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COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS

CONTRACT NO. NAS8-28377

31 AUGUST 1972

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Section 1

INTRODUCTION AND SUMMARY

Experience indicates that when proceeding from a working prototype life support system to flight-qualified hardware, a significant increase in cost is incurred. In order to assist NASA in long-range planning and allocation of resources in a cost effective manner in support of earth orbital programs, a methodology has been developed to predict the relevant contributions of the more intangible cost elements encountered in the development of flight-qualified hardware based on an extrapolation of past hardware development experience. Major items of costs within life support subsystems have been identified and related to physical and/or performance criteria. Cost and performance data from Gemini, Skylab, and other aerospace and biotechnology programs were analyzed to identify major cost elements required to establish cost estimating relationships for advanced life support subsystems. This report deals with the three leading carbon dioxide concentration systems, namely 1) the Molecular Sieves CO_2 Concentrator, 2) the Hydrogen-Depolarized Concentrator, and 3) the Regenerable Solid Desiccant Concentrator.

The cost estimated techniques utilized and associated cost elements structure are defined. The methodology used in establishing cost estimating relationships (CER) has been developed. CER's for life support system components developed in a previous study, NAS9-9018, have been modified and used whenever applicable. The CO_2 concentrator CER's were developed by collecting cost equations for individual components and summing them up to "build" the new system's CER. The effects of economic escalation were considered by applying the U.S. Bureau of Statistics Consumer Price Index.

Presented also are the cost estimates for each of the three CO_2 concentrators considered, as well as their comparative criteria, including relative characteristics, operational differences and development status. Concentrator cost estimates were based on their respective technical and performance characteristics which are also given in detail. Table I summarizes cost per flight type CO_2 concentrator, including recurring and nonrecurring, as a function of the number of units produced. It should be noted, however, that approximately 4 flight units are produced per actual flight. For example, approximately 40 flight units were procured for the Gemini program which had 10 actual flights. A similar ratio upholds for the Skylab program.

TABLE I - FLIGHT UNIT COST VS. NUMBER OF UNITS PRODUCED

Number of Flight Units Developed	Molecular Sieves Concentrator	Hydrogen-Depolarized Concentrator	Regenerable Solid Desiccant Concentrator
1	7,195,022	6,113,187	5,999,962
2	4,350,688	3,529,718	3,424,306
3	3,324,367	2,619,529	2,521,779
4	2,873,584	2,197,916	2,103,006
5	2,564,309	1,929,580	1,834,018
10	1,911,258	1,359,975	1,271,433
40	287,358	219,792	210,301

A methodology was also developed for estimating the costs of six-man capacity non-flight qualified concentrator prototypes. Costs of high-fidelity prototypes have been computed to be as follows:

1. Molecular Sieves Concentrator Prototype = 1,172,420 dollars
2. Hydrogen Depolarized Concentrator Prototype = 896,750 dollars
3. Regenerable Solid Desiccant Prototype = 858,026 dollars

Costs of prototypes may be reduced significantly depending on the degree of fidelity, packaging, and/or miniaturization required.

Subsequent sections of this report deal with the following topics:

1. Cost Estimating Techniques
2. Development of CER's
3. CO_2 Concentrators Cost Estimating
4. Prototype Cost Estimating
5. Conclusions

Section 2

COST ESTIMATING TECHNIQUES

The methodology used in establishing cost estimating techniques for life support systems is based on 1) the identification of the physical and performance characteristics of each of the system components, 2) establishing or utilizing existing cost estimating relationships (CER's) for each of the components considered, and 3) the summation of equations for respective system components to establish the total system cost estimation. CER's developed in contract NAS9-9018 were used, with appropriate modifications, to estimate the cost of the components considered. For example, a gaseous storage tank CER was used for the CO_2 accumulator and the LiOH canister CER was used for the silica gel, molecular sieve, and regenerable solid desiccant canisters. The costs of small components such as manual and sequence valves were made on a weight basis. An assembly factor for integrating the components was also used.

Definition of the cost element structure and the application of the CER's are given in the following paragraphs.

COST ELEMENT STRUCTURE:

The cost element structure provides visibility of the total project expenditures and permits identification of the significant project costs. Expenditures are divided into nonrecurring and recurring:

> Nonrecurring - The nonrecurring expenditures for each life support subsystem are segregated into Prime Contractor and Major Subcontractor efforts. The Prime Contractor effort involves specification, coordination and integration of the system into the spacecraft. The Major Subcontractor effort is divided into Design and Development, AGE, Program Management and System Engineering, Test Operations and Hardware. The Design and Development costs are segregated into major subsystems.

Recurring - The recurring expenditures are divided into the Prime Contractor and Major Subcontractor costs. The Prime Contractor efforts involve primarily the incorporation of the life support systems into the spacecraft. The Major Subcontractor costs are broken into Sustaining Engineering, Tooling and System Production. The System Production expenditures are segregated into subsystems and these are in turn segregated into components.

Table II presents a typical breakdown of the life support system expenditures, as encountered in the Gemini Program, divided in the respective non-recurring and recurring items. The major nonrecurring costs are those related to Design, AGE, and Prime Contractor's specification and procurement efforts. The major recurring cost item is that of flight hardware production.

EFFECT OF INFLATION ON COST ESTIMATES:

A major inherent feature of the methodology which is highly critical to the accuracy of the results obtained pertains to inflation and economic escalation. Since computed CER's are based on specific year dollars, they must be inflated to the proper year in order to obtain realistic future program values. Due to the lack of a specific aerospace price index, the yearly dollar value adopted in this report was considered to correspond to the Consumer Price Index. Figure 1 shows the Consumer Price Index based on data published by the U.S. Bureau of Statistics.

TABLE II - REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN

NON-RECURRING	%	RECURRING	%
Design	16.68	Flight Hardware Production	54.56
Subcontractor General & Administrative	8.62	Subcontractor G&A	9.22
Subcontractor Fee	3.62	Subcontractor Fee	3.88
Program Management	1.24	program Management	1.36
System Engineering	5.25	Sustaining Engineering	1.96
Development Test	3.44		
Qualification Test	2.54		
Reliability Test	4.09		
AGE	18.45		
Tooling	3.87	Sustaining Tooling	1.69
Non-accountable Test Hardware	1.67		
Specifications, Vendor Coordination and Procurement Expenses	13.62	Specifications, Vendor Coordination and Procurement Expenses	15.49
System Integration	8.36	System Integration	7.15
Prime's Testing	8.17	Minor Subcontracts	4.69
Minor Subcontracts	0.38		
TOTAL	100%		100%

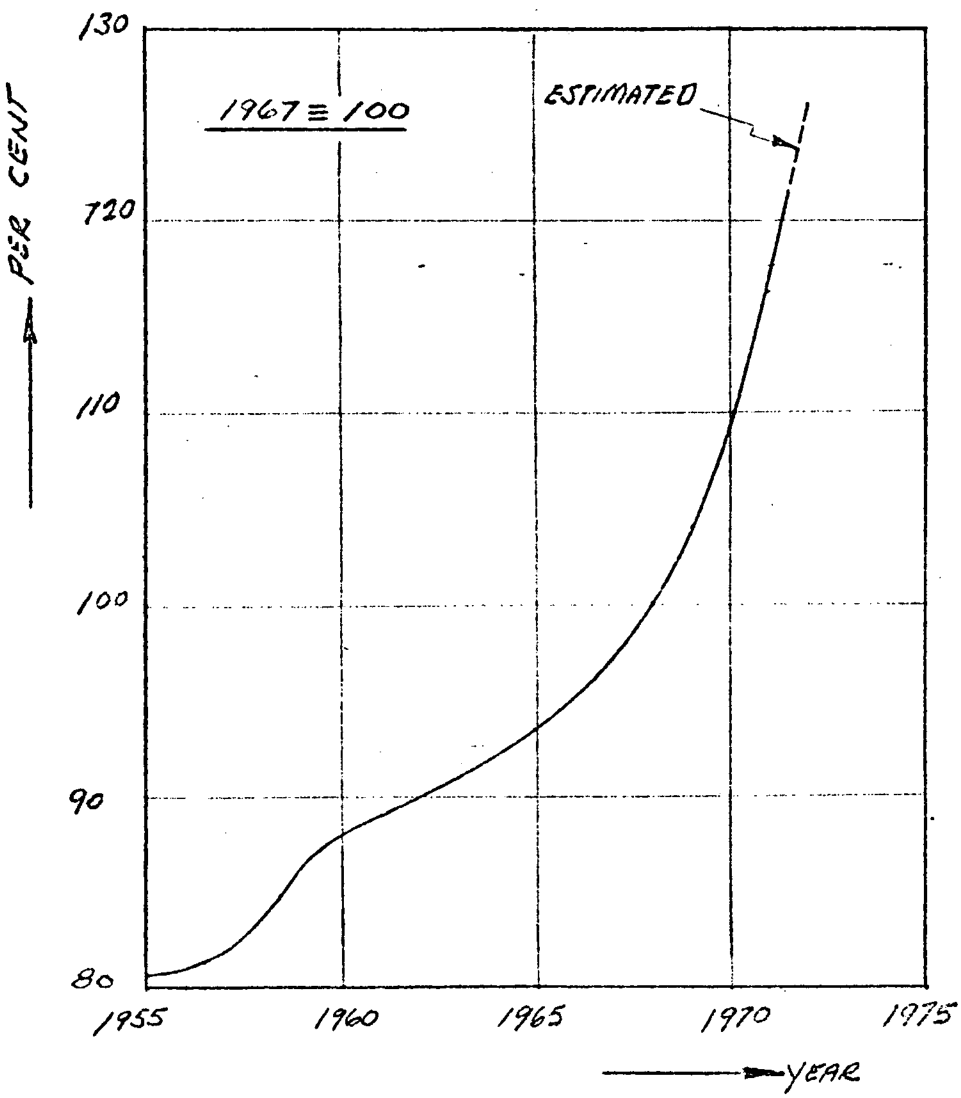

FIGURE I - Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

Section 3

DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

The methodology used in the development of CER's is illustrated by the heat exchanger CER presented below. Ideally, cost-estimating relationships should be based on consistent and well-defined physical and performance characteristics, complete and accurate cost data derived from actual programs and a sufficient number of cases to exhibit statistical significance. However, cost data actually available are very limited from a statistical standpoint. Only six heat exchangers were available for the development of the CER described herein. On the other hand, the six heat exchangers represented six various types, a fact which points to the validity of the developed CER. The CER development utilized in this study is as follows:

1. The components are analyzed to determine which physical or performance characteristics might prove useful as predictive variables.
2. Costs are arrayed graphically on logarithmic scales against the candidate variables either singly or grouped. The most promising of these arrays are selected on the basis of a subjective analysis which considers the appropriateness of the variables, the form and slope of the curves, and the relative aspects of component costs.

Utilizing the above procedure in a number of aerospace applications, it was found possible to relate costs to physical, design, and performance characteristics and, within limits, to project these relationships to more advanced systems.

