N73-27072

MDC G-4630

COST ANALYSIS OF LIFE SUPPORT SYSTEMS
SUMMARY REPORT

JUNE 1973

CASE FILE COPY

Prepared under Contract No. NAS 8-28377
by Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MDC G-4630

COST ANALYSIS OF LIFE SUPPORT SYSTEMS
SUMMARY REPORT

JUNE 1973

By
M. M. YAKUT
Biotechnology and Power Department

Prepared under Contract No. NAS 8-28377
by Biotechnology and Power Department
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

A Cost Analysis of Life Support Systems Study has been conducted by the Biotechnology and Power Department of the McDonnell Douglas Astronautics Company (MDAC), Huntington Beach, California, under Contract NAS8-28377. This project was performed for the NASA-Marshall Space Flight Center under the direction of Mr. James Moses, Deputy Chief, Life Support and Environmental Branch (S&E-ASTN-P).

The Final Report consists of a summary and four volumes each dealing with a specific life support system area as follows:

Title	Report Number
SUMMARY REPORT	MDC G4630
COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS	MDC G4631
COST ANALYSIS OF WATER RECOVERY SYSTEMS	MDC G4632
COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS	MDC G4633
COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS	MDC G4634

MASTER TABLE OF CONTENTS

MASTER TABLE OF CONTENTS

TABLE OF CONTENTS

Section 1

INTRODUCTION AND SUMMARY

A methodology was developed to predict realistic relative cost of Life Support Systems (LSS) and to define areas of major cost impacts in the development cycle. Emphasis was given to tailoring the cost data for usage by program planners and designers. Cost estimates can be completed using the developed equations for varying degrees of equipment refinement, as well as comparative costs between different functional methods. The equipment classifications used based on the degree of refinement were as follows: 1) working model, 2) low-fidelity prototype, 3) high-fidelity prototype, and 4) flight-qualified system.

Fourteen advanced life support systems were quantitatively evaluated. System characteristics, including process flows, performance and physical characteristics, were also analyzed. Additionally, the status of development of each of the systems considered and the necessary advance technology efforts required to bring conceptual and/or pre-prototype hardware to an operational prototype status were defined. The major advanced LSS evaluated included the following: 1) carbon dioxide removal (3 systems); 2) oxygen recovery systems (2 CO_2 reduction and 2 electrolysis systems); 3) water recovery systems (5 systems); and 4) atmosphere analysis system (2 systems).

The most cost effective development approach was discovered to be with the programs that initially used working models and subsequently low-fidelity prototypes to verify concept workability. The further continuation of the development of the best approaches in the advanced research and technology phase from the low-fidelity to high-fidelity level had the potential of further reducing costs prior to committing funds to produce flight-qualified hardware. It was apparent that the high-fidelity hardware should be included in the advanced research and technology phase to provide the data required to minimize design changes in the flight production and qualification program. Design changes that occur too late in the development cycle will significantly escalate costs. The advanced research and technology phase when effectively used, as previously discussed, has the overall effect of improving the production hardware development schedule and reducing the total program cost, including the expense of hardware, system certification, and testing.

The system costs were determined based on the summation of the average derived cost of each individual component for a given subsystem configuration. The system program costs were proportioned based on past recorded Gemini program experience. Figure 1 presents the approximate non-recurring program cost for a representative life support system production program. Major production milestones indicating recurring program costs are also shown in the Figure for reference. Definitions of the terms used in the Figure are presented in Section 2. The four major percentage program costs at the end of the four-year program include: 1) engineering design, 12.6%; 2) ground support, 14.3%; 3) test hardware fabrication, 23%; and 4) prime contractor's management, integration and documentation, 22.9%. The remaining 27.2% includes all other nine major cost items including system engineering, tooling and administrative costs. Also indicated is that approximately 38% of total program funds and also 38% of engineering design allocations are expended at the time of first test system completion. It is significant that more than 60% of design funds are usually expended after the "supposed" completion of system design. These expenditures are usually attributed to engineering changes necessitated by the results of system testing and by the new requirements imposed on the system after design completion. Cost of non-flight-qualified and low- and high-fidelity prototypes average approximately 5% and 10%, respectively, of the cost of flight-qualified units, as noted at the one-year point of Figure 1. This shaded area in the Figure represents the cost items that are normally allotted to the production of a high-fidelity prototype. A high-fidelity prototype is defined as the equivalent of a flight program's first test system without the cost of ground support or other functions pertinent only to a flight hardware program, such as qualification and tooling. The above resulting data agreed favorably when

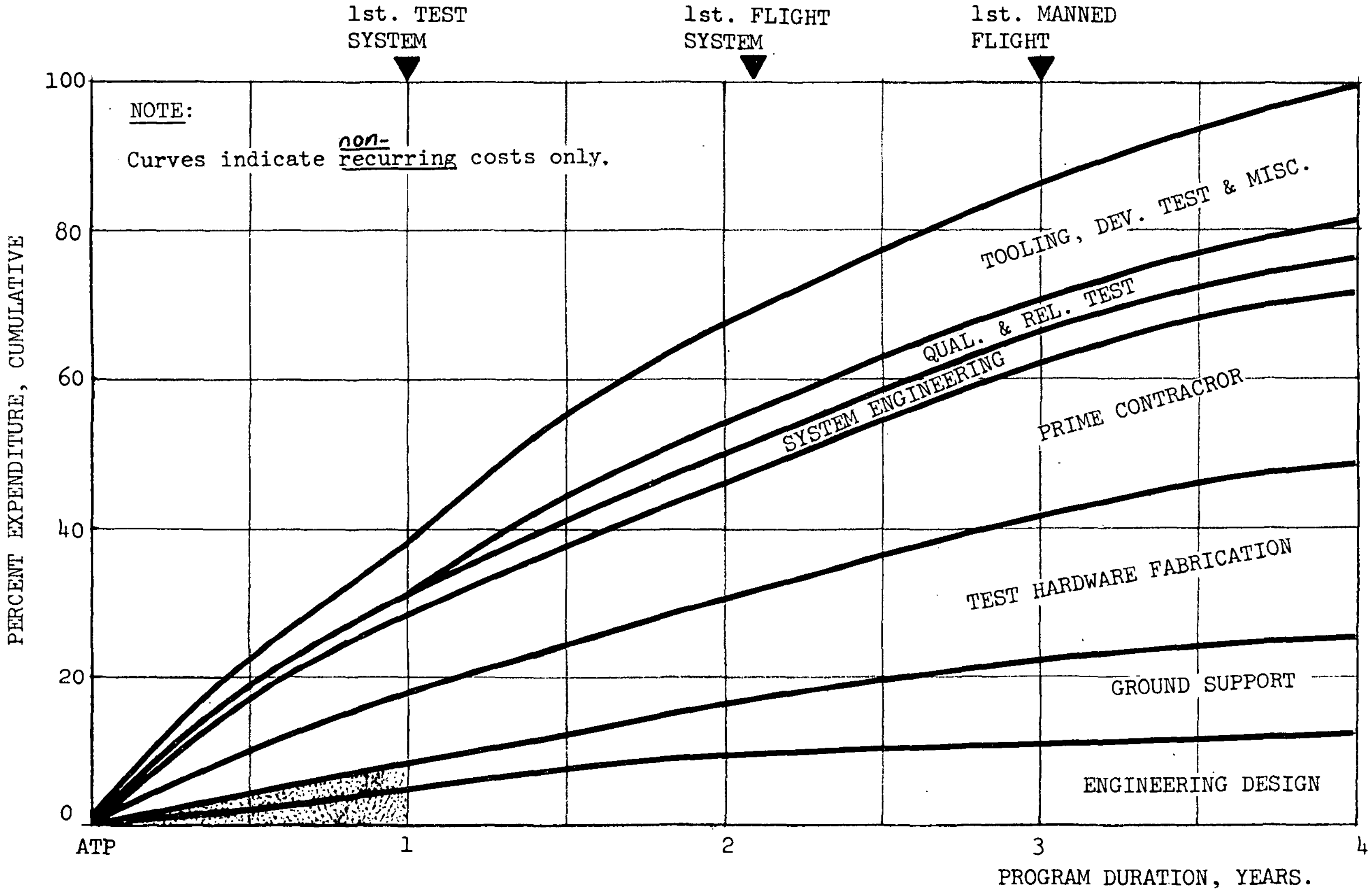

FIGURE 1 - MAJOR COST IMPACTS IN LIFE SUPPORT SYSTEM DEVELOPMENT

used and compared with past equipment cost for other low- and high-fidelity advanced research and technology developed prototype hardware. A summary of the cost analysis program is presented in the following sections:

Study Approach and Definitions
Development of Cost Estimating Relationships
Cost Estimation of Life Support Systems
Conclusions and Recommendations

Section 2

STUDY APPROACH AND DEFINITIONS

2.0 OBJECTIVES

The design and development of equipment for flight use in earth-orbital programs, when optimally approached cost effectively, proceed through the following logical progression: 1) bench testing of breadboard designs, 2) the fabrication and evaluation of prototype equipment, 3) redesign to meet flight-imposed requirements, and 4) qualification and testing of a flight-ready system. Each of these steps is intended to produce the basic design information necessary to progress to the next step. The cost of each step is normally substantially less than that of the following step. An evaluation of the cost elements involved in each of the steps cited above and their impact on total program cost are presented in this study. The major objectives of the study include the following: 1) the development of a methodology to predict realistic cost estimates of advanced LSS, the definition of areas of major cost impacts in the development of LSS, and 3) cost comparisons for various life support equipment.

