MDC G5713

COST ANALYSIS OF LIFE SCIENCES EXPERIMENTS AND SUBSYSTEMS

FEBRUARY 1975

Prepared under Contract No. NAS8-28377
by Biotechnology and Space Sciences Department
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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By
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FOREWORD

The work described in this report was performed for the NASA-Marshall Space Flight Center during the second phase of Contract No. NAS8-28377. Work performed during the first phase of the contract was reported in the following McDonnell Douglas Astronautics Company reports; 1) MDC G4630, Cost Analysis of Life Support Systems, Summary Report; 2) MDG G4631, Cost Analysis of Carbon Dioxide Concentrators, 3) MDC G4632, Cost Analysis of Water Recovery Systems, 4) MDC G4633, Cost Analysis of Oxygen Recovery Systems, and 5) MDC G4634, Cost Analysis of Atmosphere Monitoring Systems. The MSFC technical monitor was Mr. James L. Moses.

The author wishes to acknowledge the contributions that were made to this report by these MDAC personnel: D. L. Magargee, R. E. Shook, T. C. Secord, and R. V. Greco.

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

CONTENTS (Continued)

CONTENTS (Continued)

FIGURES

RECEDING PAGE BLANK NOT FILMED

FIGURES (Continued)

TABLES

TABLES (Continued)

TABLES (Continued)

Section 1
INTRODUCTION

Analyses conducted in this phase of the study to estimate the cost of selected life sciences experiments and subsystems will aid in program planning and allocation of resources and provide a better understanding of program cost elements that points out the areas and methods by which cost may be effectively reduced. Two areas identified in the first phase of the study as major causes of cost increase are the proliferation of documentation and engineering changes. A major recommendation of the first phase of the study was to "freeze" the engineering design early in the production program to eliminate the effects of engineering changes on subsystem cost. Such recommendations, if followed, would contribute to reducing the costs of the Spacelab life sciences experiments and subsystems evaluated.

This phase of the study has been devoted to establishing cost estimates for experiments and subsystems flown in the Spacelab. Ten experiments were cost analyzed. Estimated cost varied from $650,000 for the hardware development of the SPE water electrolysis experiment to $78,500,000 for the development and operation of a representative life sciences laboratory program. The cost of subsystems for thermal, atmospheric and trace contaminants control of the Spacelab internal atmosphere was also estimated. Subsystem cost estimates we: based on the utilization of existing components developed in previous space programs whenever necessary. Cost analyses were performed for each of the following:

- Spacelab Experiments
- Vapor Compression Water Recovery
- RITE Waste-Water System
- H_2-Depolarized CO_2 Concentrator
- SPE Water Electrolysis
- Boiling and Condensation at Low Gravity

- Biological Specimen Holding Facility
- Medical Emphasis Life Sciences Experiment
- Research Centrifuge
- Cloud Physics Experiment
- Space Processing Furnace Experiment

- Spacelab Subsystems
  - Cabin Thermal Control
  - Atmospheric Supply and Pressurization
  - Trace Contaminants Control

This report includes the following major chapters:

Section 1: Introduction
Section 2: Summary
Section 3: Study Approach
Section 4: Spacelab Experiments
Section 5: Spacelab Life Support Subsystems
Section 6: Conclusions and Recommendations

The cost analyses derived in this study are intended to present overall cost trends and identify areas of cost impact in the development of life sciences experiments and subsystems. They should not be construed to represent actual cost requirements or price quotations. It should also be recognized that the cost estimates were made for specific designs and based on particular assumptions. Changes in designs or assumptions could significantly change the cost estimates given.

Section 2

SUMMARY

Ten Spacelab experiments, a life support experiment facility and three Spacelab life support subsystems were investigated in this study. A summary of the work performed in this phase of the study is presented in Table 2-1. Included in the Table are the study items, their purpose and description and the levels to which cost analyses have been performed. A paragraph reference, indicating where the corresponding detailed analyses are presented in the report, is also presented.

2.1 SPACELAB EXPERIMENTS

The ten life sciences and space application experiments cost analyzed in this phase of the study were selected from those planned for the shuttle launched Spacelab. Most of the experiments were found to be in the conceptual stage with little or no equipment definition. A major part of the effort was thus devoted to the preliminary design of experiment hardware, defining their characteristics and evaluating their performance. Engineering and cost analyses were performed at the component level. Equipment cost was added from the component level up to the assembly, subsystem and system level. Cost estimates for experiments which were considered to constitute a part of larger payloads were limited to completion of hardware production phase. Examples of such experiments include the research centrifuge to be flown integrated with a medical or biological research mission. For independently operated experiments, such as the medical emphasis life sciences Spacelab, cost estimates were carried to the total project level which includes hardware and operations costs. The experiment cost summary is presented in Table 2-2, divided in significant cost items. The Table shows at a glance a comparison between different experiment costs, separated into non-recurring, recurring production and recurring operation phase costs. The costs of the five life support and

Table 2-1 - Life Support System Cost Study Summary

STUDY ITEM	PURPOSE/APPROACH	DESCRIPTION	COST ANALYSIS ITEMS	DETAILED ANALYSES
• Life Support Experiment Facility (LSEF)	• Used as test facility for life support and fluid flow experiments.	• Is comprised of: o console o instrumentation and measuring devices o heating and cooling loops, vacuum and gas flow subsystems o power control and distribution o data management and electronics	• Design, development and production of hardware • Operations phase cost not included • Integrated with cost of five life support and fluid flow experiments	• Paragraph 4.1 integrated with life support and fluid flow experiments cost.
• Life Support and Fluid Flow Experiments o vapor compression water recovery experiment o RITE waste-water system experiment o H_2-depolarized CO_2 concentrator experiment o SPE water electrolysis experiment o boiling and condensation experiment	• All five experiments use LSEF as test facility providing instrumentation, measurement devices, fluid subsystems, power and data management.	• Includes experiment or subsystem hardware and integrated instrumentations only.	• Design, development and production of subsystem or experiment hardware • Operations phase cost not included • Integrated with cost of LSEF	• Paragraph 4.1 integrated with LSEF cost.
• Biological Specimen Holding Facility Experiment	• Facility holds two unrestrained and six restrained, instrumented rhesus monkeys. • Facility is a part of biological laboratory which includes vertebrates, invertebrates, cells, tissue cultures and plants.	• Is comprised of: o environmental control system o waste management o food and water assemblies o holding cages o refrigerator/freezer o console/work station o power supply and distribution o data management and electronics o cameras and support equipment	• Design, development and production of facility hardware • Operations phase cost not included. • Instrumented primates considered GFE	• Paragraph 4.2
• Medical Emphasis Life Sciences Laboratory Experiment	• General purpose research facility for medicine, biology, life support and man-system integration experiments.	• Is comprised of: o crew station and storage unit o cells & tissue holding unit o visual & microscopic examination unit o primate & small vertebrate unit o biomedical activities unit o fluid sample analysis unit o specimen preservation unit o power control & distribution o data management	• Total program costs estimated. Design & development, production and operations phases included.	• Paragraph 4.3
• Research Centrifuge Experiments	• Centrifuge to provide a 1 g control or variable g research environment for small vertebrates and small research organisms to be flown with a biology or medical emphasis Spacelab.	• Continuous rotating centrifuge, with a load-retrieving turntable and necessary instrumentation and controls. • Specimen cages and medical instrumentation are to be supplied by experimenter.	• Design, development and production of centrifuge. • Operations phase cost not included	• Paragraph 4.4
• Cloud Physics Experiment	• Zero-g atmospheric microphysics/cloud physics laboratory facility to obtain data for weather modification and control.	• Is comprised of: o six experiment chambers o thermal control & fluid supply system o particle generators o particle detectors & analyzers o console o optical system o data management	• Total program costs estimated. Design & development, production & operations phased included.	• Paragraph 4.5
• Space Processing Furnace Experiment	• This is one of materials sciences and manufacturing in space configurations. • For study of molten zone crystal growth and other heat/melt/cool experiments.	• Is comprised of: o enclosure/furnace and accessories o vacuum system o core equipment o data management and electronic o power conditioning & distribution o consoles o support equipment	• Design, development and production of space processing furnace experiment. • Operations phase cost not included.	• Paragraph 4.6
• Spacelab Thermal Control Subsystem	• Provides temperature control for crew and equipment in Spacelab cabin.	• Is comprised of fans, heat exchangers, condensers, water separators, valves, accumulators, filters and sensors in following loops: o cabin gas loop o avionics gas loop o water loop	• Design, development and production of cabin thermal control equipment. • Operations phase cost not included.	• Paragraph 5.1
• Atmospheric Supply & Pressurization Subsystem	• Replenishes Spacelab cabin atmosphere with oxygen and nitrogen. • Maintains atmospheric total pressure and oxygen partial pressure in manned compartments.	• Is comprised of: o high pressure gas tank assemblies o regulator assemblies o controller assemblies o pressure relief assembly o repressurization assembly	• Design, development and production of subsystem hardware. • Operations phase cost not included.	• Paragraph 5.2
• Trace Contaminants Control Subsystem	• Subsystem designed to control CO, H_2, CH_4, hydrocarbons in Spacelab for missions of 30 days or longer.	• Is comprised of activated charcoal and particulate filters, catalytic oxidizer and pre- and post-sorbents.	• Design, development and production of trace contaminants control subsystem. • Operations phase cost not included.	• Paragraph 5.3

Table 2-1
LIFE SUPPORT SYSTEM COST SUMMARY

Table 2-2 EXPERIMENT COST COMPARISON SUMMARY

Table 2-2 - Experiment Cost Comparison Summary*

COST ITEM*	LIFE SUPPORT TEST FACILITY AND FIVE RELATED EXPERIMENTS		PRIMATE HOLDING FACILITY EXPERIMENT		MEDICAL EMPHASIS LSSL			RESEARCH CENTRIFUGE EXPERIMENT		SPACE PROCESSING FURNACE EXPERIMENT		CLOUD PHYSICS EXPERIMENT		
	NR	RP	NR	RP	NR	RP	RO	NR	RP	NR	RP	NR	RP	RO
Experiment Costs														
• EC/LS or Fluid Subsystems	1,984,000	187,000	2,120,000	1,010,000	0	0	0	-	-	-	-	2,501,000	864,000	969,000
• Power Control & Distribution	114,000	61,000	228,000	122,000	280,000	160,000	1,100,000	-	-	134,000	118,000	-	-	-
• Data Management & Interface Electronics	258,000	139,000	175,000	210,000	940,000	370,000	390,000	-	-	451,000	235,000	2,662,000	791,000	352,000
• Experiment Equipment	1,694,000	2,237,000	410,000	919,000	9,007,000	6,424,000	1,942,000	686,000	86,000	630,000	700,000	8,977,000	3,241,000	1,440,000
• Console(s)	363,000	195,000	Included in exp. experiment		1,320,000	380,000	0	-	-	935,000	450,000	1,711,000	792,000	53,000
• Experiment Support	-	-	423,000	174,000	1,555,000	313,000	0	-	-	420,000	85,000	793,000	273,000	-
Project Management	933,000	317,000	666,000	312,000	815,000	367,000	548,000	146,000	12,000	610,000	520,000	550,000	273,000	449,000
System Engineering & Integration	1,287,000	214,000	920,000	210,000	4,031,000	259,000	380,000	202,000	8,000	830,000	377,000	1,368,000	589,000	634,000
System Test	773,000	0	552,000	0	3,840,000	0	0	121,000	0	491,000	0	558,000	0	0
Ground Support Equipment	1,745,000	0	1,247,000	0	2,243,000	100,000	1,217,000	274,000	0	1,124,000	0	1,233,000	54,000	595,000
Facilities					0	600,000	5,400,000					0	0	0
Logistics					3,778,000	14,000	1,008,000					962,000	5,000	161,000
Flight Operations					0	0	7,200,000					0	0	5,276,000
Refurbishment Operations					0	0	16,800,000					-	-	-
Principal Investigator Operations					600,000	400,000	5,000,000					0	0	6,803,000
Total	9,151,000	3,350,000	6,741,000	2,957,000	28,409,000	9,387,000	40,985,000	1,429,000	106,000	5,625,000	2,485,000	21,315,000	6,882,000	16,732,000
Program/Project Total	12,501,000		9,698,000		78,691,000			1,535,000		8,110,000		44,929,000		

NOTE: Cost items breakdown differs from text as cost estimates are regrouped to agree with current NASA WBS.

NR: Non-Recurring
RP: Recurring - Production
RO: Recurring - Operations

fluid flow experiments are presented in Table 2-2 integrated with the cost of the life support test facility, which was designed to support such experiments.

2.2 SPACELAB LIFE SUPPORT SUBSYSTEMS

The study also included the cost analysis of the following Spacelab life support subsystems:

2.2.1 Cabin Thermal Control Subsystem (TCS)

The Spacelab cabin TCS controls the temperature and humidity of the manned module and rejects the excess heat generated by the avionics and experiments inside the pressurized compartment. The cabin TCS is comprised of three loops: 1) cabin gas loop; 2) avionics gas loop; and 3) water loop. The Spacelab is provided with 8.5 KW heat rejection capability, which includes both the module and the pallets.

The available cabin cooling includes:

- Module atmosphere — 1.0 KW at 18^{o} to $26^{o}C$
- Avionics bay atmosphere — 3.13 KW at 24^{o} to $50^{o}C$

Cost analysis of the Spacelab cabin TCS, including both recurring and non-recurring costs, was completed. Included also were the major subsystem assemblies, assembly characteristics, performance, power requirements and design status. Of the six assemblies involved in the TCS, four assemblies utilize already available components requiring modifications and/or requalification. The use of previously developed equipment results in significant reductions in the design and development phase expenditures estimated at approximately 1.5 million dollars.

2.2.2 Atmospheric Supply and Pressurization Subsystem (AS&PS)

The Spacelab AS&PS controls the cabin pressure and stores and supplies the spacecraft with atmospheric oxygen and nitrogen for a 7-day mission extendable to 30 days by the addition of extra consumables. The subsystem includes two identical 3000 psi storage tanks containing 47 lbs of oxygen and 34 lbs of nitrogen. A Skylab type two-gas controller is utilized in the subsystem which also includes an existing design O_2 and N_2 regulator assemblies. Cost analysis of Spacelab AS&PS was completed. Recurring and non-recurring costs for the subsystem's five major assemblies were calculated. Assembly characteristics, performance, power requirements and design status also were defined. The subsystem cost was estimated at approximately $5.0 million.

2.2.3 Trace Contaminants Control Subsystem

A cost analysis study of an extended duration trace contaminants control subsystem, suitable for installation in Spacelab was performed. The subsystem comprises activated charcoal and particulate filters, a catalytic oxidizer with pre- and post-sorbent beds, a regenerative heat exchanger and a temperature controller. The components are installed so as to draw an air flow of 5 CFM from downstream of the cabin fan, process it and return it to the main air flow upstream of the fan. The system cost was estimated at $2.74 million of which $2.41 million was for the design and development phase and $0.33 million for flight hardware.

2.2.4 Other Life Support Subsystems Applicable to Spacelab

Cost estimates of life support subsystems for Spacelab other than the three listed above may be readily obtained from the results of the first phase of the study reported in McDonnell Douglas Reports MDC G-4630, MDC G-4631, MDC G-4632, MDC G-4633 and MDC G-4634, all dated June 1973. Cost estimating relationships are presented in a parametric form which can be easily applied to the Spacelab vehicle and mission sizes. The subsystems investigated in the first study phase are mostly of the regenerative life support type and are categorized in four functional areas:

A. Carbon Dioxide Removal -- including molecular sieves, hydrogen depolarized concentrators and regenerable solid desiccants.

B. Water Recovery -- including RITE waste management-water system, reverse osmosis, multifiltration, vapor compression and air evaporation/electrolytic pretreatment subsystems.

C. Oxygen Recovery -- including Bosch and Sabatier CO_2 reduction and solid polymer and circulating KOH electrolysis subsystems.

D. Atmosphere Analysis -- including mass spectrometers and gas chromatographs.

The effects of inflation and economic escalation are reflected in the study results based on a factor of 6% for inflation from 1972 to 1973 and 7% for inflation from 1973 to 1974.

Section 3
STUDY APPROACH

This phase of the study was directed at the definition of representative life sciences experiments and subsystems for use in the Spacelab and the development of cost models and estimates for each of the experiments and subsystems involved. Included also was the identification of major areas of cost impact in the development and/or operation of related equipment.

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

A. Experiment and Subsystem Definition -- including preliminary design and analysis of equipment which had not been adequately defined.
B. Cost Estimating Methods -- including the updating of techniques developed in the first phase of the study and the collection of cost data of specialized equipment required for the Spacelab experiments.
C. The development of cost models and estimates for: a) life support experiment facility; b) ten Spacelab experiments, mostly dealing with life sciences; and c) three Spacelab life support subsystems.

3.1 EXPERIMENT AND SUBSYSTEM DEFINITION

Most of the equipment hardware investigated in this phase of the study were found to be in early state of development, if not just in the conceptual stage. Consequently, preliminary designs and analyses had to be performed to arrive at an adequate definition of subsystems and components to aid in the development of cost estimates at the component level.

The basic approach used for the preliminary design and analyses is as follows:

A. The requirements and design criteria for each of the experiments and subsystems investigated were developed.
B. System schematics indicating fluid flows, temperatures and pressures were defined.
C. Preliminary heat and mass analyses were performed to define basic physical characteristics and performance of pertinent components in each subsystem and experiment hardware.

3.2 COST ESTIMATING METHODS

Cost estimates and models were made utilizing cost estimating relationships (CER's) developed at the component level and then summed up to establish total system or subsystem cost. CER's were developed to estimate the recurring cost of each pertinent component in the subsystems or experiment hardware investigated. CER's developed for non-recurring cost were based on estimating system design cost, utilizing the number of component types used, and then estimating the cost of other non-recurring functions as percentages of design cost. All cost estimates and relationships are based primarily on actual cost data from space hardware, mainly the Gemini and Skylab programs. A discussion of the development of recurring and non-recurring cost estimating relationships is given in the following paragraphs.

3.2.1 Development of Recurring Cost Estimating Relationships

Recurring cost estimating relationships were developed from detailed component cost data collected from the Gemini and Skylab programs. Components analyzed include fans, blowers, absorber canisters, heat exchangers, condensers, tanks, regulators, pumps, filters and other pertinent life support and fluid flow components. Smaller components such as valves and temperature and pressure gages are included in the CER's on a weight basis after comparing and relating them to similar components in comparable assemblies. Component cost data are collected as functions of different performance and physical characteristics of each component. For example, heat exchanger costs may be tabulated as a function of unit weight, volume, flow rate, heat load, number of ports, operating temperatures and the likes. The steps used in developing recurring CER's for individual components are as follows:

A. The components are analyzed to determine which of the physical or performance characteristics tabulated as function of cost might prove useful as predictive variables.

B. 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.

In establishing the cost of a system, CER's are developed or identified for each of the pertinent components in the system and then added up in a building block fashion to obtain the total system cost estimating relationships.

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.

An example of the development of a recurring CER for a component is best illustrated by a CER developed for a heat exchanger and summarized in "Cost Analysis of Life Support Systems, Summary Report," McDonnell Douglas Report No. MDC G-4630. Cost data for six Gemini ECS heat exchangers were used to develop the CER. The cost and technical characteristics of the six heat exchangers are given in Table 3-1. 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 relationship. The resulting data were then normalized, at 10 pounds per heat exchanger, to negate the effect of weight differences. The normalized cost data were found to have a linear relation with cost, when plotted on logarithmic paper. A good

Table 3-1

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

*1963 dollars

fit for the combined relations, showing heat exchanger weight varying as a function of its weight and number of ports, is given as follows:

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

W = heat exchanger weight, lbs

N_p = number of ports per heat exchanger, and

F_{INF} = inflation factor for converting 1963 dollars into current dollars.

The calculated heat exchanger cost, utilizing the CER, was found to have an average difference of 6.3% from the actual costs of Table 3-1. The heat exchanger CER was also 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. An inflation factor of 1.64 was used to account for the inflation of 1963 dollars into 1974 dollars. Accordingly, the resulting heat exchanger CER was calculated as follows:

$$C = 190\ W^{0.267} N_p^{1.905} Q^{0.89} + 3551\ W_{OC} \text{ dollars}$$

Other individual component CER's were calculated in the same manner used in developing the heat exchanger CER. 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 Skylab heat exchangers were used for a validity check of the heat exchanger CER.

An inflation factor of 1.197 was used to account for converting 1963 dollars into 1970 dollars. The results are shown in Table 3-2, which shows an average error of approximately 6%.

A summary of cost estimating relationships (CER's) used to estimate the recurring cost of components and/or assemblies of Spacelab experiments and subsystems hardware is presented in Table 3-3. Component and assembly costs are given in Table 3-3 as a function of significant characteristic or performance parameters, such as weight, volume, frequency and power requirements.

Table 3-2

APPLICATION OF HEAT EXCHANGER CER TO SKYLAB HARDWARE

Heat Exchanger	Weight Lbs	No. of Ports	Calculated Cost, $	Actual Cost, 1970 $	Error %
Skylab regenerative heat exchanger	4.26	4	2868	2663	7.6
Skylab primary oxygen heat exchanger	4.6	4	2936	2874	2.1
Skylab ATM and ground cooling heat exchanger	6.46	6	6971	6442	8.2

Table 3-3

COST ESTIMATING RELATIONSHIPS FOR MAJOR COMPONENTS/ASSEMBLIES (in 1974 Dollars)

Component/Assembly	Cost Estimating Relationship, Dollars	Notes
Air Blower, Fan	$C = 45.8\, P_B^{0.942} Q^{0.89} + 2630\, W_{OC}$	P_B = blower's electrical power input, watts Q = number of units used W_{OC} = weight of associated components, lbs.
CO_2 and Odor Canister	$C = 19{,}038\, W_{CAN}^{0.267} Q^{0.89} + 3551\, W_{OC}$	W_{CAN} = canister weight
Condensing Heat Exchanger	$C = 190\, W_H^{0.267} N_P^{1.905} + 3551\, W_{OC}$	W_H = condenser weight, lbs. N_P = number of ports per condenser
Condensate/Water Tank	$C = 2302\, V_T^{0.267} + 3551\, W_{OC}$	V_T = volume of condensate tank, ft^3
Temperature and Humidity Controller	$C = 5754\, (W_C + W_O)$	W_C = controller weight, lbs.
Oxygen/Nitrogen Tank	$C = 2236\, V_{CT}^{0.377} + 3551\, W_{OC}$	V_{GT} = gaseous tank volume, ft^3
High Pressure Gas Regulator Assembly	$C = 4080\, W_R\, Q^{0.8}$	W_R = Regulator assembly weight
Oxygen/Nitrogen Controller Assembly	$C = 3276\, W_V + 3600\, N + 6000\, S$	W_V = weight of valves and pressure and flow sensors, lbs. N = number of controllers S = number of oxygen partial pressure sensors
Cabin Pressure Relief Assembly	$C = 7134\, W_{CR}$	W_{CR} = cabin pressure relief valve weight, lbs.
Airlock Pressurization Assembly	$C = 2220\, W_A$	W_A = airlock pressurization assembly weight, lbs.
Coolant Pump and Accumulator	$C = 109\, P_P^{0.942}\, Q^{0.89} + 2302 V^{0.267} + 3551\, W_{OC}$	P_P = pump's electrical power input, watts
Temperature Controller Assembly	$C = 2304\, W_1 + 5700\, W_2 + 3551\, W_{OC}$	W_1 = weight of temperature control valve, lbs. W_2 = weight of temperature controller, lbs.
Avionics Cooling Assembly	$C = 191\, W_H^{0.267}\, N_P^{1.905} + 109\, P_B^{0.942}\, Q^{0.89} + 3551\, W_{OC}$	
Particulate Filter	$C = 2500\, W_F$	W_F = particulate filter weight, lbs.
Catalytic Oxidizer	$C = 190\, (W_{CB}^{0.267} + 4 W_{HT}^{0.265})$	W_{CB} = catalytic oxidizer weight, lbs. W_{HT} = heater weight, lbs.
Catalytic Oxidizer Controller	$C = 5754\, W_{CN}$	W_{CN} = controller weight, lbs.
Research Centrifuge Structure/Turntable	$C = 22900\, A^{0.485}$	A = centrifuge swept area, ft^2
Drive Motor and Gear Train	$C = 99.7\, P_M^{0.942}\, F^{0.1037} + 685\, W_G$	P_M = power input to motor, watts F = operating frequency, Hz W_G = gear train weight, lbs.
Restrained Primate Waste Management Assembly	$C = 500 Q^{0.89} + 3551\, W_{OC}$	

The integration costs of components and assemblies into systems or subsystems are obtained by the use of integration factors derived in a preceding study and given by the following equations:

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

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

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

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

where

C_T = total hardware cost

n = quantity of hardware purchased

C_F = first unit cost

b = learning curve slope

The learning curve slope, b, is derived as a composite of the 90% learning experienced on labor and the 95% experienced for materials. The resulting learning curve is a 93% curve (b = 0.1047). C_F, the first unit cost, can be for one assembly or for the total system.

