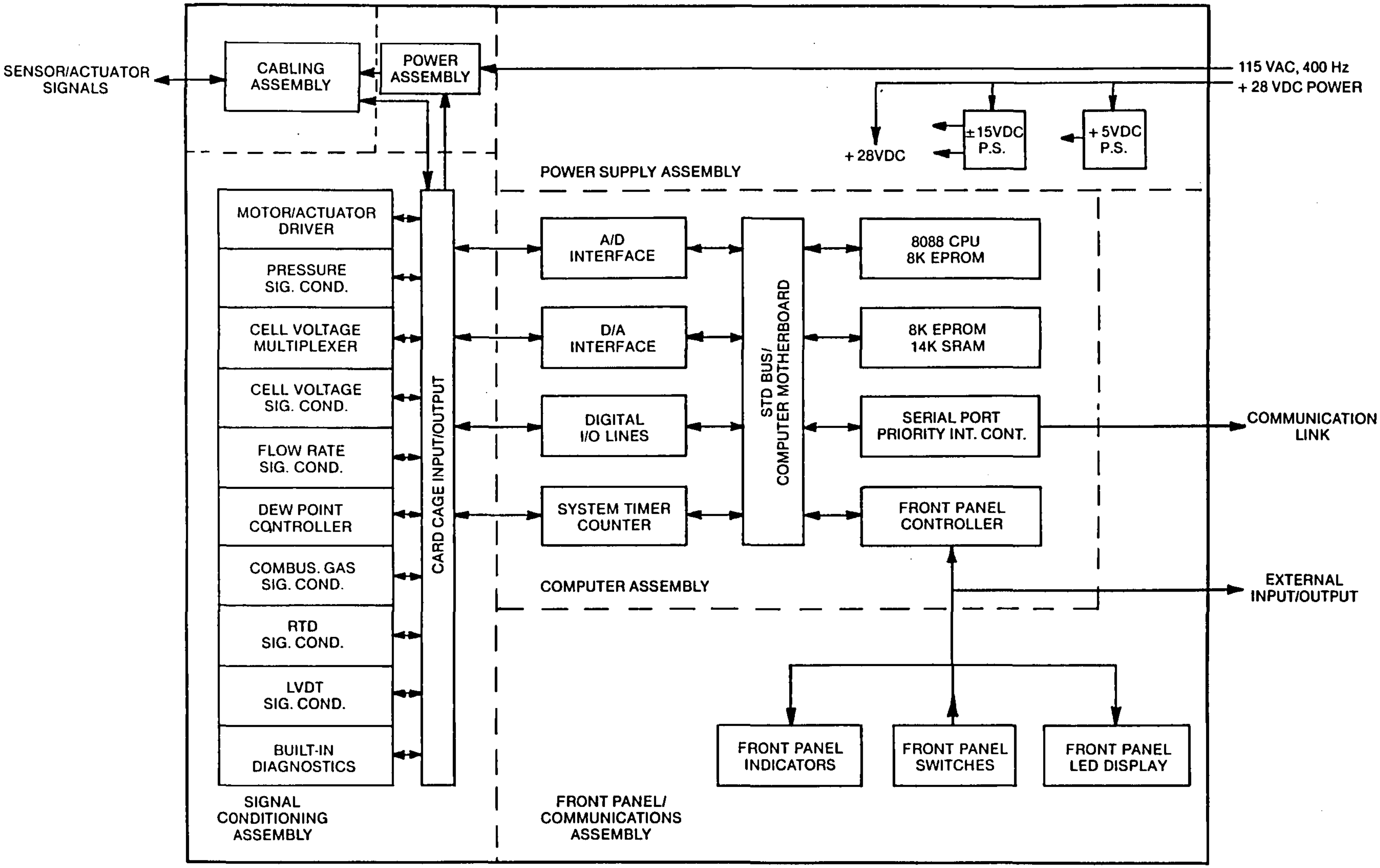


FIGURE 17 CS-1 C/M I HARDWARE FUNCTIONAL BLOCK DIAGRAM (LEVEL 2)

TABLE 8 MICROPROCESSOR-BASED COMPUTER BUS SYSTEMS AND CARD SIZES

No.	Name	Developer	Nominal Card Size, cm (in)	Card Spacing, cm (in)	Comments
1	S-100	Altair	25 x 13 (10 x 5.3)	1.9 (0.75)	Home computers, small business systems. Many sources for cards.
2	Multibus	Intel	30 x 17 (12 x 6.75)	1.5 (0.6)	All Intel 8 bit computers use this. Only Intel μP's (e.g., 8085, 8088, etc.) available.
3	STD	Prolog/Mostek	17 x 11 (6.5 x 4.5)	1.3 (0.5)	Smallest of common bus systems, used in control applications, many sources (>20) of cards. Has several μP's available.
4	EXORciser	Motorola	25 x 15 (9.75 x 6)	1.9 (0.75)	Only Motorola μP (e.g., 6800, etc.) available.
5	TM990	TI	28 x 19 (11 x 7.5)	1.5 (0.6)	Only TI μP (TM9900, etc.) available.
6	LSI-11	DEC	25 x 22 (10 x 8.5)	1.5 (0.6)	1/2 card of 13 x 22 cm (5 x 8.5 in) also available.

The computer word size (number of bits) was determined by the anticipated requirements of present and future ALSSs. The four, eight or 16-bit decision was made quite simply. Four and eight-bit processors are not powerful enough i.e., not enough instructions, execution speed and memory address capability. They are designed for high volume, low complexity applications such as appliances. The 16-bit microprocessors although of recent development have much support in terms of software and hardware. They are quite powerful machines with fast execution time and expansion flexibility. From a maturity and cost point of view they are very desirable for the C/M I application. A 16-bit microprocessor, the Intel 8088, structured with the STD bus was selected. It has addressing capability of greater than 64K, eight-bit locations, much more than is necessary for a typical ALSS subsystem, allowing for expansion.