In order to achieve the above-stated objectives, the following study tasks were accomplished:

1. Cost estimates, including design, development, test, production and support functions.
2. The completion of cost estimate predictions for low- and high-fidelity prototypes and qualified flight hardware.
3. The assessment of the costs of advanced technology required in critical development areas.
4. The establishment of cost models for fourteen life support system functional methods for: a) carbon dioxide removal, b) water recovery, c) oxygen recovery, and d) atmospheric monitoring.

2.1 APPROACH

Fourteen advanced life support systems were quantitatively evaluated in the study. System characteristics, including process flows, performance and physical characteristics were also analyzed. Additionally, the status of development of each of the systems considered and the required advance technology efforts required to bring conceptual and/or pre-prototype hardware to an operational prototype status were defined. Intimate knowledge of the operations, development status, and capabilities of the systems to meet space mission requirements were found to be essential in establishing the cost estimating relationships for advanced life support systems.

The following is a summary of the technical approach used. Included are the development of cost estimating relationships and the cost estimation of life support systems including both low- and high-fidelity prototypes and flight-qualified hardware.

2.2 DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

The methodology used in developing cost estimating relationships (CER's) for individual life support components proceeded as follows:

1. The components were analyzed to determine which physical or performance characteristics might prove useful as predictive variables.
2. Costs were arrayed graphically against the candidate variables either singly or grouped. The most promising of these arrays were 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 the component costs.

Individual CER's for respective system components were summed up to establish the total system cost estimation. The validity of a typically derived heat exchanger CER was verified when it was applied to a number of Skylab heat exchangers and was found to agree favorably with actual cost data. Other component CER's were verified in a similar manner.

2.3 COST ESTIMATION OF LIFE SUPPORT SYSTEMS

Cost estimations were established for both low- and high-fidelity prototypes and flight-qualified-type hardware utilizing the methodology discussed below.

2.3.1 Cost Estimation of Life Support Prototypes

The cost of low-fidelity prototypes was found to depend on its degree of sophistication and utilization of available space hardware and/or commercial components. A cost estimate approximately equal to half that of a corresponding high-fidelity prototype was allocated to low-fidelity prototypes. High-fidelity prototypes were assumed to be similar in construction to the first test system produced in a flight program which has not undergone any qualification or reliability testing. The cost of the high-fidelity prototype was obtained by excluding those cost items which are pertinent solely to flight articles. Cost of low- and high-fidelity prototypes constituted 5% and 10%, respectively, of the cost of a corresponding flight-type system.

2.3.2 Cost Estimation of Flight-Qualified Life Support Systems

The methodology used in developing life support system CER's is based both on system hardware characteristics and operational performance. A system schematic and a component identification list were prepared for each of the fourteen life support systems considered. System and process descriptions, including system performance and characteristics, were also given. The physical and performance parameters were identified for use in formulating the cost estimating relationships. Recurring CER's were then developed and computed for each of the system subassemblies and summed up to obtain the integrated system recurring cost estimates. The system's non recurring CER's were computed on an integrated system basis. Overall program costs, including management, fees, testing, tooling and minor procurements, were proportioned based on actual cost expenditure experience obtained from the Gemini program.

2.3.3 Cost-Related Definitions

The terminology used in this study is that practiced by the McDonnell Douglas Corporation. In order to assist users of the report who are familiar with different terms or groupings of cost-related activities, the following definitions are presented.

1. Engineering Design - involves the design and analysis of individual components and assemblies in the life support system.

2. Program Management - relates to planning, organizing, directing and controlling the project. Includes scheduling deliveries, coordinating changes and monitoring problem areas.

3. System Engineering - involves system design as opposed to component or assembly design. Includes design, analysis design support, and total system non-separable hardware design and integration effort.

4. Development Testing - involves testing with breadboard and prototype hardware that is required to evaluate component and assembly design concepts and performance.

5. Qualification Testing - deals with formal qualification testing to ensure that components and assemblies provided meet mission performance and design requirements.

6. Reliability Testing - includes component and assembly life cycle and failure analysis testing to ensure operation of the system for the required mission duration.

7. Tooling - involves the design, fabrication and maintenance of component and assembly tools.

8. Non-Accountable Test Hardware - includes prototype units, breadboards, operational mock-ups and other non-deliverable development hardware items.

9. Aerospace Ground Support - includes design and fabrication of system test and servicing, system handling and checkout and hardware necessary during acceptance testing and launch operations.

10. Sustaining Engineering - includes incorporation of changes, modifications to design and contractor's project engineering design.

11. Subcontractor General and Administrative - includes overhead expenses charged as fixed percentages of all other costs.

12. Subcontractor Fee - involves the fee charged by the subcontractor as negotiated at beginning of the contract.

13. Minor Subcontractor - includes procurement costs for minor valves, lines and other required miscellaneous parts.

14. Prime Contractor Costs - include specifications, vendor coordination, procurement and documentation expenses.

15. Recurring Costs - 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.

16. Non-recurring - non-recurring 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.

Section 3

DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

The methodology used in establishing cost estimating techniques for flight-type 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 component considered, and 3) the summation of cost equations for each respective system component to establish the total system cost. CER's were developed using existing hardware data with appropriate modifications to estimate the cost of the particular components considered. Definition of the cost element structure, comprising the detailed recurring and non-recurring cost functions, and the factors that affect application of the CER's are given in the following paragraphs.

3.1 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 recurring and non-recurring.

Table 1 presents a typical breakdown of the life support system expenditures, as encountered in the Gemini program, divided in the respective recurring and non-recurring items. The major recurring cost item was for flight hardware production. The major non-recurring costs are those related to Design, AGE, and Prime Contractor's specification and procurement efforts.

3.2 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 presented in Figure 2 that is based on data published by the U. S. Bureau of Statistics.

TABLE 1 - 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 %

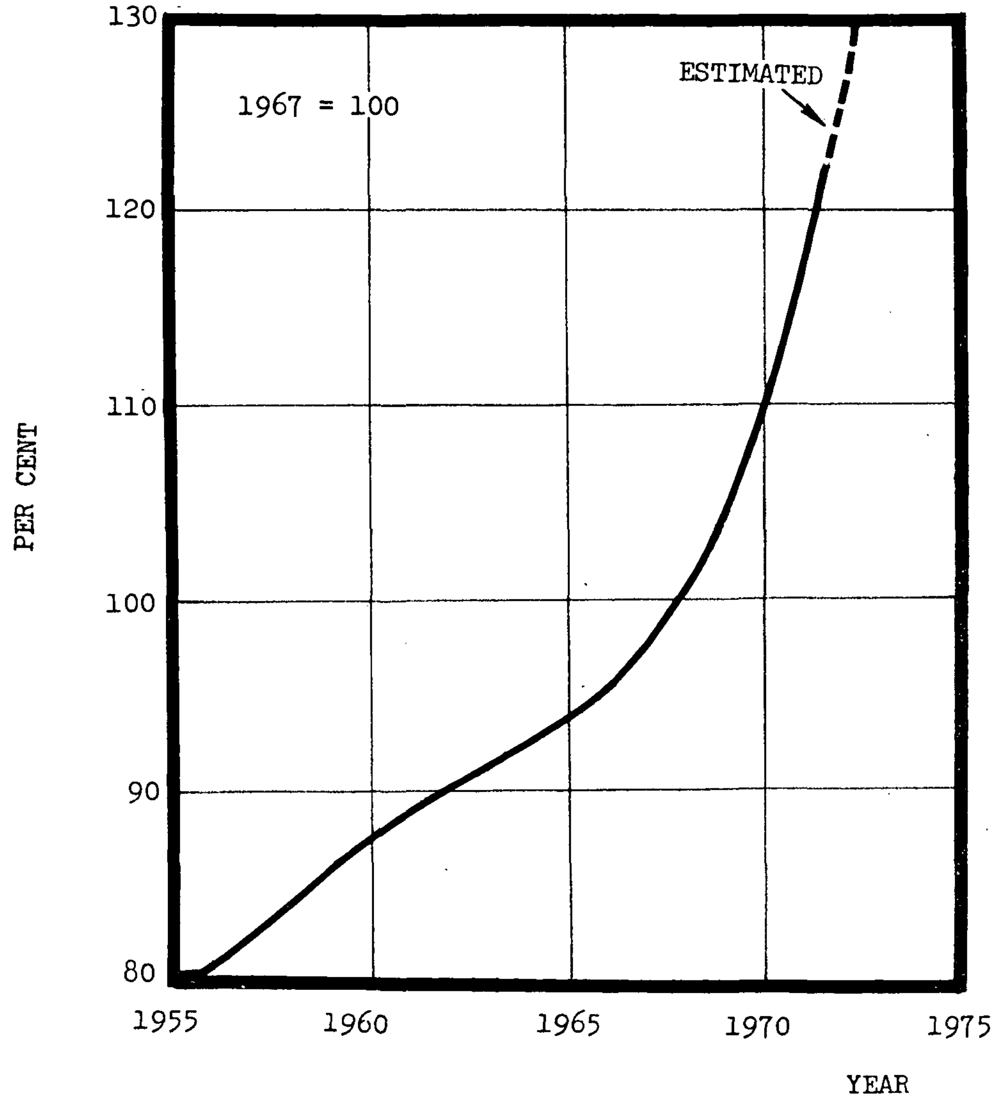

FIGURE 2 - Consumer Price Index
(Source: U. S. Bureau of Labor Statistics)

3.3 DEVELOPMENT OF RECURRING COST ESTIMATING RELATIONSHIPS

Cost estimating relationships (CER's) have been developed for various life support system components such as heat exchangers, accumulators, compressors, pumps and controllers. Smaller components such as valves and pressure and temperature gages are included in the CER's on a weight basis after comparing and relating them to similar components in a comparable assembly. Component CER's are summed up in a building block fashion to obtain the total system cost estimating relationships.

The steps used in developing recurring CER's for individual components are 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.