Table III presents the cost and technical characteristics of Gemini heat exchangers. A study of the values in the table indicates that neither the flow rates nor the heat loads can be correlated with the first unit costs shown. The heat exchanger costs, however, were found to increase progressively with unit weight and were used to establish a weight/cost factor as shown in Figure 2. The resulting data were then normalized,

Table III - COST AND TECHNICAL CHARACTERISTICS OF HEAT EXCHANGERS

TYPES OF HEAT EXCHANGERS	WEIGHT LB	FLOW RATE LB/HR	HEAT LOAD BTU/HR	NO. OF PORTS	FIRST UNIT COST
1. REGENERATIVE	1.33	81	4,720	4	1,756
2. GROUND COOLING	2.19	425	17,300	6	4,822
3. CRYOGENIC	5.29	80	1,099.3	7	7,074
4. CABIN	12.38	40	680	6	7,659
5. SUIT	19.00	80	1,500	10	19,652
6. WATER BOILER	22.60	183	11,200	13	34,851

at 10 lbs. per heat exchanger, to negate the effect of weight differences. The number of ports per heat exchanger, which were also found to increase as a function of unit cost, are shown plotted versus normalized cost data in figure 3. A good fit for the combined relations shown in figures 2 and 3 is as follows:

Heat exchanger First Unit Cost $C = 116\ W^{0.267} N_p^{1.905}$ dollars

W = heat exchanger weight, lbs., and

N_p = number of ports per heat exchanger

To check the validity of the developed heat exchanger CER, the calculated first unit cost values are tabulated in Table IV, which also includes the

Table IV - VALIDITY CHECK OF HEAT EXCHANGER CER

TYPES OF HEAT EXCHANGERS	ACTUAL FIRST UNIT COST	CALCULATED FIRST UNIT COST	CALCULATED ERROR, %
1. REGENERATIVE	1,756	1,765	0.5
2. GROUND COOLING	4,822	4,362	-9.7
3. CRYOGENIC	7,074	7,543	6.5
4. CABIN	7,659	6,959	-9.18
5. SUIT	19,652	20,671	5.18
6. WATER BOILER	34,851	35,906	3.02

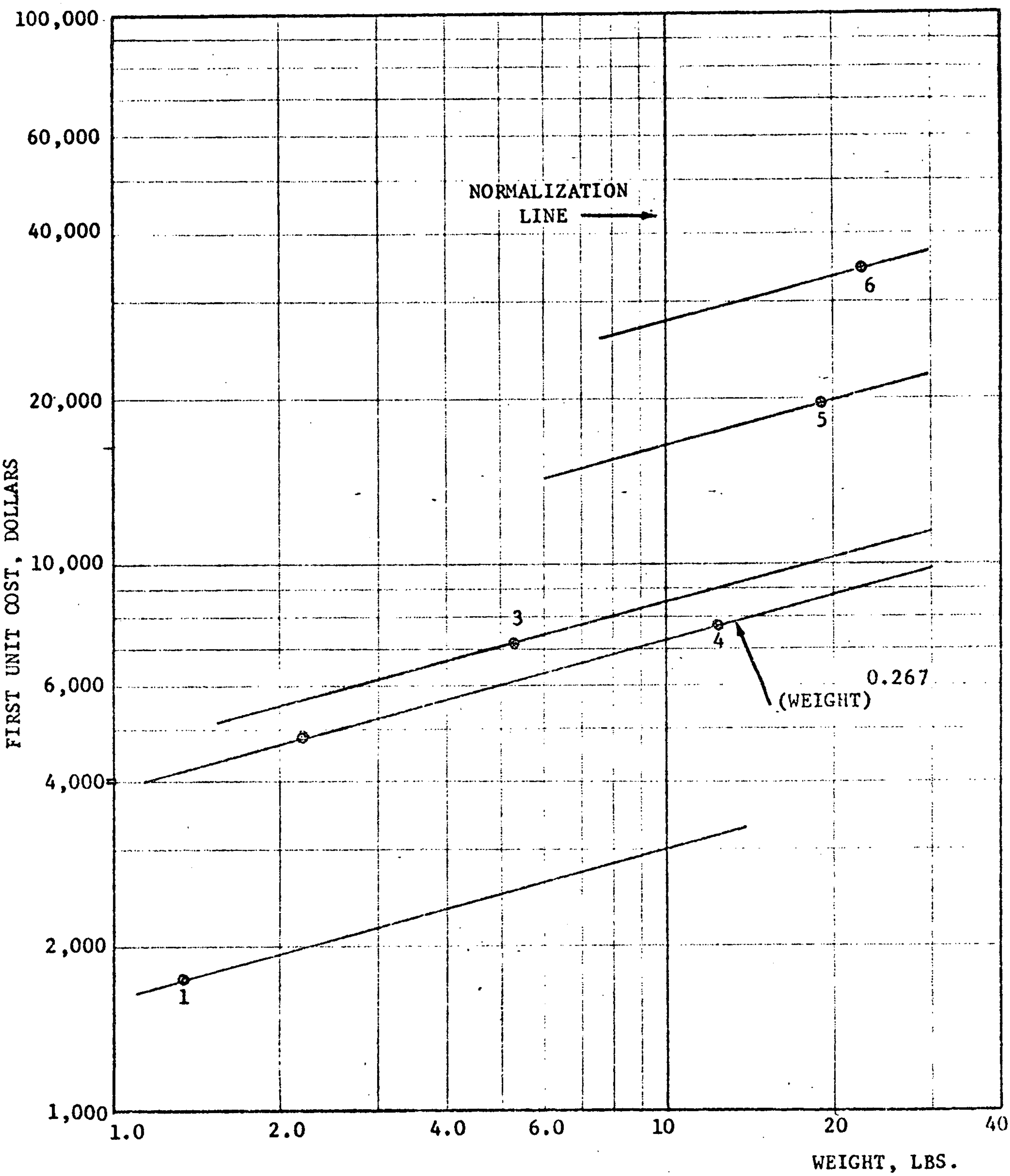

FIGURE 2 - HEAT EXCHANGER COST/WEIGHT RELATIONSHIP

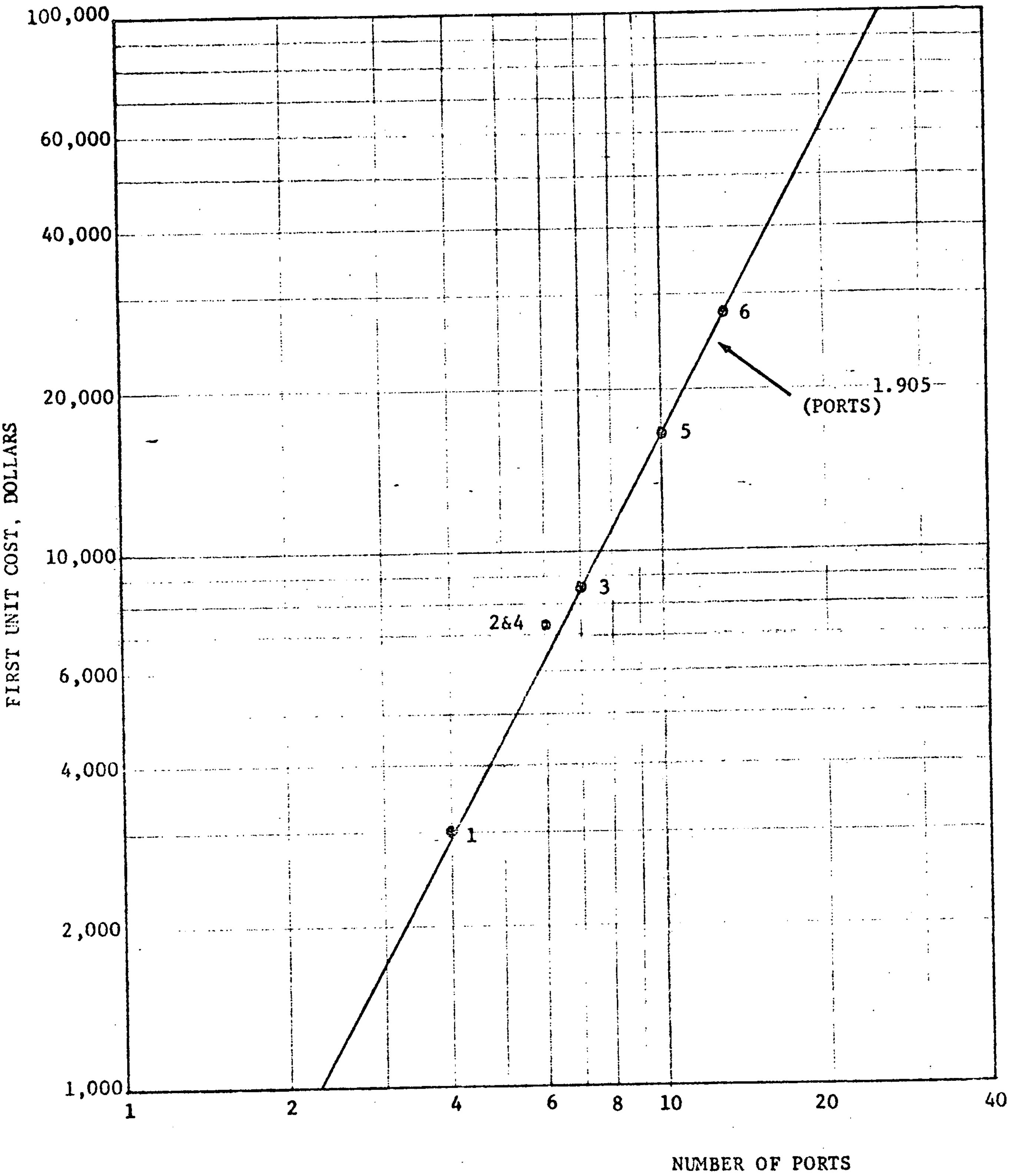

FIGURE 3 - HEAT EXCHANGER COST/NUMBER OF PORTS RELATIONSHIP

actual unit costs and computed percentage error. The average error resulting from utilizing the CER has an absolute value of 6.3%, as seen from Table IV,

The heat exchanger CER was then multiplied by a factor = $Q^{0.89}$ to account for Q, the number of heat exchanger units fabricated. The cost of valves associated with the operation of the heat exchanger was considered on a weight basis by including W_{oc}, the weight of other components in pounds, in the CER. Additionally, the Consumer Price Index was used to account for inflation. January 1972 dollars were found to be 1.37 times the value of 1963 dollars cited in Table III. Accordingly, the resulting heat exchanger CER was given as follows:

$$C = 159W^{0.267}N_p^{1.905}Q^{0.89} + 2959\ W_{oc} \qquad \text{dollars.}$$

Section 4

COST ESTIMATES FOR CARBON DIOXIDE CONCENTRATORS

Cost estimating relationships have been derived for the following CO_2 concentrator systems:

1. Molecular Sieves CO_2 Removal System
2. Hydrogen-Depolarized CO_2 Concentrator
3. Regenerable Solid Desiccant

The molecular sieves systems have undergone more development than any other CO_2 concentrator. A number of molecular sieves units has been developed and tested for extended durations in manned ground simulator tests. Additionally, a flight-type molecular sieves CO_2 removal unit has been developed for Skylab. Near-complete cost data are available for this unit. The Skylab unit varies from that considered in this report in that it requires no collection of CO_2 and thus does not include a CO_2 accumulator. The Skylab CO_2 Concentrator is regenerated by desorbing the carbon dioxide and moisture collected by the beds to space vacuum. A hydrogen-depolarized CO_2 concentrator (HDC) is currently under development for use in the Space Station Prototype (SSP) Program. HDC's have been under continuous development by TRW, Inc., and Life Systems, Inc., under NASA/ARC sponsorship, for the last six years. Another HDC is also currently being developed by Hamilton Standard as a part of the SSP Program.

The Regenerable Solid Desiccant System is in a lesser state of development than the other two systems evaluated. The system utilized a kind of regenerable solid amine resin that absorbs CO_2 in the presence of water vapor, which alleviates the need for silica gel pre-dryers as required in the case of molecular sieves. The system thus requires fewer components and a smaller air blower than molecular sieves. The system simplicity should also be manifested in higher reliability and lower cost. A limited number of solid desiccant units have been developed. One unit was developed by General American Transportation Company, in which a proprietary resin called GAT-O-SORB was used. The unit was vacuum-desorbed and did not require the collection of desorbed CO_2. Currently, a vacuum-desorbed regenerable solid desiccant unit is being developed for possible application to the Shuttle Spacecraft. Another unit, which is steam-desorbed, was built by Hamilton Standard and tested for approximately 60 days in the NASA 90-Day Manned Test. The 90-day unit included a CO_2 accumulator and delivered the collected CO_2 to the CO_2-reduction system. However, the steam-desorption mode of operation resulted in introducing complexities to the system as well as high power consumption and heat rejection requirements. For these reasons, a heat-desorbed regenerable solid desiccant system was used in this report. Such a system should be capable of collecting CO_2 and delivering it to a CO_2 reduction system. No technological problems exist that would hinder the operation of this system which resembles the GAT-O-SORB system except that it requires a condenser for the removal of entrained moisture from the desorbed CO_2 prior to its delivery to the accumulator. CO_2 concentrator system criteria for the three systems considered are presented in Table V which also presents the relative characteristics, operational differences and status of each of the three systems.