The selected CPU board has 8K of erasable programmable read only memory (EPROM). A separate memory card contains additional 8K of EPROM and 14K of static random access memory (SRAM). All of the programs and software to operate the C/M I is contained in the EPROM while the SRAM is used for data and temporary storage.

Additional cards required for the computer include the following: a serial port with a priority interrupt controller for serial communications to external devices; a front panel controller for operating the front panel indicators and alphanumeric display; two analog/digitial (A/D) interface cards for accepting analog signals from the subsystem input/output (I/O) subassembly; a digital/analog (D/A) interface board for driving actuators; a digital I/O card for digital signals input and output; and a system timer counter for providing a real time clock. These nine cards make up the total computer assembly.

Front Panel/Communications Assembly

A communications link with serial data format is provided for interface to external devices. Although the C/M I can operate independently of this link, it is provided to monitor parameters and make changes to operating setpoints. It also provides a means for data storage in an external data acquisition system. Provisions are also made for shutdown commands to be either accepted by the C/M I or sent to other subsystems.

The front panel of the Model 220 is shown in Figure 18 with the detailed functional description of each indicator or switch given in Table 9. The front panel is relatively simple. Four pushbuttons and a MODE ENABLE button allow selection of the desired operating mode. Status is given by three subsystem status indicators: NORMAL (green), WARNING (amber) and ALARM (red). An ERROR CODE display presents any errors, determined by the fault detection software, which may occur. A code is displayed and the operator uses a reference table to evaluate and take appropriate action. An advance switch is provided for advancing the error codes until all errors are noted.

System I/O Assembly

All analog signals from the M/EA require signal conditioning. Signal conditioning cards based on Life Systems standard 11 x 11 cm (4.5 x 4.5 in) cards are contained in a single card rack and motherboard. Table 10 lists the