The methodology used in the development of individual component 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. Six heat exchanger types applicable to life support systems were used to develop the CER. After the development of the heat exchanger CER, new cost data for three Skylab heat exchangers were made available and were found to agree with the developed CER.

Table 2 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 3. The resulting data were then normalized, at 10 pounds per heat exchanger, to negate the effect of weight differences.

Table 2 - 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	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

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 4. A good fit for the combined relations shown in Figures 3 and 4 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 3, which also includes the 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 3.

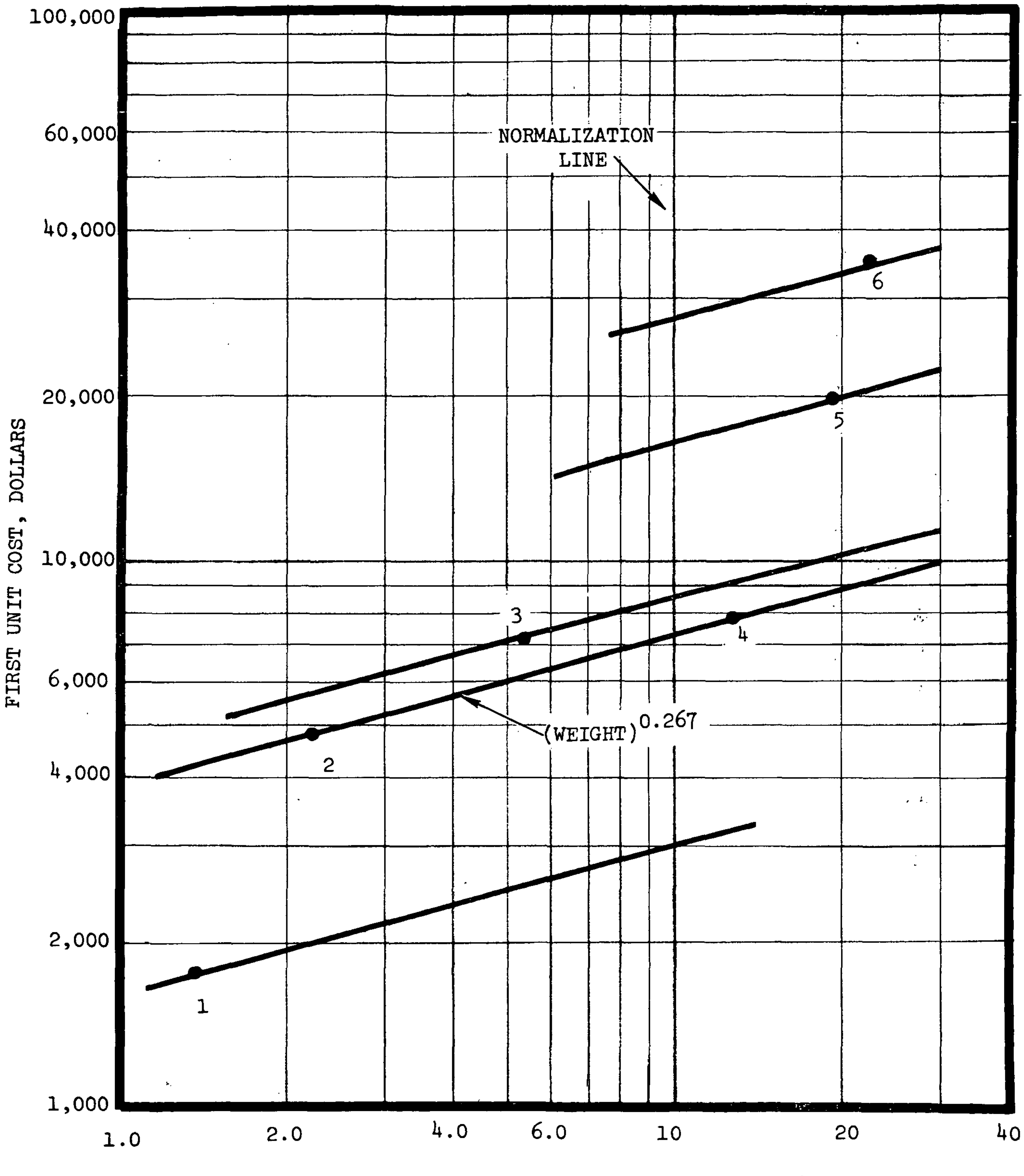

FIGURE 3 - HEAT EXCHANGER COST/WEIGHT RELATIONSHIP

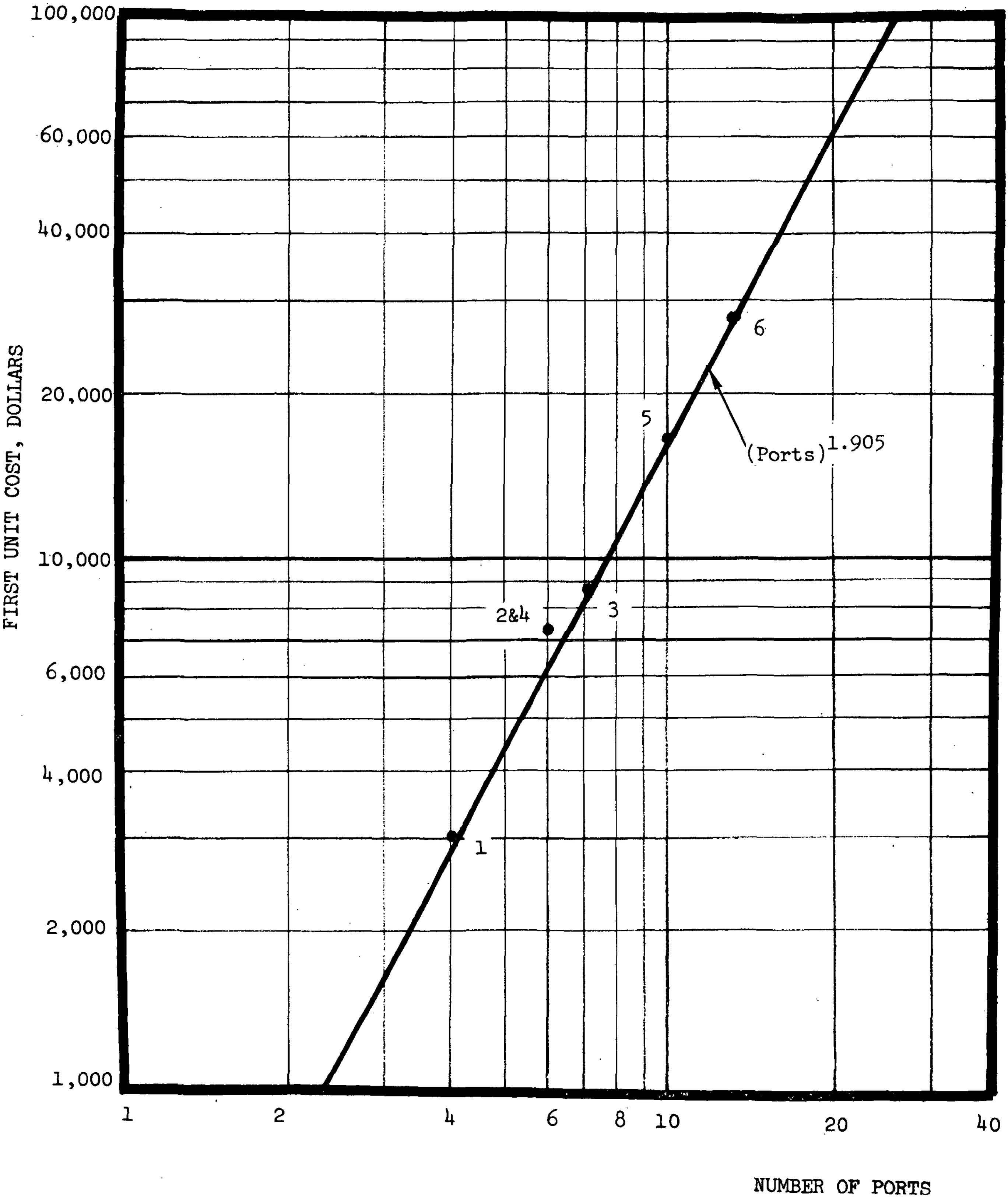

FIGURE 4 - HEAT EXCHANGER COST/NUMBER OF PORTS RELATIONSHIP

TABLE 3 - 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

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 to be proportional to their weight, W_{oc}, as based on experience with similar systems. 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 2. Accordingly, the resulting heat exchanger CER was calculated as follows:

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

Other individual life support system component CER's were developed using the same procedure as used in developing the heat exchanger CER. The CER's were then summed up to provide the projected cost estimates for integrated flight-qualified life support systems. Examples of such a procedure are presented in Section 4. Validation of the formulated heat exchanger CER was proved by applying the CER to cost data for current Skylab heat exchangers as presented in the following paragraphs. Other component CER's were developed and proven similarly.

3.3.1 Example of Validation of Component CER's for Recurring Cost

The CER's for the different life support components developed during the study were checked, utilizing data obtained from Apollo and Skylab programs.

The derived equations agreed favorably with actual component costs. Three examples, utilizing recurring cost data for heat exchangers used in the Skylab program are given in the following paragraphs to illustrate how the accuracy of the CER's was validated. The cost of each heat exchanger was calculated using the CER developed in Section 3.3 and then compared to actual component cost. A brief description of each of the heat exchanger types used is also presented as follows.