Table V - COMPARISON OF CARBON DIOXIDE CONCENTRATION SYSTEMS

System Characteristics	Molecular Sieves CO_2 Concentrator	Hydrogen Depolarized CO_2 Concentrator	Regenerable Solid Desiccant CO_2 Concentrator
Crew Size	6 men	6 men	6 men
CO_2 Produced, Average	2.2 lbs/man-day	2.2 lbs/man-day	2.2 lbs/man-day
CO_2 Partial Pressure, Nominal	3.0 mmHg	1.0 mmHg	1.5-3.8 mmHg
Heating Fluid	Coolanol 35	None	Coolanol 35
Heating Fluid Temperature	300-350°F	--	180-200°F
Coolant	Coolanol 35	Air	Coolanol 35
Cooling Fluid Temperature	50-65°F	65-75°F	60-80°F
CO_2-Accumulator Pressure	30-40 psia	30-40 psia	30-40 psia
System Operation	1. Silica gel dries air to -50°F dp 2. Cool molecular sieves absorb CO_2 3. Beds thermally regenerated	1. CO_2 electrochemically transferred from anode to cathode. 2. H_2 added to produce power and water.	1. No air predrying req'd. 2. Chemical absorption enables system to operate at low CO_2 concentrations.
System Status/Availability	1. Prototypes developed and tested, incl. that in NASA 60 & 90 Day Tests 2. Vacuum-desorbed unit will be flown on Skylab in 1973.	1. TRW, Inc. & Life Systems, Inc. developed units for 6 years. 2. Life Systems, Inc. will deliver a 6-man system in 1973. 3. Hamilton Standard is developing a back-up system under SSP Program.	1. GAT-O-SORB, a 2-man vacuum-desorbed system was developed by General Amer. Transportation Co. 2. A steam-desorbed solid amine system was tested in NASA 90-Day Test. 3. A vacuum-desorbed unit is being developed for Shuttle application.
Operational Problems	None anticipated.	Integrated manned test of system required to define operational problems	A development of a thermal desorbed unit, with a CO_2 accumulator, is required.

4.1 MOLECULAR SIEVES CARBON DIOXIDE REMOVAL SYSTEM

System Description:

The molecular sieves CO_2 removal system is used to remove the CO_2 from the cabin atmosphere. The carbon dioxide is collected in an accumulator and then delivered to the oxygen recovery system.

A schematic of a molecular sieve system patterned after the unit under development for the Space Station Prototype program is shown schematically in Figure 4. The system is comprised of the following basic components: 1) air blower, 2) two silica gel beds, with each bed consisting of two canisters in parallel, 3) two molecular sieve beds, each consisting of two canisters in parallel, 4) heat exchangers, 5) pump, 6) accumulator, and 7) timer, manifolds and sequence control valves. A detailed listing of the components is given in Table VI.

Function of the system is as follows: cabin air is drawn by the circulation blower through the adsorbing silica gel bed where the moisture in the air is removed to a dew point of -50° to -70F. The flow then enters into the heat exchanger cooling it to 40° to 50°F. The cool, dry air then passes through the adsorbing molecular sieve bed where the CO_2 is removed. Most of the dry, CO_2-free gas is discharged into the cabin. The remaining gas is passed to the desorbing silica gel canister which has been heated to approximately 300°F with the heating fluid. This dry gas flow is saturated with the water being driven off the beds by the heat and then delivered to the cabin. The desorbing molecular sieve bed is meanwhile being regenerated, heated to 300°F with the heating fluid and evacuated with a vacuum pump. The pump delivers the desorbed CO_2 to an accumulator for storage and subsequent delivery to the oxygen recovery system. Excess CO_2 may also be vented overboard via a relief valve.

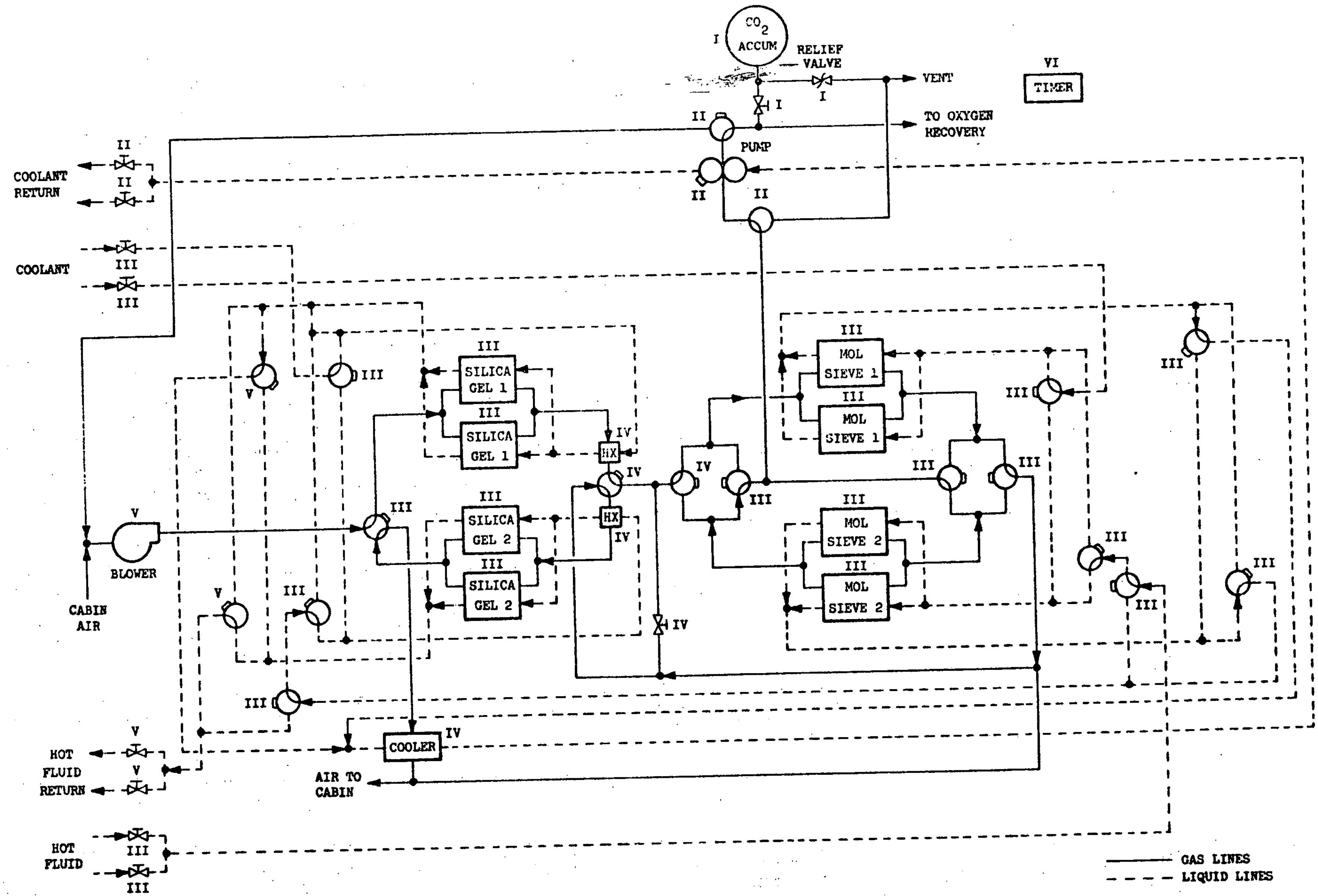

FIGURE 4. MOLECULAR SIEVES CARBON DIOXIDE REMOVAL SYSTEM SCHEMATIC

After 30 minutes of desorption, the coolant is pumped to the desorbing beds to cool them for 15 minutes before cycling to the adsorption cycle. The timer then sequences the valves to divert the cabin flow through the regenerated beds and place the beds now requiring regeneration on desorption cycle. Heating fluid will then flow through the desorbing beds and the cycle is repeated. The time for a complete adsorption, desorption, and cooling cycle is 90 minutes. The sequencing of the control valves is accomplished by a timer.

TABLE VI - MOLECULAR SIEVE SYSTEM COMPONENTS LIST

COMPONENT	QUANTITY	SPARES	UNIT WEIGHT (LBS.)	TOTAL WEIGHT (LBS.)
Valve, Shut-off, Manual, Low Press	1	1	2.4	4.8
Valve, Shut-off, Manual	4	3	.5	3.5
Valve, 4-Way, Electrical	2	3	4.4	22.0
Valve, Vacuum, 3-Way, Electrical	2	3	4.6	23.0
Valve, Shut-off, Elect., Man. Override	2	1	2.7	8.1
Valve, Vacuum, 3-Way, Manual	1	1	3.5	7.0
Valve, Press., Relief	1	1	2.5	5.0
Valve, Press., Control	1	2	2.2	6.6
Valve, 3-Way, Electrical	1	2	.7	2.1
Canister, Silica Gel	4	2	66	396.0
Canister, Molecular Sieve	4	2	68.2	408.8
Blower, CO_2 Removal	2	2	14.0	56.0
Compressor, CO_2	1	3	38.0	152.0
Heat Exchanger	3	1	16.0	64.0
Accummulator, CO_2	1	0	35.0	35.0
Timer	1	2	8.0	24.0
Valve, Vacuum, 3-Way, Electric	2	3	2.0	10.0
Controller, M. S. Heater	4	0	3.0	12.0
Sensor, M. S. Temperature	4	0	.1	0.4
Valve, Shut-off, Manual High Flow	8	0	3.9	31.2
Valve, 3-Way, Electrical	10	3	4.7	61.1
Measurement Switching Unit, OCS	1	0	15.6	15.6
Measurement Unit, OCS	1	0	12.1	12.1
Totals	61	35	-	1360.3

SYSTEM PERFORMANCE AND CHARACTERISTICS:

The physical, performance, and interface characteristics of the molecular sieves CO_2 removal system are as follows:

Crew Size	= 6 Men
CO_2 Produced, average	= 2.2 Lbs/Man-Day
CO_2 Produced, Maximum	= 3.11 Lbs/Man-Day
Design CO_2 removal rate	= 1.07 Lbs/Hr
Atmospheric Flow Rate	= 75 CFM
CO_2 partial pressure, maximum	= 3.0 mmHg
CO_2 delivery purity, percent	= 0.98
Coolant flow rate	= 1100 Lbs/Hr
Heating fluid flow rate	= 925 Lbs/Hr
Coolant inlet temperature, maximum	= 65 °F
Hot Fluid inlet temperature, minimum	= 300 °F
CO_2 delivery pressure to CO_2 Reduction Subsystem	= 30-40 Psia
Electrical Power, D.C.	= 25 Watts
Electrical Power, A.C.	= 754 Watts
Total System Volume	= 63 Ft^3

Performance characteristics of the system's major components are as follows:

1. Air Blower:

Air Flow	= 75 CFM
Pressure Rise at 10 PSIA	= 9.2 in. H_2O
Power, A.C.	= 330 Watts

2. Silica Gel Bed:

Air flow	= 75 CFM
Gas side ΔP at 10 PSIA	= 1.62 in. H_2O
Cyclic water capacity	= 1.30 Lbs
Cold coolant flow	= 330 Lbs/Hr
Hot coolant flow	= 462 Lbs/Hr
Half-cycle time	= 30 Minutes
Cold coolant inlet temperature, maximum	= 65 °F
Hot coolant inlet temperature, minimum	= 200 °F
Coolant side ΔP	= 1 PSI