3.2.2 Development of Non-Recurring Cost Estimating Relationships

Non-recurring CER's have been developed for engineering design accomplished during the design and development phase. Other non-recurring cost estimates are based on the cost breakdown ratios presented in Table 3-4, which are average values obtained from analyzing the environmental control system (ECS) cost data of the Gemini spacecraft and are assumed representative of cost-effective ECS development. The engineering design CER was based on the analysis of a number of cost influencing parameters which indicated that

Table 3-4

REPRESENTATIVE LIFE SUPPORT SYSTEM
NON-RECURRING EXPENDITURE BREAKDOWN

Cost Item	Cost Breakdown, %	
	Including GSE	Excluding GSE
Engineering design	17.31	21.41
Program management	1.29	1.60
General and administrative	8.94	11 06
System engineering	5.45	6.74
System integration	8.67	10.72
Development, qualification and reliability tests	10.45	12.92
System test	8.48	10.49
Non-accountable test hardware	1.73	2.14
Specifications, vendor coordi-nations and procurement expense	14.13	17.47
Minor subcontracts	0.39	0.48
Tooling	4.02	4.97
Ground Support Equipment (GSE)	19.14	-
Total	100.0	100.0

design cost is mainly a function of the number of component types (N) in each system and is given by the following relation:

Engineering design cost $C_D = 41{,}922\ N + 123{,}530$ dollars

The system's non-recurring cost is then obtained from applying the values listed in Table 3-4 to the engineering design cost. The non-recurring CER's developed were applied to the latest data obtained from the Skylab program and were found to agree favorably with actual program costs.

3.3 QUALIFICATION OF COMMERCIAL HARDWARE

Appreciable cost reductions may be achieved if already manufactured components are adapted for use in flight experiments. Commercial equipment, available from industrial and aircraft sources, would have to undergo qualification and reliability testing to assure its flight worthiness prior to its use in spacecraft. The equipment should also be examined to determine if it requires modification, and the degree of modification, if any, to bring it to the status of flight hardware. The types and quantities of materials of construction of every component should also be estimated and used to assess its outgassing characteristics. Highly outgassing components are unacceptable for use in spacecraft. The cost of modifying components, either for outgassing or for other physical or performance characteristics are weighed against the cost of designing a new component in order to assure a cost effective product.

The following methodology was used to assess the cost of the management, test and qualification of commercial equipment for use in flight experiments:

A. Determine typical breakdown of design and development phase expenditures for representative flight hardware components, as explained in Section 3.2 above.

B. Delete the cost of such design and development phase functions as engineering design and development test which are not required in an already manufactured product.

C. Estimate the cost of component modifications to bring it up to flight status.

D. Utilizing the design and development phase cost breakdown as a guide, determine the relative costs of the functions that have to be performed on the components.

E. Estimate the engineering design cost of flight-type equipment identical to that under consideration.

F. Calculate the design and development phase cost breakdown of the flight-qualified commercial equipment.

Table 3-5 presents the breakdown of design and development phase cost of representative flight-qualified commercial hardware based on the values presented in Table 5-2, which were then modified to account for prior design and development costs. The data given in Table 3-5 indicates that the design and

Table 3-5

FLIGHT-QUALIFIED COMMERCIAL EQUIPMENT NON-RECURRING COST AS PERCENTAGE OF FLIGHT HARDWARE

Function	Percentage of Flight Hardware Non-Recurring Cost
Program Management	0.65
System Engineering	1.36
Qualification Test	2.64
Reliability Test	4.24
Specifications, Vendor Coordination and Procurement Expenses	7.07
System Integration	8.67
Integrated System Testing	8.48
Minor Subcontracts	0.39
Ground Support Equipment	19.14
Total	52.64%

development phase cost to manage, test and flight-qualify commercial life support equipment is approximately 53% of flight-type hardware cost. This value assumes that the commercial equipment requires no significant modifications to bring it up to flight hardware status. Additional modification costs should be added to the design and development phase cost.

Recurring costs of commercial equipment include only the cost of procuring the hardware, which should be considerably lower than the recurring cost of comparable flight hardware.

3.4 DEFINITIONS

The following are definitions of major cost-related terms used in this phase of the study. Most of the terms were used in the first phase of the study. However, in detailing the cost of some experiments, some groupings of original terms were used to agree more closely with the terminology currently used by NASA in defining Work Breakdown Structure (WBS) elements.

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

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

C. 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.

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

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

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

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

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

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

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

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

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

M. System Test or Integrated System Testing -- includes costs associated with planning, coordination, design, setup, conduct and evaluation of system-level development and verification test. Included also are costs of materials, hardware and software required uniquely for system-level tests.

N. Non-Recurring Costs -- costs incurred primarily during the design, development, test and evaluation phase of the program. Specifically, costs included relate to design, development, GSE, program management, system engineering, test operations and hardware, specification, coordination and integration of system into the spacecraft.

O. Recurring Costs (Production) -- includes the costs associated with producing flight hardware through acceptance of the hardware by the Government including all costs associated with: 1) the fabrication, assembly, and checkout of flight hardware; 2) ground test and factory checkout of flight hardware; 3) initial spares; and 4) maintenance of tooling and special test equipment.

P. Recurring Costs (Operations) -- includes the costs associated with launch operations, mission operations, maintenance and refurbishment operations and operations to produce and replace spares and maintain GSE.

Section 4
SELECTED SPACELAB EXPERIMENTS

Ten representative Spacelab experiments were selected for analysis in this phase of the study. Eight of the ten experiments pertain to life support or life sciences technologies. The remaining two are general space application type experiments, which are currently under active study and consideration by NASA for early Spacelab flights, and which were selected to provide a basis of comparison with the life sciences experiments investigated. The experiments chosen are the following:

A. vapor compression water recovery system experiment
B. RITE waste-water system experiment
C. H_2-depolarized CO_2 concentrator experiment
D. SPE water electrolysis experiment
E. boiling and condensation at low gravity experiment
F. biological specimen holding facility experiment
G. medical emphasis life sciences experiment
H. research centrifuge experiment
I. cloud physics experiment
J. space processing furnace experiment

Summaries of the analyses of each of the experiments investigated are presented in the following paragraphs. Included in each paragraph are system descriptions, results of preliminary designs and engineering and cost analyses.

4.1 LIFE SUPPORT AND FLUID FLOW EXPERIMENTS

4.1.1 Purpose

The life support and fluid flow experiments will be tested in the life support experiment facility (LSEF). The LSEF is defined as a general purpose facility capable of testing and/or verification of flight operation of advanced life support subsystems or components. This facility will constitute a part of a manned Spacelab, preferably on a life sciences mission. The LSEF will be designed to accommodate a wide spectrum of life support experiments, especially those dealing with equipment handling two- or three-phase flows. The facility will have a lifetime of ten years to support technical advances and changing requirements in the life support technology. For the purpose of this study, the LSEF is designed to accommodate the following diversified life support subsystem and fluid flow experiments: 1) vapor compression water recovery subsystem; 2) RITE waste management and water recovery subsystem; 3) hydrogen-depolarized CO_2 concentrator; 4) solid polymer electrolyte (SPE) water electrolysis subsystem; and 5) boiling and condensation at low gravity. The LSEF will have the following features:

A. instrumentation and measuring devices to support all types of life support equipment
B. fixtures to accommodate hardware with varying geometrical shapes
C. maximum utilization of Spacelab resources, including heat rejection and data management
D. automated control with manual override
E. part- to full-time operation of one astronaut on a Spacelab mission
F. ground refurbishment between flights.

4.1.2 Guidelines and Constraints

4.1.2.1 The life support and fluid flow experiment program includes the definition, design, development and operations of the LSEF and experiments and the interface requirement to interconnect and maintain the payload and the Spacelab. The program also includes ground operations involving experiment mission preparation, astronaut,training, data evaluation and experiment refurbishment and checkout.

4.1.2.2 The LSEF is a general purpose facility for the performance of testing and in-flight verification of advanced life support and fluid flow experiment hardware. The LSEF will be installed within the Spacelab and be transported to and from orbit by the shuttle orbiter. The LSEF will provide the life support community with flexible, low-cost laboratory facility capable of accommodating a broad spectrum of tests and experiments, with rapid user access and minimum interference with other payloads, the Spacelab or shuttle orbiter activities.

4.1.2.3 The baseline plan will include two flight units of the LSEF, including the associated experiments mission preparation conduct, data evaluation and documentation in accordance with an assumed 1980 shuttle flight incorporating a life sciences Spacelab payload.

4.1.3 Mission Description

The LSEF will be flown as a part of a manned life sciences Spacelab mission. In a nominal mission, the shuttle is initially launched to a 100-mile, 28.5-degree inclination parking orbit where shuttle and payload systems are verified. The system is then boosted to the 200-mile altitude where the research will be carried out. Following the six or 30 days of planned research activities, the orbiter will deboost and land at the launch complex. The LSEF design is predicated on the mission crew sizes indicated in Table 4-1.

The payload has a requirement for a 10,000 class cleanliness contamination limit. Radiation, EMI, and acoustic levels should be equivalent to earth labs during the periods of research activity. Orbiter attitude maneuvers must be planned to occur at times that will not negate experiment results.

Table 4-1

SHUTTLE AND SPACELAB CREW SIZE

	Total Personnel in Orbit	Spacelab Crew	Personnel Available to LSEF
Nominal	6	2-3	1
Maximum	7	3	1-2
Minimal	4	1-2	1 or partial

4.1.4 Life Support Experiment Facility Definition

The LSEF is a self-contained unit with the external configuration shown in Figure 4-1 and occupies one side of a 2.7m experiment segment of Spacelab. The LSEF will be dependent on the Spacelab for the following support functions:

A. heat rejection
B. refrigeration
C. power
D. data management and communications
E. crewmember operation

The LSEF will provide the following test equipment, instrumentation and supplies:

A. flowmeters, gas and liquid
B. temperature, humidity and pressure sensors
C. mass measurement devices
D. timers
E. photographic equipment
F. gas analysis equipment, including gas chromatograph, mass spectrometer, IR analyzer, and sensors for CO_2, O_2 and H_2
G. water analysis equipment, including conductivity and pH meters and COD and TOC analyzers
H. radiation detectors
I. gas and liquid consumables, including O_2, CO_2, H_2, N_2 and water
J. electrical measurement devices
K. vacuum measuring devices
L. calorimetric devices
M. portable fans, pumps and blowers
N. accelerometer

In addition, the LSEF will provide space for experiment specific equipment which may be used only in a limited number of experiments. The LSEF also includes fixtures for mounting test specimens, as well as additional workbench space and storage compartments.

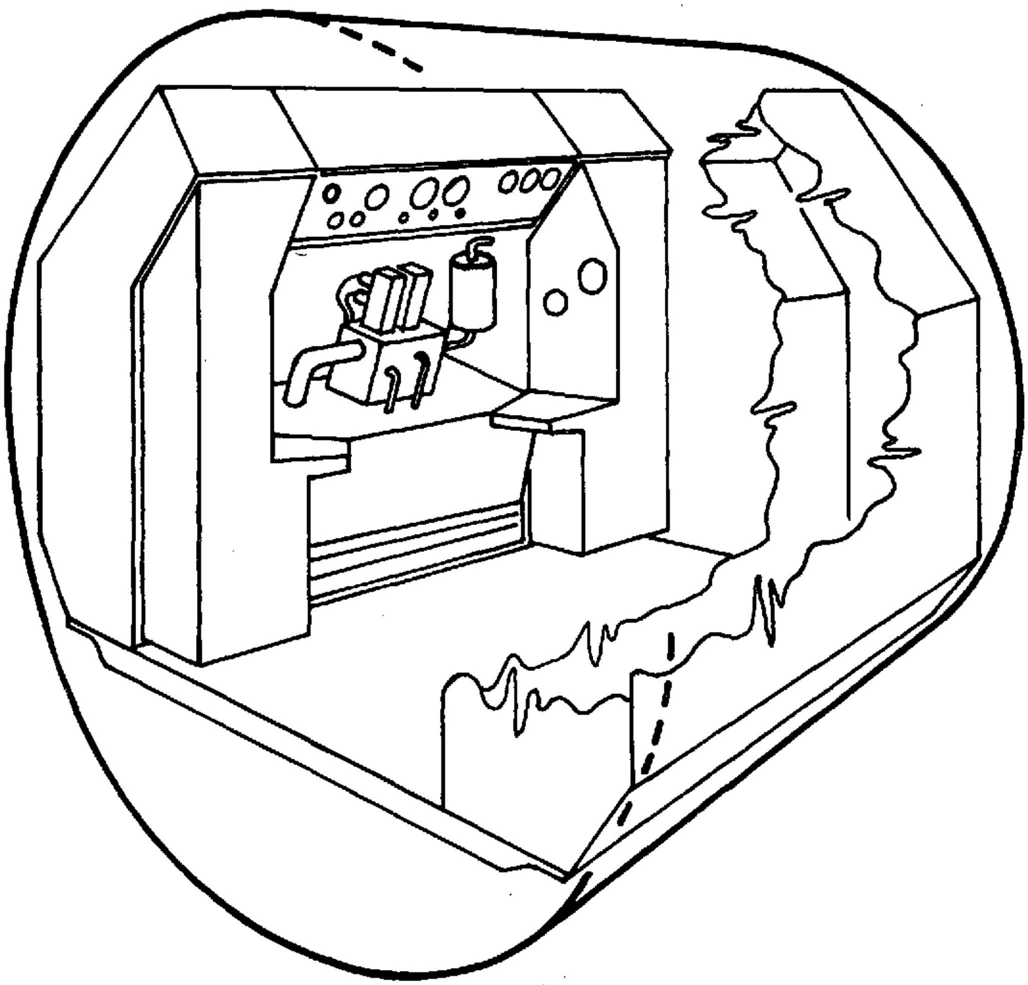

Figure 4-1. Life Support Experiment Facility External Configuration

4.1.5 Life Support and Fluid Flow Experiments Description

The LSEF is initially designed to accommodate the following advanced life support and fluid flow experiments:

A. vapor compression water recovery

B. RITE waste management and water recovery

C. hydrogen-depolarized CO_2 concentrator

D. SPE water electrolysis

E. boiling and condensation at low gravity.

One or more of the above baseline subsystems will be flown on each Spacelab mission. The LSEF will be refurbished prior to each mission to fly only the major equipment units and supplies necessary for that particular flight. A description of each of the above experiments is given in the following paragraphs.

4.1.5.1 Vapor Compression Water Recovery

4.1.5.1.1 Subsystem Description

A detailed description of this subsystem is presented in "Cost Analysis of Water Recovery Systems," McDonnell Douglas Report MDC G-4632, June 1973, which covers work achieved in the first phase of this study. A schematic of the vapor compression recovery (VCR) subsystem is presented in Figure 4-2. The subsystem is used to reclaim water from urine, flush water and condensate. Waste water distillation takes place in a motor-driven, centrifugal vapor compression still. The still includes an evaporator, a vapor compressor and a condenser. The evaporator is on the outer cylindrical surface of the evaporator. The distillate from the still is filtered, sterilized and stored in the water tanks. A bacteria/charcoal filter, a sterilizer and an ion exchange filter are used.

4.1.5.1.2 Experiment Test Setup

The vapor compression subsystem will be instrumented and installed in the LSEF. A power source, nitrogen, air and transport fluid supply lines will then be connected to the unit. Waste water will also be provided to the waste and flush water tanks.

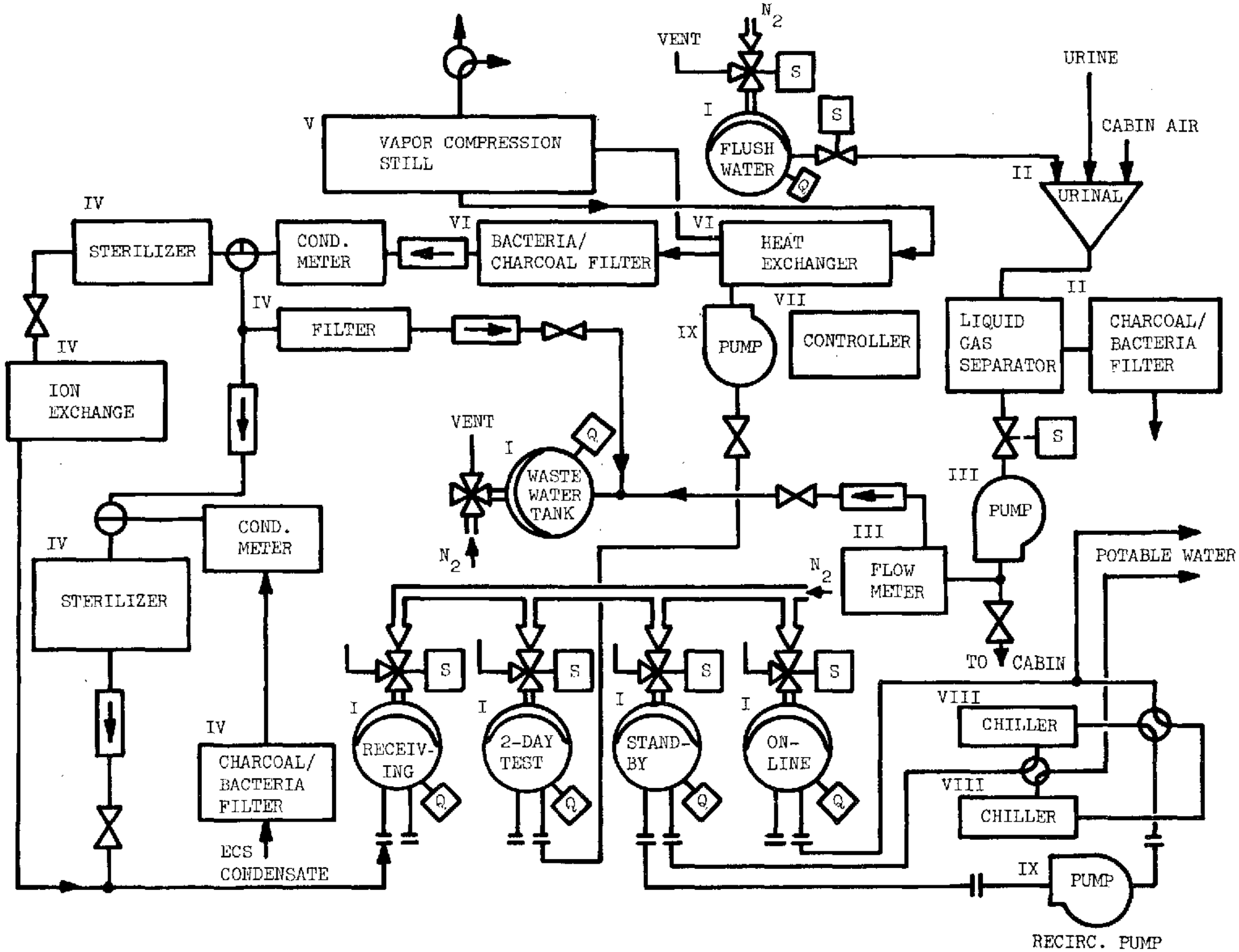

Figure 4-2. Vapor Compression Subsystem

4.1.5.1.3 Measurement Program

Monitoring and recording of experiment parameters will be accomplished automatically. Pertinent experiment parameters will be displayed to the experimenter to allow him to follow or alter the progress of the experiment. Experiment runs will be for continuous 8-hour durations to permit full processing of a complete waste water batch per run. Parameters to be measured include the following:

A. temperature - 9 locations
B. flow rate - 2 liquid flow rates
C. pressure - 4 absolute and 1 differential pressure readings
D. power - total wattage to pumps (3), compression still and liquid separator
E. quantity - 6 water quantity measurements, one per tank
F. water analysis - conductivity, pH and TOC measurements of product water
G. gas analysis - gas chromatographic analysis of evaporator vapor samples

4.1.5.1.4 Experiment Design Requirements

The vapor compression subsystem design requirements are based on the subsystem operating characteristics given as follows:

urine and urine flush (input)	= 5.44 lbs/man-day
commode flush (input)	= 3.30 lbs/man-day
wash water brine (input)	= 6.55 lbs/man-day
non-metabolic condensate (input)	= 6.61 lbs/man-day
potable water (output)	= 6.53 lbs/man-day
flush water (output)	= 5.30 lbs/man-day
wash water distillate (output)	= 10.06 lbs/man-day

The VCR subsystem used in the experiment will have a nominal one-man capacity and will have the following requirements:

A. Electrical power input of 155 watts/man will be required for the operation of three pumps, compression still and water/liquid separator.

B. ECS notrogen supply lines will be connected to the liquid and gas tanks for tank pressurization.

C. Pressurization tanks vent to cabin atmosphere.

D. Liquid-gas separator discharge of gases to cabin.

E. Input waste water and output potable water lines to cabin.

F. Sampling lines.

4.1.5.2 RITE Waste Management and Water Recovery

4.1.5.2.1 Subsystem Description

A detailed description of this subsystem is presented in "Cost Analysis of Water Recovery Systems," McDonnell Douglas Report No. MDC G-4632, June 1973, which covers work achieved in the first phase of this study. Figure 4-3 is a schematic of the RITE subsystem. The subsystem has the capability of recovering water from all spacecraft waste materials, including feces, and can also shred and process trash. Additionally, it automatically pumps the brine-sludge residue from the water recovery unit to an incinerator that reduces the solid wastes to an innocuous ash. All of the process heat used in the subsystem is produced from low penalty isotopic sources. Trash, feces, wash water, and urine are collected in the evaporator. The solids are separated by a filter and moved by a solids pump to the incinerator. The incinerator vacuum dries and thermally decomposes the solids at a temperature of 1200°F.

The effluent in the evaporator is driven centrifugally by an impeller to provide a gravitational field that permit nucleate boiling. The evaporator is operated at 105°F and 1.1 psia. This low boiling temperature is maintained to minimize volatization of impurities by thermal decomposition.

The steam from the evaporator passes through pyrolysis units which are connected in parallel and nested around the RITE heat source. The high-temperature RITE heat source superheats the incoming steam to 1200°F in the catalyst zone. The steam passes from the pyrolysis units to the condenser where it is condensed between 75 and 85°F at 0.5 to 0.7 psia. Non-condensable gases in the steam flow are vented to space vacuum from the condenser. The purified water is pumped out of the condenser periodically and stored in the water tanks.