1. Skylab Regenerative Heat Exchanger

This heat exchanger is used in the Airlock suit cooling module (a) to provide the proper temperature coolant fluid to the coolant temperature (Vernatherm) valve and (b) to cool the suit cooling water. The unit is a cross-counterflow liquid-to-liquid, plate-fin type heat exchanger. The hot fluid makes a single pass through the unit. The cold fluid makes four passes. The material is stainless steel with nickel fins. The heat exchanger has four ports and weighs 4.26 pounds.

Then,

$$\text{Heat Exchanger First Unit Cost} = 116F_{INF}W^{0.267}N_p^{1.905} \quad \text{dollars}$$

Where,

F_{INF} = inflation factor = 1.197, for converting 1963 dollars into 1970 dollars

W = weight of heat exchanger = 4.26 lbs., and

N_p = number of ports in the heat exchanger = 4

Substituting the values of the variables in the above CER yields the following:

$$C = 1.197 \times 116 \times (4.26)^{0.267} \times 4^{1.905} = 2868 \quad \text{dollars}$$

Actual Unit Cost = 2663 dollars

$$\text{Calculated Error} = \frac{2868-2663}{2663} \times 100 = 7.6\%$$

2. Skylab Primary Oxygen Heat Exchanger

This heat exchanger is interposed in the oxygen gas line from the 120 psig regulators. By a heat exchange with either primary or secondary coolant systems, the incoming O_2 gas is tempered before being added to the two-gas environment. The unit is a cylindrical tubular heat exchanger. The oxygen makes a single pass through the tubes. The coolant makes four passes per circuit across the tubes for a cross-counterflow configuration of heat exchange. Two coolant circuits are provided for increased system reliability. The heat exchanger weighs 4.6 pounds and has 4 ports.

Then,

Heat Exchanger First Unit Cost $C = 116 F_{INF} W^{0.267} N_p^{1.905}$ dollars

$= 116 \times 1.197 \times (4.6)^{0.267} \times 4^{1.905}$

$= 2936$ dollars

Actual Unit Cost $= 2874$ dollars

Calculated Error $= \frac{2936-2874}{2874} \times 100 = 2.1\%$

3. Skylab ATM and Ground Cooling Heat Exchanger

This Heat Exchanger is used in both the ATM and the Airlock as follows: (a) To provide ground cooling to the Airlock coolant loop, (b) to provide cooling to the ATM C&D Panel cooling water, and (c) to provide cooling of the suit cooling water. The unit is a cross-counterflow, plate-fin heat exchanger having three channels. The cold fluid channel makes three passes. The two hot-fluid channels each make a single pass. Material is stainless steel with nickel fins. The weight of the heat exchanger is 6.46 pounds and it has six ports.

Then,

$$\text{Heat Exchanger First Unit Cost } C = 116F_{INF}W^{0.267}N_p^{1.905} \text{ dollars}$$

$$= 116 \times 1.197 \times (6.46)^{0.267} \times 6^{1.905}$$

$$= 6971 \quad \text{dollars}$$

$$\text{Actual Unit Cost} = 6442 \quad \text{dollars}$$

$$\text{Calculated Error} = \frac{6971-6442}{6442} = 8.2\%$$

3.4 DEVELOPMENT OF NON-RECURRING COST ESTIMATING RELATIONSHIPS

Non-recurring CER's have been developed for engineering design phase. Other non-recurring cost estimates are based on the cost breakdown ratios presented in Table 1 which have been based on actual flight hardware production program data collected mainly for Gemini. The analysis of a number of cost incluencing 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.

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

The non-recurring CER's developed were also applied to the latest data obtained from the Skylab program and were found to agree favorably with actual program costs.

Section 4

COST ESTIMATION OF LIFE SUPPORT SYSTEMS

The completion of research and technology programs have shown that the development cycle of a typical life support subsystem requires three to five years to bring the system from the working model to the stage where it is satisfactory for use in a low-fidelity prototype configuration. Once the design operational acceptability is proven in integrated tests, several more years are required to develop the system into a high-fidelity prototype or a flight-qualified version using the previous research and development verification data to incrementally improve system design. Cost estimating methods using the methodology derived in Section 3.0 for both the low- and high-fidelity prototypes and the flight-qualified-type systems are presented.

4.1 DEFINITION OF LIFE SUPPORT HARDWARE CONFIGURATIONS

Life support system development usually undergoes several degrees of sophistication which are classified as: 1) working bench-type model; 2) low-fidelity prototype; 3) high-fidelity prototype; and 4) flight-qualified system. A brief definition of each of the four hardware configurations is given as follows.

1. Working bench-type model - This is defined as an operational unit built to verify feasibility and conceptual arrangement of system components. It is used to troubleshoot the design concept at the lowest hardware cost. This type unit normally comprises many commercial or laboratory components. Working models are usually not man-rated and are tested without integration with other hardware. The cost of working bench-type models varies by as much as 1000% for certain systems. In many instances the test model has been developed independently of Government contracts and as such very little factual data are made available. The number of variables associated with estimating the cost of a working model usually results in a highly unreliable estimate even on an

approximate basis. Accordingly, no attempt has been made in this study to establish cost estimates for working bench-type models other than as directly related to a low- and high-fidelity prototype unit cost.

2. Low-fidelity prototype - Defined as an operational unit whose feasibility and basic operational characteristics are proven. It is man-rated and can be tested at the bench level or as an integrated system in manned or unmanned simulator tests. A low-fidelity prototype is made primarily of flight-type but not flight-weight hardware and usually comprises some commercial-type components. Nearly all advanced EC/LSS concepts proven to date have been carried to this point of development. The flight vehicle hardware program has been relied upon to carry it to a high-fidelity system class.

3. High-fidelity prototype - Defined as a flight-qualifiable unit that is developed as a flight article but has not undergone the high expense of flight qualification. A high-fidelity prototype is required to operate as a flight unit but is not guaranteed to withstand some of the flight environment effects, such as launch stresses. It is a man-rated system that consists of all flight-type, flight-weight hardware. The high-fidelity prototype is used to obtain long life, reliability, maintainability and other related data using the most realistic, cost-effective configuration. Normally, NASA research and technology has not carried the EC/LSS hardware to this configuration level. However, the relevant data return for the very little cost difference warrants that promising systems be made to the high-fidelity level.

4. Flight-qualified system - This is the actual flight hardware, developed for flight in a manned spacecraft, that has undergone all qualification, development testing and reliability testing. Flight-qualified system costs include all items pertinent to a flight hardware program such as ground support and tooling.

4.2 COST ESTIMATES OF LOW- AND HIGH-FIDELITY PROTOTYPES

The degree of sophistication of the low-fidelity prototype and its utilization of available space hardware and/or commercial components tends to vary the cost of the unit. However, a value of approximately half of the cost of the high-fidelity prototype has been considered to be a good approximation.

The methodology used in estimating the cost of a high-fidelity prototype was based on the assumption that it possesses the same degree of hardware sophistication as a flight article but does not require the cost of ground support, qualification or reliability testing. Additionally, no tooling, test hardware or prime contractor integration are included. The various cost categories and a four-year profile of approximate percentage distribution for representative life support systems have been indicated in Figure 1. The cost of a high-fidelity prototype is exclusive of qualification test, reliability test, AGE, test hardware, tooling, G&A, fee and prime contractor costs. The functions contributing to the cost of developing a high-fidelity prototype are the following: 1) engineering design, 2) system engineering, 3) development testing, 4) first unit fabrication cost, and 5) program management. The definition of what is included in the cost for each of these five noted areas is given in Section 2.0.

In addition to the exclusion of the major cost items mentioned above, the data that were presented in Figure 1 indicate that approximately 38% of total program funds, and also 38% of engineering design allocations, are expended at the time of first test system completion. It is significant that more than 60% of design funds are usually expended after the "supposed" completion of system design. These expenditures are usually attributed to engineering changes necessitated by the results of system testing or by new requirements imposed on the system after design completion. Applying this 38% factor to engineering design, system engineering, development test, and program management costs result in an approximate cost for a high-fidelity prototype unit which is assumed to be identical in construction to the first test unit produced. The resulting percentage costs are as follows: 1) engineering design, 4.8%; 2) system engineering, 1.5%; 3) development testing, 1.0%: 4) first flight unit fabrication cost, 2.5%; and 5) program management, 0.4%; for a total of 10.2% of qualified system cost. The typical life support system cost data that were presented in Figure 1 were used in computing these percentages.

The cost of a high-fidelity prototype thus approximately equals 10% of the flight hardware cost. Qualified system cost includes the qualified units developed for backup and/or testing purposes. Experience with recent and current space programs indicates that 1 to 3 additional units are procured along with each flight unit. In this study, one backup unit is included with each flight unit. The high-fidelity model cost may thus be considered to average approximately 10% of the cost of the qualified system, including one backup unit. Similarly, the cost of a low-fidelity prototype has been considered equivalent to 5% of the qualified system cost. The costs of a number of low- and high-fidelity prototypes developed under NASA's Supporting Research and Technology (SRT) programs, when compared to the costs of corresponding flight-qualified hardware developed in this study, were found to agree favorably with the 5% and 10% values, respectively.

4.2.1 Cost Estimates of Selected System Prototypes

Examples of low- and high-fidelity prototypes resulting from using the cost data for flight-type systems presented in Section 4.3 are summarized in Table 4 for several CO_2 concentrators, water recovery systems and oxygen recovery systems. All system prototypes are of the six-man size. Data presented in Section 4.3 may also be used to parametrically evaluate the effect of varying crew size on cost.