3. Molecular Sieve Bed:

Air flow	= 75 CFM
Gas side ΔP at 10 PSIA	= 1.30 in. H_2O
Cyclic CO_2 capacity	= 1.22 Lbs/Hr
Cold coolant flow	= 220 Lbs/Hr
Hot coolant flow	= 462 Lbs/Hr
Half cycle time	= 60 Minutes
Cold coolant inlet temperature, maximum	= 65 °F
Hot coolant inlet temperature	= 275 - 300°F

4. Heat Exchangers:

Gas flow	= 75 CFM
Inlet/outlet temperature, maximum	= 240/115°F
Gas side ΔP at 10 PSIA	= 0.3 in. H_2O
Coolant flow	= 1100 Lbs/Hr
Coolant inlet temperature, maximum	= 80 °F
Coolant side ΔP	= 1.0 PSI

5. CO_2 Pump

CO_2 Flow	= 1.22 Lbs/Hr
Inlet pressure, average	= 0.5 PSIA
Outlet pressure, maximum	= 40.0 PSIA
Inlet temperature	= 100 °F
Power, A.C.	= 420 Watts

6. CO_2 Accumulator:

Operating pressure	= 30-40 PSIA
CO_2-feed rate, average	= 1.33 Lbs/Hr
CO_2 delivery rate, average	= 1.60 Lbs/Hr
Net cyclical CO_2 capacity	= 0.475 Lbs

Cost Estimating Relationships:

The molecular sieve system components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 4. The recurring and nonrecurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index, shown in Figure 1, was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's

1. CO_2 Accumulator:

The CO_2 accumulator CER, based on a CER developed for high pressure gaseous containers, is given as follows:

CO_2 accumulator fabrication cost $C = 18{,}634V^{0.377} + 2959\ W_{oc}$ dollars

where, V = volume of the accumulator, Ft^3, and

W_{oc} = weight of other components, lbs.

The other components denote the valves associated with the operation of CO_2 accumulator. An assembly integration factor is used at the assembly level to account for necessary piping and packaging.

Substituting the values for the variables in the above equation, where $V = 9.1 Ft^3$ and $W_{oc} = 4.5$ lbs., yields:

$$C = 18{,}632 \times 2.3 + 2959 \times 4.5 = 56,\ 169 \text{ dollars}$$

2. CO_2 Compressor:

The influencing parameter in the CO_2 compressor fabrication is the electrical power input to the unit. The CER is given as follows:

CO_2 compressor fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars

where, P = electrical power input to the compressor, watts, and

W_{oc} = weight of other components, lbs.

for the CO_2 compressor,

P = 420 watts, and

W_{oc} = 12.0 lbs.

Substituting these values in the above equation yields the following:

$$C = 38.223 \times 300 + 2192 \times 12 = 37{,}771 \text{ dollars}$$

3. Silica gel and molecular sieve canisters.

A CER derived for LiOH canisters was modified and used the silica gel and molecular sieve canisters. The two types of canisters were considered essentially identical for cost estimating purposes. The CER is given as follows:

Canisters fabrication cost $C = 15{,}865\ W_{can}^{0.267}\ Q^{0.89} + 2959\ W_{oc}$ dollars where, W_{can} = average canister weight, lbs.

Q = number of units used, and

W_{oc} = other components weight, lbs.

Substituting he corresponding values of the variables in the above equation, where W_{can} = 67.1 lbs., Q = 8, and W_{oc} = 66.2 lbs., yields:

$$C = 15{,}865 \times 3.08 \times 6.4 + 2959 \times 66.2 = 508{,}617 \text{ dollars}$$

4. Heat Exchangers

The following CER is used to evaluate the molecular sieve system heat exchangers fabrication cost:

$$C = 159\ W^{0.267} N_p^{1.905} Q^{0.89} + 2959\ W_{oc} \text{ dollars}$$

where, W = heat exchanger weight = 16.0 lbs.,

N_p = number of ports per heat exchanger = 4,

Q = number of heat exchangers used = 3, and

W_{oc} = weight of other components = 11.4 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 2.1 \times 14.05 \times 2.66 + 2959 \times 11.4 = 46{,}212 \text{ dollars}$$

5. Air Blower:

The same CER used for the CO_2 compressor is applied to the air blower. Thus, air blower fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars,

where,

P = electrical power input to the air blower = 330 watts, and

W_{oc} = other components weight = 17.2 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 240 + 2192 \times 17.2 = 46{,}870 \text{ dollars}$$

6. Timer and controls:

The CER used for the timer and associated controls fabrication cost was based on CER's for similar equipment encountered in Contract NAS9-9018, and is given as follows:

Timer and controls fabrication cost $C = 4795(W + W_{oc})$ dollars,

where,

W = timer weight = 8.0 lbs., and

W_{oc} = other components weight = 27.7 lbs.

substituting the values of variables in the CER yields:

$C = 4795 \times 35.7 = 171{,}182$ dollars

Molecular Sieve System's Recurring CER:

The integration costs of components and subassemblies into the molecular sieve system are obtained by the use of integration factors derived in the NAS9-9018 study and given in the following equations:

a. Subassembly fabrication cost S_i = 1.1 x component fabrication cost

b. First unit assembly cost = $1.833 \times \sum_{i=1}^{n} S_i$

Additionally, the total hardware cost is estimated through the utilization of the following learning curve formula:

$$C_T = \sum_{Q=1}^{n} C_F \quad Q^{(1-b)}$$

where

C_T = Total hardware cost

n = Quantity of hardware purchased

C_F = First unit cost

b = Learning curve slope

Since labor and materials have been added together, the learning curve slope, b, is derived as a composite of the 90% learning experienced on labor and the 95% experienced for materials. The resulting learning curve is a 93% curve ($b = -.1047$). C_F, the first unit cost, can be for one assembly or for the total system. n, the quantity of hardware, is a mission parameter and must include test hardware, flight hardware, and spares.

Applying the above equations, then:

$$\text{First unit cost } C_F = 1.833 \times 1.1 \times (56,169 + 37,771 + 508,617 + 46,212 + 46870 + 171,182)$$

$$= 2.016 \times 866,821$$

$$= 1,747,511 \text{ dollars}$$

and, assuming the production of four flight-type units, three for testing and backup and the fourth for actual flight, then the total hardware recurring cost is given by:

$$C_T = 1,747,511 \times (4)^{1-0.1047} = 6,047,287 \text{ dollars}$$

Non-Recurring CER's

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates utilize the cost breakdown ratios identified in Table II which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

$$\text{System design cost } C = 34,935N + 102,942 \text{ dollars}$$

The molecular sieve system comprises 23 component types as shown in Table 1. accordingly,

$$\text{System design cost } C = 805,505 + 102,942 = 908,447 \text{ dollars}$$

Values of other non-recurring cost items are listed in Table VII which also shows the breakdown of recurring cost items based on the production of four flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE VII- MOLECULAR SIEVE SYSTEM COST BREAKDOWN

NON-RECURRING		RECURRING	
System Engineering Design	908,447	Flight Hardware Production (4 units)	3,299,120
Subcontractor General and Administrative	469,667	Subcontractor G&A	557,551
Subcontractor Fee	197,133	Subcontractor Fee	234,238
Program Management	68,134	Program Management	82,478
System Engineering	286,160	Sustaining Engineering	118,768
Development Test	187,140		
Qualification Test	138,084		
Reliability Test	222,566		
AGE	1,004,742		
Tooling	210,760	Sustaining Tooling	102,273
Non-accountable Test Hardware	90,845		
Specifications, Vendor Coordination and Procurement Expense	742,201	Specifications, vendor Coordination and Procurement Expense	936,950
System Integration	455,131	System Integration	432,185
Prime's Testing	445,139		
Minor Subcontracts	20,894	Minor Subcontracts	283,724
Total	5,447,047		6,047,287

Total molecular sieve system cost = 5,447,047 + 6,047,287 = 11,494,334 dollars

4.2 HYDROGEN DEPOLARIZED CO_2 CONCENTRATOR

Process Description:

The hydrogen-depolarized cells are basically electro-chemical concentration cells which employ an aqueous carbonate electrolyte to transfer carbon dioxide from the cathode side of the cell, where CO_2-laden cabin atmosphere is introduced, to the anode side with the introduction of hydrogen at the anode, the chemical and electrochemical reactions occurring in the cell are as shown in Figure 5.

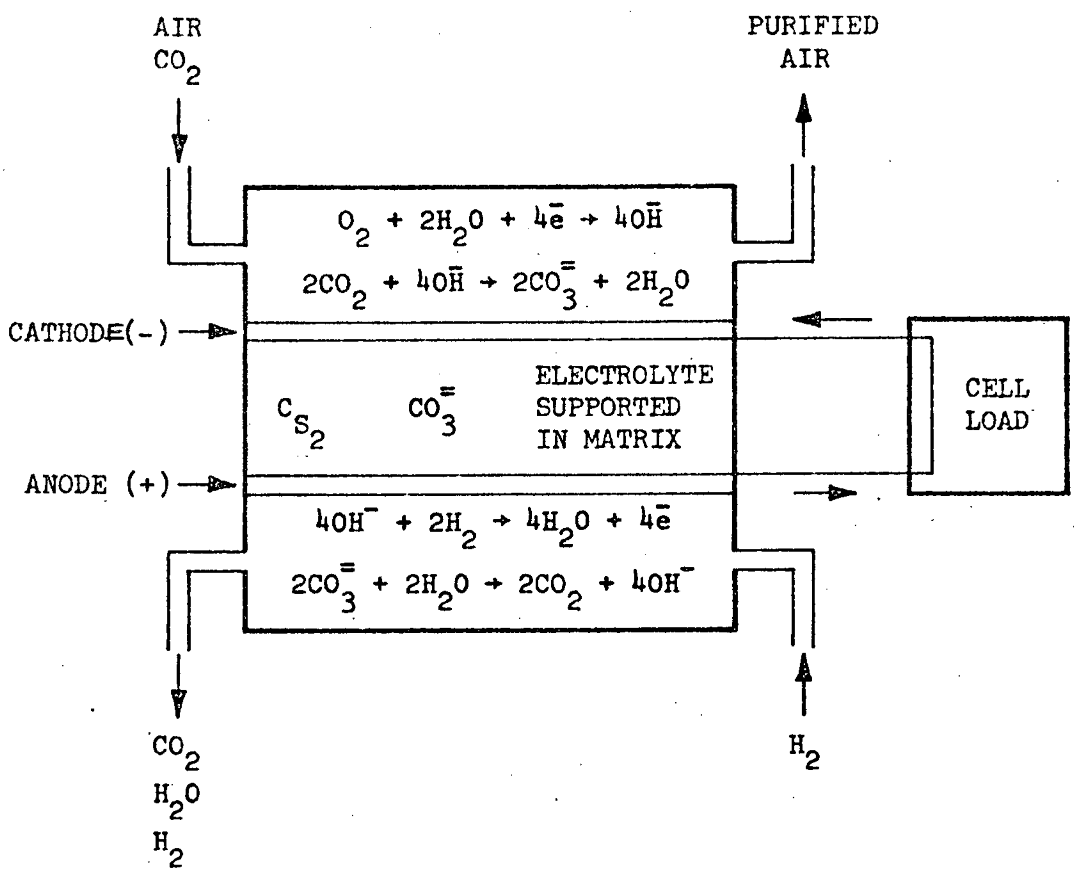

FIGURE 5. HYDROGEN DEPOLARIZED CELL

The reaction of oxygen and water forms basic hydroxyl ions (OH^-), which have an affinity for the acidic carbon dioxide. Any carbon dioxide which passes over the electrolyte, now rich in hydroxyl ions, reacts to form carbonate ions ($CO_3^=$). At the opposite electrode (anode) the reaction of hydrogen and hydroxyl ions to form water causes the electrolyte to be deficient in hydroxyl ions. Thus, carbon dioxide is given off, completing the transfer of carbon dioxide from the oxygen atmosphere to the hydrogen atmosphere. Hydrogen is available to the module as a waste product from the water electrolysis module, thereby permitting the concentrator to be operated in the hydrogen depolarized mode. In this mode of operation, the unit generates power much as a fuel cell and has the capability of supplying electrical power to other portions of the system if desired.