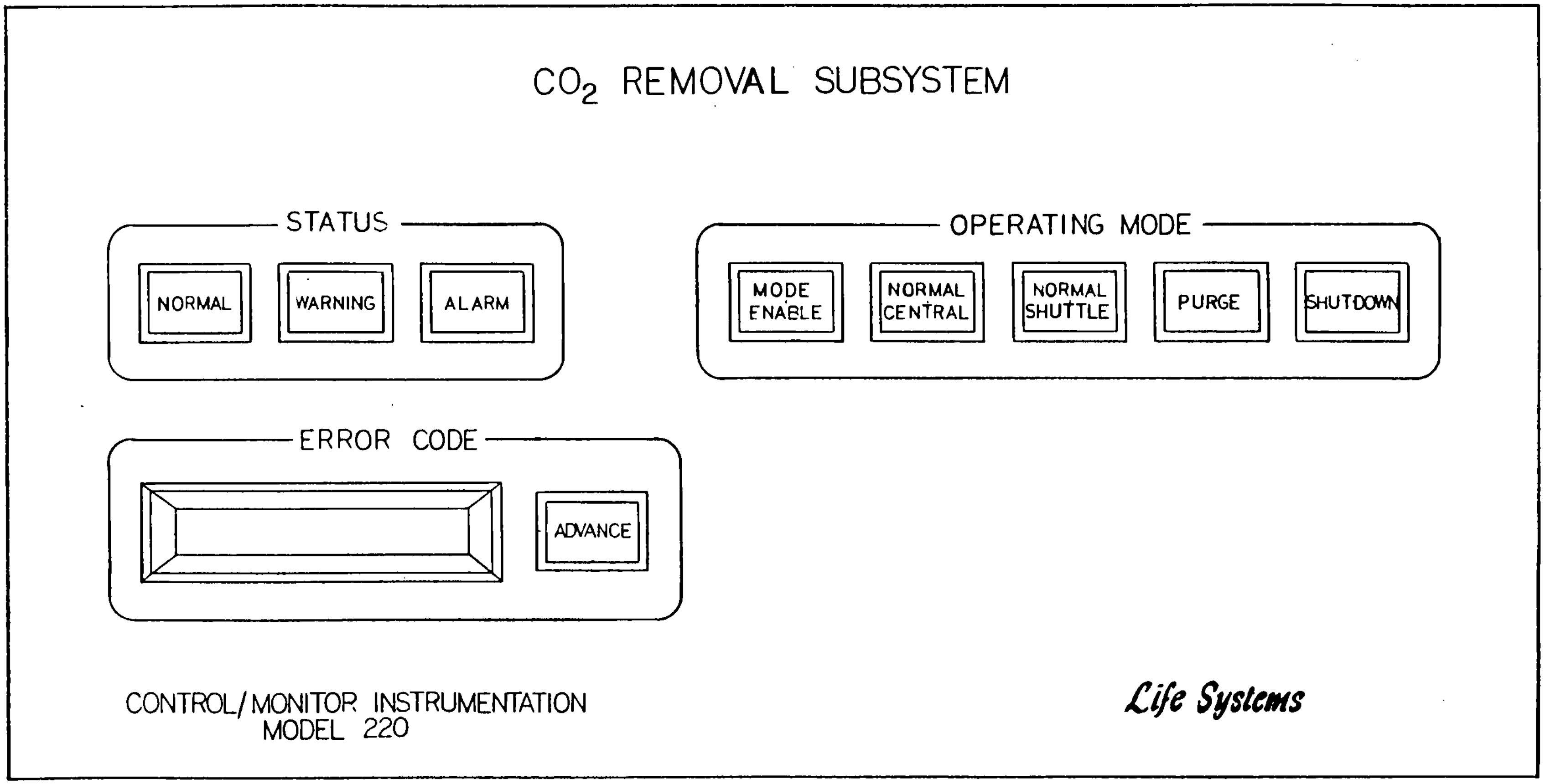


FIGURE 18 MODEL 220 OPERATOR/SUBSYSTEM INTERFACE PANEL LAYOUT

TABLE 9 CS-1 C/M I OPERATOR/SUBSYSTEM INTERFACE PANEL DESCRIPTION

Nomenclature	Description/Function
A. SUBSYSTEM CONTROL	
Operating Mode/Commands	Pushbutton switches for mode transition requests. Light displays indicate present mode (in green) or transition in process (in amber).
• MODE ENABLE	This key must be held down simultaneously with any one of the OPERATING MODE keys to allow an OPERATING MODE REQUEST.
• NORMAL SHUTTLE	Requests the subsystem to make a transition to the NORMAL SHUTTLE operating mode from present operating mode when pressed with MODE ENABLE.
• NORMAL CENTRAL	Requests the subsystem to make a transition to the NORMAL CENTRAL operating mode from present operating mode when pressed with MODE ENABLE.
• PURGE	Requests the subsystem to make a transition to the PURGE operating mode from SHUTDOWN operating mode when pressed with MODE ENABLE.
• SHUTDOWN	Requests the subsystem to make a transition to the SHUTDOWN operating mode from present operating mode when pressed with MODE ENABLE.
B. SUBSYSTEM STATUS	
Status Summary	Indicators summarizing present status of subsystem
• NORMAL	Green indicator for no faults in subsystem.
• WARNING	Amber indicator of warning level faults.
• ALARM	Red indicator of alarm level faults.

continued-

Table 9 - continued

Nomenclature	Description/Function
• ERROR CODE	Eight-digit light emitting diode (LED) display indicating the following. 1. When subsystem is in NORMAL Status display is blank. 2. When subsystem is in WARNING or ALARM status a code (e.g., A015, C013, etc.) indicating first subsystem fault detected is displayed. Subsequent fault codes are displayed by pressing ADVANCE switch.
• ADVANCE	A momentary switch which steps through and causes display of the sequential fault codes. Following last fault code RESET is momentarily displayed and then blank is displayed if status is NORMAL; otherwise any current fault is re-displayed.

TABLE 10 CS-1 SENSOR LIST

Description	Qty.	Symbols	Redundancy Levels	Notes
EDC Cell Voltage	6	E1-E6	1	Voltage Tap
EDCM Voltage	1	E7	1	Voltage Tap
EDCM Current	1	I1	1	Shunt
Air Inlet Relative Humidity	1	R1	3[a]	Calculated[b]
Air Inlet Temperature	1	T1	3[a]	RTD
Air Inlet Dew Point	1	D1	3[a]	RTD
Air Outlet Relative Humidity	1	R2	3[a]	Calculated[b]
Air Outlet Temperature	1	T2	3[a]	RTD
Air Outlet Dew Point	1	D2	3[a]	RTD
CCA Valve Position Indicator	1	W1	1	Potentiometer
FCA Valve Position Indicator	1	W2	1	LVDT
N_2 Purge/H_2 Pressure	1	P1	1	--
H_2/CO_2 Outlet Pressure	2	P2-P3	2[c]	--
H_2 Flow to EDCM	1	F1	1	--
H_2/CO_2 Flow from EDCM	1	F2	1	--
Combustible Gas Concentration	1	C1	3[a]	--
CCA Motor Speed	1	S1	1	--

(a) Triple redundancy simulated by C/M I.
(b) Calculated using dew point and dry bulb temperature.
(c) Two sensors measuring same stream parameter implies double redundancy.

sensors for the M/EA. A total of 12 cards is required to accommodate the signal conditioning. It is noted that the subsystem has capability for handling triple redundant sensors. These include five parameters: combustible gas and inlet and outlet dewpoint and dry bulb - a total of 15 triple redundant sensors. Cell voltages of the six-cell EDCM are conditioned through a cell voltage multiplexer and isolation amplifier signal conditioner. Multiplexing of these signals is done at the signal conditioning card and fed to one channel of an A/D interface card in the computer assembly.

A listing of the 12 cards required in the signal conditioning cardcage is given in Table 11. This table also lists the printed circuit cards of the computer assembly and one interface board used for the front panel alphanumeric display. In addition to the signal conditioning, the System I/O Assembly contains the connector assemblies for inputting and outputting signals from the C/M I to the M/E A and external devices. Figure 19 shows the rear panel for the Model 220 containing the interface connectors.

A power assembly is required for handling actuators that cannot be driven directly from computer level signals. Solid state relays or switches are used for controlling the actuators listed in Table 12.

Power Supply Assembly

The Series 200 C/M I will operate from a single power input of +28 VDC. Additional power supplies are required for the computer and signal conditioning. These include a +5 VDC supply and ±15 VDC power supplies. These power supplies are solid state DC-to-DC converters.

A Series 200 C/M I application may require use of other types of power. The CS-1 used 115 VAC, 400 Hz power to operate the CCA pump motor. This power is supplied to the Model 220 C/M I and passes through a relay located on the power assembly.

Software Description

The following description of the Series 200 C/M I software includes a brief description of the high level language that was selected and a functional description of the major elements of the software architecture.

All software with the exception of some specialized coding for the Series 200 C/M I will be developed using Programmer's Language/Microprocessor (PL/M). It is a high level language designed for system and application programming for microprocessors like the Intel 8088. It is closer to English and algebra than to machine or assembly languages. The latter tend to produce at most one machine language instruction for each statement in the language. A PL/M statement, on the otherhand, may be translated by the compiler into a single microprocessor instruction, an entire sequence of instructions or none as in the case of allocating storage. Often a program is organized into separate modules, as in the case of the Series 200, intended to work together as a whole but to be written, compiled and debugged individually. PL/M provides the mechanisms and controls which facilitate this process. It provides a means of programming that: (1) often reduces the time and cost of programming (2) increases software reliability (3) improves documentation and (4) facilitates software maintenance.