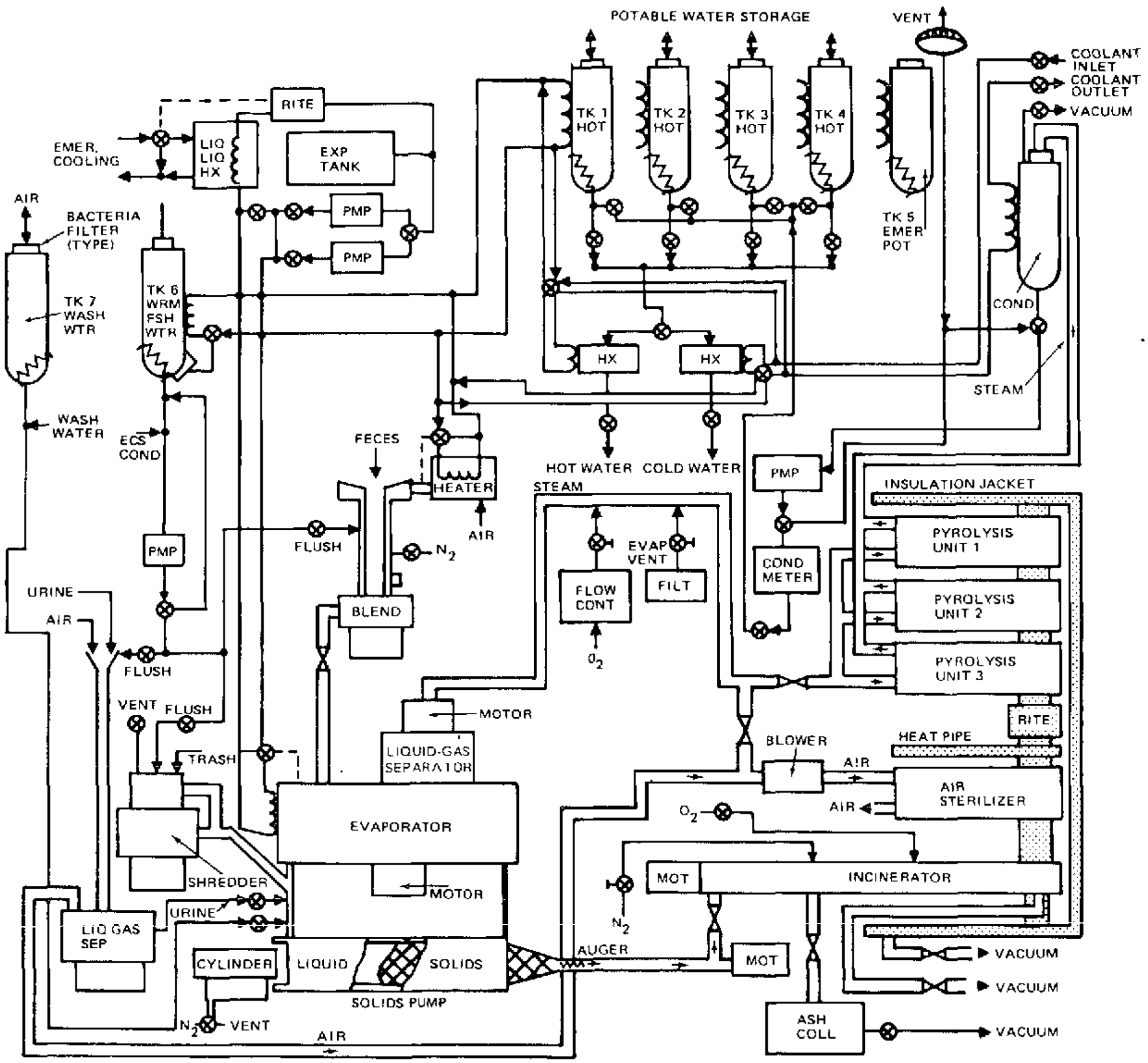

Figure 4-3. RITE Waste Management - Water Recovery System

4.1.5.2.2 Experiment Test Setup

The RITE subsystem will be instrumented and installed in the LSEF for testing. A power source, oxygen, nitrogen, air and transport fluid supply lines, as well as vacuum lines will be connected to the unit. Solid and liquid wastes will also be provided for processing by the RITE subsystem.

4.1.5.2.3 Measurement Program

The measurement program of the RITE subsystem will automatically monitor and record experiment parameters and display the pertinent parameter needed by the experimenter to allow him to follow or alter the progress of the experiment. Each experiment run will have a total operating time of 8 hours to permit full processing of a complete batch of solid and liquid wastes. Parameters to be measured include the following:

A. temperature - 40 temperature measurements
B. flow rate - two liquid and one gas flow rates
C. pressure - 4 absolute and 1 differential pressure readings
D. humidity - two locations
E. quantities - 7 water quantity measurements, one per tank
F. water analysis - conductivity, pH and TOC measurement of product water
G. gas analysis - gas chromatographic measurements from 7 locations
H. power - total wattage to pumps (4), shredder, separator, auger, blower, incinerator and blender.

4.1.5.2.4 Experiment Design Requirements

The RITE subsystem design requirements are based on the subsystem operating characteristics given as follows:

A. urine input to urinal = 3.5 lbs/man-day
B. air flow to urinal during urination = 20 CFM
C. feces input = 0.3 lbs/man-day

D.	input respiration and perspiration	=	5 lbs/man-day
E.	wash water input	=	6 lbs/man-day
F.	trash input, solids	=	0.3 lbs/man-day
G.	amount of water in trash	=	0.6 lbs/man-day
H.	air flow to blender during defecation	=	40 CFM
H.	subsystem water output	=	13.5 lbs/man-day

The RITE subsystem used in the experiment will have a nominal one-man capacity and will have the following requirements:

A. coolant flow at 35 to 50°F = 0.25 GPM/man

B. 10^{-3} and 10^{-6} mm Hg vacuum sources to condenser, incinerator and insulation jacket

C. nitrogen supply line to storage tanks, commode, incinerator, and solids pump

D. oxygen supply line to pyrolysis chambers and incinerator

E. cabin vent lines for tanks and pumps

F. sterilizer air line to cabin

G. ECS condensate line to flush water delivery line

H. input waste water and output potable water lines

I. sampling lines

4.1.5.3 H_2-Depolarized CO_2 Concentrator (HDC)

4.1.5.3.1 Subsystem Description

A detailed description of the HDC subsystem is presented in "Cost Analysis of Carbon Dioxide Concentrators," McDonnell Douglas Report MDC G-4631, June 1973, which covers work achieved in the first phase of this study. A schematic diagram of the HDC subsystem is presented in Figure 4-4. The subsystem is comprised of a hydrogen-depolarized cell module, water accumulator, process air blower, air heater, cooling air blower and associated ducting, valving and instrumentation. Cabin air is supplied to the cathode side of the cells where it is depleted of CO_2 and returned to the cabin. Hydrogen is supplied to the anode side of the cells where it reacts with hydroxyl ions to produce water and electrical power.

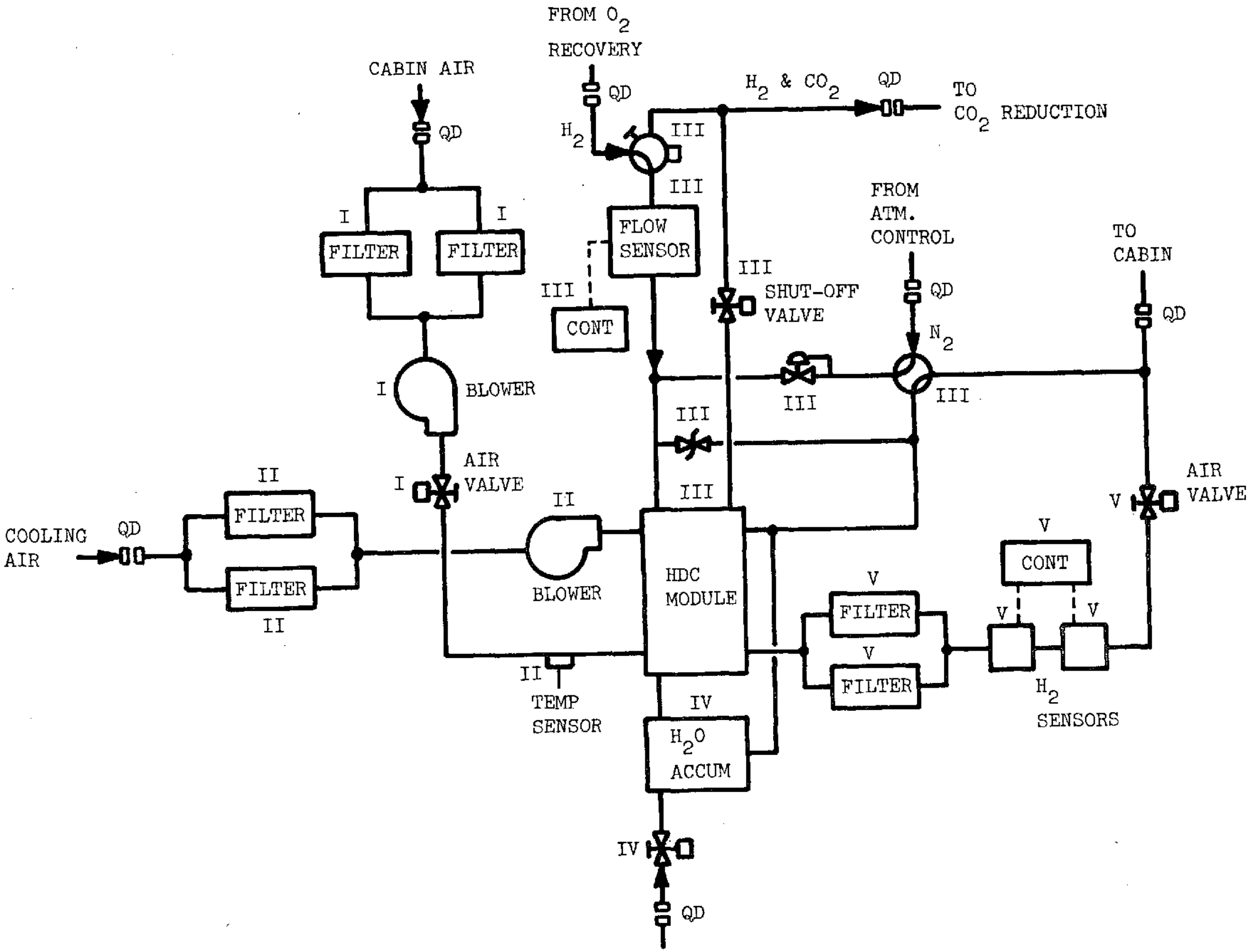

Figure 4-4. Hydrogen Depolarized CO_2 Concentrator

4.1.5.3.2 Experiment Test Setup

The HDC unit will be instrumented and installed in the LSEF for testing. An electrical power source, oxygen, nitrogen, hydrogen, air and water supply lines will then be connected to the HDC. Either cabin air or stored mixtures of CO_2 and will be supplied to the unit for processing as part of experiment operation. Product CO_2 will be stored in an accumulator.

4.1.5.3.3 Measurement Program

Experiment parameters will be monitored and recorded automatically throughout the experiment duration. Pertinent experiment parameters will be displayed to the experimenter to allow him to follow or alter the progress of the experiment at any time. The experiment will be run continuously for the entire mission duration. The HDC will be run at normal steady-state loading for 3 weeks, with the remaining week devoted to transient loading and stop and start condition runs. Parameters to be measured will include the following:

A. temperature - 5 locations
B. pressure - 2 locations, absolute pressure
C. humidity - 2 locations
D. gas analysis - gas chromatography and CO_2 analyzer for inlet and return cabin air and for product gases. Also, hydrogen sensors for for return cabin air and product gases.
E. flow rates - 3 gas flow rate measurements

4.1.5.3.4 Experiment Design Requirements

The HDC subsystem design requirements are based on the subsystem operating characteristics given as follows:

A. design CO_2 removal rate = 2.2 lbs/man-day
B. atmospheric flow rate, maximum = 10 CFM/man
C. CO_2 partial pressure, maximum = 3.0 mm Hg

D. coolant air flow rate, intermittent = 35 CFM/man

E. power requirement, AC = 50 watts/man

F. instrumentation power requirement, DC = 20 watts

The HDC used in the experiment will have a one-man nominal capacity and will need the following interface requirements:

A. cabin air supply duct

B. cooling air line

C. hydrogen supply line

D. nitrogen supply line

E. water supply line

F. CO_2 and hydrogen return line to CO_2 reduction subsystem

F. return purified air line to cabin

H. gas analysis lines.

4.1.5.4 SPE Water Electrolysis Subsystem

4.1.5.4.1 Subsystem Description

A detailed description of the SPE electrolysis subsystem is presented in "Cost Analysis of Oxygen Recovery Systems," McDonnell Douglas Report MDC G-4633, June 1973, which covers work achieved in the first phase of this study. A schematic diagram of the SPE subsystem is presented in Figure 4-5. The subsystem is comprised of electrolysis modules, pumps, deionizer columns, filters, heat exchangers, gas/liquid separators, pressure regulators, valves and associated components.

The mode of operation of the SPE electrolysis subsystem is by water feed to the cathode or hydrogen side. Since the electrolysis occurs at the anode, however, water required for this reaction diffuses through the solid polymer electrolyte at a rate just equal to that required for oxygen generation. The generated oxygen will be saturated at the cell temperature and pressure, but will contain no liquid water. The oxygen is discharged to a back-pressure regulator which is close-coupled to the electrolysis module and is set to maintain oxygen pressure at 60 - 63 psia. The dew point at the regulator valve inlet will be

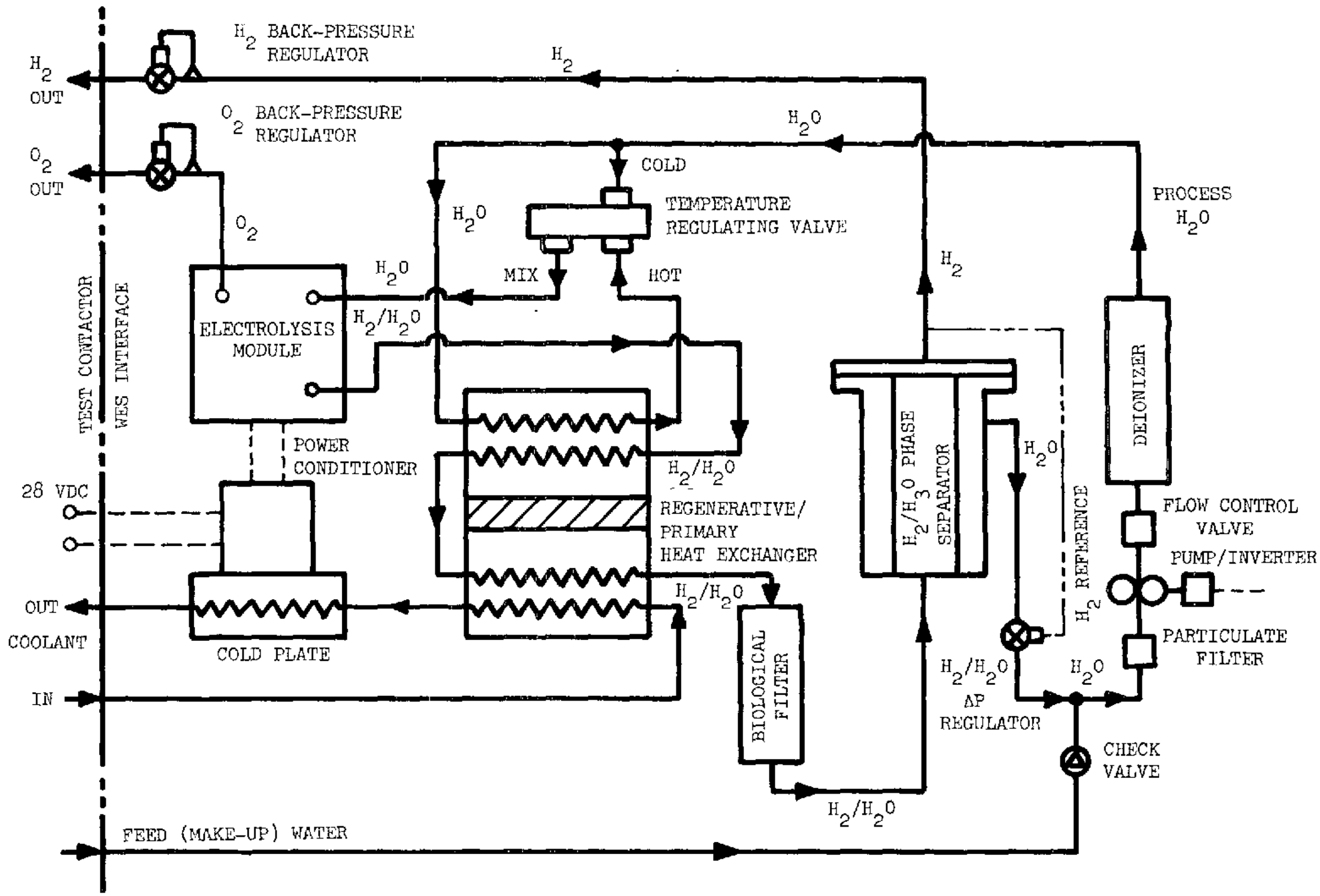

Figure 4-5. Schematic of SPE Water Electrolysis Subsystem

approximately 100°F, and that at the outlet will be a function of the downstream pressure. Free liquid water for cooling will remain on the cathode side and will exit in a two-phase mixture with the generated hydrogen. This mixture then passes through the hot side of the regenerative heat exchanger to transfer heat to the incoming process water to the electrolysis module.

4.1.5.4.2 Experiment Test Setup

The SPE subsystem will be instrumented and installed in the LSEF for testing. An electrical power source and water supply lines will then be connected to the SPE subsystem. Hydrogen output of the subsystem will be stored in an accumulator for possible use later in the HDC experiment. The SPE subsystem's oxygen output will be delivered for use in the cabin atmosphere.

4.1.5.4.3 Measurement Program

The measurement program will include the automatic monitoring and recording of experiment parameters. Pertinent parameters will be displayed to the experimenter to allow him to follow or alter the progress of the experiment at any time. The experiment will be run continuously for the entire mission duration. The SPE subsystem will be run at normal steady-state loading for 3 weeks, with the remaining week devoted to transient loading and stop and start condition runs. Parameters to be measured will include the following:

A. temperature - 12 locations
B. pressure - 3 locations, absolute pressure
C. humidity - 2 locations
D. gas analysis - gas chromatography and oxygen and hydrogen sensors will be required to analyze inlet and outlet gases at the electrolysis module and the H_2/H_2O phase separator.
E. flow rates - 3 gas and 5 liquid flow rate measurements.

4.1.5.4.4 Experiment Design Requirements

The SPE subsystem design requirements are based on the subsystem operating characteristics given as follows:

A. oxygen requirement = 2.0 lbs/man-day
B. hydrogen output rate = 0.39 lbs/man-day

C. water coolant flow rate = 10 lbs/man-hour

D. input power, continuous = 635 watts/man

The SPE water electrolysis unit used in the experiment will have a one-man capacity and will have the following requirements:

A. electrolysis module voltage = 40 to 60 VDC

B. instrumentation voltage = 25 to 31 VDC

C. power input = 386 to 463 watts/man

D. electrolysis current = 10 to 12 amps/man

E. instrumentation power = 20 watts

F. liquid coolant supply line

G. liquid coolant temperature = 50°F

H. maximum cooling requirement = 217 BTU/hr/man

I. make-up water supply line

J. hydrogen return line to CO_2 reduction subsystem

K. water vapor vent line to cabin

4.1.5.5 Boiling and Condensation at Low Gravity Experiment

4.1.5.5.1 Objective

The objective of this experiment is to determine the conditions under which nucleate boiling and condensation can be sustained in near zero-gravity conditions. A variety of submerged surfaces will be studied while subjected to varying heat fluxes and orientations. The vapor evolving from the heated liquid will then be condensed to collect its heat transfer data. Heat transfer research dealing with nucleate boiling and condensation relates to the broad objectives for development of technology for highly reliable systems to support and protect man and enhance his capability to perform space flight operations and is applicable for developing life support systems for long-duration missions which are essential to lower cost centralized earth-orbiting bases, long-duration specialized stations, and lunar and planetary exploration vehicles. Data on low-g nucleate boiling and condensation are necessary in order to design boiling heat transfer equipment inasmuch as this process is commom to virtually all of the life support and other components and systems with phase change processes. This experiment will provide basic data necessary to design and qualify efficient and practical spacecraft equipment which rely on boiling and condensation heat transfer as an integral process.

4.1.5.5.2 Experiment Description

This experiment consists of evaluation and confirmation of theory regarding the processes involved in nucleate boiling and condensation under zero-g conditions. A variety of geometric surfaces immersed in a liquid will be heated at various flux levels and incipient boiling observed. A number of condenser surfaces will also be used to obtain data necessary to assess the mechanisms of condensation in near zero-gravity conditions. The experiment will provide basic data necessary to design and qualify efficient and practical life support equipment which rely on boiling and condensation as integral processes. The research results will take the form of heat fluxes versus heating element temperature at varying pressures and accelerations. Additionally, movie film records will provide data on bubble generation, break-off, condensation and motion which are essential to the satisfactory solution of phase separation problems in very low-g equipment.

The apparatus used to assess nucleate boiling at low gravity is a cylindrical aluminum tank, one foot in diameter, 1.5 feet tall and filled with liquid. A pump is used to circulate fluid in the test loop and thus provide a degree of forced convection to help remove the bubbles from the heated surfaces. Viewing portholes are provided on the sides of the tank for visual observation and photographic purposes. Cameras will be placed 90 degrees apart to help define the 3-dimensional position of the bubbles. Several shaped surfaces, such as a sphere, horizontal plate, thin tall plate and a cylinder, are located at the bottom of the tank. Electrical heaters are imbedded within the surfaces to supply the heat fluxes required for experiment operation. A gridded surface, a scale and a clock also are provided for use in determining the size and break-off speed of the generated bubbles. A light source is used to illuminate the tank during the experiment run.

A phase separator is placed downstream of the boiler and is used to separate the evolving vapor from the liquid. The vapor is delivered to the condenser where a number of condensing surfaces, with varying geometries, are used to evaluate the effects of low gravity on condensation. Coolant flow to the condenser is varied by the use of a manual valve to provide variable heat removal rates. A subcooler is placed downstream of the condenser to liquify any vapor emanating from the condenser. Liquid from both the subcooler and the phase separator are routed to a reservoir. A pump is then used to pump the liquid into the boiler and through the loop. An accelerometer is used to record levels of acceleration during the experiment. A schematic diagram of the nucleate boiling and condensation experiment is shown in Figure 4-6.

The experiment apparatus will be placed in the Spacelab's life support experiment facility which will support its operation and supply all required interfaces.

4.1.5.5.3 Experiment Installation and Operation

The nucleate boiling and condensation experiment apparatus will be installed in the Spacelab's life support experiment facility and the following experiment setup tasks performed:

A. Connect coolant fluid lines to the condenser and subcooler.
B. Connect power source to pump and phase separator motors.
C. Connect make-up liquid source to reservoir.
D. Connect instrumentation and measurement devices, indicated in Figure 4-6, to signal conditioning and/or monitoring and data management equipment.

Each experiment run will involve heating the surface to be tested for nucleate boiling, controlling fluid flows to the condenser and subcooler, initiating the circulating pump and monitoring and recording test parameters. The experiment will be conducted at a number of selected gravity levels. Parameters to be considered include: start of bubble formation, number of bubbles, bubble size and velocity, gravity level and direction, test liquid and vapor flow

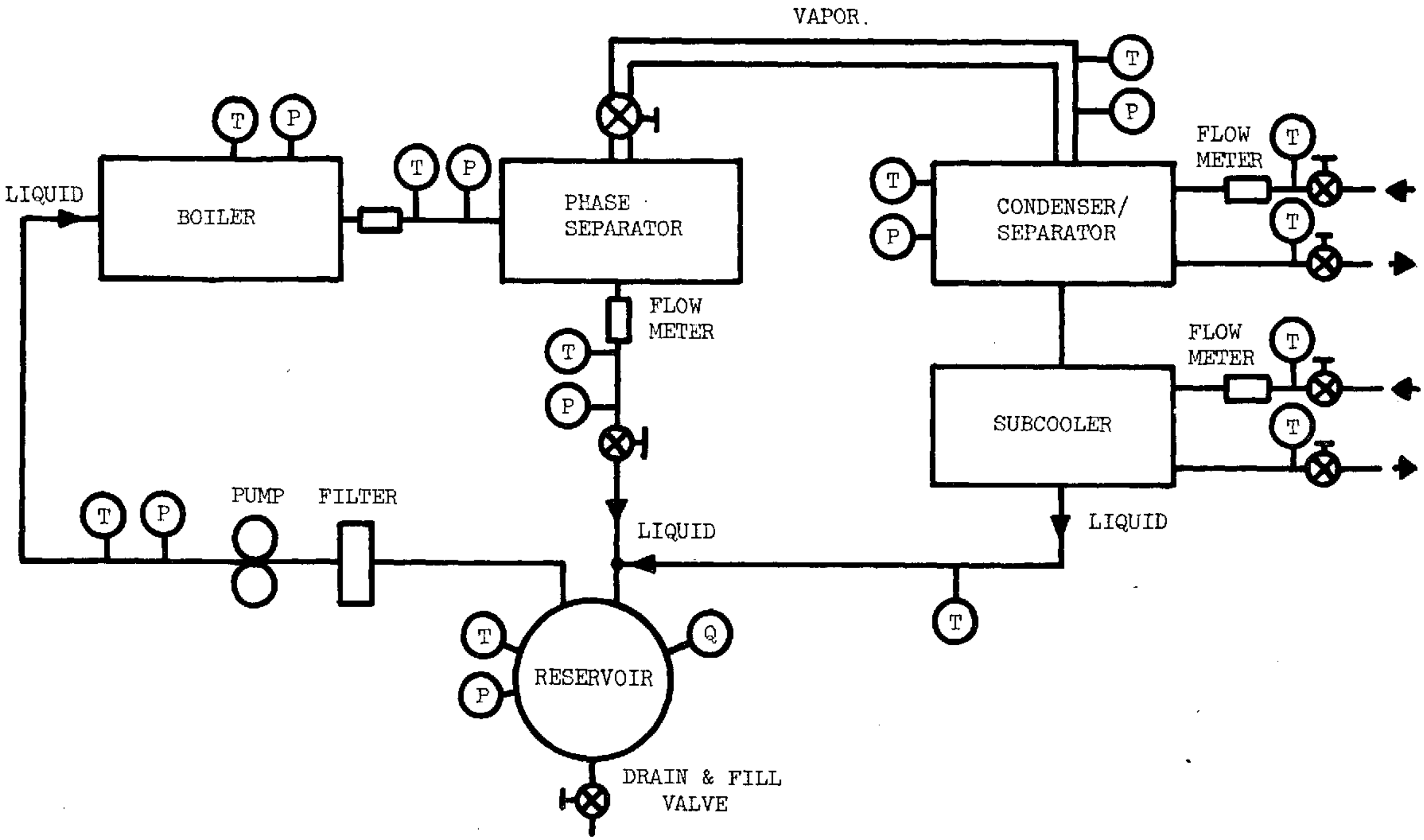

Figure 4-6. Boiling and Condensation at Low Gravity Experiment Schematic

rates, coolant flow rate, power input to pump, liquid quantity in reservoir, surface temperatures and fluid temperatures and pressure. Movie film records will provide data on bubble generation, break-off, and motion, the onset of condensation and condensate formation on various surfaces, all of which are essential to the satisfactory solution of phase separation problems in very low-g equipment operation.