TABLE 4 - ESTIMATED COSTS OF SELECTED SYSTEM PROTOTYPES (IN DOLLARS)

Life Support System	Low-Fidelity Prototype	High-Fidelity Prototype
Molecular Sieves CO_2 Concentrator	434,803	886,999
Hydrogen-Depolarized CO_2 Concentrator	352,277	718,645
Solid Desiccant CO_2 Concentrator	342,072	697,828
RITE Waste-Water System	533,102	1,087,968
Reverse Osmosis Wash Water System	321,643	656,415
Multifiltration Wash Water System	243,106	496,135
Vapor Compression System	410,721	838,207
Air Evaporation/Electrolytic Pretreatment System	453,013	924,517
Sabatier CO_2 Reduction System	220,500	449,860
Bosch CO_2 Reduction System	232,100	472,414
SPE Electrolysis System	415,300	837,144
KOH Electrolysis System	385,800	731,899

4.3 METHODOLOGY FOR COST ESTIMATION OF FLIGHT-QUALIFIED SYSTEMS

Cost-estimating relationships have been established for fourteen life support systems to provide meaningful costs for projected advanced LSS as follows:

1. Carbon Dioxide Removal
    - Molecular Sieves
    - Hydrogen-Depolarized Concentrator
    - Regenerable Solid Desiccant

2. Water Recovery
    - RITE Waste Management-Water System
    - Reverse Osmosis
    - Multifiltration
    - Vapor Compression
    - Air Evaporation/Electrolytic Pretreatment

3. Oxygen Recovery
   - Bosch
   - Sabatier
   - Solid Polymer Electrolysis
   - Circulating KOH Electrolysis

4. Atmosphere Analysis
   - Mass Spectrometer
   - Gas Chromatograph

The methods used in developing life support system CER's are based on both system hardware characteristics and operational performance. System Schematics and component identification lists are first prepared for each of the systems involved. Physical performance parameters are then identified for use in formulating the respective system CER's. The recurring CER's are prepared for each major component in the system and then summed up to obtain the integrated system recurring cost estimate. The integrated system's nonrecurring CER's are computed on a total system basis.

A brief discussion of the systems evaluated, their development status and performance requirements are presented. Included also is a summary of the cost estimating relationships formulated for each of the fourteen life support systems studied. A detailed example of the usage of the methodology discussed in Section 3.0 is presented for the molecular sieves CO_2 concentrator system. The recurring and non-recurring cost breakdown for each of the other systems is summarized.

4.3.1 Review of Carbon Dioxide Concentrators Evaluation

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, and 3) Regenerable Solid Desiccant Concentrator. The CER's configuration information and other data required to perform cost analysis for a variety of CO_2 concentrator configurations and conditions are given in volume MDC G4631 entitled, "Cost Analysis of Carbon Dioxide Concentrators."

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. The HDC, when brought to a high-fidelity prototype, as expected under the SSP program, would cost up to 20% less than a comparable molecular sieves system. In addition, the HDC has superior performance characteristics as it potentially can provide <3 mmHg of CO_2 in the cabin atmosphere as compared to 3 mmHg to 5 mmHg provided by the state-of-the-art molecular sieves system.

The regenerable solid desiccant system is in a lesser state of development than the other two systems evaluated. The system utilizes 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.

A comparison between the three types of CO_2 concentrators is presented in Table 5. System characteristics, including performance and system operation, are outlined. Included also are availability, status of development and anticipated operational problems for each of the systems considered.

4.3.1.1 Example Usage of CER Methodology to Determine Cost

The technique used in calculating the cost estimates is illustrated by using the molecular sieves CO_2 concentrator as an example. The CO_2 concentrator system shown in Figure 5 is comprised of six major component types and associated valves, instrumentations and controls. Cost estimates for producing one and two flight-qualified concentrator systems are derived in five major steps as follows:

1. Recurring Costs for Components

The molecular sieves CO_2 concentrator's components have been grouped in six groups, designated as I through VI, as shown in the system schematic, Figure 5. The CER's used for calculating major component group CER's are presented in Table 6, along with other major CO_2 concentrator components. The weight, volume and power characteristics of the components of a typical six-man thermally-desorbed molecular sieves concentrator that were used in the CER calculations are presented in Table 7. Thus, applying the values of the variables given in Table 7 to the individual component CER's results in the following recurring costs:

Table 5 - 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.

Table 6

CARBON DIOXIDE CONCENTRATORS
RECURRING COST ESTIMATING

	ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
(1)	CO_2 ACCUMULATOR	$C = 18{,}634\ V^{0.377} + 2959\ W_{oca}$
(2)	COMPRESSOR/AIR BLOWER	$C = 38.2\ P^{0.942} + 2192\ W_{occ}$
(3)	SOLID DESICCANT CANISTERS	$C = 15{,}865\ W_{CAN}^{0.267}\ Q_c^{0.89} + 2959\ W_{ocd}$
(4)	SOLID DESICCANT CANISTERS WITH BUILT-IN PLATE-AND-FIN HEAT EXCHANGER	$C = 158.65\ (100\ W_{CAN}^{0.267} + W_{HX}^{0.267}\ N_P^{1.905})\ Q_{HX}^{0.89} + 2959\ W_{ocdh}$
(5)	HEAT EXCHANGER CONDENSER	$C = 159\ W_{HX}^{0.267}\ N_P^{1.905} + 2959\ W_{och}$
(6)	TIMER AND CONTROLS	$C = 4795\ (W_T + W_{oct})$
(7)	ELECTRO-CHEMICAL CELL MODULE	$C = 400\ W_M + 2192\ W_{oce} + 2000$

TOTAL HARDWARE COST $C_T = \sum_{Q=1}^{N} F_A F_I \left(\sum_{I=1}^{M} C_I\right) Q^{1-B}$ Dollars

Where,

N = No. of Units Purchased

F_A = Component Assembling Factor

F_I = Assembly Integration Factor

M = No. of Components in Assembly

C_I = Component Fabrication Cost

B = Learning Curve Slope

TABLE 7 - CHARACTERISTICS OF SIX-MAN
MOLECULAR SIEVES CO_2 CONCENTRATOR

VARIABLE	FUNCTION	VALUE
V	VOLUME OF ACCUMULATOR	9.1 FT^3
W_{oca}	WEIGHT OF COMPONENTS ASSOCIATED WITH V ACCUMULATOR	4.5 LBS
P	ELECTRICAL POWER INPUT TO COMPRESSOR	420 WATTS
W_{occ}	WEIGHT OF COMPONENTS ASSOCIATED WITH COMPRESSOR	12.0 LBS
W_{CAN}	WEIGHT OF SILICA GEL/MOLECULAR SIEVE CANISTER	67.1 LBS
Q_c	NUMBER OF CANISTERS USED	8
W_{ocd}	WEIGHT OF COMPONENTS ASSOCIATED W/CANISTERS	66.2 LBS
W_{HX}	WEIGHT OF HEAT EXCHANGER	16.0 LBS
N_P	NUMBER OF PORTS PER HEAT EXCHANGER	4
Q_{HX}	NUMBER OF HEAT EXCHANGERS USED	3
W_{och}	WEIGHT OF COMPONENTS ASSOCIATED W/HEAT EXCHANGERS	11.4 LBS
P_1	ELECTRICAL POWER INPUT TO AIR BLOWER	330 WATTS
W_{occ_1}	WEIGHT OF COMPONENTS ASSOCIATED W/AIR BLOWER	17.2 LBS
W_T	WEIGHT OF TIMER	8.0 LBS
W_{oct}	WEIGHT OF COMPONENTS ASSOCIATED WITH TIMER	27.7 LBS