TABLE 11 CS-1 C/M I 220 PRINTED CIRCUIT CARD LIST

Description	No. Req'd.	Schematic Ref. Symbol	Manu. Part No.	Manufacturer
Signal Conditioning (SC) Cardcage				
Cell Voltage Isolation Amplifier	1	E1 to E7, I1, W1	85	LSI
Cell Scan Multiplexer	1	E1 to E7, I1, W1	84	LSI
Flow/Combustible Gas S/C	2	F1, F2, C1	64	LSI
LVDT Position S/C	1	W2	D30	LSI
Pressure Sensor S/C	1	P1, P2, P3	58	LSI
Thermistor Temp. S/C	3	T1, T2, D1, D2	82	LSI
Dew Point Sensor Controller	1	D1, D2		LSI
Motor/Actuator Drivers	1	V1, V2, M1		LSI
Built-in Diagnostic	1	N/A	77	LSI
Subtotal	12			
Computer Assembly				
CPU	1	-	DM8800	Dessert Microsystems
Memory-EPROM/RAM	1	-	7704	Prolog
Digital I/O	1	-	7604	Prolog
A/D Interface	2	-	DT2744	Data Translation
D/A Interface	1	-	RTI-1262	Analog Devices
Front Panel Controller	1	-	97072	Microlink
Serial Comm/Interrupt	1	-	97073	Microlink
System Timer/Counter	1	-	SB8355	Micro-Systems
Subtotal	9			
Other				
Alphanumeric Driver Assy.	1	-	-	LSI
Subtotal	1			

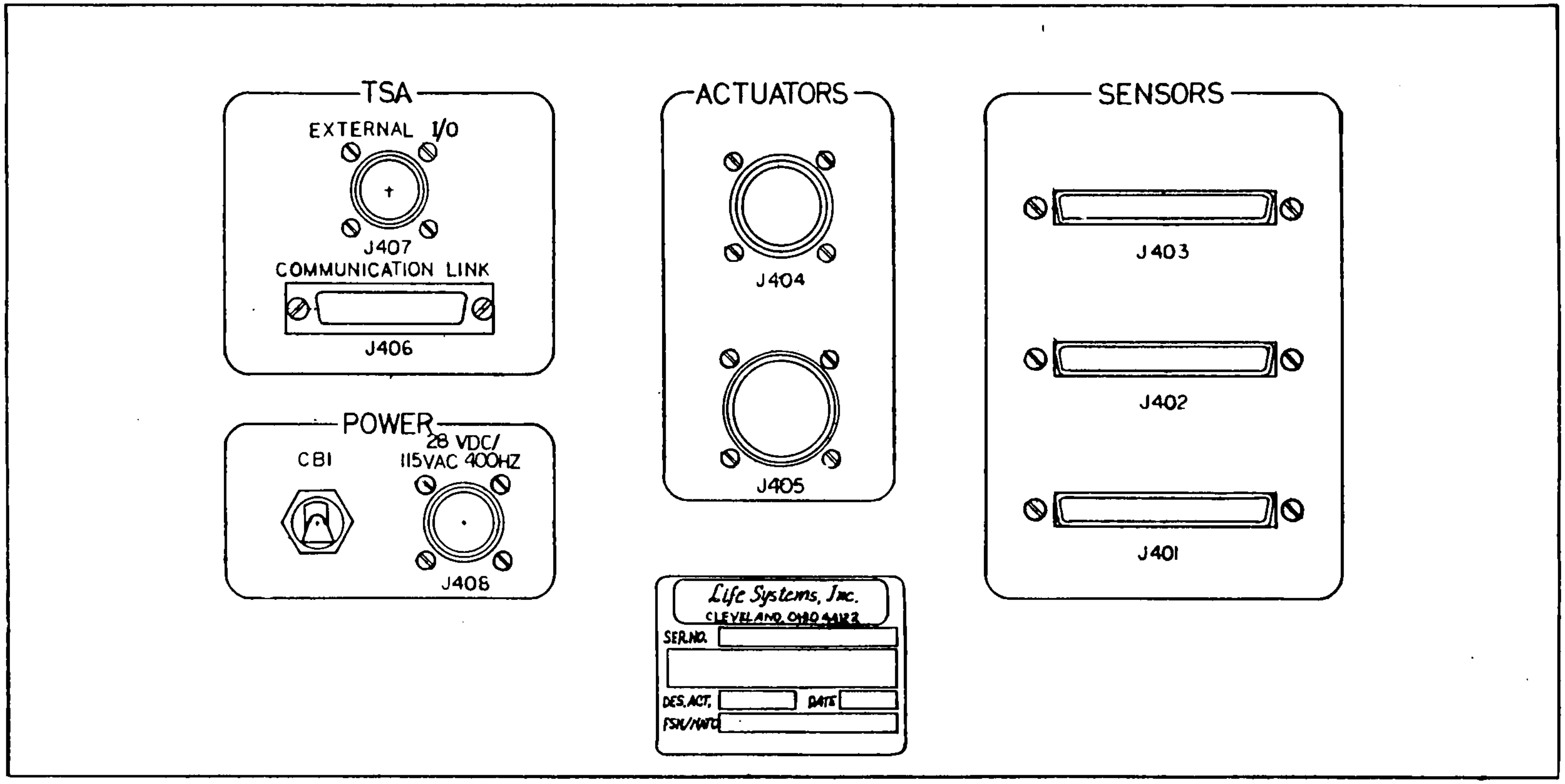


FIGURE 19 MODEL 220 REAR PANEL LAYOUT

TABLE 12 CS-1 ACTUATOR LIST

Description	Qty.	Symbol	Redundancy Level	Notes
CCA Diverter Valve	1	V1	1	Variable - full open to full bypass[a]
CCA Pump	1	M1	1	On/Off
FCA Valve	1	V2	1	See position table below[b]
EDCM Current Control				
On/Off	1	X11	1	On/Off
Current Level	1	X12	1	Variable, 0 to 25 A