The hydrogen-depolarized CO_2 concentrator (HDC) module is comprised of a number of cells similar in construction to that shown in Figure 6. Each cell consists of two porous electrodes separated by a porous matrix containing an aqueous solution of cesium carbonate (Cs_2CO_3). Plates adjacent to the electrodes provide passageways for distributing the gases over the electrode surface.

The necessary number of hydrogen-depolarized cells are to be series connected. NASA tests have indicated that uniform distribution of hydrogen flow to hydrogen-depolarized cells could not be continuously achieved when the cells were in a parallel H_2 flow configuration. On the other hand, when a series configuration was used in which the first of ten cells received pure hydrogen and the last cell received approximately 70 percent hydrogen and 30 percent carbon dioxide, a stable performance was obtained. Cesium carbonate was found to be much more desirable in the CO_2 collection application than other electrolytes with lesser solubility in water. Electrochemical devices that employ aqueous electrolytes are especially sensitive to water balance. When the electrolyte becomes too concentrated as a result of a water imbalance, precepitates form at the anode of the cell, reducing the cell voltage and CO_2 transfer rate and may even result in gas crossover from anode to cathode. Consequently, electrolytes with high solubility in water are favored.

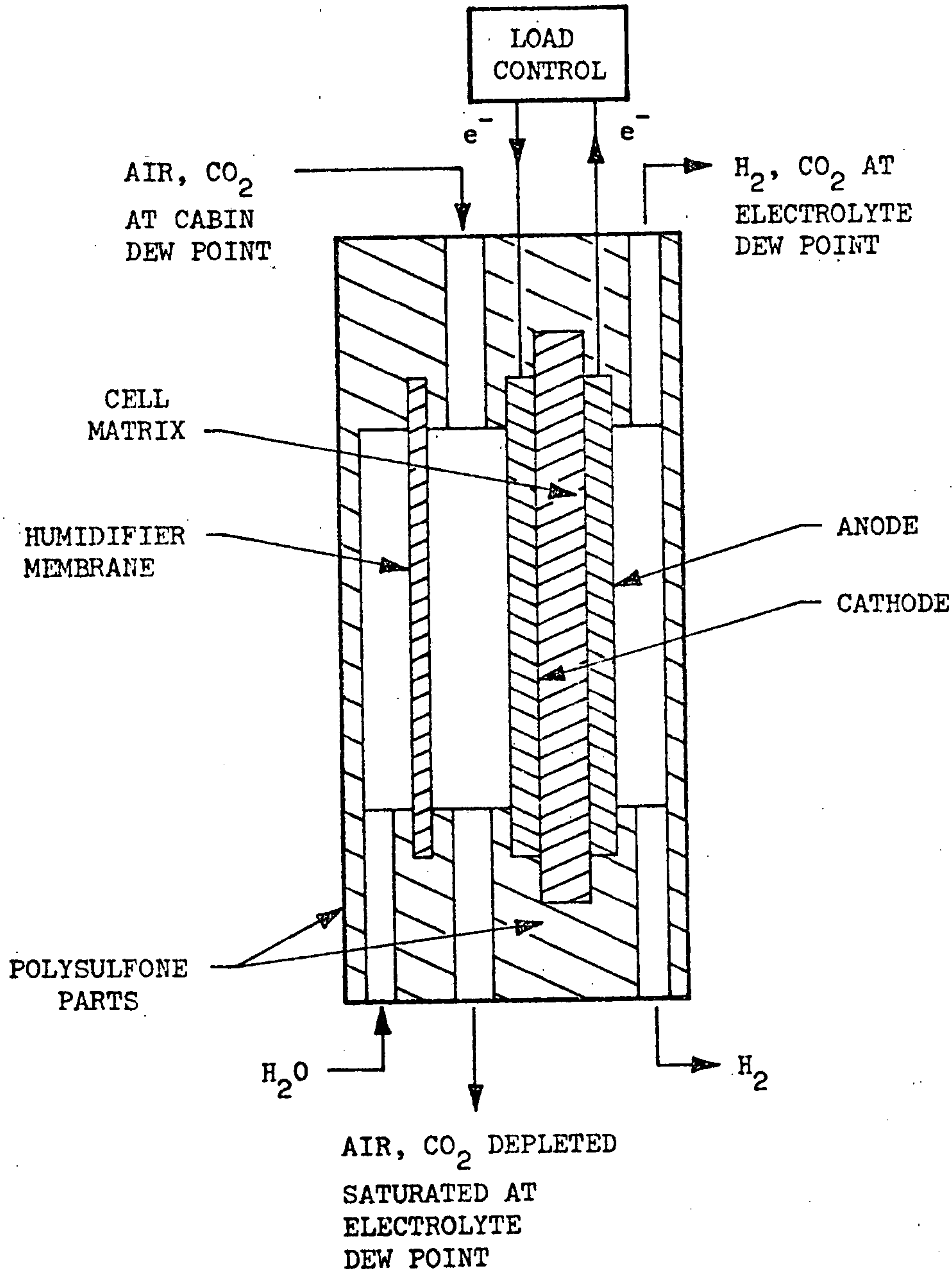

FIGURE 6. HDC SCHEMATIC

A schematic of the HDC is shown in Figure 7. The system is comprised of the following major components: 1) the hydrogen-depolarized cell module, 2) water accumulator, 3) process air blower, 4) air heater, and 5) cooling air blower. A detailed listing of the system components is given in Table VIII.

Function of the system is as follows: cabin air is drawn by the process air blower, through a particulate filter and delivered to the cathode side of the HDC module. The purified air is returned to the cabin through a filter which collects electrolyte mist entrained in the air stream. Hydrogen sensors are used to monitor trace hydrogen levels in the purified air. The anode side is provided with hydrogen from the oxygen recovery system. The CO_2 transferred from the cathode and the unreacted hydrogen are then delivered to the CO_2 reduction system. A nitrogen line, from the atmospheric control system, provides nitrogen to purge residual hydrogen from the system following system shutdown. The process air is humidified as follows: when the air enters the cathode compartment having a dew point lower than that of the original charge concentration, H_2O is transferred from the electrolyte in the humidifier and the cell matrix to the air. As H_2O is lost to the process air, the concentration of electrolyte increases and its volume decreases. Only the humidifier cavities are connected to an external supply of H_2O which, therefore, becomes the source of H_2O used for internal humidification. The decrease in liquid volume in the humidifier cavities causes H_2O to be drawn into the cavities from an external H_2O accumulator. The accumulator is cyclically and automatically refilled, as its H_2O is used in humidification.

System Performance and Characteristics:

The physical, performance and interface characteristics of the hydrogen depolarized CO_2 concentrator are as follows:

Crew Size	= 6 Men
Design CO_2 Removal Rate	= 2.2 Lbs/Man-Day
Atmospheric Flow Rate, maximum	= 60 CFM
CO_2 Partial Pressure, maximum	= 3.0 mmHg

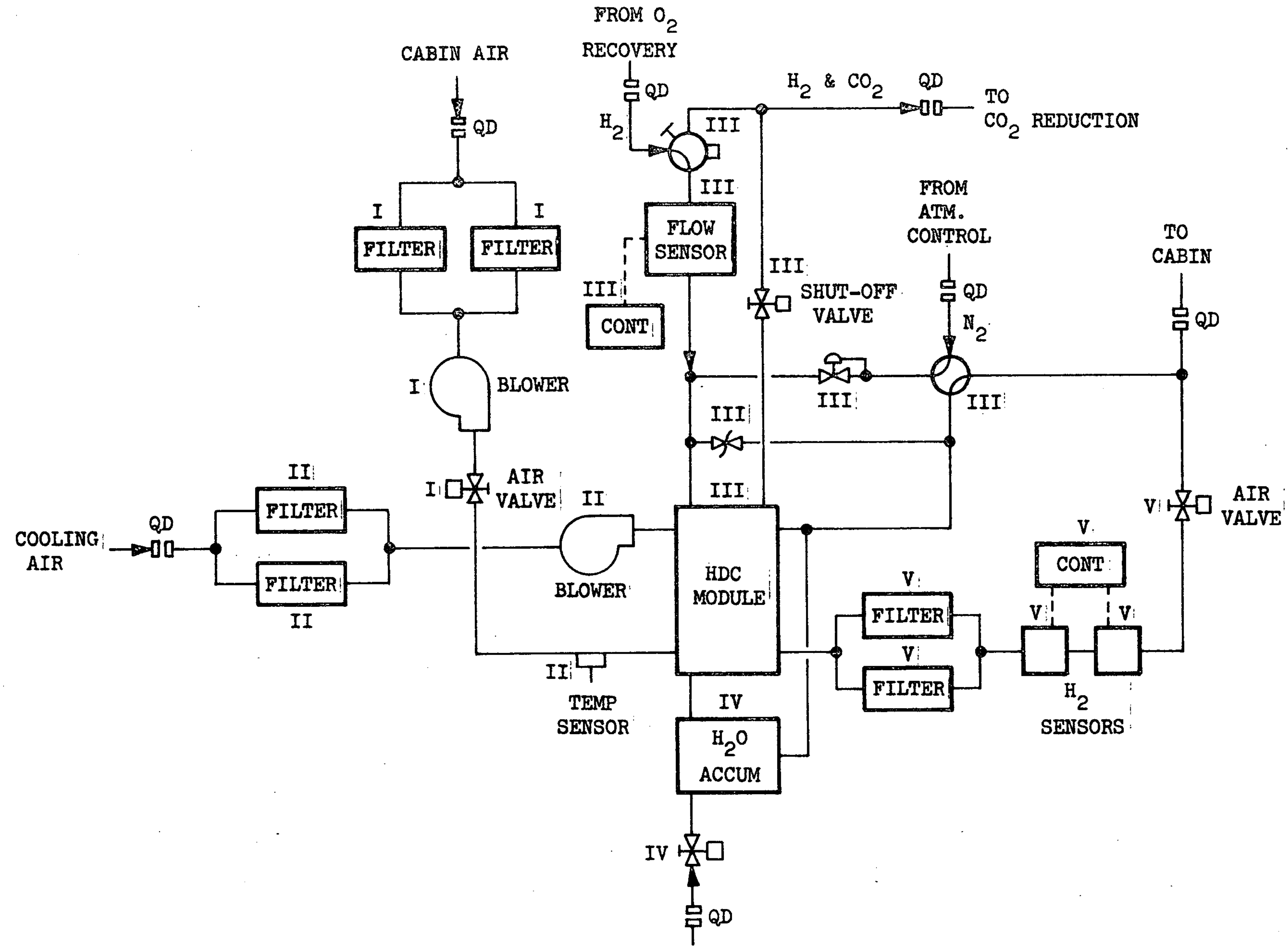

FIGURE 7. HYDROGEN DEPOLARIZED CO_2 CONCENTRATOR SYSTEM SCHEMATIC

Table VIII - H_2-DEPOLARIZED CO_2 CONCENTRATOR COMPONENTS LIST

Component	Quantity	Spares	Unit Weight Lbs.	Total Weight Lbs.
Valve, Shutoff, Elect., Man. Override	2	1	3.0	9.0
Valve, Relief	1	1	3.0	6.0
Regulator, Pressure, Nitrogen Purge	1	2	3.0	9.0
Valve, 4-Way, Electrical	1	1	4.4	13.2
Valve, Quick Disconnect	7	5	0.5	6.0
Valve, 3-Way, Electrical, M. O.	1	1	4.6	9.2
Filter	6	4	4.6	46.0
Air Blower	2	1	14.0	42.0
Valve, Shutoff, Electrical, Liquid	1	1	2.0	4.0
H_2 Flow Sensor Controller	1	2	13.0	39.0
H_2 Flow Sensor	2	2	2.2	8.8
H_2 Transducer Controller	1	1	13.0	46.0
H_2 Transducer	2	2	0.3	1.2
Water Accumulator	1	1	2.0	4.0
H_2-Depolarized Cell Module	3	3	15.0	90.0
Sensor, Temperature, Air	2	1	0.25	0.75
Measurement Switching Unit, OCS	1	0	15.6	15.6
Measurement Unit, OCS	1	0	12.1	12.1
Valve, Solenoid, Liquid	1	1	1.0	2.0
Temperature Signal Conditioner	1	1	1.0	2.0
Subsystem Control Electronics	1	2	7.6	22.8
TOTALS	40	34		368.7

