COST ANALYSIS OF LIFE SUPPORT SYSTEMS
SUMMARY REPORT

JUNE 1973

Distribution of this report is provided in the
interest of information exchange.
Responsibility for the contents resides in the
author or organization that prepared it.

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
COST ANALYSIS OF LIFE SUPPORT SYSTEMS
SUMMARY REPORT

JUNE 1973

By
M. M. YAKUT
Biotechnology and Power Department

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or organization that prepared it.

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
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:

<table>
<thead>
<tr>
<th>Title</th>
<th>Report Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMARY REPORT</td>
<td>MDC G4630</td>
</tr>
<tr>
<td>COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS</td>
<td>MDC G4631</td>
</tr>
<tr>
<td>COST ANALYSIS OF WATER RECOVERY SYSTEMS</td>
<td>MDC G4632</td>
</tr>
<tr>
<td>COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS</td>
<td>MDC G4633</td>
</tr>
<tr>
<td>COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS</td>
<td>MDC G4634</td>
</tr>
</tbody>
</table>
MASTER TABLE OF CONTENTS

Report No. MDC G4630: COST ANALYSIS OF LIFE SUPPORT SYSTEMS - SUMMARY REPORT

Section 1 INTRODUCTION AND SUMMARY
Section 2 STUDY APPROACH AND DEFINITIONS
Section 3 DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS
Section 4 COST ESTIMATING METHODS OF LIFE SUPPORT SYSTEMS
Section 5 CONCLUSIONS AND RECOMMENDATIONS
REFERENCES

Report No. MDC G4631: COST ANALYSIS OF CARBON DIOXIDE CONCENTRATORS

Section 1 INTRODUCTION AND SUMMARY
Section 2 COST ESTIMATING TECHNIQUES
Section 3 COST ESTIMATES FOR CARBON DIOXIDE CONCENTRATORS
   3.1 Molecular Sieves Carbon Dioxide Removal System
   3.2 Hydrogen Depolarized CO₂ Concentrator
   3.3 Regenerable Solid Desiccant
Section 4 CONCLUSIONS
REFERENCES

Report No. MDC G4632: COST ANALYSIS OF WATER RECOVERY SYSTEMS

Section 1 INTRODUCTION AND SUMMARY
Section 2 COST ESTIMATING TECHNIQUES
Section 3 COST ESTIMATES OF WATER RECOVERY SYSTEMS
   3.1 RITE Waste Management-Water System (WM-WS)
   3.2 Reverse Osmosis System
   3.3 Multifiltration Wash Water System
   3.4 Vapor Compression System
   3.5 Closed Air Evaporation System with Electrolytic Pretreatment
Section 4 CONCLUSIONS
REFERENCES
MASTER TABLE OF CONTENTS

Report No. MDC G4633: COST ANALYSIS OF OXYGEN RECOVERY SYSTEMS

Section 1 INTRODUCTION AND SUMMARY
Section 2 COST ESTIMATING TECHNIQUES
Section 3 COST ESTIMATES OF OXYGEN RECOVERY SYSTEMS
  3.1 Sabatier Carbon Dioxide Reduction System
  3.2 Bosch Carbon Dioxide Reduction System
  3.3 Solid Polymer Electrolyte (SPE) Electrolysis System
  3.4 Circulating KOH Electrolyte Water Electrolysis System

Section 4 CONCLUSIONS
REFERENCES

Report No. MDC G4634: COST ANALYSIS OF ATMOSPHERE MONITORING SYSTEMS

Section 1 INTRODUCTION AND SUMMARY
Section 2 COST ESTIMATING TECHNIQUES
Section 3 COST ESTIMATING OF ATMOSPHERIC MONITORING SYSTEMS
  3.1 Mass Spectrometer
  3.2 Gas Chromatograph

Section 4 CONCLUSIONS
REFERENCES
**TABLE OF CONTENTS**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOREWORD</td>
<td>ii</td>
</tr>
<tr>
<td>Section 1 INTRODUCTION AND SUMMARY</td>
<td>1</td>
</tr>
<tr>
<td>Section 2 STUDY APPROACH AND DEFINITIONS</td>
<td>5</td>
</tr>
<tr>
<td>Section 3 DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS</td>
<td>10</td>
</tr>
<tr>
<td>Section 4 COST ESTIMATING METHODS OF LIFE SUPPORT SYSTEMS</td>
<td>21</td>
</tr>
<tr>
<td>Section 5 CONCLUSIONS AND RECOMMENDATIONS</td>
<td>51</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>52</td>
</tr>
</tbody>
</table>
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 CO₂ 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