FCA Valve positions:

Position	N_2	H_2 Feed[b] Low	H_2 Feed[b] High	Vent
1	O	C	C	O
2	C	C	C	C
3	C	O	C	O
4	C	O	O	O

(a) Full bypass implies no coolant flow to liquid/liquid heat exchanger.
(b) C = Closed, O = Open

Software Functional Overview

Figure 20 gives an overview of the software for the Series 200 C/M I. There are nine major functional blocks of the software. These nine functional blocks are:

a. Real Time Executive
b. Communication Link
c. Mode Request
d. Process Control Loops
e. Data Input Handler
f. Data Output Handler
g. System Services
h. Data Base
i. Fault Diagnostics

Each of these are explained in more detail below.

Real Time Executive

Managing the systems application programs and real time events describes the main function of the real time executive. It is driven by a real time clock (a hardware function) and its task scheduler arranges to have required tasks execute in a timely fashion resolving multi-task priority levels. The operating system also performs interrupt handling, inter-task coordination and communication and services external system communication requests from the system communication link.

Communication Link

The communication link module manages the external data communications and interrupts the data link "requested" commands. The link provides a two-way communication via a standard RS-232C link between the C/M I and external peripheral devices. The principal peripheral device will be a diagnostic test unit (DTU) which is considered to be a part of Test Support Accessories (TSA). This DTU will be a general purpose terminal able to be used with any Series 200 C/M I. It also contains provisions for data logging.

Mode Request

The Mode Request module determines which of several states the subsystem is in. It also handles requests from either the front panel or the subsystem for mode changes and executes those mode changes in a controlled manner. Mode transitions, for instance from Shutdown to Normal Central, are handled with this module. The CS-1 modes and conditions for mode transitions were previously defined in Table 6.

Process Control Loops

The process parameter control loops execute the actual control algorithms to maintain the subsystem parameters within specified ranges. The types of control algorithms that can be implemented include open loop, pre-program controls, supervisory control, feedback proportional, integral and differential controls. Table 13 lists the controls required for the CS-1.