Total Pressure, Nominal	= 14.7 psia
Total Pressure, range	= 5 to 15 psia
Air temperature	= 70 $\pm$ 5°F
Coolant air flow rate, intermittent	= 200 CFM
HDC dimensions	= 48" x 28" x 29"
Power requirement, AC	= 300 watts
Power requirements, DC	= 20 watts

Cost Estimating Relationships:

The hydrogen depolarized CO_2 concentrator system components have been grouped in five groups, designated as I through V, as shown in the system scehmatic, Figure 7. The recurring and non-recurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's:

1. Process Air Blower:

   The process air blower CER is primarily dependent on the electrical power input to the unit and is given by the following relation:

   Process air blowe fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars where, P = electrical power input to the compressor = 100 watts and W_{oc} = weight of other components = 20.69 lbs.

   Substituting the values of variables in the CER yields:

   $C = 38.2 \times 77 + 2192 \times 20.69 = 48{,}293.9$ dollars

2. Cooling Air Blower:

   The same CER used for the process air blower is applied to the cooling air blower. Thus, cooling air blower fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars where,

   P = electrical power input to the air blower = 200 watts, and

   W_{oc} = other components weight = 16.19 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 148 + 2192 \times 16.19 = 41,142 \text{ dollars}$$

3. The Hydrogen-Depolarized Cell Module:

Study of the cost of similar electrochemical cells, manufactured for water electrolysis and electrolytic pre-treatment systems indicates that the cost of fabrication of a hydrogen depolarized cell module may be given by the following relation:

$$C = 400\ W_m + 2192\ W_{oc} + 2000 \text{ dollars}$$

where,

W_m = weight of module = 15.0 lbs., and

W_{oc} = weight of other components = 92.3 lbs.

Then,

$$C = 9000 + 262,322 + 2000 = 213,322 \text{ dollars}$$

4. Water Accumulator:

The water accumulator CER is assumed to be as follows:

The water accumulator fabrication cost $C = 18,6347^{0.377} + 2959\ W_{oc}$ dollars

where, V = volume of the accumulator, Ft^3, and

W_{oc} = weight of other components, lbs.

The other components denote the values associated with the operation of the accumulator. An assembly integration factor is used at the assembly level to account for necessary piping and packaging.

Substituting the values for the variables in the above equation,

where, $V = 1.0\ Ft^3$ and $W_{oc} = 5.36$ lbs.

then, $C = 18{,}634 + 2959 \times 5.36 = 34{,}494$ dollars

5. Hydrogen Sensors and Controller:

The CER used for the fabrication of hydrogen sensors and controller was based on CER's developed for similar equipment encountered in Contract NAS9-9018, and is given as follows:

Sensors and controller fabrication cost:

$$C = 4795\ (W_s + W_c + W_{oc})\ \text{dollars}$$

where,

W_s = sensor's weight = 8.8 lbs.

W_c = controller's weight = 39.0 lbs, and

W_{oc} = other components weight = 20.7 lbs.

Substituting the values of variables in the CER yields:

$$C = 4795 \times 42.5 = 203{,}788\ \text{dollars}$$

Integrated Hydrogen Deplarized Concentrator's Recurring CER:

The integration costs of components and assemblies into the hydrogen-depolarized concentrator system are obtained by utilizing the CER developed for the molecular sieve system, and defined in a preceeding system. Applying the said CER, then:

$$\text{First unit cost } C_f = 1.833 \times 1.1 \times (48{,}294 + 41{,}142 + 213{,}322 + 34{,}494 + 203{,}788)$$

$$= 2.016 \times 541{,}040 = 1{,}097{,}737\ \text{dollars}$$

and, assuming the production of four flight-type units, three for testing and backup and the fourth for actual flight, then the total hardware recurring cost is given by:

$$C_T = 1{,}097{,}737 \times (4)^{1-0.1047} = 3{,}776{,}215\ \text{dollars}$$

Integrated Hydrogen Depolarized Concentrator System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breadkown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation:

System design cost C = 34,935N + 102,942 dollars

The hydrogen depolarized concentrator system comprises 21 component types as shown in Table 1. Accordingly, system design cost C = 733,635 + 102,942 = 836577 dollars.

Values of other non-recurring cost items are listed in Table IX, which also shows the breakdown of recurring cost items based on the production of four flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE IX - HYDROGEN DEPOLARIZED CONCENTRATOR SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	836,577	Flight Hardware Production (4 units)	2,060,128
Subcontractor General and Administrative	432,332	Subcontractor G&A	348,162
Subcontractor Fee	181,559	Subcontractor Fee	146,269
Program Management	62,192	Program Management	51,503
System Engineering	263,311	Sustaining Engineering	74,165
Development Test	172,531		
Qualification Test	127,392		
Reliability Test	205,132		
AGE	925,351		
Tooling	194,098	Sustaining Tooling	63,864
Non-accountable Test Hardware	83,758		
Specifications, Vendor Coordination and Procurement Expense	683,104	Specifications, Vendor Coordination and Procurement Expense	585,076
System Integration	419,292	System Integration	269,877
Prime's Testing	409,762		
Minor Subcontracts	19,059	Minor Subcontracts	177,171
Total	5,015,450		3,776,215

Total Hydrogen Depolarized Concentrator System Cost =

5,015,450 + 3,776,215 = 8,791,665 dollars

4.3 REGENERABLE SOLID DESICCANT

Process Description:

The regenerable solid desiccant process removes CO_2 from cabin air by means of cyclic absorption/desorption in suitable granular resins. One of such resins, the GAT-O-SORB, developed by General American Transportation Corporation, was formulated by suspending sodium sarcosinate on silica gel. The chemical nature of the bonding between CO_2 and these resins provides a CO_2 removal method which is feasible for cabin P_{CO_2} levels of 3 mm Hg or less. Dynamic CO_2 absorption and desorption processes, as well as equilibrium CO_2 bed loading conditions, are extremely sensitive to the amount of water present. With the bed cooler than approximately 140°F, and water is present, the absorption process takes place according to the following relationship:

$$R * NH_2 + CO_2 + H_2O \rightarrow RNH_3^+ + HCO_3^-$$

During regeneration the carbonated absorbent breaks down into fresh absorbent plus CO_2 and water. The absorption equation above shows that the regeneration molar ratio for H_2O to CO_2 is one. The corresponding weight ratio is 18/44 or 0.41. Reference 4 shows that the water collected during desorption of a prototype unit varied between 0.1 to 0.5 lb H_2O/lb CO_2. This indicates the feasibility of the method from the standpoint of maintaining adequate bed wetness.

System regeneration may be accomplished either by heating or by combined heating and evacuation to vacuum. The GAT-O-SORB unit was vacuum/thermal desorbed, and since it constitutes the only solid desiccant unit developed, further tests are required to establish the operational feasibility of thermally desorbed units.

A condensing heat exchanger is provided to dehumidify the desorbed carbon dioxide before its delivery to the accumulator. The heat transfer fluids are phased during the absorption/desorption cycle in a manner similar to that employed in cyclic molecular sieve/silica gel operation. One fundamental advantage to the solid regenerable desiccant system is that desorption requires heating fluid temperatures in the vicinity of 200°F rather than the 300°F and higher temperatures required for molecular sieve/silica gel desorption.

A schematic of the solid regenerable desiccant is shown in Figure 8. The system is comprised of the following basic components:

1) air blower,
2) two regenerable solid desiccant beds, with each bed consisting of two canisters in parallel,
3) pump,
4) accumulator, and
5) timer, manifolds and sequence control valves.

Each solid desiccant bed incorporates a plate-and-fin type heat exchanger inside the canister and in direct contact with the granules, as shown in Figure 9. A detailed listing of the components used in the system is given in Table X.

Function of the system is as follows: cabin air is drawn by the circulation blower through the absorbing desiccant bed where the CO_2 is removed from the air which is then returned to the cabin. The CO_2 is simultaneously being evacuated by a vacuum pump from the other regenerable desiccant bed. The pump delivers the desorbed CO_2 to an accumulator for storage and subsequent delivery to the oxygen recovery system. Excess CO_2 may also be vented overboard via a relief valve.