Note: Curves indicate non-recurring costs only.
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 hard-
ware 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>
<thead>
<tr>
<th>NON-RECURRING</th>
<th>%</th>
<th>RECURRING</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>16.68</td>
<td>Flight Hardware Production</td>
<td>54.56</td>
</tr>
<tr>
<td>Subcontractor General &amp; Administrative</td>
<td>8.62</td>
<td>Subcontractor G&amp;A</td>
<td>9.22</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>3.62</td>
<td>Subcontractor Fee</td>
<td>3.88</td>
</tr>
<tr>
<td>Program Management</td>
<td>1.24</td>
<td>Program Management</td>
<td>1.36</td>
</tr>
<tr>
<td>System Engineering</td>
<td>5.25</td>
<td>Sustaining Engineering</td>
<td>1.96</td>
</tr>
<tr>
<td>Development Test</td>
<td>3.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualification Test</td>
<td>2.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability Test</td>
<td>4.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGE</td>
<td>18.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooling</td>
<td>3.87</td>
<td>Sustaining Tooling</td>
<td>1.69</td>
</tr>
<tr>
<td>Non-accountable Test Hardware</td>
<td>1.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expenses</td>
<td>13.62</td>
<td>Specifications, Vendor Coordination and Procurement Expenses</td>
<td>15.49</td>
</tr>
<tr>
<td>System Integration</td>
<td>8.36</td>
<td>System Integration</td>
<td>7.15</td>
</tr>
<tr>
<td>Prime's Testing</td>
<td>8.17</td>
<td>Minor Subcontracts</td>
<td>4.69</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100 %</strong></td>
<td><strong>TOTAL</strong></td>
<td><strong>100 %</strong></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>TYPES OF HEAT EXCHANGERS</th>
<th>WEIGHT LB</th>
<th>FLOW RATE LB/HR</th>
<th>HEAT LOAD BTU/HR</th>
<th>NO. OF PORTS</th>
<th>FIRST UNIT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. REGENERATIVE</td>
<td>1.33</td>
<td>81</td>
<td>4,720</td>
<td>4</td>
<td>1,756</td>
</tr>
<tr>
<td>2. GROUND COOLING</td>
<td>2.19</td>
<td>425</td>
<td>17,300</td>
<td>6</td>
<td>4,822</td>
</tr>
<tr>
<td>3. CRYOGENIC</td>
<td>5.29</td>
<td>80</td>
<td>1,099</td>
<td>7</td>
<td>7,074</td>
</tr>
<tr>
<td>4. CABIN</td>
<td>12.38</td>
<td>40</td>
<td>680</td>
<td>6</td>
<td>7,659</td>
</tr>
<tr>
<td>5. SUIT</td>
<td>19.00</td>
<td>80</td>
<td>1,500</td>
<td>10</td>
<td>19,652</td>
</tr>
<tr>
<td>6. WATER BOILER</td>
<td>22.60</td>
<td>183</td>
<td>11,200</td>
<td>13</td>
<td>34,851</td>
</tr>
</tbody>
</table>

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:

\[ \text{Heat exchanger First Unit Cost } C = 116 \cdot W^{0.267} \cdot N_p^{1.905} \text{ dollars} \]

\( W \) = 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

<table>
<thead>
<tr>
<th>Types of Heat Exchangers</th>
<th>Actual First Unit Cost</th>
<th>Calculated First Unit Cost</th>
<th>Calculated Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Regenerative</td>
<td>1,756</td>
<td>1,765</td>
<td>0.5</td>
</tr>
<tr>
<td>2. Ground Cooling</td>
<td>4,822</td>
<td>4,362</td>
<td>-9.7</td>
</tr>
<tr>
<td>3. Cryogenic</td>
<td>7,074</td>
<td>7,543</td>
<td>6.5</td>
</tr>
<tr>
<td>4. Cabin</td>
<td>7,659</td>
<td>6,959</td>
<td>-9.18</td>
</tr>
<tr>
<td>5. Suit</td>
<td>19,652</td>
<td>20,671</td>
<td>5.18</td>
</tr>
<tr>
<td>6. Water Boiler</td>
<td>34,851</td>
<td>35,906</td>
<td>3.02</td>
</tr>
</tbody>
</table>

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, $W_{oe}$, 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:

$$C = 159W^{0.267}Q^{1.905}W_{oe}^{0.89} + 295W_{oe}$$ 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,

\[ \text{Heat Exchanger First Unit Cost} = 116F_{\text{INF}}W^{0.267}N^{1.905} \text{ dollars} \]

Where,

\[ F_{\text{INF}} = \text{inflation factor} = 1.197, \text{ for converting 1963 dollars into 1970 dollars} \]

\[ W = \text{weight of heat exchanger} = 4.26 \text{ lbs.}, \text{ and} \]

\[ N = \text{number of ports in the heat exchanger} = 4 \]

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

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

Actual Unit Cost = 2663 dollars

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 $C = 116F_{NP}W_{NP}^{0.267} \times 1.905$ dollars

\[ = 116 \times 1.197 \times (4.6)^{0.267} \times 1.905 \]

\[ = 2936 \text{ dollars} \]

Actual Unit Cost \hspace{1cm} = 2874 \text{ dollars} \]

Calculated Error \hspace{1cm} = \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,

Heat Exchanger First Unit Cost \( C = 116F_{\text{INF}}W^{0.267}N^{1.905} \) dollars

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

\[ = 6971 \text{ dollars} \]

Actual Unit Cost = 6442 dollars

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 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.