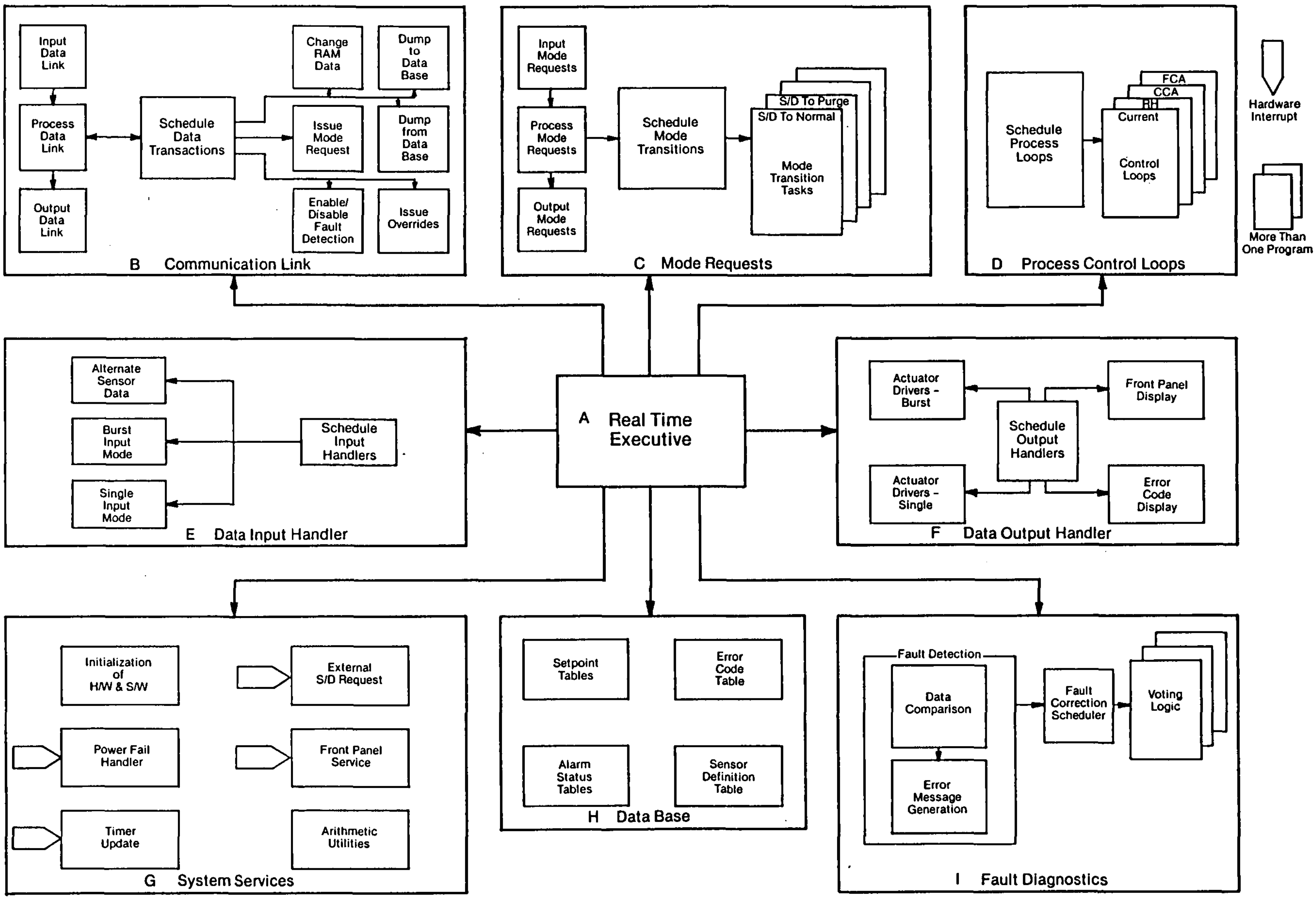


FIGURE 20 SERIES 200 C/M I SOFTWARE BLOCK DIAGRAM

TABLE 13 CS-1 CONTROL DEFINITIONS

No.	Control	Parameter	Description	Actuator(s)	Sensor(s)	Setpoint	Range
I	Current	EDCM Current	EDCM Current Control with power generated available for external use or dissipated as waste heat. EDCM current is controlled at a constant level	X11, X12	I1	(a)	0-25 A
II	Relative Humidity	Outlet EDCM RH	Regulate Coolant Control Assembly (CCA) based on inlet air RH to control EDCM temperature thereby controlling outlet air RH	CC1	R2	(b)	50-70% RH

(a) Current setpoint for Normal Shuttle is 9.0 A; Normal Central is 9.9 A.
(b) RH setpoint is a function of current and inlet dew point (RH, % = 76.7 - 0.16 (DP,F) -0.84 (I, A) - 0.0044 (DP) (I)).

Data Input Handler

The Data Input Handler brings analog and digital data into the C/M I data base. It can input data discretely from an individual port or input a block of data from several sequential port locations. The data input handler will also default to an alternative data input table if requested to do so.

Data Output Handler

Maintaining digital and analog actuator output data is the responsibility of this handler. Like the input handler, the output handler can output data to discrete ports, blocks of data to sequential ports or default to an alternate data table.

System Services

The system services contain the interrupt routines and any special processing required by a specific 200 application. Examples of these would be internal timer updates, a power-fail handler or arithmetic routines.

Data Base

The software design of the C/M I is "table" driven with all constants and variables stored in tables so that indices and pointers can be used to locate data. This technique allows the system to be changed easily and be adapted to various applications. The sytem defintion and data base modules define these tables and provides system interface to them.

Fault Diagnostics

The fault diagnostics monitor process variables and set flags if parameters have exceeded operating tolerance. Upon the detection of a fault the C/M I will light the warning or alarm indicator and, if necessary, shutdown the system. In addition, an error code is provided for listing fault diagnostic errors. Table 14 presents the Model 220 error code listing.

Packaging

Figure 21 is a photograph of the mockup of the Series 200, specifically the Model 220, C/M I. It consists of essentially four major assemblies - the signal conditioning, computer, power supply and power assembly (not shown). Most of the wiring interconnections between assemblies will be made with mass-terminated ribbon cable. This is a major reliability improvement over prior point-to-point wiring techniques.

Characteristics of the C/M I are given in Table 15. Table 16 summarizes the size, weight and power consumption for the Model 220. The packaging selected for the Series 200 C/M I is an industry standard for flight avionics equipment. A standard ARINC enclosure is used. Figure 21 illustrates the ARINC chassis to be used which is enclosed with a dust cover.

TABLE 14 MODEL 220 C/M I ERROR DISPLAY CODES

Error Code[a]	Sensor	Condition	Fault Detection Mode That is Active[c]							
			NC		NS		P		S/D	
			A	W	A	W	A	W	A	W
001	E1	Low Cell 1 Voltage	X	X	X	X			X	X
002	E2	Low Cell 2 Voltage	X	X	X	X			X	X
003	E3	Low Cell 3 Voltage	X	X	X	X			X	X
004	E4	Low Cell 4 Voltage	X	X	X	X			X	X
005	E5	Low Cell 5 Voltage	X	X	X	X			X	X
006	E6	Low Cell 6 Voltage	X	X	X	X			X	X
007	E7	Low Module Voltage		X		X				
008	D11	Low Inlet DP, Sensor 1		X		X				
009	D12	Low Inlet DP, Sensor 2		X		X				
010	D13	Low Inlet DP, Sensor 3		X		X				
011	D11	High Inlet DP, Sensor 1		X		X				
012	D12	High Inlet DP, Sensor 2		X		X				
013	D13	High Inlet DP, Sensor 3		X		X				
014	T11	Low Inlet Temp., Sensor 1		X		X				
015	T12	Low Inlet Temp., Sensor 2		X		X				
016	T13	Low Inlet Temp., Sensor 3		X		X				
017	T11	High Inlet Temp., Sensor 1		X		X				
018	T12	High Inlet Temp., Sensor 2		X		X				
019	T13	High Inlet Temp., Sensor 3		X		X				
020	T21	Low Outlet Temp., Sensor 1		X		X				
021	T22	Low Outlet Temp., Sensor 2		X		X				
022	T23	Low Outlet Temp., Sensor 3		X		X				
023	T21	High Outlet Temp., Sensor 1	X	X	X	X				
024	T22	High Outlet Temp., Sensor 2	X	X	X	X				
025	T23	High Outlet Temp., Sensor 3	X	X	X	X				
026	R11	Low Inlet RH, Sensor 1[b]		X		X				
027	R12	Low Inlet RH, Sensor 2[b]		X		X				
028	R13	Low Inlet RH, Sensor 3[b]		X		X				
029	R11	High Inlet RH, Sensor 1[b]		X		X				
030	R12	High Inlet RH, Sensor 2[b]		X		X				
031	R13	High Inlet RH, Sensor 3[b]		X		X				
032	R21	Low Outlet RH, Sensor 1[b]	X	X	X	X				
033	R22	Low Outlet RH, Sensor 2	X	X	X	X				
034	R23	Low Outlet RH, Sensor 3	X	X	X	X				
035	R21	High Outlet RH, Sensor 1	X	X	X	X				
036	R22	High Outlet RH, Sensor 2	X	X	X	X				
037	R23	High Outlet RH, Sensor 3	X	X	X	X				
038	I1	Low Module Current								
039	I1	High Module Current		X		X			X	X