The experiment operation and data collection will be automatic, subject to manual change of run conditions or interruption of operation by the experimenter.

4.1.5.5.3.1 Measurement Program

The measurement program will include the automatic monitoring and recording of the experiment parameters and the display of pertinent parameters for the experimenter to allow him to follow or alter the progress of the experiment. The experimenter may also adjust heater test surface positions of fluid flow controls to obtain the desired experimental conditions. Each experiment run is expected to extend from 5 to 30 minutes, following the attainment of steady-state conditions. Parameters to be measured include the following:

A. temperature - 8 surface and 16 fluid positions
B. pressure - 7 positions, as indicated in Figure 4-6
C. power input - electrical power to pump, phase separator and each boiling surface
D. acceleration - accelerometer to measure acceleration prior to and throughout experiment duration
E. bubble activity - measurement of size and motion of bubbles in boiler will utilize a gridded surface, a scale and a digital clock. Cameras will be used to monitor and record bubble activity for analysis at a later date.
F. flowmeters - to measure test liquid and vapor flow rates and also to measure the flow of coolant fluids into the condenser and subcooler.

4.1.5.5.3.2 Crew Skills and Task Times

An experimenter is required to initiate each experiment run, adjust the cameras, set power level, select and control position of boiling and condensation surfaces and terminate experiment after each experiment run. The camera films will be removed for processing, analysis and storage. The experimenter will also be required to manually record some of the data and perform calculations to make rapid assessments of experiment progress and modify or alter subsequent runs if deemed advisable. Experience with heat transfer and fluid dynamics is a required crew skill for operating this experiment.

4.1.6 Life Support Experiment Facility Description

The LSEF will be comprised of the console shown in Figure 4-1, the fluid supply subsystems, power distribution, signal conditioning, instrumentation and measurement devices. The LSEF design requirements and fluid supply subsystem configurations are presented in the following paragraphs.

4.1.6.1 LSEF Design Requirements

A study was conducted to study the requirements and interfaces of the life support and fluid flow experiments to be conducted in the LSEF. Table 4-2 presents a summary of the measurements, expendables and support requirements obtained from analyzing the performance and operating characteristics of the life support and fluid flow experiments indicated. Table 4-2 also shows the commonality of measurement devices required for various experiments.

4.1.6.2 LSEF Fluid Supply Subsystems

The LSEF requires the following four fluid supply subsystems to provide the fluid flows needed for experiment operations:

A. conditioned air supply
B. heating fluid supply
C. cooling fluid supply
D. vacuum supply

The heating, cooling fluid and power supply requirements by the LSEF were found in some instances to exceed the current Spacelab capabilities. It is recommended that provisions be made for the following: 1) An integrated Spacelab Refrigeration System to supply the LSEF requirements, and 2) A storage battery system to supply peak power loads during LSEF experiment operations. A schematic of the

Table 4-2

LIFE SUPPORT EXPERIMENT FACILITY MEASUREMENTS, SUPPORT REQUIREMENTS AND EXPENDABLES

Experiment	Consumables	Power	Flow Meters	Temperature Sensors	Pressure Sensors	ΔP	Humidity	Transport Fluids	Water Analysis	Photography	Gas Analysis	Other
Vapor Compression	N_2, air	Pump (3), Compressor Still, Liquid Separator	2 Liq.	9	4	1	-	35-50°F (Chiller) 160°F (Tanks)	Cond. pH TOC	X	Gas Chromatograph	Quantity (tanks) Vent to Cabin
RITE	O_2, N_2, Air	Condensate Pump Shredder Separator Motors, Auger, Incinerator, Blower, Water Pump (2), Blender, Evaporator Motor, Transfer Fluid Pump	1 Gas 2 Liq.	40	4	1	2	75°F 35-50°F 160°F	Cond. pH TOC	X	Gas Chromatograph	Quantity (tanks) Vacuum 10^{-3} mm Hg 10^{-6} mm Hg Radiation Detector
H_2O-Depolarized CO_2 Concentrator	O_2, N_2, H_2, Air H_2O	HDC Modules Blower (2)	3 Gas	5	2	-	2	-	-	X	CO_2 Analyzer, Gas Chromatograph H_2 Sensor	
SPE Water Electrolysis	H_2O	Electrolysis Modules, Pump	3 Gas 3 Liq.	12	3	-	2	35-50°F	-	X	O_2 Sensor H_2 Sensor Gas Chromatograph	
Boiling and Condensation at Low Gravity	H_2O	Pump, Phase Sep.	1 Gas, 3 Liq.	12	7	-	-	35-50°F	-	X	-	Quantity

fluid subsystems, which shows the main components and the interacting fluid loops, presented in Figure 4-7. A discussion of each of the subsystems is presented in the following paragraphs.

4.1.6.2.1 Conditioned Air Supply Subsystem

This subsystem is used to supply air to the experiment apparatus at widely varying conditions of temperature and humidity. Closed loop or cabin air is drawn into the subsystem gas loop and heated, cooled, humidified or dehumidified and then returned to the test unit. Gases from stored bottles may also be introduced into the loop if a gas with different composition is desired. Included in the air supply subsystem are the following major components.

4.1.6.2.1.1 Compressor

This is a motor driven centrifugal compressor designed for the mode-rate flow and high pressure rise compatible with life support subsystems of approximately a one-man capacity. The compressor has the following characteristics at design point:

rotational speed	22,800 rpm
flow	35 CFM
pressure rise	10 in H_2O
inlet pressure	10.42 in Hg abs
voltage	115/200 volts
frequency	400 cps
power	3 phase ac
current	0.3 amp
weight	5.5 lb
operating temperature range	$-65°$ to $200°F$

Air flow through the compressor is controlled by the utilization of a throttle valve upstream of the compressor or by a by-pass to the cabin.

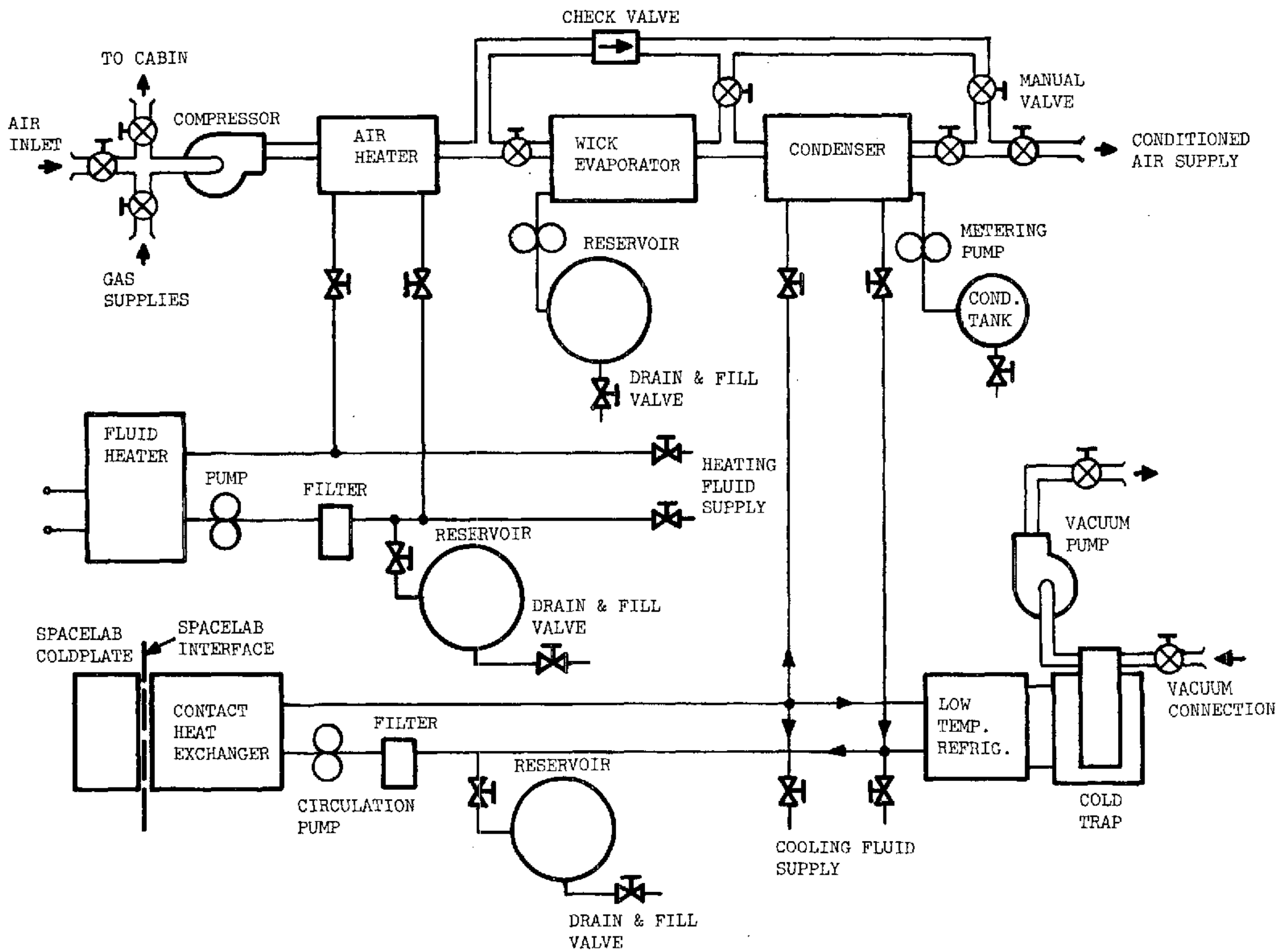

Figure 4-7. LSEF Fluid Subsystems Schematic

4.1.6.2.1.2 Air Heater

The air heater utilizes heating fluid from the LSEF heating loop to heat the air supplied to the experiment module when desired. The heater has the following design characteristics:

air heater's heating capacity, maximum	=	3000 Btu/Hr
process air flow rate, maximum	=	30 CFM
process air inlet temperature range	=	60 to 120°F
process air outlet temperature range	=	120 to 200°F

4.1.6.2.1.3 Wick Evaporator

The wick evaporator is used to humidify the air circulating in the air supply loop, when desired. A metering pump is used to deliver water, through water distribution tubes, to the evaporator wick. Hot air, from the air heater, is then passed over the wick and humidified in the process. The evaporator assembly includes the wick, casing, water feed lines and controls. The evaporator has the following performance and design characteristics:

process air flow, maximum	=	30 CFM
process water flow, maximum	=	1.8 Lbs/Hr
process air temperature range	=	60 to 200°F

Valves are provided to divert air flow around the wick evaporator by any desired amount.

4.1.6.2.1.4 Condenser

The condenser is used to cool and dehumidify the incoming air to any desired humidity by controlling the amount of coolant flow from the cooling fluid supply loop. The condenser is of the wick water separator type and has the following characteristics:

gas side inlet temperature, minimum	=	42°F
gas flow, maximum	=	30 CFM
water separation rate, maximum	=	2 Lbs/Hr

liquid coolant inlet temperature	=	42°F
coolant type	=	water
coolant flow rate, maximum	=	160 Lbs/Hr

4.1.6.2.1.5 Metering Pumps

The wick evaporator pump meters a preselected amount of water to the wick evaporator. The condensate pump receives water from the condensing heat exchanger and stores it in the condensate tank. The metering pumps have the following performance and design requirements:

type of pump	=	semi positive displacement
drive	=	electric motor
pressure relief	=	built into pump
rated flow	=	0.48 gallons/hr
pressure rise	=	50 psid
fluid	=	water
fluid temperature	=	40°F to 240°F
fluid pressure in	=	≤ 2 psi
inlet filter	=	98% of 40μ, 100%, of 70
duty cycle	=	continuous
power input	$<$	5 W

4.1.6.2.2 Heating Fluid Supply Subsystem

The heating fluid supply subsystem provides heating fluid to the air heater and to all life support subsystems experiments requiring hot transport fluids, such as humidity and CO_2 removal desiccant beds and water recovery subsystems. The heating fluid supply loop comprises a heating tank with an electric heater, a pump, filter, reservoir and associated valving and controls. Characteristics of the major subsystem components are as follows.

4.1.6.2.2.1 Fluid Heater

A 5 Kw electrical heating element, with a rheostat to control its thermal output, is used to heat the transport fluid. A storage battery is used to store electrical energy and supply it during experiment run, as the heater power requirements may be higher than the system capabilities. The fluid heater has the following performance and design characteristics:

fluid heater's heating capacity, maximum	=	17,000 Btu/Hr
process fluid flow rate, H_2O, maximum	=	85 Lbs/Hr
process fluid temperature rise, maximum	=	200°F

4.1.6.2.2.2 Fluid Circulation Pump

The fluid circulation pump is used to pump the transport fluid into the fluid heater enclosure, where it is heated, and then circulates it through the air heater and life support subsystem test components requiring hot fluid supply. The circulation pump has the following characteristics:

type of pump	=	positive displacement
drive	=	electric motor
rated flow	=	0.3 GPM
pressure rise	=	170 psid
fluid	=	water
fluid temperature	=	40 to 240°F
duty cycle	=	continuous
power	=	60 watts
weight, with motor	=	3.25 lbs
similar unit	=	Eastern Pump Model 1102

4.1.6.2.2.3 Reservoir

The reservoir is a spherical tank, with a fill and drain valve, used to prime and provide make-up for the heating fluid loop. The reservoir has the following characteristics:

reservoir capacity	=	6 gallons
reservoir size, diameter	=	7.5 inches
operating pressure, maximum	=	190 psia

4.1.6.2.3 Cooling Fluid Supply Subsystem

The cooling fluid supply subsystem comprises a contact heat exchanger, pump, filter, reservoir and coolant supply lines to life support test equipment. A brief description of subsystem components is given in the following paragraphs.

4.1.6.2.3.1 Contact Heat Exchanger

The contact heat exchanger provides a means to transport heat from test components to the Spacelab 40°F coldplate. The use of the contact heat exchanger eliminates the need for a liquid line interface between the LSEF and the Spacelab at the expense of some reduction in heat transfer efficiency. The contact heat exchanger has the following performance and design characteristics:

coolant fluid inlet temperature	=	52°F
coolant fluid outlet temperature	=	45°F
Spacelab coldplate operating temperature	=	42°F

The Spacelab coldplate will require coolant flow directly from the payload heat exchanger to meet the requirements of the condenser, the low temperature refrigerator and other experiment cooling requirements.

4.1.6.2.3.2 Pump

The pump is used to circulate the coolant between the contact heat exchanger and the test components requiring cooling fluid. The pump has the following characteristics:

type of pump	=	positive displacement
drive	=	electric motor
rated flow	=	55 GPH
pressure rise	=	65 psid
fluid	=	water
duty cycle	=	continuous
weight, with motor	=	1.75 lbs
similar unit	=	Eastern Pump Model 1733

4.1.6.2.3.3 Reservoir

The reservoir is a spherical tank, with a fill and drain valve, used to prime and provide make-up for the coolant fluid loop. The reservoir has the size and design characteristics as the reservoir used in the heating fluid supply subsystem.

4.1.6.2.4 Vacuum Subsystem

The vacuum subsystem provides a vacuum pump and a cold trap loop for high vacuum desorption processes where some of the desorbed gases are needed for analysis or for further use in the experiment. Following are the major vacuum subsystem components.

4.1.6.2.4.1 Vacuum Pump

The vacuum pump is designed to operate either through a cold trap or a direct intake. The pump has the following design and performance characteristics:

type of pump	=	mechanical, rotary, single stage
drive	=	electric motor
free air capacity	=	5 CFM
ultimate pressure	=	1 micron
power, rated	=	0.5 HP

4.1.6.2.4.2 Cold Trap

The cold trap utilizes 45°F coolant from the cooling fluid loop which is cooled further in a low-temperature refrigerator before it is calculated in the cold trap jacket at a temperature of -76°F. The cold trap, together with the vacuum pump, will be operated intermittently.

4.1.7 Cost Estimates

The LSEF equipment cost was calculated at the component level, then added up to the assembly, subsystem and system levels. System level cost elements were then included to arrive at the total LSEF cost. A discussion of the various cost estimates is given in the following paragraphs. Cost items are provided for both non-recurring design and development and recurring production phases.

4.1.7.1 Fluid Supply Subsystem

A list of fluid supply subsystems components is presented in Table 4-3, which also includes component quantities and weights. Equipment cost has been calculated utilizing the cost estimating relationships derived in the first phase of this study. The CER's derivation is based on cost data from actual space programs such as Gemini and Skylab. Both non-recurring and recurring costs were calculated. A summary of fluid subsystems cost results, given by subsystem and divided into a non-recurring and recurring, is presented in Table 4-4.

Table 4-3

FLUID SUPPLY SUBSYSTEMS COMPONENTS LIST

Component	Quantity	Unit Weight, Lbs
Air Compressor	1	1.95
Air Heater	1	8.0
Wick Evaporator	1	4.5
Condenser	1	6.0
Pump, Metering	2	1.5
Fluid Heater	1	6.0
Fluid Circulation Pump	1	2.0
Reservoir	2	3.0
Contact Heat Exchanger	1	4.0
Coolant Pump	1	2.0
Vacuum Pump	1	12.0
Cold Trap	1	9.5
Valve, Air, Shutoff, Manual	8	0.75
Valve, Air, Check	1	0.50
Valve, Liquid, Shutoff, Manual	14	0.35
Valve, Vacuum	2	1.5
Filter, Liquid	1	0.25
Filter, Air	1	0.5

Table 4-4

LSEF FLUID SUBSYSTEMS COST ESTIMATES

Subsystem	Non-Recurring Cost, Dollars	Recurring Production Cost, Dollars	Total
Conditioned Air Supply	1,877,240	98,335	1,975,575
Heating Fluid Supply	645,390	34,009	679,399
Cooling Fluid Supply	552,025	29,080	581,105
Vacuum Subsystem	485,995	25,610	511,605
Total	3,560,650	187,034	3,747,694

4.1.7.2 Power Control and Distribution Subsystem

This subsystem comprises a power monitoring panel and power distribution and control equipment. The subsystem receives power from available bus lines or battery storage system and distributes it according to the requirements and characteristics of individual measurement devices and test equipment. Power control and distribution costs are given as follows:

non-recurring cost = $210,000

recurring production cost = $125,000

4.1.7.3 Console

The cost of the LSEF console includes the integration, assembly and checkout of the console, including the panel assemblies, instrumentation and displays. The cost of the consoles is given as follows:

consoles non-recurring cost = $660,000

consoles recurring production cost = $397,450

4.1.7.4 Data Management

The data management subsystem comprises the experiment monitoring instrumentation and the data acquisition, control and storage. The Spacelab computers will process, display, store and/or telemeter the data, as required. The data management and interface electronic equipment cost includes the signal conditioners and other experiment electronic interface equipment, as well as procuring and installing physiological and environmental instrumentation. The total subsystem cost is given as follows:

data management subsystem non-recurring cost = \$470,000

data management subsystem recurring production cost = \$280,000

4.1.7.5 Experiment Hardware

The experiment hardware utilized in the life support and fluid flow experiments is divided in two categories. The life support equipment is comprised of scaled and/or modified models of life support subsystems developed in previous NASA SRT programs. Fluid flow experiment hardware, on the other hand, is made of new equipment developed specifically for the experiment program. The hardware cost of both types of experiments is given in the following paragraphs.

4.1.7.5.1 Life Support Experiments

Cost estimates of life support experiment hardware is presented in Table 4-5. The development cost estimates shown in Table 4-5 represent the cost of equipment modifications necessary for developing the experiment hardware. Production costs of one-man units to be used in the experiments were based on technical judgment and experience with costs of scaled models and are thus estimated at half the cost of six-man flight units whose cost was developed in the first phase of this study and reported in McDonnell Douglas Reports MDC G-4631, MDC G-4632 and MDC G-4633, all dated June 1973.

Table 4-5

LIFE SUPPORT EXPERIMENT HARDWARE COST

Experiment	Development Cost, Dollars	Production Cost, Dollars
Vapor Compression Water Recovery	200,000	525,000
RITE Waste and Water Recovery	400,000	505,000
H_2-Depolarized CO_2 Concentrator	100,000	550,000
SPE Water Electrolysis	250,000	550,000

4.1.7.5.2 Boiling and Condensation Experiment

The cost of the boiling and condensation experiment hardware also was estimated at the component level and then summed up to obtain subsystem cost. Allowances were made to account for integrating, packaging and testing at the subsystem level by the introduction of cost factors obtained from previous program costs. Cost estimating relationships developed in the first phase of this study were used to establish component costs. Table 4-6 presents a listing of the boiling and condensation experiment components, as well as their quantities and unit weights.

Table 4-6

BOILING AND CONDENSATION EXPERIMENT COMPONENTS LIST

Component	Quantity	Unit Weight, Lbs
Boiler	1	4
Phase Separator	1	3.5
Condenser Separator	1	6
Subcooler	1	4
Reservoir	1	8
Circulation Pump	1	2.5
Flow Meter, Liquid	4	1.0
Filter, Liquid	1	0.25
Valve, Gas	1	1.5
Valve, Liquid	6	0.5
Quantity Sensor	1	0.05
Temperature Sensor	12	0.02
Pressure Sensor	7	0.05

A summary of the costs of the boiling and condensation experiment hardware is given as follows:

boiling and condensation experiment hardware development cost = $2,144,000

boiling and condensation experiment hardware production cost = $ 230,000

4.1.7.5.3 Life Support and Fluid Flow Experiment Hardware Total Costs

The total costs of the life support and fluid flow experiment hardware, obtained from the above two paragraphs are the following:

experiment hardware development cost	=	\$3,094,000
experiment hardware production cost	=	\$2,360,000

4.1.7.6 Final Assembly, Integration and Checkout

This cost item includes the integration of the experiment assemblies in the LSEF and providing the necessary interfaces with the Spacelab subsystems. Final subsystem checkouts, including ground support system interfaces, are also included in this cost estimate. The cost of this item is as follows:

final assembly, integration and checkout non-recurring cost	=	\$1,156,635

4.1.7.7 Life Support Experiment Facility Cost

The LSEF cost is obtained from the summation of all the cost items listed in the above paragraphs. Note that the resulting cost represents only hardware costs and does not include project level costs such as logistics, flight operations, ground support, facilities and principal investigator operations. The LSEF total costs are as follows:

LSEF development cost	=	\$9,151,285
LSEF production cost	=	\$3,349,483

4.2 BIOLOGICAL SPECIMEN HOLDING FACILITY EXPERIMENT

4.2.1 Objective

The objective of this experiment is to understand the role of gravity in growth, development, physiology and behavior of organisms. A biological specimen holding facility is used in which testing is conducted on six instrumented and restrained rhesus monkeys and two unrestrained rhesus monkeys. The six rhesus monkeys are used in the experiment to provide an adequate statistical sample. The two unrestrained monkeys are used as control specimens to provide a basis for estimating the effects of restraint on the animals.