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

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 CO₂ 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)

<table>
<thead>
<tr>
<th>Life Support System</th>
<th>Low-Fidelity Prototype</th>
<th>High-Fidelity Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Sieves CO₂ Concentrator</td>
<td>434,803</td>
<td>886,999</td>
</tr>
<tr>
<td>Hydrogen-Depolarized CO₂ Concentrator</td>
<td>352,277</td>
<td>718,645</td>
</tr>
<tr>
<td>Solid Desiccant CO₂ Concentrator</td>
<td>342,072</td>
<td>697,828</td>
</tr>
<tr>
<td>RITE Waste-Water System</td>
<td>533,102</td>
<td>1,087,968</td>
</tr>
<tr>
<td>Reverse Osmosis Wash Water System</td>
<td>321,643</td>
<td>656,415</td>
</tr>
<tr>
<td>Multifiltration Wash Water System</td>
<td>243,106</td>
<td>496,135</td>
</tr>
<tr>
<td>Vapor Compression System</td>
<td>410,721</td>
<td>838,207</td>
</tr>
<tr>
<td>Air Evaporation/Electrolytic Pretreatment System</td>
<td>453,013</td>
<td>924,517</td>
</tr>
<tr>
<td>Sabatier CO₂ Reduction System</td>
<td>220,500</td>
<td>449,860</td>
</tr>
<tr>
<td>Bosch CO₂ Reduction System</td>
<td>232,100</td>
<td>472,414</td>
</tr>
<tr>
<td>SPE Electrolysis System</td>
<td>415,300</td>
<td>837,144</td>
</tr>
<tr>
<td>KOH Electrolysis System</td>
<td>385,800</td>
<td>731,899</td>
</tr>
</tbody>
</table>

**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 non-recurring 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 CO₂ 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 CO₂ concentrator systems: 1) Molecular Sieves CO₂ Removal System, 2) Hydrogen-Depolarized CO₂ Concentrator, and 3) Regenerable Solid Desiccant Concentrator. The CER's configuration information and other data required to perform cost analysis for a variety of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ and thus does not include a CO₂ accumulator. The Skylab CO₂ concentrator is regenerated by desorbing the carbon dioxide and moisture collected by the beds to space vacuum. A hydrogen-depolarized CO₂ 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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂ accumulator and delivered the collected CO₂ to the CO₂-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 CO₂ and delivering it to a CO₂ 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 CO₂ prior to its delivery to the accumulator.

A comparison between the three types of CO₂ 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 CO₂ concentrator as an example. The CO₂ 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 CO₂ 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 CO₂ 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>
<thead>
<tr>
<th>System Characteristics</th>
<th>Molecular Sieves CO₂ Concentrator</th>
<th>Hydrogen Depolarized CO₂ Concentrator</th>
<th>Regenerable Solid Desiccant CO₂ Concentrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew Size</td>
<td>6 men</td>
<td>6 men</td>
<td>6 men</td>
</tr>
<tr>
<td>CO₂ Produced, Average</td>
<td>2.2 lbs/man-day</td>
<td>2.2 lbs/man-day</td>
<td>2.2 lbs/man-day</td>
</tr>
<tr>
<td>CO₂ Partial Pressure, Nominal</td>
<td>3.0 mmHg</td>
<td>1.0 mmHg</td>
<td>1.5-3.8 mmHg</td>
</tr>
<tr>
<td>Heating Fluid</td>
<td>Coolanol 35</td>
<td>None</td>
<td>Coolanol 35</td>
</tr>
<tr>
<td>Heating Fluid Temperature</td>
<td>300-350°F</td>
<td>--</td>
<td>180-200°F</td>
</tr>
<tr>
<td>Coolant</td>
<td>Coolanol 35</td>
<td>Air</td>
<td>Coolanol 35</td>
</tr>
<tr>
<td>Cooling Fluid Temperature</td>
<td>50-65°F</td>
<td>65-75°F</td>
<td>60-80°F</td>
</tr>
<tr>
<td>CO₂-Accumulator Pressure</td>
<td>30-40 psia</td>
<td>30-40 psia</td>
<td>30-40 psia</td>
</tr>
<tr>
<td>System Operation</td>
<td>1. Silica gel dries air to -50°F dp</td>
<td>1. CO₂ electrochemically transferred from anode to cathode.</td>
<td>1. No air predrying req'd.</td>
</tr>
<tr>
<td></td>
<td>2. Cool molecular sieves absorb CO₂</td>
<td>2. H₂ added to produce power and water.</td>
<td>2. Chemical absorption enables system to operate at low CO₂ concentrations.</td>
</tr>
<tr>
<td></td>
<td>3. Beds thermally regenerated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Status/Availability</td>
<td>1. Prototypes developed and tested, incl. that in NASA 60 &amp; 90 Day Tests</td>
<td>1. TRW, Inc. &amp; Life Systems, Inc. developed units for 6 years.</td>
<td>1. GAT-O-SORB, a 2-man vacuum-desorbed system was developed by General Amer. Transportation Co.</td>
</tr>
<tr>
<td></td>
<td>2. Vacuum-desorbed unit will be flown on Skylab in 1973.</td>
<td>2. Life Systems, Inc. will deliver a 6-man system in 1973.</td>
<td>2. A steam-desorbed solid amine system was tested in NASA 90-Day Test.</td>
</tr>
<tr>
<td></td>
<td>3. Hamilton Standard is developing a back-up system under SSP Program.</td>
<td>3. A vacuum-desorbed unit is being developed for Shuttle application.</td>
<td>3. A vacuum-desorbed unit is being developed for Shuttle application.</td>
</tr>
<tr>
<td>Operational Problems</td>
<td>None anticipated.</td>
<td>Integrated manned test of system required to define operational problems</td>
<td>A development of a thermal desorbed unit, with a CO₂ accumulator, is required.</td>
</tr>
</tbody>
</table>
Table 6