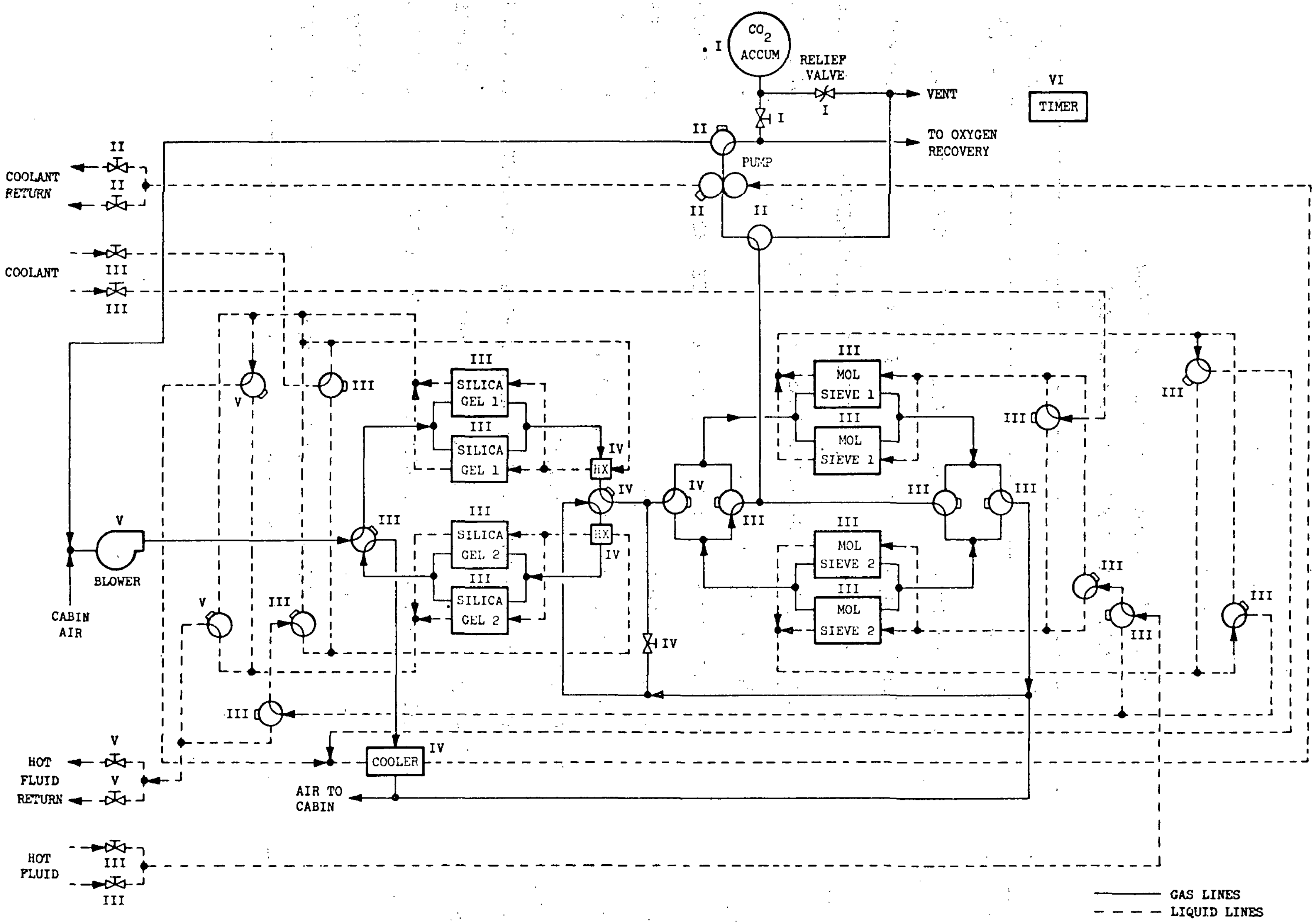

FIGURE 5. MOLECULAR SIEVES CARBON DIOXIDE REMOVAL SYSTEM SCHEMATIC

a.	CO_2 Accumulator	Equation 1, Table 6 = \$ 56,169
b.	CO_2 Compressor	Equation 2, Table 6 = \$ 37,771
c.	Silica Gel/Molecular Sieves Canisters	Equation 3, Table 6 = \$508,617
d.	Heat Exchangers	Equation 5, Table 6 = \$ 46,212
e.	Air Blower	Equation 2, Table 6 = \$ 46,870
f.	Timer and Controls	Equation 6, Table 6 = \$171,182

2. Recurring Costs for Assembly Integration:

The costs of the physical integration of individual components into the molecular sieves CO_2 concentrator, including piping, ducting, and structural support were provided by introducing the component integration factor, F_A. Additionally, an assembly integration factor, F_I is used to account for the physical integration of the solid desiccant canister assembly into the overall CO_2 concentrator system. Average values of above factors are as follows:

$$F_A = 1.833$$

$$F_I = 1.10$$

Applying the F_A and F_I factors to the combined recurring costs of the molecular sieves concentrator components yields the following:

$$C = 1.833 \times 1.1 \times (56,169 + 37,771 + 508,617 + 46,212 + 46,870 + 171,182)$$

$$C = 1.747,511 \text{ dollars}$$

The above cost is for one assembly without additional flight-test or back-up assemblies. The recurring cost breakdown for the molecular sieves CO_2 concentrator was determined by using the developed ratios given in Table 1.

3. Non-Recurring Costs for the Integrated System:

The CER for non-recurring engineering design cost is as follows:

Assembly Engineering Design Cost

$$C_D = 34{,}935N + 102{,}942 \text{ dollars}$$

Where,

N = Number of component types in assembly = 23

Substituting for N in the CER yields the following

$$C_D = \$908{,}447$$

Values of non-recurring costs other than engineering design are proportional ratios, given in Table 1, of the engineering design cost of $908,447. A summary of these values is given as follows: a) subcontractor general and administrative = $469,667; b) subcontractor fee = $197,133; c) program management = $68,134; d) system engineering = $286,160; e) development test = $187,140; f) qualification test = $138,084; g) reliability test = $22,566; h) ground support = $1,004,742; i) tooling = $210,760; j) non-accountable test hardware = $90,845; k) specification, vendor coordination and procurement expense = $742,201; l) system integration = $455,131; m) prime's testing = $445,139; n) minor subcontracts = $20,894.

Then,

a total of integrated system's non-recurring cost = 5,447,047 dollars

4. Obtain Total Molecular Sieves Concentrator costs by adding recurring and non-recurring costs.

Then,

total Concentrator costs = 908,447 + 5,447,047 = 6355,494 dollars

5. Obtain total costs for the production of two concentrators:

In this case, the non-recurring costs remain the same at 5,447,047 dollars. The recurring costs, however, increase by applying the learning curve factor $Q^{0.8953}$, for Q=2 units. The recurring costs for two concentrators are thus = $1,747,511 \times 2^{0.8953}$ = $3,247,391.

Then,

total cost for production of 2 concentrators
= 5,447,047 + 3,247,391 = $8,694,438

The recurring and non-recurring cost breakdown for the molecular sieves CO_2 concentrator is tabulated in Tables 8 and 9 which indicate also the cost items for the hydrogen-depolarized and the regenerable solid desiccant concentrators. The procedure used for the molecular sieves system was followed to develop the other two CO_2 concentrator cost data in Tables 8 and 9.

4.3.2 Review of Water Recovery Systems

Cost estimating relationships were derived for the following water recovery systems: 1) RITE Waste Management-Water System, 2) Reverse Osmosis Wash Water System, 3) Multifiltration Wash Water System, 4) Vapor Compression Water System, and 5) Air Evaporation System with Electrolytic Pretreatment. The CER's configuration information and other data required to perform cost analysis for a variety of water recovery system configurations and conditions are given in volume MDC G4632 entitled, "Cost Analysis of Water Recovery Systems."

A manned spacecraft has at least four sources of waste water, including 1) urine, 2) condensate, 3) fecal and/or flush water, and 4) wash water. Each water source may be processed by one of the systems cited above. Current plans indicate that the RITE system may be used to process all waste products including urine, flush water, wash water, feces and trash. The reverse osmosis and multifiltration systems, on the other hand, may be

TABLE 8 - RECURRING COST BREAKDOWN FOR CARBON DIOXIDE CONCENTRATORS

RECURRING COST ITEM	MOLECULAR SIEVES	HYDROGEN DEPOLARIZED	REGENERABLE SOLID DESICCANT
Flight Hardware Production	1,771,627	1,106,289	995,152
Subcontractor G&A	299,405	186,693	168,169
Subcontractor Fee	125,785	78,546	70,770
Program Management	44,291	27,657	24,806
Sustaining Engineering	63,778	39,827	35,750
Sustaining Tooling	54,921	34,295	30,825
Specifications, Vendor Coordination and Procurement Expense	503,142	314,186	282,531
System Integration	232,083	144,924	130,413
Minor Subcontracts	152,360	95,141	85,544
TOTAL	3,247,391	2,027,827	1,823,960

TABLE 9 - NON-RECURRING COST BREAKDOWN FOR CARBON DIOXIDE CONCENTRATORS

NON-RCURRING COST ITEM	MOLECULAR SIEVES	HYDROGEN DEPOLARIZED	REGENERABLE SOLID DESICCANT
System Engineering Design	908,447	836,577	801,642
Subcontractor General and Administrative	469,667	432,332	414,449
Subcontractor Fee	197,133	181,559	173,956
Program Management	68,134	62,192	60,123
System Engineering	286,160	263,311	252,517
Development Test	187,140	172,531	165,138
Qualification Test	138,084	127,392	121,850
Reliability Test	222,566	205,132	196,402
AGE	1,004,742	925,351	886,616
Tooling	210,760	194,098	185,981
Non-accountable Test Hardware	90,845	83,758	80,164
Specifications, Vendor Coordination and Procurement Expense	742,201	683,104	654,942
System Integration	455,131	419,292	401,623
Prime's Testing	445,139	409,762	392,805
Minor Subcontracts	20,894	19,059	18,438
TOTAL	5,447,047	5,015,450	4,806,646

used to process only wash water which includes shower, handwash, and housekeeping wash water. The vapor compression and air evaporation/ electrolytic pretreatment systems, both of which are phase-change processes, are used primarily for urine recovery. Wash water is not normally processed in a phase-change-type process due to the large energy requirements per unit weight of such processes and the high liquid-to-solid ratio of wash water. When using reverse osmosis for wash water recovery, the resulting concentrated brine may be processed further in either the RITE, vapor compression, or the air evaporation/electrolytic pretreatment systems.

The major assembly CER's derived for use in computing water recovery system cost estimates are summarized in Table 10. Cost breakdowns for flight-type hardware for each of the five water recovery systems evaluated are presented in Tables 11 and 12 for both recurring and non-recurring cost items. Recurring costs are shown for two flight-type units each, one for actual flight and the second for back-up purposes. For this reason, non-recurring costs are considerably higher than recurring costs. The procedure used for the molecular sieves system in Section 4.2.1.1 was followed to develop the data in Tables 11 and 12. It is noted that cost comparisons between water recovery systems should be based on the capability of the respective system to process comparable amounts of the same kind of waste water. For example, reverse osmosis may be compared to multifiltration for processing wash water and vapor compression may be compared to air evaporation/electrolytic pretreatment for processing urine.