(a) Error Code is given by YXXX where Y = A - Alarm, W - Warning and XXX is three digit number given in table.
(b) Claculated
(c) NC - Normal Central, NS = Normal SHuttle, P = Purge, S/D = Shutdown, A = Alarm, W = Warning

Table 14 - continued

Error Code[a]	Sensor	Condition	Fault Detection Mode That is Active[c]							
			NC		NS		P		S/D	
			A	W	A	W	A	W	A	W
040	P1	Low Inlet Pressure	X	X	X	X				
041	P1	High Inlet Pressure	X	X	X	X	X	X		
042	P2	Low Outlet Pres., Sensor 1	X	X	X	X				
043	P3	Low Outlet Pres., Sensor 2	X	X	X	X				
044	P2	High Outlet Pres., Sensor 1	X	X	X	X	X	X		
045	P3	High Outlet Pres., Sensor 2	X	X	X	X	X	X		
046	F1	Low Inlet Flow		X		X		X		
047	F1	High Inlet Flow				X		X		
048	F2	Low Outlet Flow		X				X		
049	F2	High Outlet Flow						X		
050	S1	Low Pump Speed		X		X				
051	C11	High Combus. Gas, Sensor 1	X	X	X	X	X	X	X	X
052	C12	High Combus. Gas, Sensor 2	X	X	X	X	X	X	X	X
053	C13	High Combus. Gas, Sensor 3	X	X	X	X	X	X	X	X
054	W1	Diverter Valve Not Correct Position								
055	W2	FCA Failed to Purge								
056	W2	FCA Failed to Close								
057	W2	FCA Failed to Open								
058	E1-E6	EDC Voltage Timed Out								