CARBON DIOXIDE CONCENTRATORS
RECURRING COST ESTIMATING

<table>
<thead>
<tr>
<th>ASSEMBLY</th>
<th>COST ESTIMATING RELATIONSHIP (FABRICATION COST, DOLLARS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) ( \text{CO}_2 ) ACCUMULATOR</td>
<td>( C = 18.634 , V^{0.377} + 2959 , W_{\text{oca}} )</td>
</tr>
<tr>
<td>(2) COMPRESSOR/AIR BLOWER</td>
<td>( C = 38.2 , P^{0.942} + 2192 , W_{\text{occ}} )</td>
</tr>
<tr>
<td>(3) SOLID DESICCANT CANISTERS</td>
<td>( C = 15.865 , W_{\text{can}}^{0.267} , Q_{\text{c}}^{0.89} + 2959 , W_{\text{oed}} )</td>
</tr>
<tr>
<td>(4) SOLID DESICCANT CANISTERS WITH BUILT-IN</td>
<td>( C = 158.65 ) (100 ( W_{\text{can}}^{0.267} + W_{\text{hx}}^{0.267} , N_{\text{p}}^{0.905} )) ( Q_{\text{hx}}^{0.89} + 2959 , W_{\text{oedh}} )</td>
</tr>
<tr>
<td>PLATE-AND-FIN HEAT EXCHANGER</td>
<td></td>
</tr>
<tr>
<td>(5) HEAT EXCHANGER CONDENSER</td>
<td>( C = 159 , W_{\text{hx}}^{0.267} , N_{\text{p}}^{0.905} + 2959 , W_{\text{och}} )</td>
</tr>
<tr>
<td>(6) TIMER AND CONTROLS</td>
<td>( C = 4795 ) (( W_{\text{T}} + W_{\text{oct}} ))</td>
</tr>
<tr>
<td>(7) ELECTRO-CHEMICAL CELL MODULE</td>
<td>( C = 400 , W_{\text{M}} + 2192 , W_{\text{ocf}} + 2000 )</td>
</tr>
</tbody>
</table>

TOTAL HARDWARE COST

\[
C_T = \sum_{Q=1}^{N} F_A F_I (\sum_{I=1}^{M} C_I) Q^{1-B} \quad \text{Dollars}
\]

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 CO₂ CONCENTRATOR

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>FUNCTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>VOLUME OF ACCUMULATOR</td>
<td>9.1 FT³</td>
</tr>
<tr>
<td>W₀ca</td>
<td>WEIGHT OF COMPONENTS ASSOCIATED WITH V ACCUMULATOR</td>
<td>4.5 LBS</td>
</tr>
<tr>
<td>P</td>
<td>ELECTRICAL POWER INPUT TO COMPRESSOR</td>
<td>420 WATTS</td>
</tr>
<tr>
<td>W₀cc</td>
<td>WEIGHT OF COMPONENTS ASSOCIATED WITH COMPRESSOR</td>
<td>12.0 LBS</td>
</tr>
<tr>
<td>WᵋCAN</td>
<td>WEIGHT OF SILICA GEL/MOLECULAR SIEVE CANISTER</td>
<td>67.1 LBS</td>
</tr>
<tr>
<td>Qₖ</td>
<td>NUMBER OF CANISTERS USED</td>
<td>8</td>
</tr>
<tr>
<td>W₀cd</td>
<td>WEIGHT OF COMPONENTS ASSOCIATED W/CANISTERS</td>
<td>66.2 LBS</td>
</tr>
<tr>
<td>WᵋHX</td>
<td>WEIGHT OF HEAT EXCHANGER</td>
<td>16.0 LBS</td>
</tr>
<tr>
<td>NᵫP</td>
<td>NUMBER OF PORTS PER HEAT EXCHANGER</td>
<td>4</td>
</tr>
<tr>
<td>QᵫₗⱽX</td>
<td>NUMBER OF HEAT EXCHANGERS USED</td>
<td>3</td>
</tr>
<tr>
<td>Wᵋocht</td>
<td>WEIGHT OF COMPONENTS ASSOCIATED W/HEAT EXCHANGERS</td>
<td>11.4 LBS</td>
</tr>
<tr>
<td>P₁</td>
<td>ELECTRICAL POWER INPUT TO AIR BLOWER</td>
<td>330 WATTS</td>
</tr>
<tr>
<td>W₀cc₁</td>
<td>WEIGHT OF COMPONENTS ASSOCIATED W/AIR BLOWER</td>
<td>17.2 LBS</td>
</tr>
<tr>
<td>Wₜ</td>
<td>WEIGHT OF TIMER</td>
<td>8.0 LBS</td>
</tr>
<tr>
<td>W₀ct</td>
<td>WEIGHT OF COMPONENTS ASSOCIATED WITH TIMER</td>
<td>27.7 LBS</td>
</tr>
</tbody>
</table>
a. CO\textsubscript{2} Accumulator \quad \text{Equation 1, Table 6} = \$ 56,169 \\
b. CO\textsubscript{2} Compressor \quad \text{Equation 2, Table 6} = \$ 37,771 \\
c. Silica Gel/Molecular Sieves Canisters \quad \text{Equation 3, Table 6} = \$ 508,617 \\
d. Heat Exchangers \quad \text{Equation 5, Table 6} = \$ 46,212 \\
e. Air Blower \quad \text{Equation 2, Table 6} = \$ 46,870 \\
f. Timer and Controls \quad \text{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\textsubscript{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\textsubscript{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\textsubscript{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,

\[ N = \text{Number of component types in assembly} = 23 \]