4.2.2 Description

Figure 4-8 shows the layout of the animal holding cages and support equipment as part of an integrated biological specimen holding facility which includes primates, small vertebrates, invertebrates, plants, cells and tissue cultures. The total facility is designed on a modular basis, so as to permit the experimenter or system designer to use any one or combination of specimens for a particular mission. The holding cages used in the facility utilize only two envelope sizes compatible with the current design of the Spacelab. The cages and laboratory support equipment are designed to fit the standard 19- or 38-inch wide Spacelab racks.

The primate holding facility is comprised of the following subsystems and support equipment:

A. Environmental Control Subsystem - This subsystem provides thermal, humidity, CO_2 and contaminant control for the primates. The environmental control subsystem has been oversized to accommodate 20 small vertebrates whenever they are included in the facility. Oxygen for the specimens is obtained from a small amount of air drawn off from the cabin and returned to the cabin after being filtered. Air in cages is kept at a slightly lower pressure than that in the cabin to minimize the spread of animal odors to the Spacelab cabin atmosphere. The lower pressure is attained by locating the air supply to cages at the suction side of system blower. No additional equipment is needed for this purpose.

B. Waste Management - Fecal and urine bags are used to collect the restrained monkey's wastes. The primates are catheterized and restrained in their seats to insure proper flow of urine and feces into the bags. Technical judgment was used to assess the complexity of waste management units of the unrestrained monkeys. No attempt was made to design the unrestrained monkey's waste management units in this phase of the study.

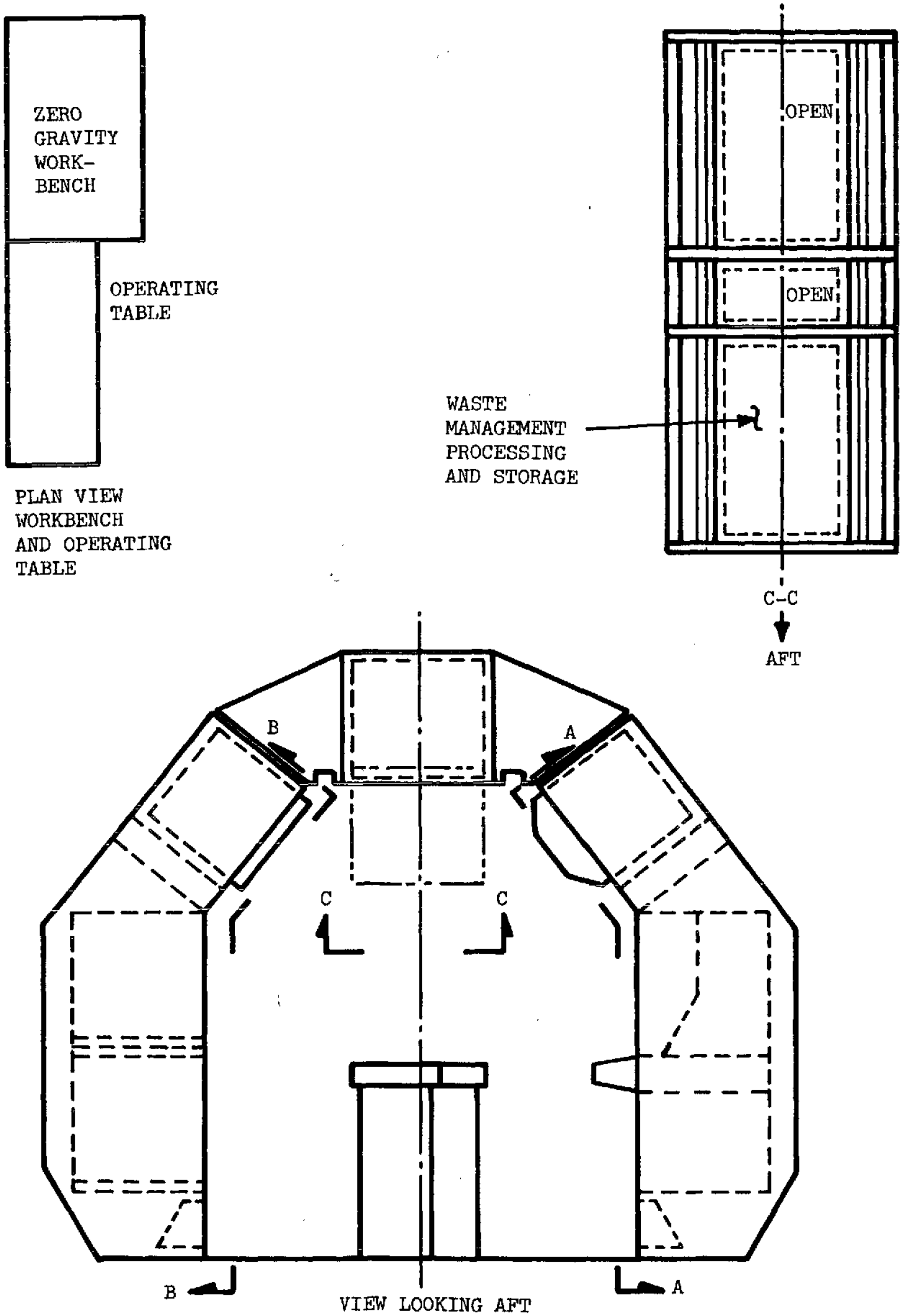

Figure 4-8a. Biological Specimens Holding Facility

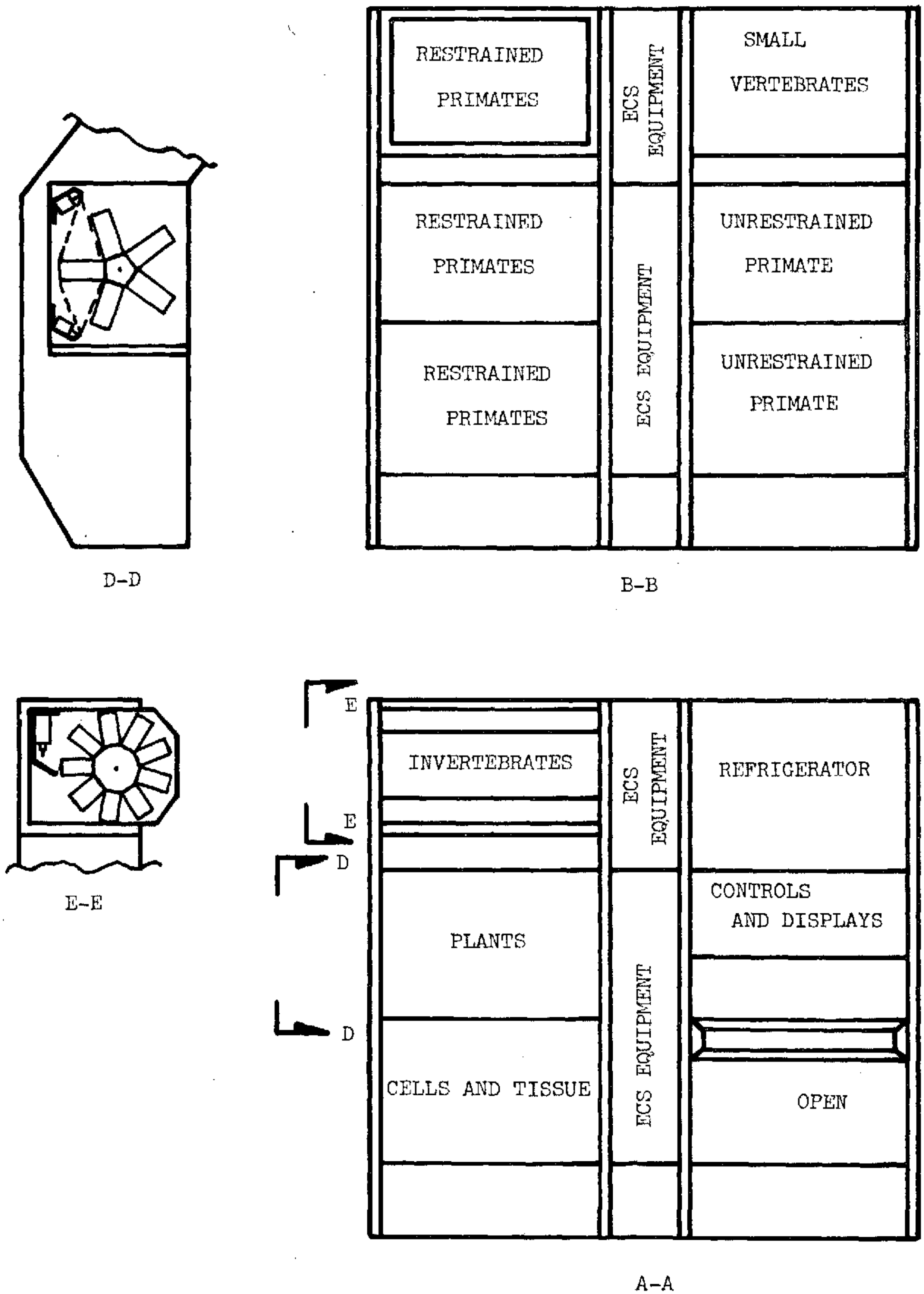

Figure 4-8b. Holding Facility Sections

C. Food and Water Assemblies - Food is provided from a pellet dispenser which may be activated by commands from psychomotor test panel.

D. Instrumentation, Controls and Data Management Subsystem - This subsystem monitors both the environmental conditions in the cages and the primates' physiological parameters obtained through the use of implanted sensors. The data are relayed to the computer, displayed on a controls and displays console, reduced and stored, or telemetered to ground.

E. Holding Cages - The cages are designed to accommodate the primates and their support equipment and provide interfaces with the environmental control, water storage and data management subsystems.

F. Refrigerator and Freezer - These units provide cold storage for biological samples. Freezing temperatures of -20°C and -60°C are provided, with the lower temperature required for blood samples.

G. Photographic Assemblies - Cameras are provided inside each cage and are activated either when the primates perform specific functions on the psychomotor test panel or by command from the data management subsystem.

H. Power Control and Distribution - This subsystem comprises control and distribution equipment to supply and manage experiment power supplies.

Cost estimating methods have been employed to cost all subsystems and equipment and may be used to cost other facilities with varied sizes or equipment allocations. The cost of the instrumented primates and the costs of ground support equipment and facilities were not included in the calculations. The estimated costs of the facilities' subsystems and equipment are summarized as follows:

1.	Environmental control subsystem	$4,321,943
2.	Waste management	612,310
3.	Food and water assemblies	717,480
4.	Instrumentation, controls and data management	620,938
5.	Holding cages	1,982,018

6.	Refrigerator and freezer	784,044
7.	Photographic assembly	179,255
8.	Holding facility construction interfaces	129,983
9.	Power control and distribution	350,377
	Total	9,698,348

A description of the primate holding facility's subsystem and equipment, their performance and cost estimating relationships is presented in the following sections.

4.2.3 Environmental Control Subsystem for Primates and Vertebrates

The environmental control subsystem (ECS) for the primate and small vertebrate cages provides the thermal, humidity, carbon dioxide and contaminant control, and ventilation requirements. The temperature and humidity requirements for biological specimen holding facilities are shown on a psychometric chart in Figure 4-9. Additional life support subsystem requirements are presented in Table 4-7. Make-up oxygen required for metabolic consumption is part of the ventilation flow. Ventilation flow is also used to aid in waste collection. The system consists of a debris filter, two circulation blowers, two LiOH/ activated charcoal canisters, condensing heat exchanger, water separator and necessary valving, ducting and controls. A schematic of the holding facility environmental control subsystem is shown in Figure 4-10.

4.2.3.1 Subsystem Performance

Air is drawn from the animal cages through a debris filter to remove particulate matter which might damage the fan or contaminate ohter components such as valve seats and/or the surfaces of the condensing heat exchanger. Air leaving the filter enters either of two fans which provide air movement through the system. Two fans are used in order to utilize existing spacecraft hardware which can accommodate the moderately high pressure drop of the system. Air leaving the fans is diverted by a selector valve to one of the two installed canisters to remove CO_2, trace contaminants, and odors. The two identical canister assemblies and appropriate valves are installed in such a manner that each

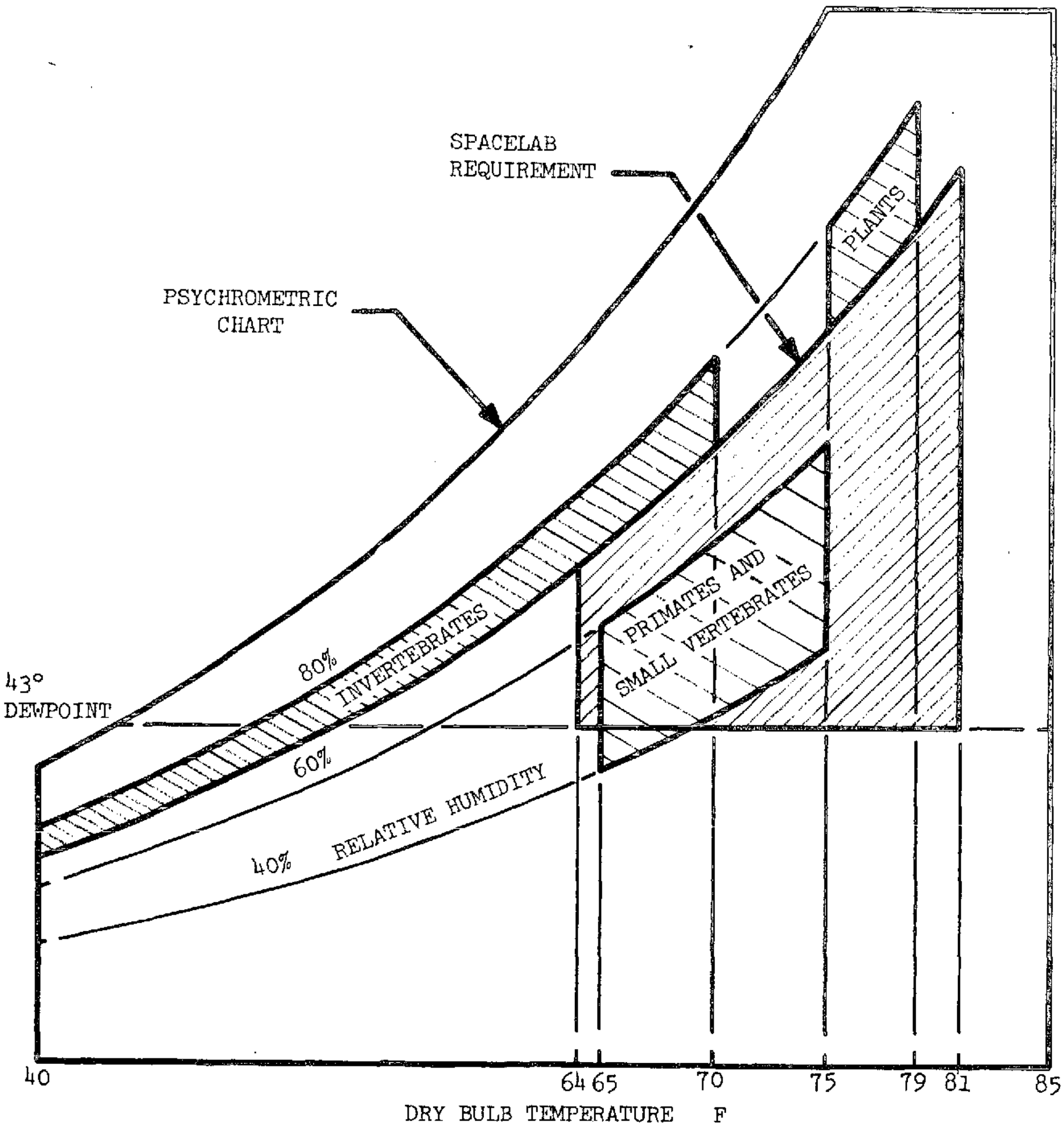

Figure 4-9. Temperature & Humidity Requirements for Animals and Specimen Holding Facilities

Table 4-7
BIOLOGICAL SPECIMEN HOLDING FACILITY LIFE SUPPORT SYSTEM REQUIREMENTS

Holding Unit	Atmosphere	Temperature	Humidity	Waste Management	Food
Primate (Rhesus)	Cabin atmosphere	70 ± 5°F	50 ± 10%	(1) Restrained: urethral catheter & fecal bag, 24-hour collection and sampling (2) Unrestrained: provide waste collection & sampling methods	120 g/day per primate (+300g/day water per primate)
Small Vertebrate	Cabin atmosphere	70 ± 5°F	50 ± 10%	May use air flow for waste collection	Experiment specific
Invertebrate	Cabin atmosphere	40 to 70°F	75 ± 5%	Usually not required	Experiment specific
Plant	Cabin atmosphere	77 ± 2°F	75 ± 5%	None required	Supplied with plant
Cells and Tissue	Supply different requirements usually in incubators: (1) cabin atmosphere (2) air with up to 20% CO_2 (3) anaerobic atmosphere (e.g.,: 80% N_2, 10% H_2, 10% CO_2)	variable, selectable (100°F ± 0.5°F most common)	0 to 100%	None required	None

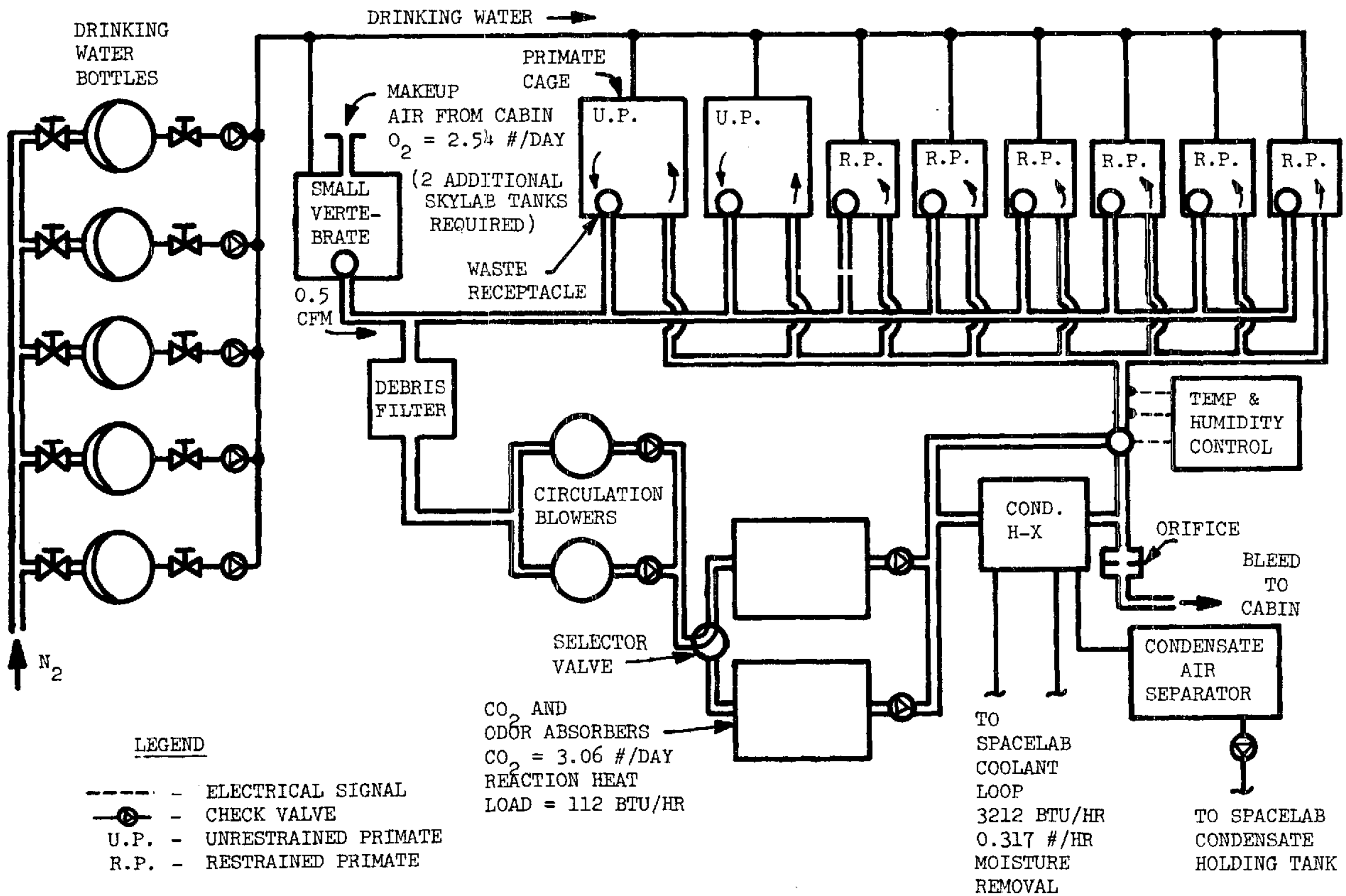

Figure 4-10. Holding Facility Environmental Control Subsystem

canister is on line for contaminant removal. The canister selected is the same unit as that used in the orbiter EC/LS system. From the LiOH/activated charcoal canister air flows through the condensing heat exchanger or bypasses the heat exchanger as required by the temperature and humidity controller. Within the heat exchanger the temperature of the gas stream is reduced for cage thermal control and condensation takes place for humidity control. Condensed moisture adheres to the surface of the heat exchanger fins by surface tension and is drawn off by in-flow through a series of holes at the outlet. This mixture then passes through the water separator assembly containing redundant motor-driven rotary separators. The water is separated from the air by centrifugal effect and delivered into the spacelab condensate storage tank. The dry air is then returned to the cabin. Downstream of the condensing heat exchanger, the air which bypassed the heat exchanger is mixed with the heat exchanger airflow and supplied to the cages through the air distribution system. Air is distributed in the cages through outlets oriented to direct the flow along the sidewalls of the cages and toward the waste collection outlet so as to provide ventilation, as well as to entrain free solid wastes and moisture and direct them to the waste collector. A component list for the ECS is presented in Table 4-8, which also shows the weight and size of the components.

4.2.3.2 Cost Estimating Relationship

Cost estimating relationships for the holding facility's ECS are given in the following paragraphs. Both recurring and non-recurring costs are included.