4.2.3 Review of Oxygen Recovery Systems Evaluation

Oxygen may be recovered from exhaled carbon dioxide by a number of physico-chemical processes by the reduction of CO_2 to carbon or methane and water, followed by the electrolysis of water to metabolic oxygen and hydrogen. Direct conversion of CO_2 to carbon and oxygen has also been under investigation. However, solid electrolyte, which is the leading direct conversion process, has not been yet proven operationally feasible and was not included in the study. Oxygen recovery processes considered are the following: 1) Sabatier CO_2 reduction, 2) Bosch CO_2 reduction, 3) solid

TABLE 10 - WATER RECOVERY SYSTEM

RECURRING COST ESTIMATING RELATIONSHIPS

ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
A. ELECTROLYTIC PRETREATMENT LOOP:	
1. ACCUMULATORS	$C = 1918\ V^{0.267}\ Q^{0.89} + 2959\ W_{oc}$
2. PUMPS	$C = 91\ (P_{w1}^{\ 0.942} + P_{w2}^{\ 0.942} Q^{0.89}) \times 670\ W_{oc}$
3. ELECTROLYTIC CELL MODULE	$C = 6250\ W_m + 2192\ W_{oc} + 2000$
4. METERING PUMPS	$C = 91\ P_w^{\ 0.942} Q^{0.89} + 670\ W_{oc}$
B. WATER DISTILLATION LOOP:	
1. BLOWER	$C = 38.2\ P^{0.942}$
2. HEATER	$C = 600\ (W_H + W_{oc})$
3. DISTILLATION MODULE	$C = 15{,}885\ W^{0.267} + 2959\ W_{oc}$
4. HEAT EXCHANGER	$C = 159\ W^{0.267}\ N_p^{\ 1.905} + 2959\ W_{oc}$
5. FILTRATION MODULE	$C = 200\ W_{mf} + 670\ W_{oc}$
C. WATER DISPENSING LOOP:	
1. CHILLERS	$C = 159\ W^{0.267}\ N_p^{\ 1.905} + 2959\ W_{oc}$
2. CIRCULATION PUMP	$C=91\ P_w^{\ 0.942} + 670\ W_{oc}$
3. CONTROLLER	$C = 4795\ (W + W_{oc})$

$$\text{TOTAL HARDWARE COST } C_T = \sum_{Q=1}^{n} F_A F_I \left(\sum_{I=1}^{m} C_I\right) Q^{(1-b)} \quad \text{Dollars}$$

Where,

n = Number of Units Purchased

F_A = Component Assembling Factor

F_I = Assembly Integration Factor

m = Number of Components in Assembly

C_I = Component Fabrication Cost

b = Learning Curve Slope

TABLE 11 - RECURRING COST BREAKDOWN FOR WATER RECOVERY SYSTEMS

RECURRING COST ITEM	RITE	REVERSE OSMOSIS	MULTI-FILTRATION	AIR EVAP/ ELECTROLYTIC	VAPOR COMPRESSION
Flight Hardware	1,025,608	317,234	259,554	494,164	1,061,066
Subcontractor G&A	173,318	53,609	43,862	83,508	179,308
Subcontractor Fee	72,935	22,560	18,458	35,142	75,457
Program Management	25,565	7,908	6,470	12,318	26,449
Sustaining Engineering	36,841	11,396	9,324	17,752	38,117
Sustaining Tooling	31,768	9,826	8,040	15,307	32,867
Specifications, Vendor Coordination and Procurement Expense	291,178	90,065	73,689	140,297	301,245
System Integration	134,404	41,573	34,014	64,759	139,051
Minor Subcontracts	88,161	27,269	22,311	42,478	91,210
TOTAL	1,879,780	581,440	475,722	908,725	1,944,770

TABLE 12 - NON-RECURRING COST BREAKDOWN FOR WATER RECOVERY SYSTEMS

NON-RECURRING COST ITEM	RITE	REVERSE OSMOSIS	MULTI-FILTRATION	AIR EVAP/ ELECTROLYTIC	VAPOR COMPRESSION
System Engineering Design	1,465,407	976,317	731,772	1,360,602	1,046,187
Subcontractor General and Administrative	757,615	504,759	378,326	703,431	540,879
Subcontractor Fee	317,993	211,861	158,795	295,251	227,023
Program Management	109,906	73,224	54,883	102,045	78,464
System Engineering	461,603	307,540	230,508	428,590	329,549
Development Test	301,874	201,121	150,745	280,284	215,515
Qualification Test	222,742	148,400	111,229	206,812	159,020
Reliability Test	359,025	239,198	179,284	333,347	256,316
AGE	1,620,740	1,079,807	809,340	1,504,826	1,157,083
Tooling	339,974	226,506	169,771	315,660	242,715
Non-accountable Test Hardware	146,541	97,632	73,772	136,060	104,619
Specifications, Vendor Coordination and Procurement Expense	1,197,238	797,651	597,858	1,111,612	854,735
System Integration	734,169	489,135	366,618	681,662	524,140
Prime's Testing	718,049	478,395	358,568	666,695	512,632
Minor Subcontracts	33,704	22,455	16,831	31,294	24,062
TOTAL	8,786,580	5,854,001	4,388,290	8,158,171	6,272,939

polymer electrolyte (SPE) water electrolysis, and 4) circulating KOH electrolyte water electrolysis. The CER's, configuration information and other data required to perform cost analysis for a variety of oxygen recovery system configurations and conditions are given in Volume MDC G4633 entitled, "Cost Analysis of Oxygen Recovery Systems."

Either one of the CO_2 reduction processes may be combined with one of the two water electrolysis methods to attain oxygen recovery from CO_2. The Sabatier process has been operated successfully in two consecutive manned simulator tests of sixty and ninety days in duration. The methane produced in the Sabatier process leads to the loss of large amounts of hydrogen when it is vented overboard. The Bosch process, by contrast, produces solid carbon and water and requires no hydrogen make-up for continuous operation. An operational drawback to the Bosch process is the deposition of solid carbon on the reactor. This problem has been partially alleviated by the use of expendable cartridges containing the required catalyst. The Bosch process has been bench-tested, but has not undergone any extended tests as a part of integrated life support systems to prove its operational feasibility. Of the two water electrolysis methods, only the KOH electrolyte subsystem has undergone integrated manned testing. The SPE process has been life-tested and currently appears to be more promising in performance and less troublesome in operation than processes utilizing KOH electrolyte. A summary of major component CER's is presented in Table 13 for each of the systems considered. Additionally, Tables 14 and 15 present recurring and non-recurring cost breakdowns for flight-type CO_2 reduction and water electrolysis systems. Note that the recurring cost breakdown given in Table 15 is for two flight-type units, one unit for actual flight and the second to be used as a back-up. Recurring costs will naturally increase with increasing number of flight units required. The procedure used for the molecular sieve system in Section 4.2.1.1 was followed to develop the data in Tables 14 and 15.

4.3.4 Review of Atmosphere Monitoring Systems Evaluation

Spacecraft life support systems must cope with a wide variety of compounds produced both metabolically and from the vehicle systems. The presence of

TABLE 13 - OXYGEN RECOVERY SUBSYSTEM RECURRING COST ESTIMATING

ASSEMBLY	COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)
A. SABATIER CO_2 REDUCTION SUBSYSTEM	
1. Reactor Assembly	$C = 159 W^{0.267} N_p^{1.905} + 3900 W_{oc}$
2. Blower	$C = 38.2 P^{0.942} + 2192 W_{oc}$
3. Condenser/Separator	$C = 159 W^{0.267} N_p^{1.905} + 2959 W_{oc}$
4. Accumulator	$C = 1{,}918 V^{0.267} + 2959 W_{oc}$
5. Pump	$C = 91 P^{0.942} + 670 W_{oc}$
6. Controller	$C = 4795 W$
B. BOSCH CO_2 REDUCTION SUBSYSTEM	
1. Reactor Assembly	$C = 159 W^{0.267} N_p^{1.905} Q^{0.89} + 3900 W_{oc}$
2. Compressor	$C = 38.2 P^{0.942}$
3. Condenser/Separator	$C = 159 W^{0.267} N_p^{1.905} + 2959 W_{oc}$
4. Accumulator	$C = 1918 V^{0.267} + 2959 W_{oc}$
5. Pump	$C = 91 P_w^{0.942} + 670 W_{oc}$
6. Controller	$C = 4795 W$
C. SPE ELECTROLYTE SUBSYSTEM	
1. Electrolysis Modules	$C = (6250 W_M + 2192 W_{oc} + 2000) Q^{0.89}$
2. Pumps	$C = 91 P_w^{0.942} Q^{0.89} + 670 W_{oc}$
3. Deionizers	$C = 200 W_o Q^{0.89} + 670 W_{oc}$
4. Power Conditioner/Coldplate	$C = (14.9 P^{0.942} + W^{0.267} N_p^{1.905}) Q^{0.89}$
5. Condenser/Separator	$C = 159 W^{0.267} N_p^{1.905} Q^{0.89} + 2959 W_{oc}$
D. CIRCULATING KOH ELECTROLYTE SUBSYSTEM	
1. Electrolysis Modules	$C = (6250 W_M + 2000) Q^{0.89} + 2192 W_{oc}$
2. Electrolysis Modules	$C = 38.2 P^{0.942} + 2192 W_{oc}$
3. Reservoir	$C = 1918 V^{0.267} + 2959 W_{oc}$
4. Pumps	$C = 91 P_w^{0.942} Q^{0.89} + 670 W_{oc}$
5. Heat Exchanger	$C = 159 W^{0.267} N_p^{1.905} + 2959 W_{oc}$

TOTAL HARDWARE COST $C_T = \sum_{Q=1}^{N} F_A F_I \left(\sum_{I=1}^{M} C_I\right) Q^{(1-B)}$ **DOLLARS**

WHERE,

N = NUMBER OF UNITS PURCHASED

F_A = COMPONENT ASSEMBLING FACTOR

F_I = ASSEMBLY INTEGRATION FACTOR

M = NUMBER OF COMPONENTS IN ASSEMBLY

C_I = COMPONENT FABRICATION COST

B = LEARNING CURVE SLOPE

TABLE 14 - RECURRING COST BREAKDOWN FOR OXYGEN RECOVERY SYSTEMS

RECURRING COST ITEM	SABATIER	BOSCH	SPE ELECTROLYSIS	KOH ELECTROLYSIS
Flight Hardware Production (2 Units)	240,951	252,651	1,108,932	721,004
Subcontractor G&A	40,718	42,695	187,397	121,841
Subcontractor Fee	17,135	17,967	78,861	51,274
Program Management	6,006	6,298	27,642	17,972
Sustaining Engineering	8,656	9,076	39,837	25,901
Sustaining Tooling	7,463	7,826	34,349	22,333
Specifications, Vendor Coordination and Procurement Expense	68,408	71,730	314,834	204,698
System Integration	31,576	33,110	145,324	94,486
Minor Subcontracts	20,712	21,718	95,324	61,978
TOTAL	441,625	463,071	2,032,500	1,321,487