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 = \( \$90,815 \); 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,

\[ \text{total Concentrator costs} = 908,447 + 5,447,047 = 6355,494 \text{ dollars} \]
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,

\[
\text{total cost for production of 2 concentrators} = 5,447,047 + 3,247,391 = 8,694,438
\]

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

<table>
<thead>
<tr>
<th>RECURRING COST ITEM</th>
<th>MOLECULAR SIEVES</th>
<th>HYDROGEN DEPOLARIZED</th>
<th>REGENERABLE SOLID DESICCANT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Hardware Production</td>
<td>1,771,627</td>
<td>1,106,289</td>
<td>995,152</td>
</tr>
<tr>
<td>Subcontractor G&amp;A</td>
<td>299,405</td>
<td>186,693</td>
<td>168,169</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>125,785</td>
<td>78,546</td>
<td>70,770</td>
</tr>
<tr>
<td>Program Management</td>
<td>44,291</td>
<td>27,657</td>
<td>24,806</td>
</tr>
<tr>
<td>Sustaining Engineering</td>
<td>63,778</td>
<td>39,827</td>
<td>35,750</td>
</tr>
<tr>
<td>Sustaining Tooling</td>
<td>54,921</td>
<td>34,295</td>
<td>30,825</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expense</td>
<td>503,142</td>
<td>314,186</td>
<td>282,531</td>
</tr>
<tr>
<td>System Integration</td>
<td>232,083</td>
<td>144,924</td>
<td>130,413</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>152,360</td>
<td>95,141</td>
<td>85,544</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3,247,391</strong></td>
<td><strong>2,027,827</strong></td>
<td><strong>1,823,960</strong></td>
</tr>
</tbody>
</table>
## Table 9 - Non-Recurring Cost Breakdown for Carbon Dioxide Concentrators

<table>
<thead>
<tr>
<th>Non-Recurring Cost Item</th>
<th>Molecular Sieves</th>
<th>Hydrogen Depolarized</th>
<th>Regenerable Solid Desiccant</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Engineering Design</td>
<td>908,447</td>
<td>836,577</td>
<td>801,642</td>
</tr>
<tr>
<td>Subcontractor General and Administrative</td>
<td>469,667</td>
<td>432,332</td>
<td>414,449</td>
</tr>
<tr>
<td>Subcontractor Fee.</td>
<td>197,133</td>
<td>181,559</td>
<td>173,956</td>
</tr>
<tr>
<td>Program Management</td>
<td>68,134</td>
<td>62,192</td>
<td>60,123</td>
</tr>
<tr>
<td>System Engineering</td>
<td>286,160</td>
<td>263,311</td>
<td>252,517</td>
</tr>
<tr>
<td>Development Test</td>
<td>187,140</td>
<td>172,531</td>
<td>165,138</td>
</tr>
<tr>
<td>Qualification Test</td>
<td>138,084</td>
<td>127,392</td>
<td>121,850</td>
</tr>
<tr>
<td>Reliability Test</td>
<td>222,566</td>
<td>205,132</td>
<td>196,402</td>
</tr>
<tr>
<td>AGE</td>
<td>1,004,742</td>
<td>925,351</td>
<td>886,616</td>
</tr>
<tr>
<td>Tooling</td>
<td>210,760</td>
<td>194,098</td>
<td>185,981</td>
</tr>
<tr>
<td>Non-accountable Test Hardware</td>
<td>90,845</td>
<td>83,758</td>
<td>80,164</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement</td>
<td>742,201</td>
<td>683,104</td>
<td>654,942</td>
</tr>
<tr>
<td>Expense</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Integration</td>
<td>455,131</td>
<td>419,292</td>
<td>401,623</td>
</tr>
<tr>
<td>Prime's Testing</td>
<td>445,139</td>
<td>409,762</td>
<td>392,805</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>20,894</td>
<td>19,059</td>
<td>18,438</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,447,047</strong></td>
<td><strong>5,015,450</strong></td>
<td><strong>4,806,646</strong></td>
</tr>
</tbody>
</table>
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.

4.3.3 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 CO₂ to carbon or methane and water, followed by the electrolysis of water to metabolic oxygen and hydrogen. Direct conversion of CO₂ 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 CO₂ reduction, 2) Bosch CO₂ reduction, 3) solid
### TABLE 10 - WATER RECOVERY SYSTEM