A. Recurring Cost Estimates:

The recurring cost estimates for each of the ECS components is given by CER's derived from the components and presented in Table 4-9. The CER derivation is based on cost data for similar components flown in previous space programs and modified to reflect specific component characteristics. The recurring cost of the ECS is obtained from

Table 4-8

ECS COMPONENT LIST FOR BIOLOGICAL SPECIMAN HOLDING FACILITY

Item	Quantity	Size	Unit Weight (lbs)
Debris and H_2O filter	1	3" dia x 4"	2
- spare	2	3" dia x 4"	2
Circulation blower	2	5" dia x 4.5"	4.9
Odor and CO_2 canister assembly	2	3.8" dia x 10"	6.4
Selector valve	2	3" x 3" x 2"	1.5
Check valve	4	2" dia x 2"	.3
Condensing H-X (H_2O to air)	1	5" x 5" x 5"	5.0
H-X bypass valve	1	4" x 3" x 3"	3.0
Humidity and temperature controller	1	6" x 6" x 6"	2.0
Temperature readout	1	3" x 4" x 4"	2.4
Temperature sensor	1	1" x 4"	.9
CO_2 readout	1	3" x 4" x 4"	2.4
CO_2 sensor	1	1" x 2"	.3
O_2 readout	1	3" x 4" x 4"	2.4
O_2 sensor	1	1" x 4"	.9
Condensate air separator	1	6" dia x 4"	3.5
Condensate check valve	1	.8" x 1.6"	.2

Table 4-9

BIOLOGICAL SPECIMEN HOLDING FACILITY
ECS RECURRING COST ESTIMATES
(in 1974 Dollars)

Component/Assembly	Cost Estimating Relationships	Notes
Circulating Blower Assembly	Cost = $45.8P^{0.942}Q^{0.89} + 2630W_{OC}$	P = blower's electrical power input = 383 watts Q = number of blowers used = 2, and W_{OC} = weight of associated components = 2.1 lbs
CO_2 and Odor Canister Assembly	Cost = $19038W_{CAN}^{0.267}Q^{0.89} + 3551W_{OC}$	W_{CAN} = canister weight = 6.4 lbs Q = number of units used = 2, and W_{OC} = weight of associated components = 2.1 lbs
Condensing Heat Exchanger Assembly	Cost = $190W^{0.267}N_P^{1.905} + 3551W_{OC}$	W = condenser weight = 5.0 lbs, N_P = number of ports per condenser = 4, W_{OC} = weight of other components = 4.8 lbs
Condensate Tank Assembly	Cost = $2302V^{0.267} + 3551W_{OC}$	V = volume of condensate tank = 1 ft^3, and W_{OC} = weight of associated components = 0.2 lbs
Controller Sensors and Readouts	Cost = $5754 (W_C + W_{OC})$	W = controller weight = 2.0 lbs, and W_{OC} = other components weight = 11.9 lbs

solving the individual CER's listed in Table 4-9 and then applying factors that account for the cost of packaging and interface hardware, resulting in the following:

Item	Recurring Cost, $
Circulating Blower Assembly	28,482
CO_2 and Odor Canister Assembly	65,444
Condensing Heat Exchanger Assembly	21,172
Condensate Tank Assembly	3,012
Controller, Sensors and Readouts	79,980

Holding Facility's ECS Recurring Cost

$= 1.833 \times 1.1 \times 198{,}090 = 19038 \times 1.642 \times 12^{0.89}$

$= 702{,}113$ dollars

B. Non-Recurring Cost Estimates:

The holding facility's ECS non-recurring cost is obtained by utilizing a CER developed for engineering design and adding to it the cost of other non-recurring functions on a percentage basis by utilizing the cost breakdown ratios given in Table 3-4. The cost breakdown ratios used are average values obtained from analyzing the ECS cost data of the Gemini spacecraft and are assumed representative of cost-effective ECS development. The costs of ground support equipment and major subcontractors were excluded from Table 3-4. The engineering design CER was based on the analysis of a number of cost influencing parameters which indicated that design cost is mainly a function of the number of component types (N) in each system and is given by the following relation:

Holding facility's ECS design cost $= 41{,}922N + 123{,}530$ dollars

The ECS comprises 12 different component types. Accordingly, the subsystem design cost C = 626,594 dollars.

Utilizing the non-recurring cost breakdown ratios given in Table 3-4, the non-recurring cost of the ECS = 3,619,830 dollars.

C. Holding Facility's Total ECS Cost:

The cost of the ECS is thus = 3,619,830 + 702,113 = 4,321,943 dollars

4.2.4 Waste Management Subsystem

The waste management subsystem comprises a waste management assembly and a waste processing and storage compartment. The waste management assembly for the restrained primates is comprised of fecal and urine collection bags which are replaced daily. Skylab-type fecal bag are attached to the underside of the primate's seat and are accessible through the frontal access panel as may be seen in Figure 4-11. In addition, a waste processing and storage compartment is included for the storage of fecal samples to be returned to earth after the mission. No attempt was made to design a waste management assembly for unrestrained monkeys in this phase of the study due to the complexity of such assemblies.

4.2.4.1 Subsystem Performance

Perforated holes in the sides of the seat are used to admit air flow to direct the feces into the bag. Bags are provided with Zitex air filters which were used in the Skylab program to filter particulates and bacteria from the airstream. The compartment housing the fecal and urine bags is provided with air from the air distribution duct. The primate cages air supply is provided on the suction side of the blower and is designed such as to maintain a slightly lower pressure in the waste management compartment than in the cabin so as to prevent odors from propagating into the cabin atmosphere. A shutoff valve is provided in the return air duct to prevent the back-flow of air in the ducts when the access panel is opened to replace used bags. Supply and return air diffusers are also included in the waste management compartments. The urine bags are bladder type bags with quick-disconnect valves connected to the urethral catheter tubes. The fecal bags are placed in an overhead compartment used for waste processing and storage. The processing is accomplished by exposure to space vacuum in an isolated part of the compartment to minimize gas losses to space.

4.2.4.2 Cost Estimating Relationships

Cost estimating relationships are given in the following paragraphs for the restrained primates' waste management assemblies. Both recurring and nonrecurring cost estimating relationships are included.

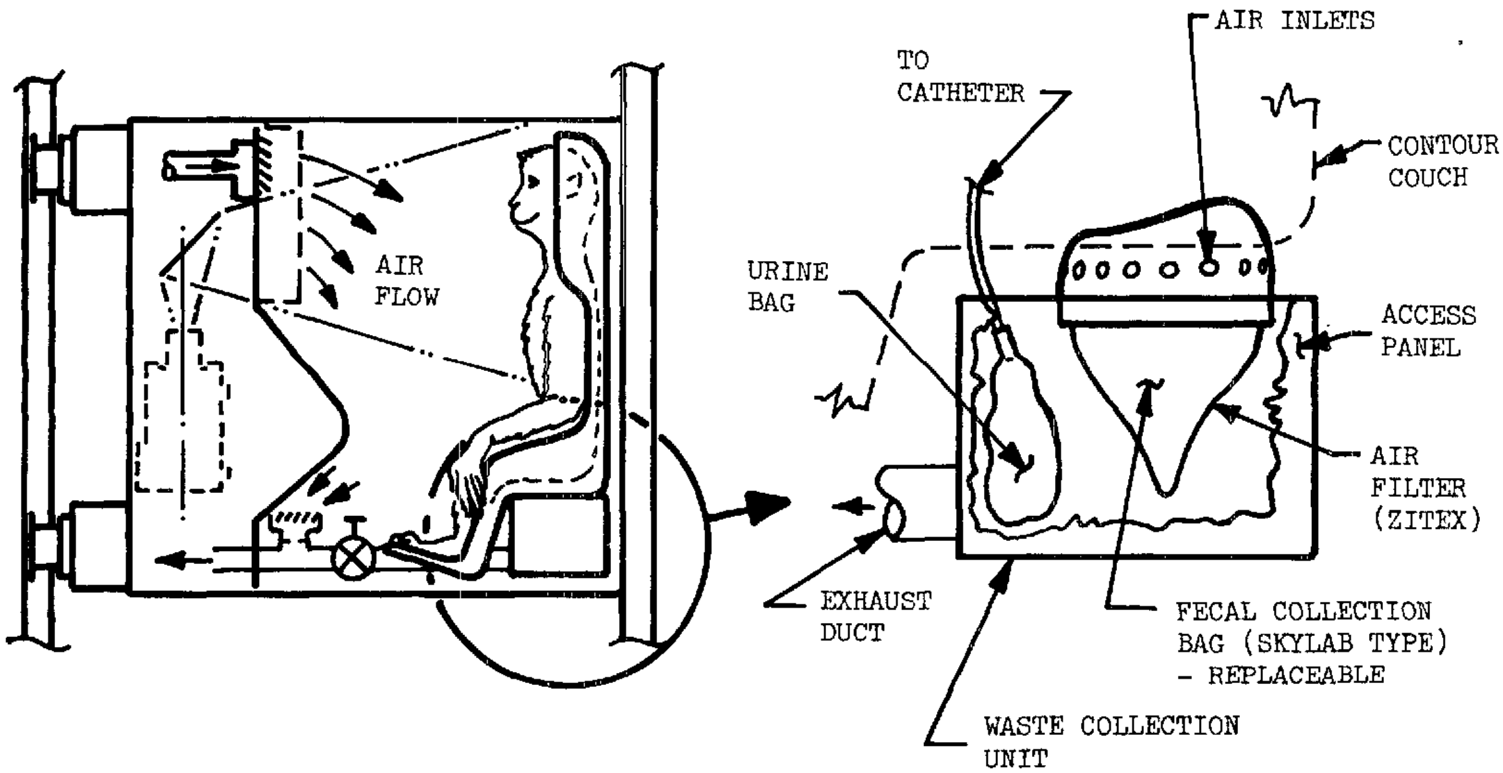

Figure 4-11. Restrained Primate Waste Management Unit

The recurring cost estimating relationship for the waste management assembly is given by the following relationship based on similar assembly costs and on the utilization of available off-the-shelf components such as the Apollo waste management bag.

$$\text{Waste management assembly cost } C = 600Q^{0.89} + 3551W_{OC} \quad \text{dollars}$$

where,

W_{OC} = weight of components other than the fecal and urine bags
= 2.0 lbs, and

Q = number of waste management assemblies required
= 6

then,

$$C = 600 \times 6^{0.89} + 2 \times 3551 = 10{,}060 \quad \text{dollars}$$

The non-recurring costs of the waste management assembly based on establishing a design and development phase expenditure breakdown based on actual cost data from the Gemini program. Allowances were made for the fact that no major subcontractor is involved. The resulting non-recurring cost breakdown percentage distribution was presented in Table 3-4.

The engineering design of the waste management assembly was assumed to require the expenditure of 1000 man-hours. Utilizing the percentage distribution listed in Table 3-4, we obtain the following estimate:

waste management assembly non-recurring cost = 173,310 dollars

The waste processing and storage compartment design cost is based on similar compartments used in the Skylab program refrigeration system, and is given as follows:

waste processing and storage compartment design cost = 59,400 dollars

The waste processing and storage compartment non-recurring cost is then obtained,

using the cost breakdown values given in Table 3-4,
to be = 343,152 dollars

The waste processing and storage compartment hardware production cost is estimated, also from Skylab experience,

to cost 25% of the design and development phase cost,
or = 85,788 dollars

The total waste management subsystem costs, including the waste management assembly and the waste processing and storage compartment, is thus given as

= 10,060 + 173,310 + 85,788 + 343,152 = 612,310 dollars

4.2.5 Food, Water and Psychomotor Complex Assemblies

The psychomotor complex is designed to evaluate the primate's performance, to monitor its eating and drinking behavior and to dispense the food and water to the primate by actuating the dispenser mechanisms. The following paragraphs present a description of the food, water and psychomotor assemblies and their cost estimating relationships.

4.2.5.1 Psychomotor Complex

The psychomotor complex comprises a psychomotor task panel and associated electronics and switching devices. The panel includes lighted visual response pushbutton, response levers and food and water light switch combinations.

4.2.5.1.1 Subsystem Performance

Details of the psychomotor task panel are shown in Figure 4-12. The visual monitoring switch-light assemblies located on the psychomotor panel house four incandescent lights mounted in holders inside the aluminum case. The plexiglass lens, which the animal depresses, is retained by the case and the panel face. When the animal depresses the plexiglass lens, the force is transmitted

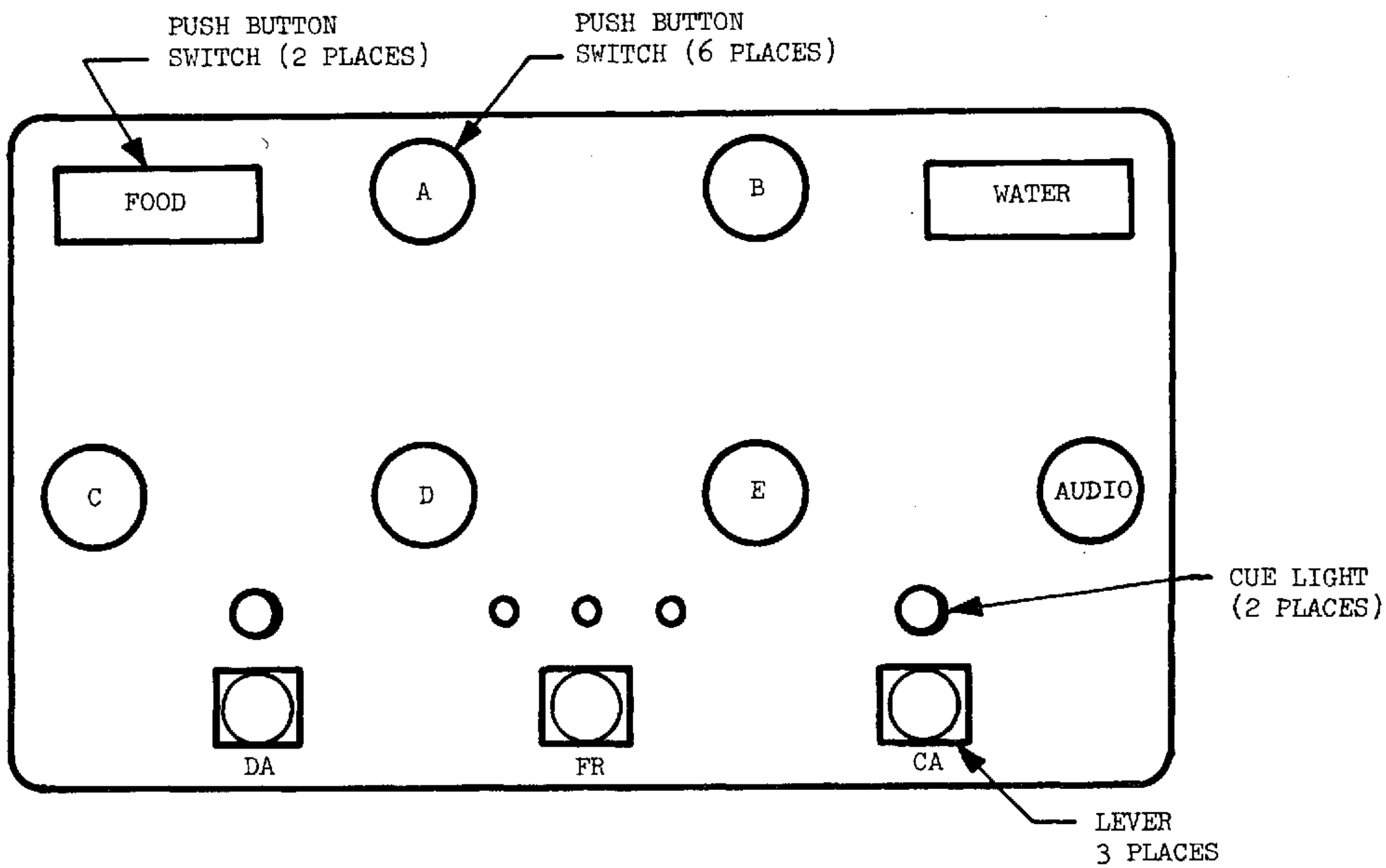

Figure 4-12. Primate Psychomotor Control Panel

to the actuation mechanism. The mechanism is mounted approximately in the center of the case and the center of the response lens. This mechanism in turn trips the miniature switches mounted on the back surface of the case. The audio device utilizes the same basic unit as the visual monitor with the exception that a speaker is mounted on the vertical panel above the psychomotor complex.

The animal's performance of tasks is indicated by lever presses and pushbutton action. A psychomotor program will be planned for the primate to test his psychological behavior and monitor his eating and drinking habits in orbit. The program will time-line the primate's test, eating and rest periods. The animal will be required to push buttons or press levers whenever required to do so by either a light or an auditory signal. The psychomotor complex will be programmed for the animal to receive an electrical shock, food or water as a result of his responses. The pushbuttons and levers shown in Figure 4-12 perform in the following manner:

A. Continuous Avoidance (CA): The animal must press the CA lever in response to the red light above the lever, at least once every 10 seconds, to avoid an electrical shock.

B. Discrete Avoidance (DA): The animal must press the DA level within 5 seconds in response to the blue light above the lever to avoid an electrical shock.

C. Fixed Ratio (FR): The animal must press the lever 50 times and then pushes either the food or water pushbuttons, to obtain food or water reinforcements.

D. Visual Monitor: The animal should respond within 5 seconds to the blue light behind any of the five pushbuttons (A, B, C, D or E) to avoid a shock.

E. Auditory Monitoring: Animal must respond within 5 seconds to the sound signal from the speaker, by pushing the auditory pushbutton, to avoid a shock.

The frequency and order of signals will be dictated by the psychomotor program.

4.2.5.1.2 Cost Estimating Relationships

Cost estimates for the psychomotor complex are included as a part of the animal holding cage's construction described in Paragraph 4.2.7.

4.2.5.2 Drinking Water Assembly

The drinking water assembly incorporates five 15-inch diameter spherical tanks shown in Figure 4-10, the biological specimen holding facility ECS schematic. The assembly provides a 32-day water supply to 8 monkeys, each consuming 290 grams/day for a total of 74.2 kilograms, or 163 lbs.

4.2.5.2.1 Subsystem Performance

A schematic showing the water dispensing assembly operation is presented in Figure 4-13. A lip lever is inset but protruding slightly from the bottom of the drinking tube. Depression of the lip lever by the animal's mouth, while the cue light is illuminated, actuates the solenoid operated valve and delivers a 7 to 8 cubic centimeters of water reinforcement. Direct current connected through the normally open and common points of the microswitch can be connected in series with the solenoid valve to provide ad libitum dispensing. Thus, every sucking response operates the valve which emits a stream of liquid. Water may be supplied either as ad libitum or as reward for performance on psychomotor tests.

The water storage tanks are bladder type developed in the LEM program. Each tank has a storage capacity of 39.5 lbs of usable water. The weight of an empty tank is 5.7 lbs.

4.2.5.2.2 Cost Estimating Relationships

The cost estimating relationships, both recurring and non-recurring, are given in the following paragraphs for the water supply tanks and the water dispenser assemblies.

A. Water Supply Tanks Assembly:

The following CER is used for the recurring cost of the water supply tanks assembly:

$$\text{Water supply tanks cost } C = 2302V^{0.267}Q^{0.89} + 3551W_{OC} \quad \text{dollars}$$

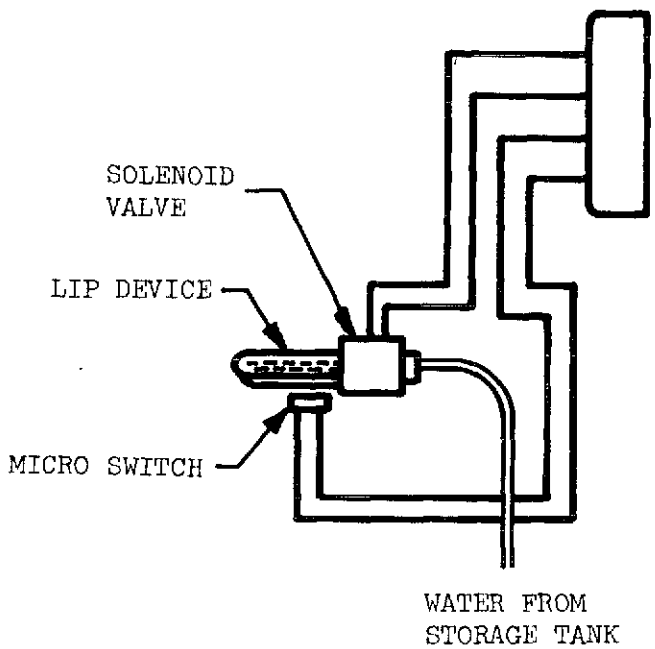

Figure 4-13. Water Dispensing Assembly Schematic

where,

V = volume of water tank, ft^3

Q = number of tanks, and

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

Substituting the values of variables in the above equation,

where,

V = $1.02\ ft^3$, $Q = 5$ and $W_{OC} = 6.0$ lbs, yields:

C = 28,296 dollars

The non-recurring cost of the tanks is estimated at four times the recurring cost = 113,184 dollars

Total cost of water supply tanks assembly = 141,480 dollars.

B. Water Dispenser Assembly:

The cost estimate of the water dispenser assembly was made based on an estimate of the required engineering time to design the assembly and then utilizing the design and development phase expenditure breakdown ratios listed in Table 3-4 to obtain the assembly's non-recurring cost. The hardware production cost was taken as = 25% of the non-recurring cost of the assembly.

Utilizing the above assumption and assuming an engineering design time of 400 man-hours, the following cost estimates have been obtained:

Non-recurring cost of water dispenser assembly	=	69,324	dollars
Hardware production cost	=	17,330	dollars
Total cost of 8 water dispenser assemblies, utilizing a learning curve factor of 93% = $69{,}324 + 17{,}330 \times 8^{0.89}$	=	179,370	dollars

4.2.5.3 Feeder Assembly

The feeder is similar to the water dispenser in that it is operated by a signal from the psychomotor complex. The food pellets may be supplied either ad libitum or as a reward for performing tasks. Each dispenser will provide the primate with 120 grams (0.26 lbs) of pellets per day, and has a storage capacity of 3.84 kg (8.5 lbs) for a 32-day supply.

4.2.5.3.1 Subsystem Performance

The feeder shown in Figure 4-14 is comprised of a chamber with a flexible diaphragm containing a load of food pellets. A gas source is used to apply pressure on the diaphragm, initiating the expulsion of food pellets. A pellet advancement mechanism, driven by a drive motor and a gear box, is used to deliver the pellets into a rubber boot type dispenser where they are held until removed by the subject. When a 28-volt DC is applied to the solenoid, it drives the pellet advancement mechanism which in turn delivers a pellet into the rubber boot dispenser.

4.2.5.3.2 Cost Estimating Relationships

The cost estimating relationships for the feeder are obtained utilizing the same method used for the water dispenser, and assuming an engineering design time of 1200 man-hours, resulting in the following estimates:

Total non-recurring cost of feeder assembly	=	207,972	dollars
Hardware production cost	=	51,993	dollars
Total cost of 8 feeder assemblies, utilizing a learning curve factor of 93% $= 207{,}972 + 51{,}993 \times 8^{0.89}$	=	538,110	dollars

4.2.6 Instrumentation, Controls and Data Management Subsystem (ICDMS)

The instrumentation, controls and data management subsystem comprises all the monitoring instrumentation required by the experiments, as well as data acquisition, processing, control and storage. The primates will be considered to be fully instrumented and provided with implanted electrodes and the matched signal conditioners for the transducers which need amplification prior to input to the multiplexers. Full use will be made of the equipment and capabilities supplied by the Spacelab. The Spacelab computers will process, display, store and/or telemeter the data, as required.

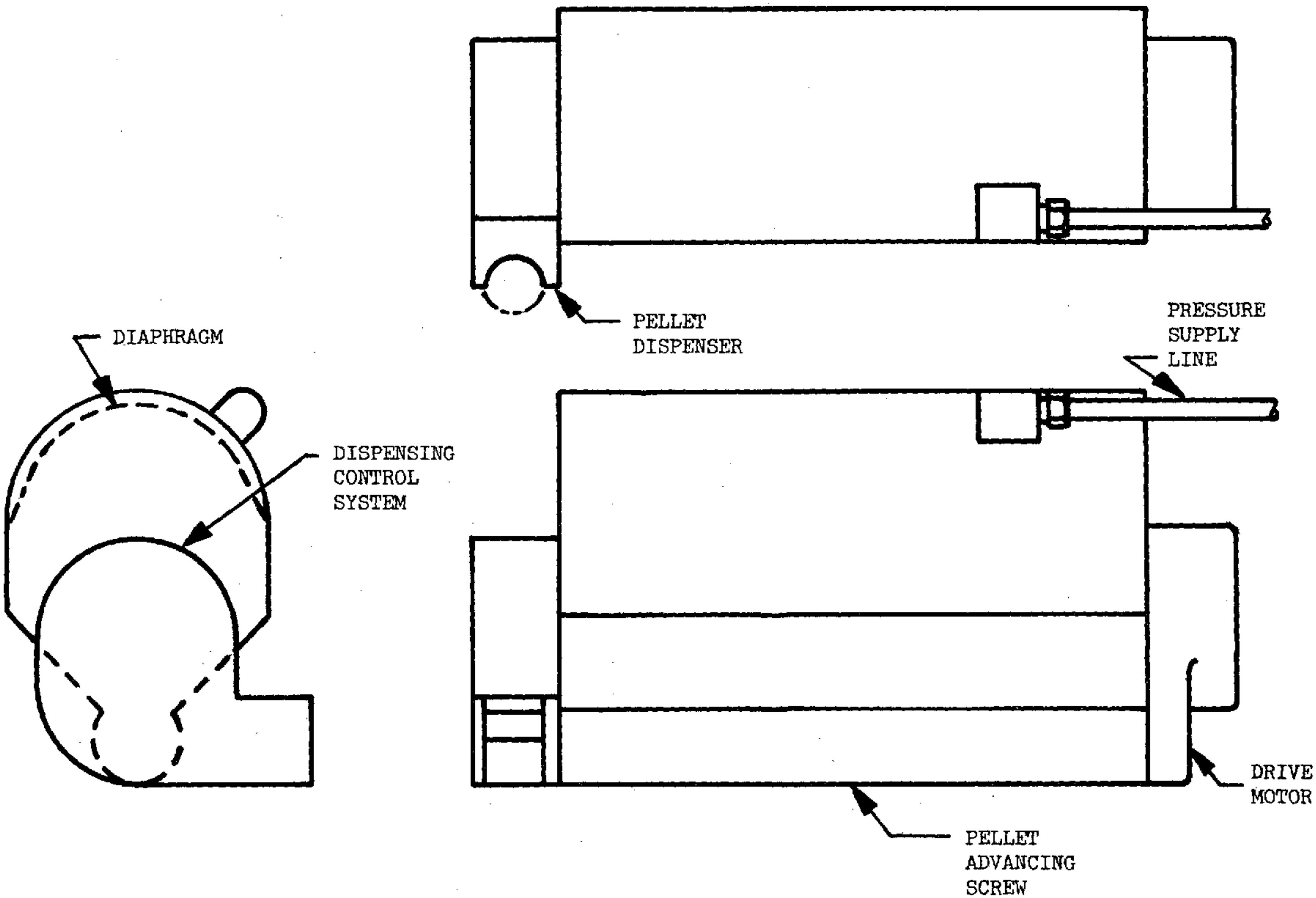

Figure 4-14. Primate Feeding Unit

A study was made of the most probable experiments that would be conducted on the Spacelab primates. A listing of instrumentation and data equipment required for the measurements involved in such experiments is presented in Table 4-10. Each hardware item listed in the Table is identified either as experiment-supplied (E) or Spacelab-supplied (S). A study of the Table indicates that in addition to the instruments and signal conditioners provided with the primates, the following equipment should also be supplied with the experiments.