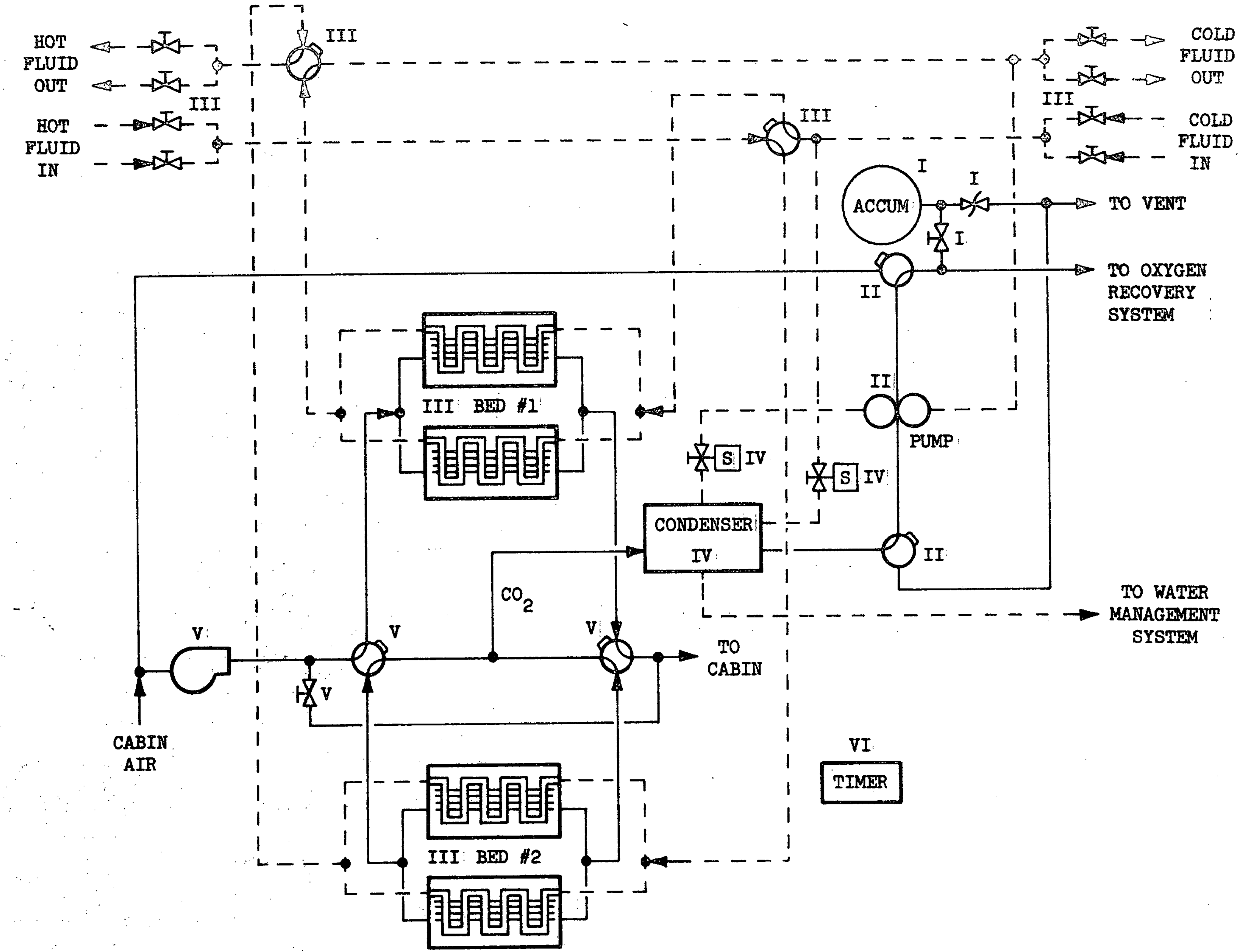

FIGURE 8. REGENERABLE SOLID DESICCANT CARBON DIOXIDE REMOVAL SYSTEM SCHEMATIC

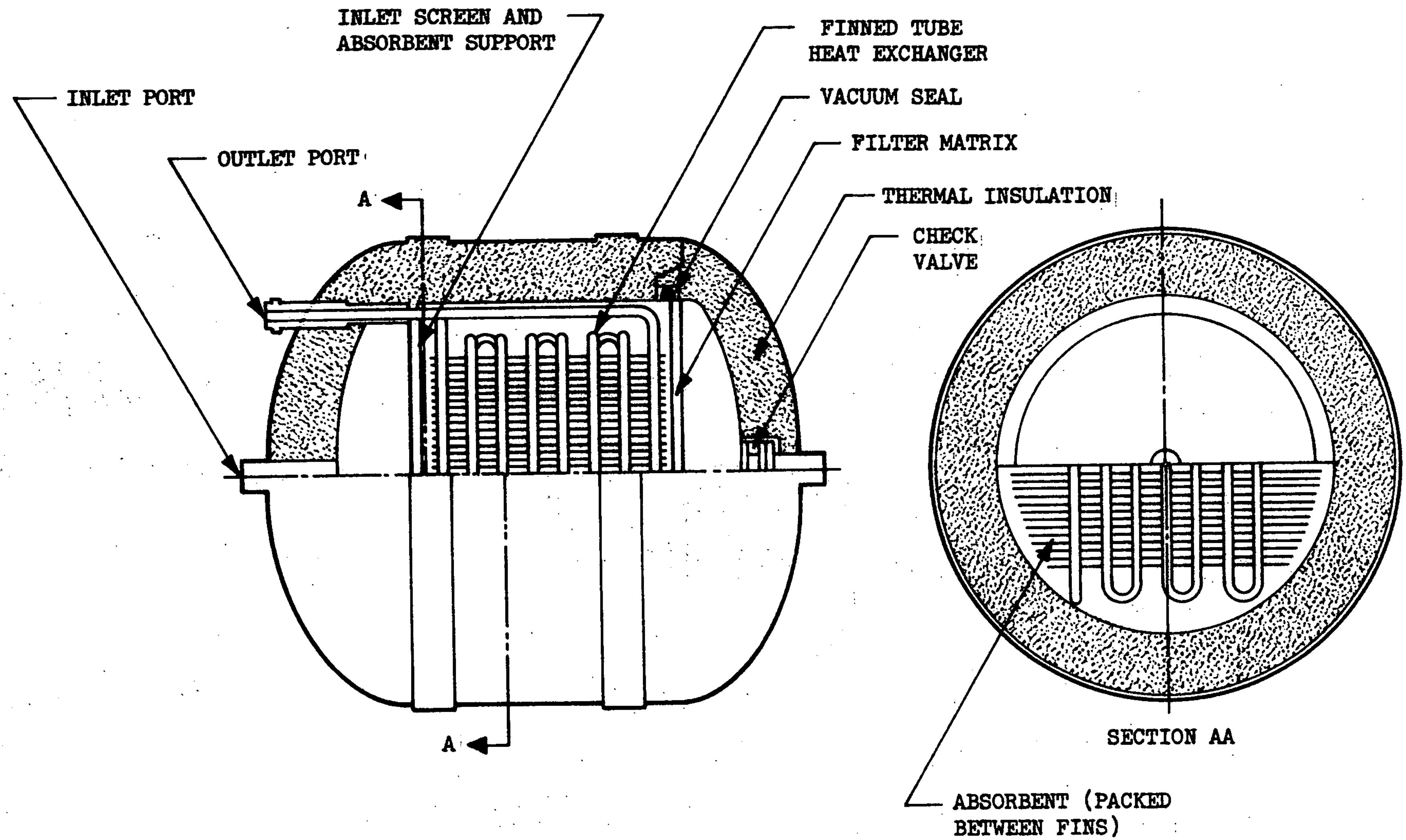

FIGURE 9. REGENERABLE SOLID DESICCANT BED CONFIGURATION

TABLE X - REGENERABLE SOLID DESICCANT COMPONENTS LIST

COMPONENT	QUANTITY	SPARES	UNIT WEIGHT (LBS.)	UNIT WEIGHT (LBS.)
Valve, Shut-off, Manual, Low Press	1	1	2.4	4.8
Valve, Shut-off, Manual	4	3	.5	3.5
Valve, Vacuum, 3-Way, Electrical	2	3	2.0	10.0
Valve, Vacuum, 3-Way, Electrical	1	2	4.6	13.8
Valve, Shut-off, Elect., Man. Override	2	1	2.7	8.1
Valve, Vacuum, 3-Way, Manual	1	1	3.5	7.0
Valve, Press., Relief	1	1	2.5	5.0
Valve, Press., Control	1	]	2.2	6.6
Valve, 3-Way, Electrical	1	2	.7	2.1
Canister, Solid Desiccant	4	2	66.0	396.0
Blower, CO_2 Removal	1	2	14.0	42.0
Compressor, CO_2	1	3	38.0	152.0
Heat Exchanger, in absorbent beds	4	4	4.0	32.0
Heat exchanger condenser	1	0	4.0	4.0
Accumulator, CO_2	1	0	35.0	35.0
Timer	1	2	8.0	24.0
Sensor, Absorbent Bed Temperature	4	0	.1	0.4
Valve, Shut-off, Manual High Flow	8	0	3.9	0.4
Valve, 4-Way Electrical	2	2	4.4	17.6
Measurement Switching Unit, OCS	1	0	15.6	15.6
Measurement Unit, OCS	1	0	12.1	12.1
Totals	40	31	-	822.8

SYSTEM PERFORMANCE AND CHARACTERISTICS:

The physical, performance, and interface characteristics of the regenerable solid desiccant CO_2 removal system are as follows:

Crew size	= 6 Men
CO_2 Produced, average	= 2.2 Lbs/Man-Day
Design CO_2 removal rate	= 0.6 Lbs/Hr
Atmospheric Flow Rate	= 45 CFM
Air Temperature	= 75 - 90°F
Inlet CO_2 Partial Pressure	= 1.5 - 3.8 mm Hg
CO_2 delivery purity, percent	= 0.98
Coolant flow rate	= 100 Lbs/Hr
Heating fluid flow rate	= 100 Lbs/Hr
Coolant inlet temperature	= 60 - 80°F
Hot fluid inlet temperature	= 180 - 200°F
CO_2 delivery pressure to CO_2 reduction System	= 30 - 40 Psia
Electrical Power, D. C.	= 25 watts
Electrical Power, A. C.	= 620 watts
Total System Volume	= 24 Ft^3

The desorption cycle is set at 30 minutes, after which the coolant is pumped to the desorbing beds to cool them for 10 minutes before cycling to the absorption cycle. The timer then sequences the valves to divert the cabin flow through the regenerated beds and place the beds now requiring regeneration on desorption cycle. Heating fluid will then flow through the desorbing beds and the cycle is repeated. The time for a complete absorption, desorption, and cooling cycle is 80 minutes. The sequencing of the control valves is accomplished by the timer.

Cost Estimating Relationships:

The regenerable solid desiccant system components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 8. The recurring and nonrecurring CER's presented in the following paragraphs are based on estimated January 1972 dollars. The consumer price index was used to adjust CER's developed and based on prior years dollar values.

Recurring CER's

1. CO_2 Accumulator:

The CO_2 accumulator is assumed to be identical to that used for the molecular sieves CO_2 removal system. The accumulator CER is given as follows:

CO_2 accumulator fabrication cost $C = 18{,}634V^{0.377} + 2959\ W_{oc}$ dollars

where, V = volume of the accumulator, Ft^3, and

W_{oc} = weight of other components, lbs.

The other components denote the valves associated with the operation of CO_2 accumulator. An assembly integration factor is used at the assembly level to account for necessary piping and packaging.

Substituting the values for the variables in the above equation, where $V = 9.1\ Ft^3$ and $W_{oc} = 4.5$ lbs., yields:

$$C = 18{,}632 \times 2.3 + 2959 \times 4.5 = 56{,}169 \text{ dollars}$$

2. CO_2 Compressor:

The influencing parameter in the CO_2 compressor fabrication is the electrical power input to the unit. The CER is given as follows:

CO_2 compressor fabrication cost $C = 38.2P^{0.942} + 2192\ W_{oc}$ dollars

where, P = electrical power input to the compressor, watts, and

W_{oc} = weight of other components, lbs.

for the CO_2 compressor,

P = 420 watts, and

$W_{oc} = 2.1$ lbs.

Substituting these values in the above equation yields the following:

$$C = 38.223 \times 300 + 2192 \times 2.1 = 16070 \text{ dollars}$$

3. Regenerable Solid Desiccant Canisters:

The regenerable solid desiccant canisters incorporate built-in plate-and-fin heat exchangers. The solid desiccant canister CER thus includes elements for the canister itself, the built-in heat exchanger and the associated valves. The CER is given as follows:

$$\text{Canister fabrication } C = 158.65\ (100\ W_{can}^{\ 0.267} + W_{HX}^{\ 0.267}\ N_p^{\ 1.905})$$

$$Q^{0.89} + 2959\ W_{oc} \text{ dollars}$$

where, W_{can} = average canister weight = 16.5 lbs.

W_{HX} = heat exchanger weight = 4.0 lbs.,

N_p = number of ports per heat exchanger = 2

Q = number of units used = 4, and

W_{oc} = other components weight = 31.2 lbs.

then,

$$C = 158.65\ (100 \times 2.12 + 1.45 \times 3.75) \times 3.43 + 2959 \times 31.2$$

$$= 158.65 \times 217.44 \times 3.43 + 92{,}320$$

$$= 118{,}085 + 92{,}320 = 210{,}405 \text{ dollars}$$

4. Heat Exchanger Condenser

The following CER is used to evaluate the heat exchanger condenser fabrication cost:

$$C = 159\ W^{0.267}\ N_p^{\ 1.905} + 2959\ W_{oc} \text{ dollars}$$

where,

W = heat exchanger weight = 4.0 lbs.
N_p = number of ports per heat exchanger = 4, and
W_{oc} = weight of other components = 8.1 lbs.

Substituting the values of the variable in the CER yields:

$$C = 159 \times 1.45 \times 14.05 + 2959 \times 8.1 = 27{,}207 \text{ dollars}$$

5. Air Blower:

The same CER used for the CO_2 compressor is applied to the air blower. Thus, air blower fabrication cost $C = 38.2P^{\ 0.942} + 2192\ W_{oc}$ dollars,

where,

P = electrical power input to the air blower = 200 watts, and

W_{oc} = other components weight = 17.6 lbs.