**RECURRING COST ESTIMATING RELATIONSHIPS**

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

**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

39
<table>
<thead>
<tr>
<th>RECURRING COST ITEM</th>
<th>RITE</th>
<th>REVERSE OSMOSIS</th>
<th>MULTI-FILTRATION</th>
<th>AIR EVAP/ELECTROLYTIC</th>
<th>VAPOR COMPRESSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Hardware</td>
<td>1,025,608</td>
<td>317,234</td>
<td>259,554</td>
<td>494,164</td>
<td>1,061,066</td>
</tr>
<tr>
<td>Subcontractor G&amp;A</td>
<td>173,318</td>
<td>53,609</td>
<td>43,862</td>
<td>83,508</td>
<td>179,308</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>72,935</td>
<td>22,560</td>
<td>18,458</td>
<td>35,142</td>
<td>75,457</td>
</tr>
<tr>
<td>Program Management</td>
<td>25,565</td>
<td>7,908</td>
<td>6,470</td>
<td>12,318</td>
<td>26,449</td>
</tr>
<tr>
<td>Sustaining Engineering</td>
<td>36,841</td>
<td>11,396</td>
<td>9,324</td>
<td>17,752</td>
<td>38,117</td>
</tr>
<tr>
<td>Sustaining Tooling</td>
<td>31,768</td>
<td>9,826</td>
<td>8,040</td>
<td>15,307</td>
<td>32,867</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expense</td>
<td>291,178</td>
<td>90,065</td>
<td>73,689</td>
<td>140,297</td>
<td>301,245</td>
</tr>
<tr>
<td>System Integration</td>
<td>134,404</td>
<td>41,573</td>
<td>34,014</td>
<td>64,759</td>
<td>139,051</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>88,161</td>
<td>27,269</td>
<td>22,311</td>
<td>42,478</td>
<td>91,210</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1,879,780</strong></td>
<td><strong>581,440</strong></td>
<td><strong>475,722</strong></td>
<td><strong>908,725</strong></td>
<td><strong>1,944,770</strong></td>
</tr>
<tr>
<td>NON-RECURRING COST ITEM</td>
<td>RITE</td>
<td>REVERSE OSMOSIS</td>
<td>MULTI-FILTRATION</td>
<td>AIR EVAP/ELECTROLYTIC</td>
<td>VAPOR COMPRESSION</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------</td>
<td>----------------</td>
<td>------------------</td>
<td>-----------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>System Engineering Design</td>
<td>1,465,407</td>
<td>976,317</td>
<td>731,772</td>
<td>1,360,602</td>
<td>1,046,187</td>
</tr>
<tr>
<td>Subcontractor General and Administrative</td>
<td>757,615</td>
<td>504,759</td>
<td>378,326</td>
<td>703,431</td>
<td>540,879</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>317,993</td>
<td>211,861</td>
<td>158,795</td>
<td>295,251</td>
<td>227,023</td>
</tr>
<tr>
<td>Program Management</td>
<td>109,906</td>
<td>73,224</td>
<td>54,883</td>
<td>102,045</td>
<td>78,464</td>
</tr>
<tr>
<td>System Engineering</td>
<td>461,603</td>
<td>307,540</td>
<td>230,508</td>
<td>428,590</td>
<td>329,549</td>
</tr>
<tr>
<td>Development Test</td>
<td>301,874</td>
<td>201,121</td>
<td>150,745</td>
<td>280,284</td>
<td>215,515</td>
</tr>
<tr>
<td>Qualification Test</td>
<td>222,742</td>
<td>148,400</td>
<td>111,229</td>
<td>206,812</td>
<td>159,020</td>
</tr>
<tr>
<td>Reliability Test</td>
<td>359,025</td>
<td>239,198</td>
<td>179,284</td>
<td>333,347</td>
<td>256,316</td>
</tr>
<tr>
<td>AGE</td>
<td>1,620,740</td>
<td>1,079,807</td>
<td>809,340</td>
<td>1,504,826</td>
<td>1,157,083</td>
</tr>
<tr>
<td>Tooling</td>
<td>339,974</td>
<td>226,506</td>
<td>169,771</td>
<td>315,660</td>
<td>242,715</td>
</tr>
<tr>
<td>Non-accountable Test Hardware</td>
<td>146,541</td>
<td>97,632</td>
<td>73,772</td>