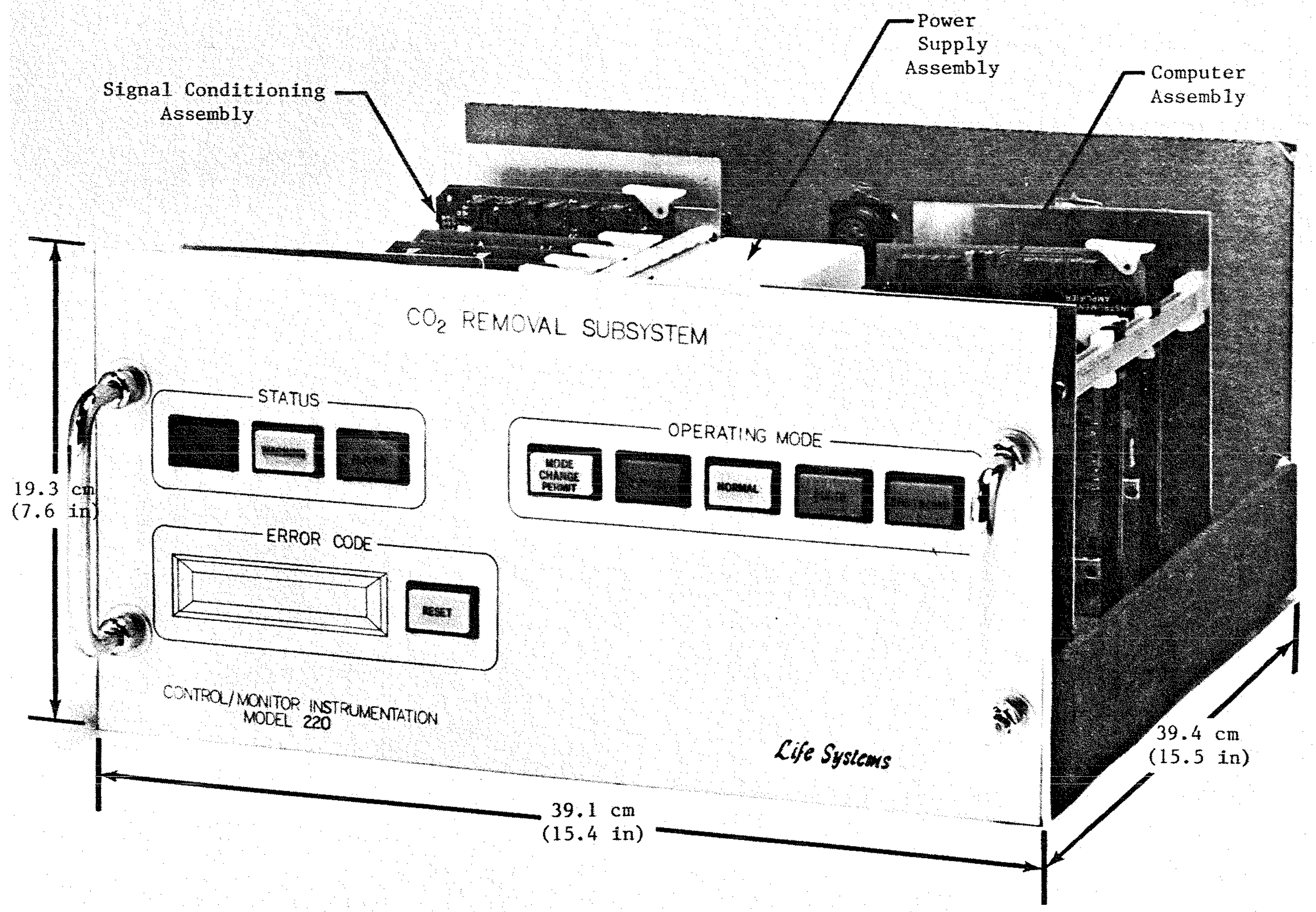


FIGURE 21 MODEL 220 C/M I MOCKUP

TABLE 15 CS-1 CONTROL/MONITOR INSTRUMENTATION CHARACTERISTICS

Dimensions (HXWxD), cm (in)	19.3 x 39.1 x 39.4 (7.6 x 15.4 x 15.5)
Power Input, W	83
C/M I Power Consumption, W	67
Input Voltage	
VDC	28 ± 4
VAC	115, 400 Hz, 1Ø
Computer Assembly	
Bus	STD - 8088
Microprocessor	Intel 8088
Machine Cycle Time, nsec	200 (5 MHz)
EPROM Memory, Bytes	16 K
RAM Memory, Bytes	14 K
Digital I/O	64 TTL Lines
A/D Converter	
Channels	32 single ended
Resolution	12 bits
Full Scale Ranges	±10 mV to ±10 V
D/A Converter	
Channels	4 Single Ended
Resolution	12 Bits
Full Scale Range	±10 VDC @ 5 mA
Serial Communications	1 RS232 Port
Signal Conditioning Assembly	
Card Slots	12
Input Sensor Types:	Differential Voltage Wein Bridge RTD Reluctance Pickup (Speed) Dew Point Sensor LVDT
Total Number of System Inputs	31
System Outputs:	
Total Number	7
Thermoelectric Cooler	2 @ 2 Amps Max.
DC Motors (28 VDC)	2
AC Motor (115 Vac @ 400 Hz)	1 On/Off
Analog Current Setpoint	1 @ 0 to 5 VDC
Current Control - On/Off	1 @ 0 to 5 VDC

continued-

Table 15 - continued

Communications	
Front Panel	
Operating Mode	5 Pushbuttons
Status	3 Indicators
Error Code	8 Digit Display
Error Code - Advance	1 Pushbutton
Communication Link	1 Asynchronous RS-232C Port
Shutdown Inputs	1 @ 5 VDC
Shutdown Outputs	1 @ 5 VDC
Operating Modes	
Number of Operating Modes	4
Number of Allowable Mode Transitions	9

TABLE 16 MODEL 220 CONTROL/MONITOR INSTRUMENTATION DESIGN, COMPONENT SIZE, WEIGHT AND POWER CONSUMPTION SUMMARY

Component	Dimensions, H x W x D, cm (in)	Volume, dm^3 (ft^3)	Weight, kg (lb)	Power, W
Enclosure	19.3 x 39.1 x 39.4 (7.6 x 15.4 x 15.5)	29.7 (1.05)	3.2 (7)	--
Computer Assembly	18.8 x 14.5 x 19.0 (7.4 x 5.7 x 7.5)	5.2 (0.18)	2.3 (5)	18
Front Panel Switches/Indicators, Max. 9	2.0 x 3.0 x 4.3 (0.8 x 1.2 x 1.7)	0.026 (0.001)	0.4 (1)	--
Front Panel Lamps, Max 8	--	--	--	1
Power Supplies (5V, ±15V)	16.0 x 7.1 x 23.4 (6.8 x 2.8 x 9.2)	2.7 (0.10)	3.2 (7)	13
Signal Conditioning Assembly	16.8 x 13.2 x 23.4 (6.6 x 5.2 x 9.2)	5.2 (0.18)	3.6 (8)	28
Power Assembly	16.5 x 16.5 x 5.1 (6.5 x 6.5 x 2.0)	1.4 (0.05)	1.4 (3)	7
Connectors and Cables	--	--	1.4 (3)	--
Total	19.3 x 39.1 x 39.4 (7.5 x 15.4 x 15.5) (Envelope)	29.7 (1.05) (Envelope)	15.5 (34)	67

CONCLUSIONS

The following conclusions are a direct result of the analysis and design activities of the advanced C/M I program.

1. The Series 200 will be drastically "smaller" than the Series 100. Reductions of 85% are projected for each the weight, volume, power and heat rejection requirements for CS-1 (i.e., Model 220) compared to the equivalent in the Series 100. This has been achieved by (1) basing the design on a microprocessor and a STD bus which drastically reduces the computer requirements; (2) retaining only those requirements for operator system interface which are absolutely required, i.e., mode changes and simplified error detection; (3) selecting a standard electronics package. Because of these hardware designs and non-volatile EPROM memory, the reliability of the Series 200 is projected to be substantially higher than the Series 100.

2. The use of a microprocessor, non-volatile EPROM memory, a flight qualifiable enclosure and improved fabrication techniques such as mass-terminated interconnection of assemblies will substantially improve reliability of the Series 200 C/M I.

3. Advanced fault diagnostic capabilities will be utilized in the Series 200. This includes fault detection of all sensors and fault correction based on voting logic of triple redundant sensors.

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16. Abstract Development of regenerative Advanced Life Support Systems requires instrumentation characteristics which evolve with successive development phases. As the development phase moves toward flight hardware, the system availability becomes an important design aspect which requires high reliability and maintainability. As part of a continuing development effort, a program to evaluate, design and demonstrate major advances in control and monitor instrumentation was undertaken. This program was directed toward a specific subsystem, a carbon dioxide removal process, one whose maturity level makes it a prime candidate for early flight demonstration. As such, the instrumentation design incorporates features which are compatible with anticipated flight requirements. Current electronics technology and projected advances are included. In addition, the program established commonality of components for all Advanced Life Support Subsystems.

It was concluded from the studies and design activities conducted under this program that the next generation of instrumentation will be greatly "smaller" than the prior one. Not only physical size but weight, power and heat rejection requirements have been reduced in the range of 80-85% from the former level of research and development instrumentation. Using a microprocessor-based computer, a standard computer bus structure and non-volatile memory, improved fabrication techniques and aerospace packaging this instrumentation will greatly enhance overall reliability and total system availability.

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