TABLE 15 - NON-RECURRING COST BREAKDOWN FOR OXYGEN RECOVERY SYSTEM

NON-RECURRING COST ITEMS	SABATIER	BOSCH	SPE ELECTROLYSIS	KOH ELECTROLYSIS
System Engineering Design	661,902	696,837	1,046,187	976,317
Subcontractor General and Administrative	342,203	360,265	540,879	504,756
Subcontractor Fee	143,633	151,214	227,023	211,861
Program Management	49,643	52,263	78,464	73,224
System Engineering	208,499	219,504	329,549	307,540
Development Test	136,352	143,548	215,515	201,121
Qualification Test	100,609	105,919	159,020	148,400
Reliability Test	162,166	170,725	256,316	239,198
AGE	732,063	770,702	1,157,082	1,079,807
Tooling	153,561	161,666	242,715	226,506
Non-accountable Test Hardware	66,190	69,684	104,619	97,632
Specifications, Vendor Coordination and Procurement Expense	540,774	569,316	854,735	797,651
System Integration	331,613	349,115	524,140	489,135
Prime's Testing	324,332	341,450	512,632	478,395
Minor Subcontracts	15,224	16,027	24,062	22,455
TOTAL	3,968,764	4,178,235	6,272,938	5,853,998

certain trace contaminants in closed space cabin atmospheres can have very serious consequences, leading to loss of crew efficiency, incapacitation and even mission abort. Consideration of these possibilities has lead to the definition of lists of critical contaminants, development of monitoring procedures, and control of allowable materials to prevent excessive offgassing. This section deals with atmosphere monitoring systems.

In selecting an instrument for gas analysis, two major requirements must be considered. The first is the capability to sense a large number of gases which are most commonly found in the atmosphere and the second is the growth capability of the instrument to enable detection of additional compounds that may be specified at a later date, as well as to provide information to identify unexpected contaminants. Gas analysis equipment with such capabilities falls in three distinct categories: 1) Absorption Spectroscopy, 2) Mass Spectrometry, and 3) Gas Chromatography. Instruments utilizing absorption spectroscopy have the disadvantage of having some gases mask the absorption peaks of other gases. For example, CO cannot normally be detected by this technique since it would be masked by the presence of N_2O which displays an absorption band at essentially the same wave length.

The disadvantages cited for absorption spectroscopy are not shared by the other two major analysis methods: Mass Spectrometry and Gas Chromatography. Mass Spectrometers have long been used in the petroleum and chemical industries. Gas Chromatography also has found widespread use in process industries. Both techniques have been regarded as reliable means of analysis. Their use in spacecraft applications, previously in unmanned vehicles and currently as an experiment in the Skylab Program, has been mainly involved with miniaturizing the units to reduce their size and power requirements. Subsequently, the number of contaminants monitored by either a Mass Spectrometer or a Gas Chromatograph has been limited to few essential gases. For example, the Perkin-Elmer Company developed a four-gas Mass Spectrometer, sensing O_2, N_2, CO_2 and water vapor. Other units have been since developed with capabilities to sense six or seven gases. A new unit is now under development which is potentially capable of monitoring up to forty trace contaminants.

The new unit will be a scan-type Mass Spectrometer and will not be larger in size than the current 4- to 7-gas Mass Spectrometers. The comparative characteristics of the two systems considered, Mass Spectrometers and Gas Chromatograph, are given in MDC G4634 which also presents the physical differences, operational characteristics and status of each system. The CER's, configuration information and data required to perform cost analysis for a variety of atmosphere monitoring system applications is given in MDC G4634 entitled, "Cost Analysis of Atmosphere Analysis Systems."

Tables 16 and 17 present the recurring and non-recurring cost breakdowns estimated for flight-type atmosphere monitoring systems. The recurring costs shown in the tables are for two flight-type units each, one for actual flight and the other for back-up purposes. Recurring costs would naturally increase proportionally with the increased number of flight systems required. The procedure used for the molecular sieve system in Section 4.3.1.1 was followed to develop the data in Tables 16 and 17.

The state of development of the types of Gas Chromatograph and Mass Spectrometers considered in this study is already more advanced than that of low- and high-fidelity prototypes of other life support systems. Consequently, low-fidelity prototypes, which have been considered for other life support systems, are not presented in this report. The cost of a high-fidelity prototype is estimated to be approximately 20 to 30% of the cost of flight-type systems.

TABLE 16 - RECURRING COST BREAKDOWN FOR
ATMOSPHERE MONITORING SYSTEMS

RECURRING COST ITEM	MASS SPECTROMETER	GAS CHROMATOGRAPH
Flight Hardware Production (2 units)	28,059	66,394
Subcontractor G&A	4,742	11,220
Subcontractor Fee	1,995	4,722
Program Management	700	1,655
Sustaining Engineering	1,008	2,385
Sustaining Tooling	8,690	2,056
Specifications, Vendor Coordination and Procurement Expense	7,966	18,850
System Integration	3,677	8,701
Minor Subcontracts	2,412	5,707
TOTAL	51,428	121,690

TABLE 17 - NON-RECURRING COST BREAKDOWN FOR ATMOSPHERE MONITORING SYSTEM

NON-RECURRING COST ITEM	MASS SPECTROMETER	GAS CHROMATOGRAPH
System Engineering Design	49,935	81,870
Subcontractor General and Administrative	25,816	42,326
Subcontractor Fee	10,836	17,766
Program Management	3,745	6,140
System Engineering	15,729	25,789
Development Test	10,281	16,865
Qualification Test	7,590	12,444
Reliability Test	12,234	20,058
AGE	55,228	90,548
Tooling	11,585	18,994
Non-accountable Test Hardware	4,994	8,187
Specifications, Vendor Coordination and Procurement Expense	40,797	66,888
System Integration	25,017	41,107
Prime's Testing	24,468	40,116
Minor Subcontracts	1,149	1,883
TOTAL	299,410	490,890

Section 5

CONCLUSIONS AND RECOMMENDATIONS

A new method has been developed to predict realistic cost estimates for prototype and projected flight-qualified hardware for manned earth orbital programs. The validity of the cost estimating relationships developed in the study was confirmed with prototype and flight equipment cost data obtained from current prototype and flight programs. The cost estimating relationships can be applied parametrically to obtain estimated costs of varying sizes of any of fourteen life support systems studied for carbon dioxide removal, water recovery, oxygen recovery and atmospheric monitoring. The system component costs are identified with respect to such performance-related variables as volume, weight, power and physical characteristics. The results are given in sufficient depth to provide program planners and designers with the necessary cost data for allocation of available resources in a cost effective manner.

Some of the more pertinent study conclusions include the following:

1. Cost of non-flight-qualified low- and high-fidelity prototypes average approximately 5% and 10%, respectively, of the cost of flight-qualified units.

2. The four major cost impact areas in a life support system flight hardware production program are: 1) engineering design; 2) ground support; 3) test hardware fabrication; and 4) prime contractor's management, integration and documentation.

3. Engineering changes, after the production of the first flight system, tend to significantly increase the cost of test hardware as well as the overall program costs, and should thus be minimized by an adequate advanced research and technology program.

4. More than 60% of design costs in a flight hardware production program are expended after the "supposed" completion of basic system design and the production of the first test system.

It is recommended that the development of the most promising system concepts which have been proven, in advanced technology programs, by working bench type models and low-fidelity prototypes, be continued to the level of high-fidelity prototypes. In this manner, flight-type hardware production may be initiated with the least number of engineering design changes which have been proven to significantly escalate production costs. The overall effect would be that of improving production hardware development schedule and reducing the total program cost, including the expense of hardware, system certification, and testing. In flight hardware programs it is also recommended that system design be "frozen" early in the program to minimize the cost escalations associated with engineering changes.

Further effort to evaluate other systems not considered in this study should provide program planners and system designers with a more complete tool to better understand and estimate the resource requirements for future earth-orbital programs. Systems recommended for future study include (1) hygiene and waste management; (2) atmosphere pressurization and control; (3) thermal control; (4) trace contaminants; (5) food management; and (6) data management and checkout.

REFERENCES

1. Advanced Spacecraft Subsystem Cost Analysis, Environmental Control System, Contract No. NAS9-9018, McDonnell Douglas Astronautics Company, Report No. MSC-01245, 2 January 1970.

2. Optimized Cost Performance Design Methodology, Contract No. NAS2-5022, McDonnell Douglas Astronautics Company, Report No. G975, 15 April 1969.

3. A Graphical Costing Procedure for Advanced Manned Spacecraft (MASCOT G), by H. C. Mandell, Manned Spacecraft Center, Report No. NASA TM X-58012, October 1967.

4. Manned Spacecraft Cost Estimating Relationships, by H. G. Campbell and D. J. Dreyfuss, the Rand Corporation, Report No. RM-5317-NASA, June 1967.

5. Development of Cost Estimating Techniques and Relationships for Unmanned Space Exploration Missions, by F. E. Hoffman, et al., Planning Research Corporation, Report No. PRC R-870, 28 October, 1966.

6. Life Sciences Payload Definition and Integration Study, Integration Phase Presentation, Contract No. NAS8-29150, Convair Aerospace Division of General Dynamics, 6 March 1973.