<td>136,060</td>
<td>104,619</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expense</td>
<td>1,197,238</td>
<td>797,651</td>
<td>597,858</td>
<td>1,111,612</td>
<td>854,735</td>
</tr>
<tr>
<td>System Integration</td>
<td>734,169</td>
<td>489,135</td>
<td>366,618</td>
<td>681,662</td>
<td>524,140</td>
</tr>
<tr>
<td>Prime's Testing</td>
<td>718,049</td>
<td>478,395</td>
<td>358,568</td>
<td>666,695</td>
<td>512,632</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>33,704</td>
<td>22,455</td>
<td>16,831</td>
<td>31,294</td>
<td>24,062</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>8,786,580</strong></td>
<td><strong>5,854,001</strong></td>
<td><strong>4,388,290</strong></td>
<td><strong>8,158,171</strong></td>
<td><strong>6,272,939</strong></td>
</tr>
</tbody>
</table>
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 CO₂ reduction processes may be combined with one of the two water electrolysis methods to attain oxygen recovery from CO₂. 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 CO₂ 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>
<thead>
<tr>
<th>ASSEMBLY</th>
<th>COST ESTIMATING RELATIONSHIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. SABATIER CO₂ REDUCTION SUBSYSTEM</td>
<td>(FABRICATION COST, DOLLARS)</td>
</tr>
<tr>
<td>1. Reactor Assembly</td>
<td>$C = 159 W^{0.267} N^{1.905} + 3900 W_{oc}$</td>
</tr>
<tr>
<td>2. Blower</td>
<td>$C = 38.2 P^{0.942} + 2192 W_{oc}$</td>
</tr>
<tr>
<td>3. Condenser/Separator</td>
<td>$C = 159 W^{0.267} N^{1.905} + 2959 W_{oc}$</td>
</tr>
<tr>
<td>4. Accumulator</td>
<td>$C = 1918 V^{0.267} + 2959 W_{oc}$</td>
</tr>
<tr>
<td>5. Pump</td>
<td>$C = 91 P^{0.942} + 670 W_{oc}$</td>
</tr>
<tr>
<td>6. Controller</td>
<td>$C = 1795 W$</td>
</tr>
<tr>
<td>B. KODCH CO₂ REDUCTION SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>1. Reactor Assembly</td>
<td>$C = 159 W^{0.267} N^{1.905} Q^{0.89} + 3900 W_{oc}$</td>
</tr>
<tr>
<td>2. Compressor</td>
<td>$C = 38.2 P^{0.942}$</td>
</tr>
<tr>
<td>3. Condenser/Separator</td>
<td>$C = 159 W^{0.267} N^{1.905} + 2959 W_{oc}$</td>
</tr>
<tr>
<td>4. Accumulator</td>
<td>$C = 1918 V^{0.267} + 2959 W_{oc}$</td>
</tr>
<tr>
<td>5. Pump</td>
<td>$C = 91 P^{0.942} + 670 W_{oc}$</td>
</tr>
<tr>
<td>6. Controller</td>
<td>$C = 1795 W$</td>
</tr>
<tr>
<td>C. SPE ELECTROLYTE SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>1. Electrolysis Modules</td>
<td>$C = (6250 W_{oc} + 2192 W_{oc} + 2000) Q^{0.89}$</td>
</tr>
<tr>
<td>2. Pumps</td>
<td>$C = 91 P^{0.942} Q^{0.89} + 670 W_{oc}$</td>
</tr>
<tr>
<td>3. Deionizers</td>
<td>$C = 200 W_{oc} Q^{0.89} + 670 W_{oc}$</td>
</tr>
<tr>
<td>4. Power Conditioner/Coldplate</td>
<td>$C = (14.9 P^{0.942} W^{0.267} N^{1.905}) Q^{0.89}$</td>
</tr>
<tr>
<td>5. Condenser/Separator</td>
<td>$C = 159 W^{0.267} N^{1.905} Q^{0.89} + 2959 W_{oc}$</td>
</tr>
<tr>
<td>D. CIRCULATING KOH ELECTROLYTE SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>1. Electrolysis Modules</td>
<td>$C = (6250 W_{oc} + 2000) Q^{0.89} + 2192 W_{oc}$</td>
</tr>
<tr>
<td>2. Electrolysis Modules</td>
<td>$C = 38.2 P^{0.942} + 2192 W_{oc}$</td>
</tr>
<tr>
<td>3. Reservoir</td>
<td>$C = 1918 W^{0.267} + 2959 W_{oc}$</td>
</tr>
<tr>
<td>4. Pumps</td>
<td>$C = 91 P^{0.942} Q^{0.89} + 670 W_{oc}$</td>
</tr>
<tr>
<td>5. Heat Exchanger</td>
<td>$C = 159 W^{0.267} N^{1.905} + 2959 W_{oc}$</td>
</tr>
</tbody>
</table>