Substituting the values of the variables in the CER yields:

$$C = 38.2 \times 148 + 2192 \times 17.6 = 44,239 \text{ dollars}$$

6. Timer and Controls:

The CER used for the timer and associated controls fabrication cost was based on CER's for similar equipment encountered in Contract NAS9-9018, and is given as follows:

Time and controls fabrication cost $C = 4795\ (W + W_{oc})$ dollars,

where,

W = timer weight = 8.0 lbs., and

W_{oc} = other components weight = 20.0 lbs.

substituting the values of variables in the CER yields:

$$C = 4795 \times 28 = 134,260 \text{ dollars}$$

Integrated Regenerable Solid Desiccant System's Recurring CER:

The integration costs of components and assemblies into the regenerable solid desiccant system are obtained by utilizing the system's recurring CER defined for the molecular sieve system, defined above. Applying the said CER, then:

$$\begin{aligned} \text{First unit cost } C_F &= 1.833 \times 1.1 \times (56,169 + 16,070 + 210,405 + \\ &\quad 27,207 + 44,239 + 134,260) \\ &= 2.016 \times 488,350 \\ &= 984,514 \text{ dollars} \end{aligned}$$

and, assuming the production of four flight-type units, three for testing and backup and the fourth for actual flight, then the total hardware recurring cost is given by:

$$CT = 984,514 \times (4)^{1-0.1047} = 3,396,573 \text{ dollars}$$

Integrated Regenerable Solid Desiccant System's Non-Recurring CER's:

Non-recurring CER's have been developed for engineering design only. Other non-recurring cost estimates are based on the cost breakdown ratios utilized in the case of the molecular sieves system which have been based on actual cost data collected in NAS9-9018 study. The analysis of a number of cost influencing parameters indicated that engineering design CER is mainly a function of the number of component types (N) in each system and is given by the following relation.

System design cost C = 34,935N + 102,942 dollars

The regenerable solid desiccant system comprises 21 component types as shown in Table 1. Accordingly, system design cost C = 733,635 + 102,942 = 836577 dollars.

Values of other non-recurring cost items are listed in Table XI, which also shows the breakdown of recurring cost items based on the production of four flight hardware units. All cost figures are in estimated January 1972 dollars.

TABLE XI - REGENERABLE SOLID DESICCANT SYSTEM COST BREAKDOWN

Non-Recurring		Recurring	
System Engineering Design	836,577	Flight Hardware Production (4 units)	1,853,170
Subcontractor General and Administrative	432,332	Subcontractor G&A	313,164
Subcontractor Fee	181,559	Subcontractor Fee	131,787
Program Management	62,192	Program Management	46,194
System Engineering	263,311	Sustaining Engineering	66,573
Development Test	172,531		
Qualification Test	127,392		
Reliability Test	205,132		
AGE	925,351		
Tooling	194,098	Sustaining Tooling	57,402
Non-accountable Test Hardware	83,758		
Specifications, Vendor Coordination and Procurement Expense	683,104	Specifications, Vendor Coordination and Procurement Expense	526,129
System Integration	419,292	System Integration	242,855
Prime's Testing	409,762		
Minor Subcontracts	19,059	Minor Subcontracts	159,299
Total	5,015,450		3,396,573

Total Regenerable Solid Desiccant System Cost = 5,015,450 + 3,396,573 = 8,412,023 dollars

Section 5

PROTOTYPE COST ESTIMATING

Cost estimates for flight-type advanced regenerative CO_2 concentrators have been developed and presented in the preceding sections, based on actual flight hardware cost data. Major cost items have been identified and their approximate percentage distribution determined. However, it is also essential, in many instances, to estimate the cost of a working prototype after its technological feasibility has been established. A working prototype will be construed to have the same degree of hardware sophistication as a flight article but would not require ground support or qualification and reliability testing. Additionally, since the prototype will most likely be one of a kind, no tooling, test hardware or prime contractor integration effort will be required either. Figure 10, obtained from the results of Study NAS9-9018, shows the categories and approximate percentage distribution for representative life support components. The cost of an operational prototype would be exclusive of qualification test, reliability test, AGE, test hardware, tooling, G&A, fee and prime contractor costs, as depicted in Figure 11.

In addition to the exclusion of the major cost items mentioned above, the data in NAS9-9018 indicated that in analyzing development/cost overlays with respect to the status of design at the delivery of the first test unit, approximately 38% of the design cost has been expended at this point in time. Applying this factor to Engineering Design, Development Test, Program Management, and System Engineering results in an approximate cost of a flight prototype unit. That percentage cost is as follows.

		%
1.	Engineering Design	4.8
2.	Program Management	0.4
3.	System Engineering	1.5
4.	Development Testing	1.0
5.	First Flight Unit Fabrication Cost	2.5
		10.2%

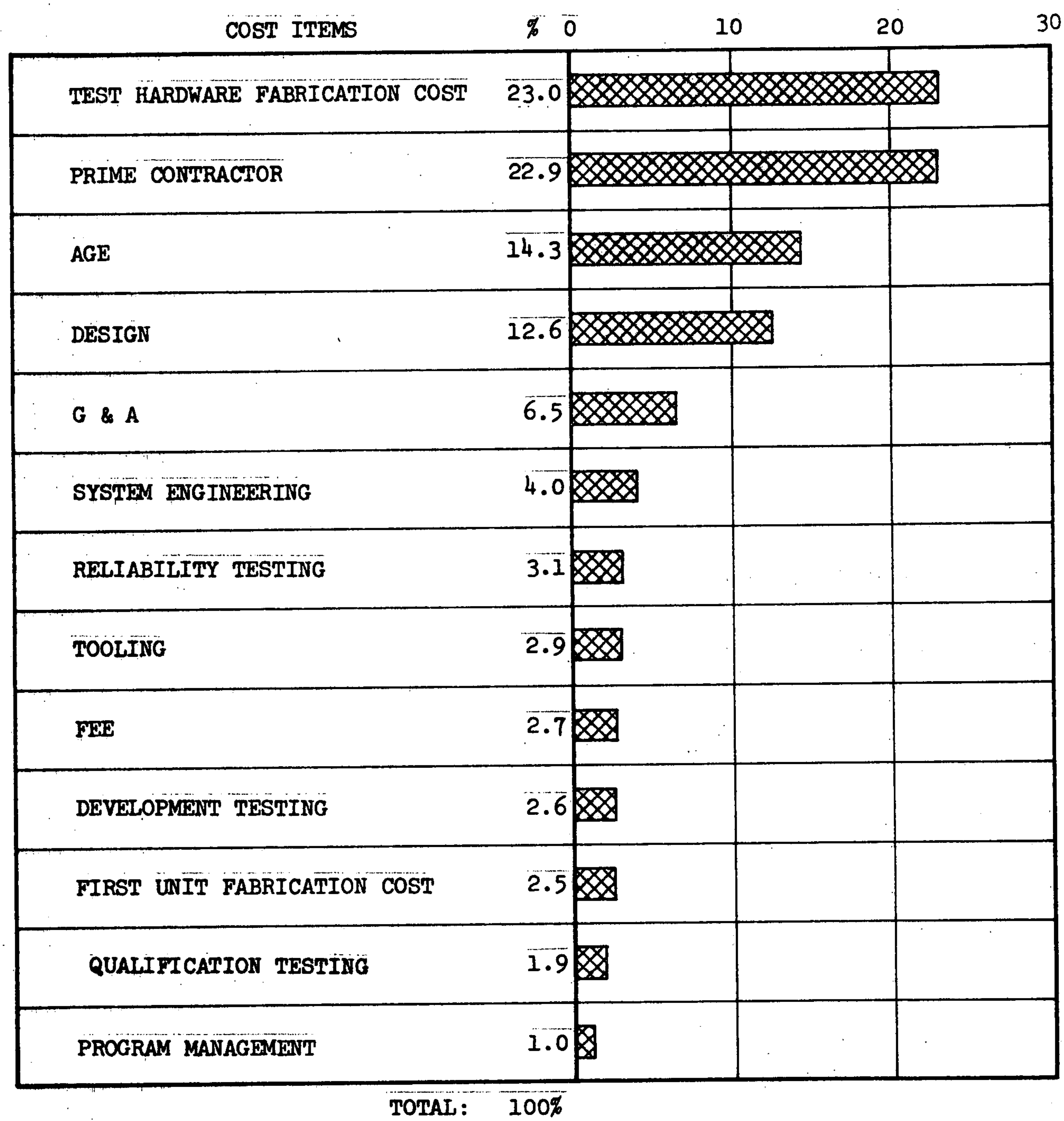

Figure 10. REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN (FIRST FLIGHT UNIT DEVELOPMENT COST)

COST ITEMS	%
TEST HARDWARE FABRICATION COST	0
PRIME CONTRACTOR	0
AGE	0
DESIGN	12.6
G&A	0
SYSTEM ENGINEERING	4.0
RELIABILITY TESTING	0
TOOLING	0
FEE	0
DEVELOPMENT TESTING	2.6
FIRST UNIT FABRICATION COST	2.5
QUALIFICATION TESTING	0
PROGRAM MANAGEMENT	1.0

TOTAL: 22.7% OF QUALIFIED UNIT COST

Figure 11. REPRESENTATIVE LIFE SUPPORT SYSTEM EXPENDITURE BREAKDOWN (OPERATIONAL PROTOTYPE DEVELOPMENT COST)

Table XII gives the estimated costs of high-fidelity, but not flight-qualified prototype concentrators, based on the percentage cost values given above.

Table XII. PROTOTYPE COST ESTIMATES

Cost Item	Molecular Sieves Concentrator	Hydrogen Depolarized Concentrator	Regenerable Solid Desiccant Concentrator
Engineering	551,728	422,000	403,777
Program Management	45,977	35,167	33,648
System Engineering	172,415	131,875	126,180
Development Testing	114,943	87,917	84,120
First Flight Unit Fabrication Cost	287,358	219,792	210,301
Prototype Cost	1,172,421	896,751	858,026

The cost of prototype units may be lowered further depending on the degree of fidelity, packaging and/or miniaturization required.

Section 6

CONCLUSIONS

Methodology and cost estimating relationships, for flight-type and prototype CO_2 concentrators, have been developed and presented. The study results are based on the assumption that feasibility and advance technology requirements of the systems, including possibly some manned testing, have been achieved. This assumption is fulfilled only for the molecular sieves concentrator where one system has undergone continuous 60 days of manned testing. Additional development is required to bring the other two concentrator types to the same status.

A validity check was made by comparing the molecular sieves system considered here and that developed for Skylab. The system evaluated here is twice the size of the Skylab system and is also more complex as it desorbs CO_2 thermally and stores it in an accumulator, while the Skylab system is desorbed to vacuum with all the previously adsorbed CO_2 and moisture being vented overboard. The cost estimates developed in this report were found to be approximately 50 to 70% higher than the actual cost of the Skylab unit. Considering the example evaluated and its results indicates that the methodology used is valid and the cost estimates are reasonably accurate. However, the restricted amount of actual cost data available and the complexity of other systems indicate that additional data are required in order to establish a higher level of confidence in the developed CER's.

Areas where additional efforts are warranted include the following:

1. The completion and manned test data of the six-man hydrogen-depolarized concentrator currently under development for the SSP Program.
2. The development of thermal desorbed regenerable solid desiccant CO_2 collection system.
3. The collection and analysis of additional CO_2 concentrator cost data, especially that from the SSP Program.

4. The inclusion of cost elements pertaining to operating system parameters, such as power, heat rejection, expendables, subsystem interfaces, and crew time, to cost estimating relationships so that all the systems considered would be compared on a common basis encompassing all the penalties incurred by each system on the spacecraft for the duration of the mission. For example, the hydrogen-depolarized concentrator is lighter, smaller, less expensive, requires no heating fluid loop, and is capable of maintaining a lower CO_2-level concentration than the molecular sieves unit. However, the HDC consumes daily expendables of hydrogen and oxygen while the molecular sieves concentrator requires no expendables. Thus, system comparisons will be meaningful only if all the penalties incurred by each system are taken into consideration.

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