A. Oscillograph (1)
B. Mass Spectrometer (1)
C. Air Flow Transducers (4)
D. Air Temperature Transducers (4)
E. Humidity Transducers (4)

Additionally, an experiment control module will provide the experimenter with a switching capability to select between experiments and display those which he requires to monitor. The experiment control module will be installed in the holding facility's control and displays console. The air temperature, flow and humidity transducers will be mounted to monitor the inlet and outlet air in two of the cages, one for restrained and one for unrestrained primates.

The oscillograph and mass spectrometer will be located in the controls and displays console which will also display air temperatures, flow and humidity and the primate's physiological parameters.

4.2.6.1 Cost Estimating Relationships

The cost of the ICDMS includes the cost of installing the signal conditioners and other interface equipment supplied with the primates, as well as procuring and installing the oscillograph, mass spectrometer and the environmental and physiological readout meters. Included will also be the design, integration and checkout of the instrumentation and control equipment and the controls and displays console.

The non-recurring cost of the ICDMS is based on an estimate of 1800 man-hours for designing the instrumentation, controls and data management provisions and an additional 300 man-hours for the design of the controls and displays console, for a total of 2,100 man-hours.

Table 4-10

SPACELAB PRIMATE EXPERIMENTS INSTRUMENTATION AND DATA EQUIPMENT LIST

	Parameter/Measurement	Equipment
I	Cardiac Output/Aortic Blood Flow	1. Implanted Electromagnetic Flow Transducer with trancutaneous connector (E)* 2. Power Supply (S) 3. Signal Conditioner (E) 4. Oscillograph (strip chart) (E) 5. Magnetic Tape Recorder and TM (S)**
II	Coronary Flow/Coronary Blood Flow	1. Implanted Electromagnetic Flow Transducer with trancutaneous container (E) 2. Power Supply (S) 3. Signal Conditioner (E) 4. Oscillograph (strip chart) (E) 5. Magnetic Tape Recorder and TM (S)
III	Cerebral Blood Flow/Internal Carotid Artery Blood Flow	1. Implanted Electromagnetic Flow Transducer with transcutaneous container (E) 2. Power Supply (S) 3. Signal Conditioner (E) 4. Oscillograph (strip chart) (E) 5. Magnetic Tape Recorder and TM (S)
IV	Direct, Continuous, Arterial Blood Pressure/Radial or Illiac Blood Pressure	1. Implanted physiological resistance transducer with trancutaneous connector (E) 2. Signal Conditioner (E) 3. Power Supply (S) 4. Oscillograph (E) 5. Tape Recorder and TM (S)
V	Direct, Central Venous Pressure/Pressure in Vena Cava or Right Atrium	1. Catheter - Tip Blood Pressure Transducer (E) 2. Signal Conditioner (E) 3. Power Supply (S) 4. Oscillograph (E) 5. Magnetic Tape Recorder and TM (S)

(*) Equipment supplied by Experiment
(**) Equipment supplied by Spacelab

Table 4-10

SPACELAB PRIMATE EXPERIMENTS INSTRUMENTATION AND DATA EQUIPMENT LIST (Continued)

	Parameter/Measurement	Equipment
VI	Heart Rate and Electrical Activity/Electrocardiogram (ECC)	1. Implanted subcutaneous Ag-AgCl electrodes (3-6) (E) 2. Signal Conditioner (E) 3. Cardiotachometer (E) 4. Oscillograph (E) 5. Magnetic Tape Recorder and TM (S)
VII	Vestibular Nerve Activity/ Vestibular Nerve Electrical Activity	1. Implanted Vestibular Nerve Electrode (E) 2. Signal Conditioner (E) 3. Frequency Analyzer (S) 4. Oscilloscope (S) 5. Magnetic Tape Recorder and TM (S)
VIII	Neck Muscle Tension/Electromyograms of Trapezius, Splenius Capitus, Splenius Cerric	1. Implanted EMG Electrodes (6) (E) 2. Signal Conditioner (E) 3. Oscilloscope (E) 4. Magnetic Tape Recorder and TM (S)
IX	Brain Electrical Activity/ Electroencephalogram (EEG)	1. Subcutaneous Electrodes (8) (E) 2. Signal Conditioner (E) 3. Oscillograph (E) 4. Frequency Analyzer (S) 5. Magnetic Tape Recorder and TM (S)
X	Eye Movement/Electro-oculogram	1. Subcutaneous Ag-Ag Cl Electrode (E) 2. Signal Conditioner (E) 3. Oscillograph (E) 4. Magnetic Tape Recorder and TM (S)
XI	Body Temperature/Arterial Blood Temperature	1. Temperature Thermistor Associated with blood pressure transducer (E) 2. Signal Conditioner (E) 3. Oscillograph (E) 4. Magnetic Tape Recorder and TM (S) 5. Digital Display (S)
XII	O_2 Consumption and CO_2 Production/Cage Inlet and Outlet PO_2 and PCO_2	1. Airflow transducers - inlet and outlet for each cage (E) 2. Mass spectrometer (E) 3. Oscillograph (E) 4. Signal Conditioners (2) (E) 5. Magnetic Tape Recorder and TM (S)

(*) Equipment supplied by Experiment
(**) Equipment supplied by Spacelab

Table 4-10
SPACELAB PRIMATE EXPERIMENTS INSTRUMENTATION
AND DATA EQUIPMENT LIST (Continued)

	Parameter/Measurement	Equipment
XIII	Body Heat Exchange Rate/Cage Inlet and Outlet PH_2O, Temperature Flow	1. Airflow transducers - inlet and outlet for each cage (E) 2. Air temperature transducers - inlet and outlet (E) 3. Humidity Transducers - inlet and outlet (E) 4. Signal Conditioners - 6/cage (E) 5. Digital display (S) 6. Oscillograph (E) 7. Magnetic Tape Recorder and TM (S)
XIV	Blood Analysis/O_2, CO_2, pH, Radio Active Tracers, RBC and WBC counts, WBC differential, Na, K, Cl, Ca	1. Blood Gas Analyzer (E) 2. pH meter (E) 3. Liquid scintillation counter (E) 4. Well scintillation counter (E) 5. Coulter counter (E) 6. Microscope (E) 7. Specific ion electrodes (E) 8. Signal conditioners (8) (E) 9. Digital display (S) 10. Oscilloscope (S) 11. Magnetic Tape Recorder and TM (S)
XV	Blood, Urine, and Fecal Storage/Refrigerator and Freezer Temperatures	1. Refrigerator and freezers temperature transducers (E) 2. Signal conditioners (3) (E) 3. Digital Display (S) 4. Magnetic Tape Recorder and TM (S)

(*) Equipment supplied by Experiment
(**) Equipment supplied by Spacelab

Utilizing the design and development phase expenditure breakdown given in Table 3-4, the total non-recurring cost of the ICDMS is estimated at

363,950 dollars

The recurring cost will include the hardware production cost, estimated at 25% of the design and development phase cost, and the cost of purchsing the major parts. Included are the oscillograph at $14,000, the mass spectrometer at $100,000 and the transducers and meters at $52,000, for a total of $166,000. The total recurring cost is then

$$= 0.25 \times 363{,}950 + 166{,}000 = 256{,}988 \quad \text{dollars}$$

The total cost of the instrumentation, controls and data management subsystem

$$= 363{,}950 + 256{,}988 = 620{,}938 \quad \text{dollars.}$$

4.2.7 Holding Cages

Two types of primates holding cages are required for the holding facility, one for restrained primates and the second for unrestrained primates. Each of the cages will include a couch and restraints, waste management, psychomotor task panel, food and water dispensers, camera, viewing port, air distribution ducts and diffusers, lights and wiring for instrumentation and controls. A description of each of the cages is given in the following paragraphs.

4.2.7.1 Restrained Primate Cage

This cage, shown in Figure 4-15, has outside dimensions of 17" x 24" x 22.5", and has a double wall stainless steel construction with 0.5 inch insulation and double-pane glass viewping port to prevent condensation of the hot humid air on the inside walls of the cage. The cage slides in and out of its rack space on two slide bars mounted on one side of the cage. Quick-disconnect valves are provided for inlet and outlet air ducts. Cannon-type plugs are also used for transmission of instrumentation signals and electrical power for lighting and psychomotor panel operation.

A contoured couch is provided for the primate. The couch is installed on tracks so that it can be rotated 90 degrees during launch in order to have the launch G-forces exerted on the monkey in the chest-to-back axis.

The psychomotor complex is located in a slanted panel in front of the primate, when seated in his on-orbit position. The camera is located behind the psychomotor panel. An opening in the vertical panel, together with a mirror at a

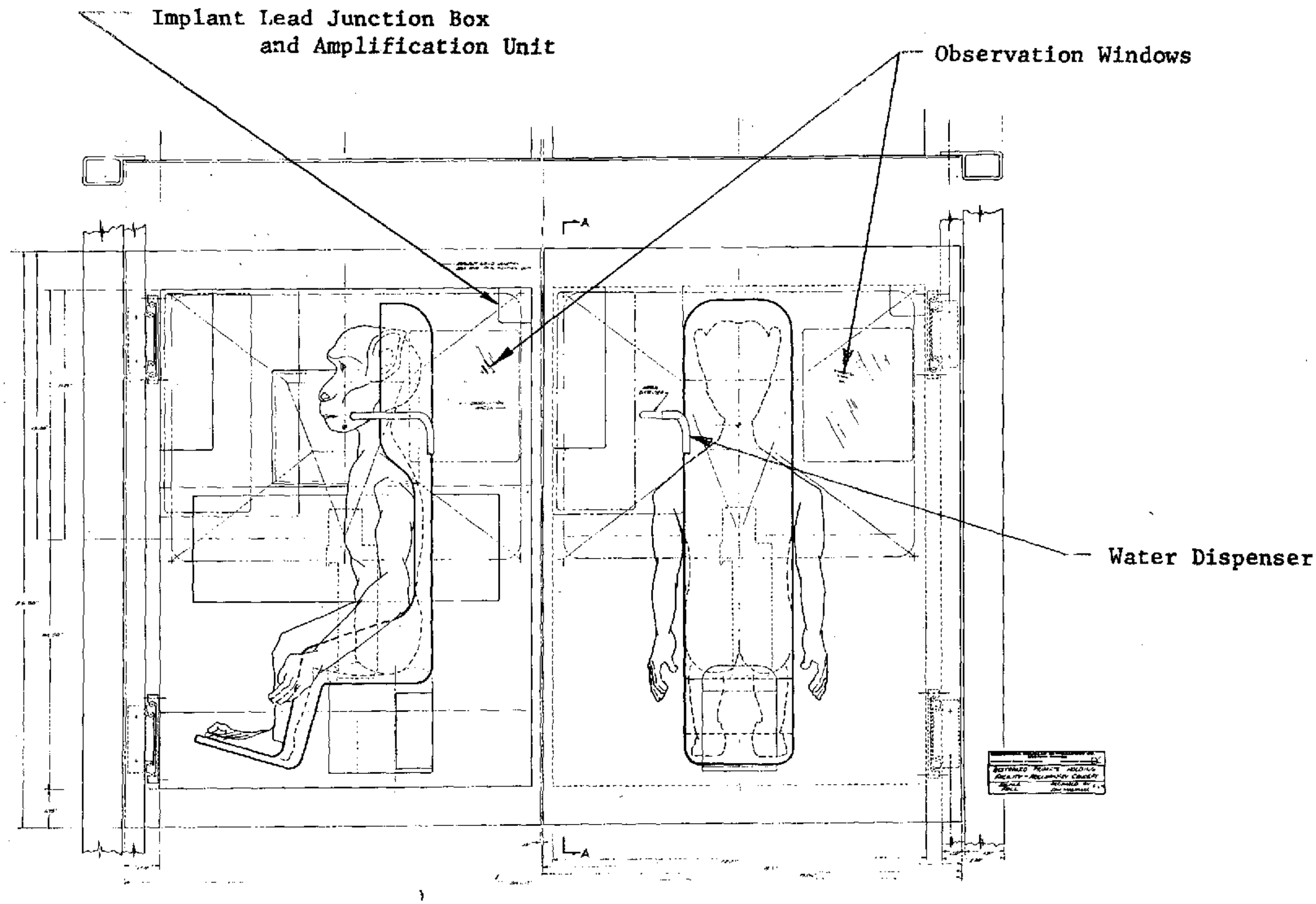

Figure 4-15. Restrained Primate Holding Cage - Front View

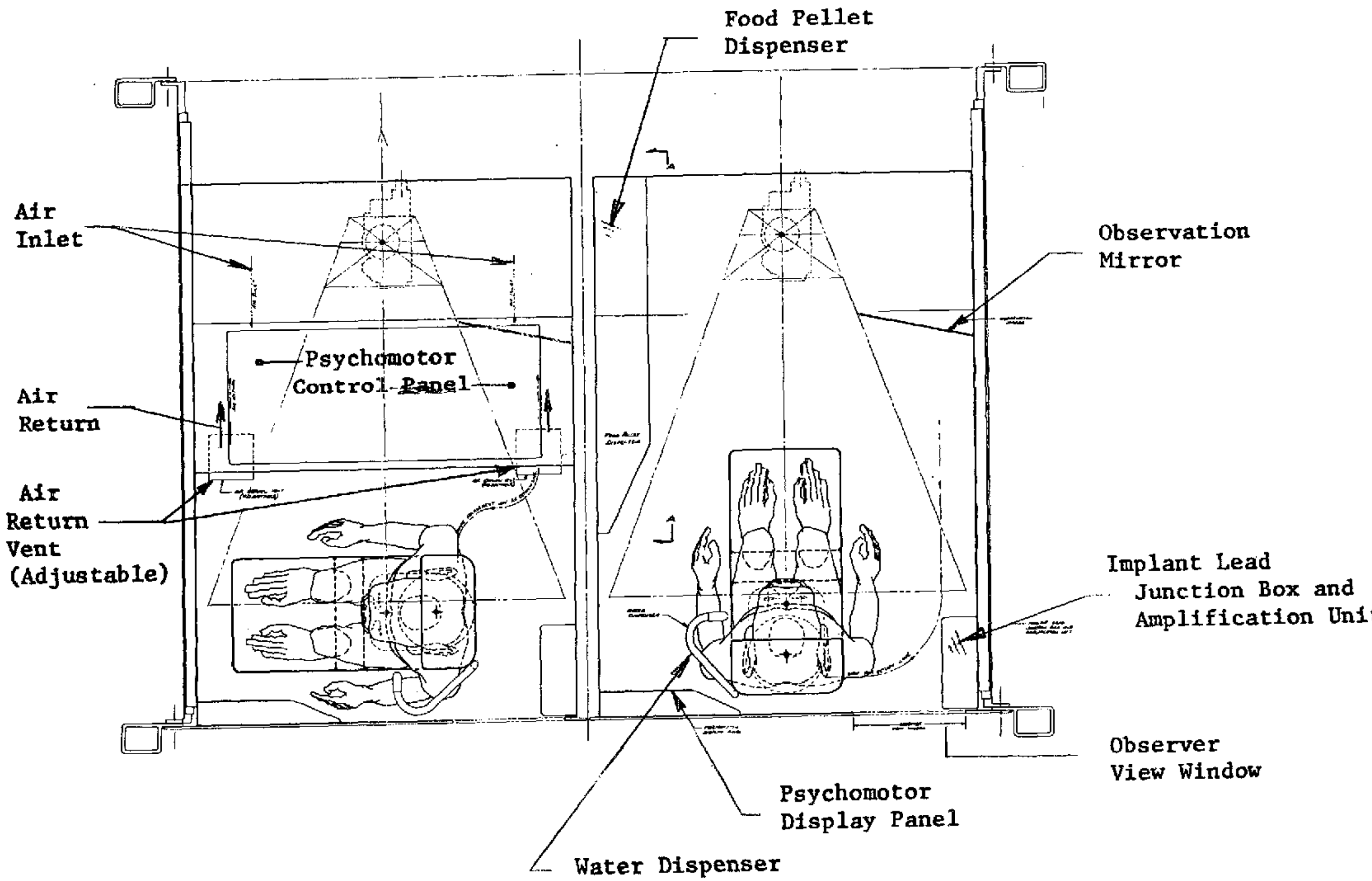

Figure 4-15. (Cont). Restrained Primate Holding Cage - Top View

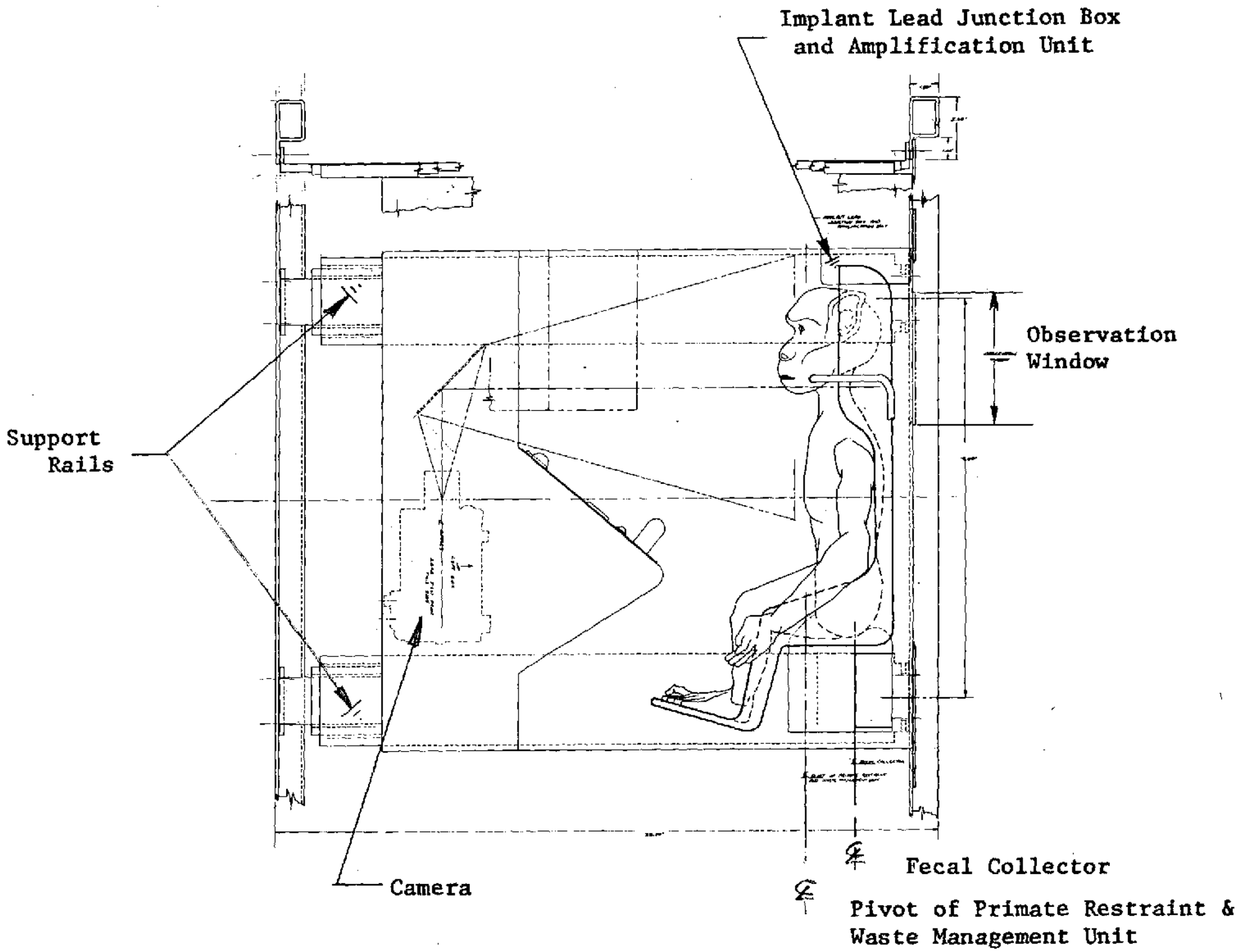

Figure 4-15. (Cont.) Restrained Primate Holding Cage - Side View

45° angle, permit the camera to record primate's activity. The camera is activated only when certain, previously assigned, panel levers or pushbuttons are pressed by the monkey. Manipulations and results of psychomotor tests are also displayed on the wall behind the primate's left shoulder so as to be in view to be recorded by the camera. The feeder and the water dispenser are placed to the left of the vertical panel. A mirror inside the cage is used to enable the attenting scientist to view the activities of the monkey from the viewport in the front wall of the cage. Air distribution in the cage is made through outlets that direct the flow along the sidewalls of the cage and then to the waste management compartment.

4.2.7.1.1 Cost Estimating Relationships

The cost of primate's cage includes the cost of constructing the cage and psychomotor task panel and the installation in the cage of the other support equipment described above. No cost data for similar systems were found to provide the basis for developing a new CER for the cage. Accordingly, cost estimates were made, based on an engineering design requirement of 2500 man-hours, resulting in the following:

Total non-recurring cost of holding cage	= 433,275 dollars
Hardware production cost	= 108,319 dollars
Total cost of six cages	
$= 433,275 + 108,319 \times 6^{0.89}$	= 967,288 dollars

4.2.7.2 Unrestrained Primate Cage

This cage is twice the size of the restrained cage. It also utilizes the same construction and equipment as the restrained cage, with two exceptions: 1) a new, yet undefined waste management subsystem will have to be used to accommodate the unrestrained primate; and 2) a biological telemetry system should be provided to monitor and transfer the primate's physiological parameters. A modified air distribution system should also be installed in the unrestrained primate cage, which will be compatible with both the waste management subsystem and the enlarged cage size. A couch and restraints will also be included in the cage to protect the primate during launch. No detail design of the unrestrained primate cage, similar to that conducted for the restrained primate cage, was performed in this phase of the study.

4.2.7.2.1 Cost Estimating Relationships

Cost estimates for the unrestrained primate cage were based on technical judgments to assess the increased complexity of the cage as compared to a restrained primate cage. Cost estimates were then scaled, utilizing the same procedure and assumptions employed in the restrained primate cage, but with increased engineering design time of 4000 man-hours to account for the additional effort required for waste management, air distribution and instrumentation modifications. The following cost estimates are thus obtained:

Total non-recurring cost of holding cage	= 693,240 dollars
Hardware production cost	= 173,310 dollars
Total cost of two cages	
$= 693{,}240 + 173{,}310 \times 2^{0.89}$	= 1,014,730 dollars

4.2.8 Refrigerator and Freezer Assembly

The refrigerator/freezer assembly is located in a 35" x 21-1/2" x 21" enclosure. The space is divided into three compartments: a 5°C (40°F) refrigerator occupying half the volume, a -20°C (-4°F) freezer occuping one quarter of the volume and a -60°C (-76°F) freezer occupying the remaining quarter of the volume. The refrigerator will be used for the storage of perishables. The -20°C freezer will be used mainly for the storage of urine samples while blood plasma will be stored in the -60°C freezer.