TOTAL HARDWARE COST $C_T = \sum_{i=1}^{M} F_A F_I (C_i I_i) Q^{(1-B)}$ 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

43
<table>
<thead>
<tr>
<th>RECURRING COST ITEM</th>
<th>SABATIER</th>
<th>BOSCH</th>
<th>SPE ELECTROLYSIS</th>
<th>KOH ELECTROLYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Hardware Production (2 Units)</td>
<td>240,951</td>
<td>252,651</td>
<td>1,108,932</td>
<td>721,004</td>
</tr>
<tr>
<td>Subcontractor G&amp;A</td>
<td>40,718</td>
<td>42,695</td>
<td>187,397</td>
<td>121,841</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>17,135</td>
<td>17,967</td>
<td>78,861</td>
<td>51,274</td>
</tr>
<tr>
<td>Program Management</td>
<td>6,006</td>
<td>6,298</td>
<td>27,642</td>
<td>17,972</td>
</tr>
<tr>
<td>Sustaining Engineering</td>
<td>8,656</td>
<td>9,076</td>
<td>39,837</td>
<td>25,901</td>
</tr>
<tr>
<td>Sustaining Tooling</td>
<td>7,463</td>
<td>7,826</td>
<td>34,349</td>
<td>22,333</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expense</td>
<td>68,408</td>
<td>71,730</td>
<td>314,834</td>
<td>204,698</td>
</tr>
<tr>
<td>System Integration</td>
<td>31,576</td>
<td>33,110</td>
<td>145,324</td>
<td>94,486</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>20,712</td>
<td>21,718</td>
<td>95,324</td>
<td>61,978</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>441,625</td>
<td>463,071</td>
<td>2,032,500</td>
<td>1,321,487</td>
</tr>
<tr>
<td>NON-RECURRING COST ITEMS</td>
<td>SABATIER</td>
<td>BOSCH</td>
<td>SPE ELECTROLYSIS</td>
<td>KOH ELECTROLYSIS</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------</td>
<td>-------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>System Engineering Design</td>
<td>661,902</td>
<td>696,837</td>
<td>1,046,187</td>
<td>976,317</td>
</tr>
<tr>
<td>Subcontractor General and Administrative</td>
<td>342,203</td>
<td>360,265</td>
<td>540,879</td>
<td>504,756</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>143,633</td>
<td>151,214</td>
<td>227,023</td>
<td>211,861</td>
</tr>
<tr>
<td>Program Management</td>
<td>49,643</td>
<td>52,263</td>
<td>78,464</td>
<td>73,224</td>
</tr>
<tr>
<td>System Engineering</td>
<td>208,499</td>
<td>219,504</td>
<td>329,549</td>
<td>307,540</td>
</tr>
<tr>
<td>Development Test</td>
<td>136,352</td>
<td>143,548</td>
<td>215,515</td>
<td>201,121</td>
</tr>
<tr>
<td>Qualification Test</td>
<td>100,609</td>
<td>105,919</td>
<td>159,020</td>
<td>146,400</td>
</tr>
<tr>
<td>Reliability Test</td>
<td>162,166</td>
<td>170,725</td>
<td>256,316</td>
<td>239,198</td>
</tr>
<tr>
<td>AGE</td>
<td>732,063</td>
<td>770,702</td>
<td>1,157,082</td>
<td>1,079,807</td>
</tr>
<tr>
<td>Tooling</td>
<td>153,561</td>
<td>161,666</td>
<td>242,715</td>
<td>226,506</td>
</tr>
<tr>
<td>Non-accountable Test Hardware</td>
<td>66,190</td>
<td>69,684</td>
<td>104,619</td>
<td>97,632</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and</td>
<td>540,774</td>
<td>569,316</td>
<td>854,735</td>
<td>797,651</td>
</tr>
<tr>
<td>Procurement Expense</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Integration</td>
<td>331,613</td>
<td>349,115</td>
<td>524,140</td>
<td>489,135</td>
</tr>
<tr>
<td>Prime's Testing</td>
<td>324,332</td>
<td>341,450</td>
<td>512,632</td>
<td>478,395</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>15,224</td>
<td>16,027</td>
<td>24,062</td>
<td>22,455</td>
</tr>
<tr>
<td>TOTAL</td>
<td>3,968,764</td>
<td>4,178,235</td>
<td>6,272,938</td>
<td>5,853,998</td>
</tr>
</tbody>
</table>
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 N₂O which displays an absorption band at essentially the same wavelength.

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 O₂, N₂, CO₂ 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>
<thead>
<tr>
<th>RECURRING COST ITEM</th>
<th>MASS SPECTROMETER</th>
<th>GAS CHROMATOGRAPH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Hardware Production (2 units)</td>
<td>28,059</td>
<td>66,394</td>
</tr>
<tr>
<td>Subcontractor G&amp;A</td>
<td>4,742</td>
<td>11,220</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>1,995</td>
<td>4,722</td>
</tr>
<tr>
<td>Program Management</td>
<td>700</td>
<td>1,655</td>
</tr>
<tr>
<td>Sustaining Engineering</td>
<td>1,008</td>
<td>2,385</td>
</tr>
<tr>
<td>Sustaining Tooling</td>
<td>8,690</td>
<td>2,056</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expense</td>
<td>7,966</td>
<td>18,850</td>
</tr>
<tr>
<td>System Integration</td>
<td>3,677</td>
<td>8,701</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>2,412</td>
<td>5,707</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>51,428</strong></td>
<td><strong>121,690</strong></td>
</tr>
<tr>
<td>NON-RECURRING COST ITEM</td>
<td>MASS SPECTROMETER</td>
<td>GAS CHROMATOGRAPH</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>System Engineering Design</td>
<td>49,935</td>
<td>81,870</td>
</tr>
<tr>
<td>Subcontractor General and Administrative</td>
<td>25,816</td>
<td>42,326</td>
</tr>
<tr>
<td>Subcontractor Fee</td>
<td>10,836</td>
<td>17,766</td>
</tr>
<tr>
<td>Program Management</td>
<td>3,745</td>
<td>6,140</td>
</tr>
<tr>
<td>System Engineering</td>
<td>15,729</td>
<td>25,789</td>
</tr>
<tr>
<td>Development Test</td>
<td>10,281</td>
<td>16,865</td>
</tr>
<tr>
<td>Qualification Test</td>
<td>7,590</td>
<td>12,444</td>
</tr>
<tr>
<td>Reliability Test</td>
<td>12,234</td>
<td>20,058</td>
</tr>
<tr>
<td>AGE</td>
<td>55,228</td>
<td>90,548</td>
</tr>
<tr>
<td>Tooling</td>
<td>11,585</td>
<td>18,994</td>
</tr>
<tr>
<td>Non-accountable Test Hardware</td>
<td>1,994</td>
<td>8,187</td>
</tr>
<tr>
<td>Specifications, Vendor Coordination and Procurement Expense</td>
<td>40,797</td>
<td>66,888</td>
</tr>
<tr>
<td>System Integration</td>
<td>25,017</td>
<td>41,107</td>
</tr>
<tr>
<td>Prime's Testing</td>
<td>24,468</td>
<td>40,116</td>
</tr>
<tr>
<td>Minor Subcontracts</td>
<td>1,149</td>
<td>1,883</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>299,410</strong></td>
<td><strong>490,890</strong></td>
</tr>
</tbody>
</table>
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