4.2.8.1 Subsystem Performance

Spacelab coolant supply lines will be extended to the refrigerator/freezer compartments to cool them to 5°C (40°F). The two freezer spaces will then be lowered further to -20°C (-4°F) and -60°C (-76°F), utilizing thermoelectric refrigeration modules. The 5°C refrigerator is-designed for cooling load of 300 watts while each of the freezer spaces is designed for a cooling load of 30 watts. The thermoelectric assembly includes a total of 28 thermoelectric modules, each weighing 23.0 grams, which are used in a series-parallel arrangement to provide the required freezer compartments cooling. The thermoelectric assembly also includes a variable power supply and two bipolar-type temperature controllers. The power supply and temperature controllers are especially designed for operation with the thermoelectric assembly.

4.2.8.2 Cost Estimating Relationships

Cost estimating relationships for the refrigerator/freezer assembly are presented in the following paragraphs. Included are the refrigerator/freezer compartments and the thermoelectric refrigeration assembly. The cost of the compartments is based on the Skylab refrigeration system compartments cost data and is given as follows:

Refrigerator/freezer compartment design cost = 59,400 dollars

The design and development phase expenditure breakdown is obtained from the expenditure breakdown ratios listed in Table 3-4, resulting in a total design and development phase cost of the refrigerator/freezer compartments

= 343,152 dollars.

The hardware production phase cost of the refrigerator/freezer compartment is estimated at 25% of the design and development phase cost, or

= 85,788 dollars.

The total cost of the compartments

= 85,788 + 343,152 = 428,940 dollars.

The cost of the thermoelectric refrigeration assembly is based on the procurement of commercially available components, followed by the integration and test of the assembly. The components comprise 28 thermoelectric modules, one power supply and two temperature controllers. The non-recurring cost is based on 1) making an estimate of the number of man-hours required to design the thermoelectric refrigeration assembly; and 2) utilize the design and development phase expenditure breakdown shown in Table 3-4 to obtain the total non-recurring cost of the assembly. The design of the thermoelectric assembly is estimated to require an estimated 2000 engineering hours. Applying the design and development phase expenditure breakdown factors yields the following:

Thermoelectric refrigeration assembly non-recurring cost = 346,620 dollars

The recurring cost of components comprises $1400 for 28 thermoelectric modules, $1300 for power supply, $4340 for two temperature controllers and an additional 20% for supporting materials and supplies, for a total of $8448.

Thus,

Total cost of thermoelectric refrigeration assembly
= 346,620 + 8,448 = 355,068 dollars

and,

Total cost of refrigerator/freezer assembly
= cost of compartments + cost of thermoelectric assembly
= 428,940 + 355,068 = 784,008 dollars

4.2.9 Photographic Assembly

Cameras used are the commercially available 16mm Data Acquisition Cameras, Model 308, developed by J. I. Maurer, Inc., for the Apollo program. The cameras can be used for 1, 6, 12 or 24 frames per second are are each equipped with an attachment for single frame photography. Each of the cameras used is provided with a lens suitable for the focal length and dimensions of the animal or specimen container in which the camera is used.

4.2.9.1 Cost Estimating Relationships

The recurring cost estimating relationship for cameras used in the primate and small vertebrate cages are given as follows:

Photographic assembly cost
$C = 7550N + 2000$ dollars

where,

N = number of cameras used.

The cost of each camera comprises $500 for the base unit without lens, $1750 for the single frame attachment and $300 for the lens.

Thus,

N = 12:

C = 92,600 dollars

The non-recurring cost of the photographic assembly is based on estimating the requirement of 500 man-hours of engineering design for camera mounts, drives and mirrors. Utilizing the design and development expenditure breakdown listed in Table 3-4 to obtain the non-recurring cost of the assembly, we obtain the following:

Photographic assembly
non-recurring cost = $86,655

and,

Total cost of photographic
assembly = 92,600 + 86,655 = $179,255

4.2.10 Holding Facility Construction Interfaces

The construction of the primate holding facility includes the design, development and assembly of the primate cages, the ECS equipment compartment, refrigerator, waste management processor, zero-gravity workbench, operating table and the controls and displays console.

4.2.10.1 Cost Estimating Relationships

Utilizing the same methodology used in previous sections to estimate the cost of the holding facility construction and assuming an engineering design requirement of 600 man-hours results in the following:

Non-recurring cost of holding facility construction = 103,986 dollars

Hardware production cost = 25,977 dollars

Total cost of holding facility construction

= 103,986 + 25977 = 129,873 dollars

4.2.11 Power Control and Distribution System

The power control and distribution system comprises the controls and distribution equipment to supply and manage electrical power to the experiment hardware. Power control and distribution system cost is summarized as follows:

Non-recurring cost	=	$228,219
Recurring production cost	=	$122,158

4.2.12 Primate Holding Facility Experiment Cost

The total cost of the primate holding facility experiment is obtained from the summation of the cost items given in the preceding paragraphs and summarized in Table 4-11.

Table 4-11

COST OF PRIMATE HOLDING FACILITY EXPERIMENT

Cost Item*	Cost in 1974 $	
	Design and Development	Production
Environmental Control Subsystem	3,619,830	702,113
Waste Management Subsystems	516,462	95,848
Food Water Subsystems	277,296	440,184
Instrumentation, Controls and Data Management	363,950	256,988
Holding Cages	854,803	1,127,215
Refrigerators/Freezers	689,772	94,272
Photographic Assembly	86,655	92,600
Construction Interfaces	103,986	25,997
Power Control and Distribution	228,219	122,158
Total	6,740,973	2,957,375

(*) Project management, system engineering, system test and other non-recurring cost estimates are allocated to subsystem cost estimates.

4.3 MEDICAL EMPHASIS LIFE SCIENCES SPACELAB EXPERIMENT

4.3.1 Purpose

The Life Sciences Spacelab (LSSL) is a flight laboratory intended for use as a general purpose research facility to conduct research and technology experiments in the areas of medicine, biology, life support and man-system integration. The laboratory will contain the experiment subjects, research equipment and instrumentation, and data handling capability to conduct limited onboard research and analysis in each of the stated life science disciplines. The operation of the laboratory will be by discipline scientists plus a mission specialist. Research will be accomplished on a range of test subjects, including man, on (1) problems related to the zero-g and radiation characteristics of space; (2) problems of short term (30 days) adaptation of biological organisms to weightlessness; (3) the role of gravity in maintaining selected normal functions of organisms on the earth's surface; and (4) a variety of advanced technology research in the areas of life support and man-system integration, including extravehicular activities and teleoperators.

The laboratory is planned to have 14.7 psia sea level atmosphere to permit shirt sleeve operations. It will be as near zero-g operation as the Shuttle environment will permit. It will be designed for post-flight refurbishment and for reuse on subsequent flights. The laboratory will have a lifetime of ten years to support the research and technical requirements of manned space flight programs.

4.3.2 Objectives

The Life Sciences Spacelab will be used to conduct the following:

A. Research directed at understanding the origin of life and the search for extraterrestrial evidence or precursors of life.

B. Biomedical research necessary to understand mechanisms and provide the criteria for countermeasures in support of manned space flight.

C. Advanced technology development on life support and work aids to provide as near an earth atmospheric environment for man as possible in order to provide him with protection from hazards of the space environment, optimize his ability to work in space, and to maintain his health.

D. Research in biology to investigate those mechanisms observed to have changed in space on man-models wherein the investigation cannot be done on man, and to study basic bological functions at all levels or organization (subcellular, cellular, system, and organism) influenced by gravity, radiation, and circadian rhythms; factors which are inherent in the space flight environment.

4.3.3 Guidelines and Constraints

4.3.3.1 The Life Sciences Spacelab project includes the definitions, design, development and operations of the Life Sciences Spacelab and interface requirement to interconnect and maintain the payload and the Spacelab spacecraft. The project also includes ground operations involving experiment mission preparation, astronaut training, data evaluation and experiment refurbishment and checkout.

4.3.3.2 The Life Sciences Spacelab is a general purpose facility for the performance of biomedical and biological research and for in-flight verification and testing of advanced technology and man-system integration equipment. The Life Sciences Spacelab will be installed with the Spacelab spacecraft and be transported to and from orbit by the shuttle orbiter. The Life Sciences Spacelab will provide the life sciences community with a flexible, low-cost laboratory facility capable of accommodating a broad spectrum of tests and experiments, with rapid user access and minimum interference with payloads or shuttle orbiter activities.

4.3.3.3 The 30-day Life Sciences Spacelab will be initially launched in the shuttle to a 100-mile, 28.5 degree inclination parking orbit where shuttle and payload systems are verified. The system is then boosted to the 200-mile altitude where the research will be carried out. Following 30 days of planned research activities, the orbiter will deboost and land at the launch complex.

4.3.3.4 The baseline plan will include the design, development and production of the flight units of the Life Sciences Laboratory, associated experiment mission preparation conduct, data evaluation and documentation in accordance with an initial 1980 shuttle flight.

4.3.3.5 The flight program plan will involve two flights per year for a 12-year program lifetime. One laboratory will undergo refurbishment, equipment removal and replacement and updating while the other unit is in flight. Each LSSL mission will include a different combination of experiments selected from the various disciplines of life sciences.

4.3.4 Life Sciences Spacelab Description

A medical emphasis mission configuration, featuring biomedical and biological research, is shown in Figure 4-16 and described in the following paragraphs.

The medical emphasis mission LSSL is designed to support biomedical research mainly in the cardiovascular, respiratory, neurological, musculoskeletal, gastrointestinal, and metabolic areas. Facilities are also provided for research in cell and tissue culture, primate and small vertebrate research. A limited amount of research in man-system integration and life support technologies could also be accomplished in this LSSL configuration.

The LSSL, as shown in Figure 4-16, is comprised of nine basic wall units, overhead cabinets, a work and surgical bench and four individual Skylab-type experiment devices. The Skylab-type experiments are: 1) lower body negative pressure device; 2) body mass measurement device; 3) physiological exercise equipment; and 4) rotating litter chair. A description of the nine basic wall units and the research to be used in each is as follows:

4.3.4.1 Crew Work Station and Stowage Unit

This unit is primarily a crew work station, comprising a work bench, Betadine cleaners unit, film vault and stowed vacuum cleaner. Included also are an organism holding kit and a veterinary kit, used primarily for animal and biological research.

4.3.4.2 Cells and Tissues Holding Unit

This unit is used primarly for cells and tissue culture research activities. Major components in the unit are an incubator and a sealable colony chamber.

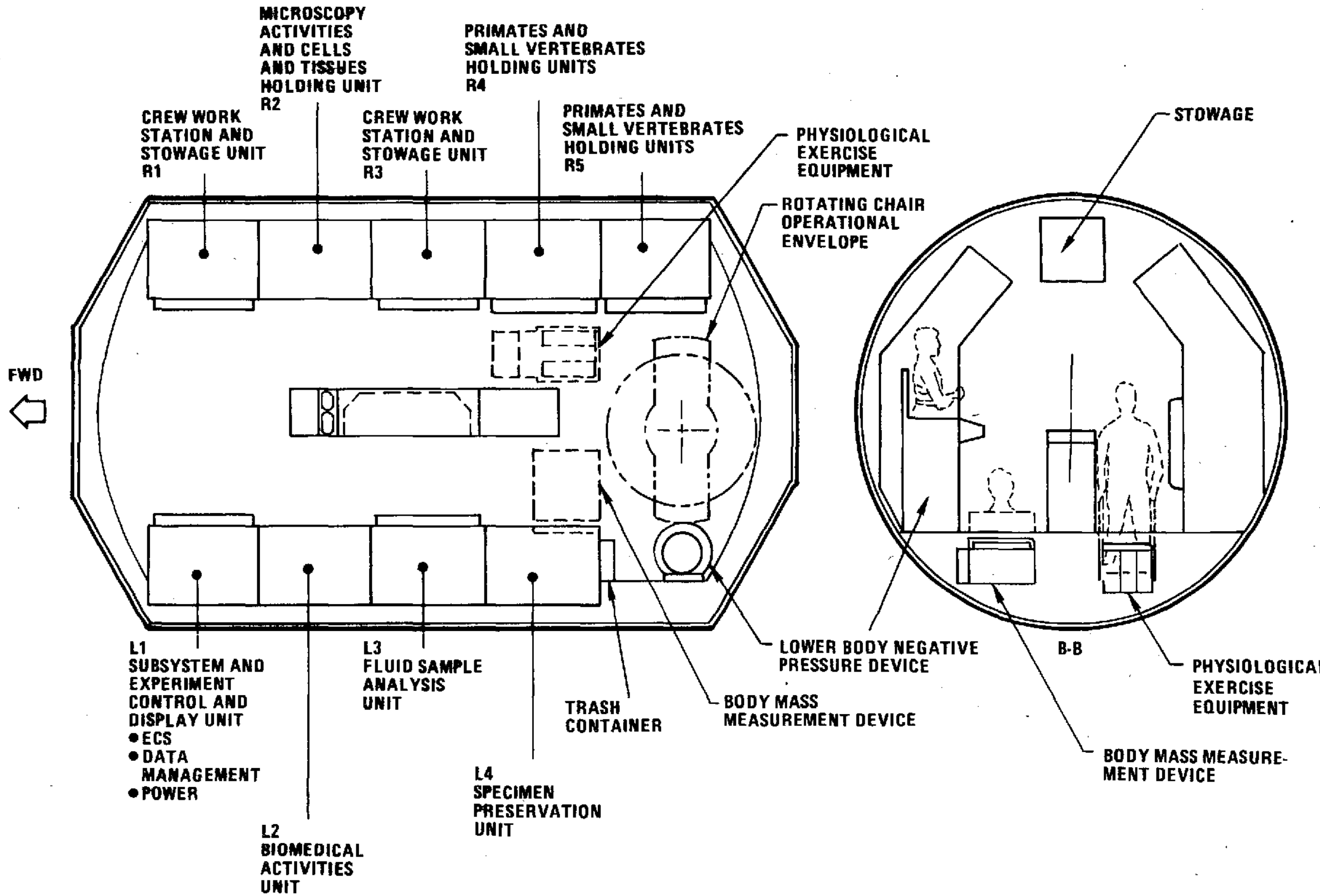

Figure 4-16. Life Sciences Spacelab - Medical Emphasis Mission Configuration

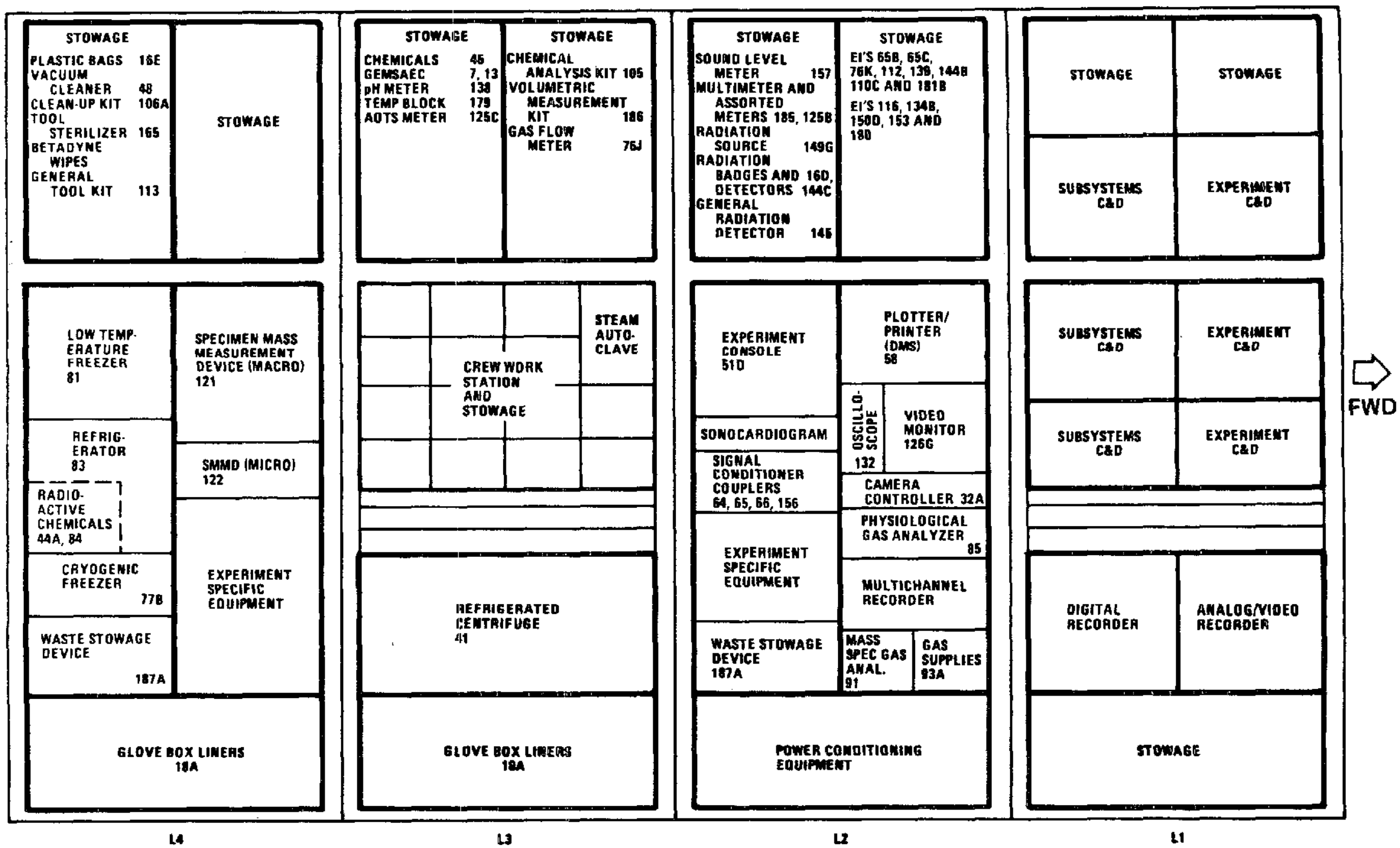

Figure 4-16 (Cont.) Life Sciences Spacelab - Medical Emphasis Mission Configuration - Left Elevation

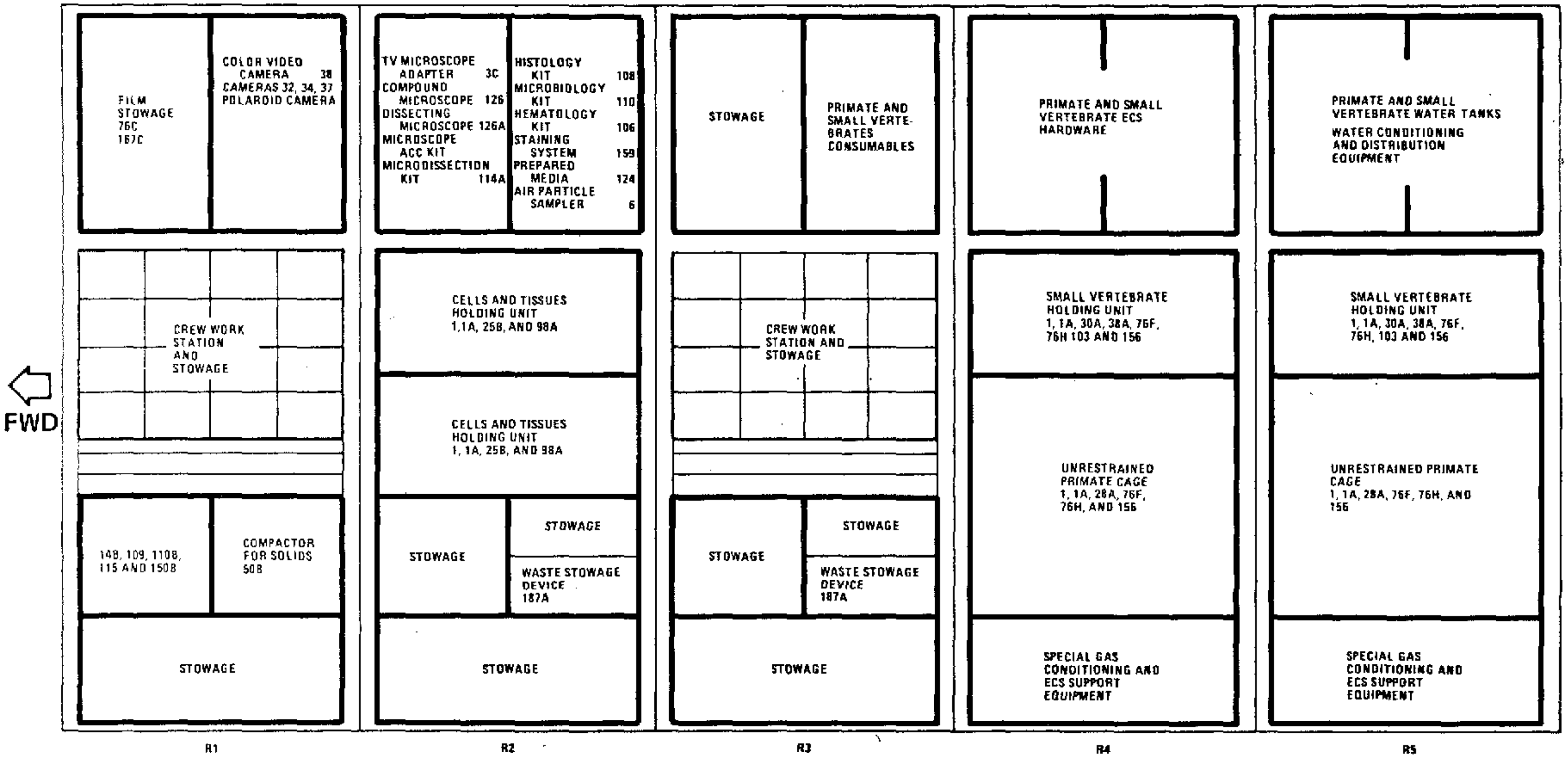

Figure 4-16 (Cont.) Life Sciences Spacelab - Medical Emphasis Mission Configuration - Right Elevation

Included also in this unit are an air particle sampler, a waste storage device and an assortment of prepared media. Antennas and a receiver used to support animal biological instrumentation are stowed in this unit.

4.3.4.3 Visual and Microscopic Examination Unit

This is a basic support unit where major microscopy work for all biomedical and biological research activities are conducted. A compound microscope, a dissecting microscope, a microscope accessory kit and a TV/microscope adapter for viewing and transmitting microscope images are provided in this unit. Included also are a microdissection kit, as well as kits for research in microbiology, histology and hematology. The unit also includes a crew work station where visual and microscopic examination work is performed and a waste storage device for disposal of experiment waste materials and chemicals.

Included in this unit also are the following cameras: 1) cine camera for visual recording of experiments; 2) still camera to provide still photographic records of various experiment phenomena; 3) black and white video camera for recording and monitoring experiments and organisms; and 4) video color camera for recording and monitoring experiment phenomena for down-linking data. A polaroid camera is also provided.

4.3.4.4 Primate and Small Vertebrate Holding Units

Two of the nine basic wall units are devoted to primate and small vertebrate research. Included are two unrestrained primate cages, two small vertebrate holding units, associated environmental control equipment and stored consumables. The unrestrained primate cage includes the cage, water and food dispensers, water flowmeter, flowmeter coupler, signal conditioner coupler, accelerometer and accelerometer coupler. The small vertebrate holding unit includes a rat/hamster cage, food and water dispensers, water manifold flowmeter, flowmeter coupler, basic holding unit, signal conditioner couplers, accelerometer and accelerometer coupler. The ECS equipment includes filters, condensing heat exchanger, condensate collection assembly, controller, blowers, ducting, tubing and valves. Stored consumables include water, food, oxygen and LiOH canisters.

4.3.4.5 Display Control Console and Data Management

This unit is supplied as a part of the Spacelab which provides the computers and all support equipment. The major components supplied by Spacelab include the following:

A. Data display system, comprising keyboards, CRT displays, symbols, type display, TV camera, video monitor and intercom.
B. Three computers with 32K word memory.
C. Input/output unit.
D. Mass memory.
E. Ten remote acquisition units.
F. Control panel.
G. High bit rate recorder
H. Video/analog recorder.
I. Recorder and communication control unit.
J. Caution and warning logic unit.
K. Caution and warning panel.

4.3.4.6 Biomedical Activities Unit

Included in this unit is the equipment required to support the researchers in conducting a wide variety of biomedical research activities including those in cardiovascular, respiratory, neurological, musculoskeletal, gastrointestinal and metabolic research areas. The equipment is primarily for human research but may also be used in other animal and biological experiments. The following equipment items are provided in this unit: psychogalvanometer, doppler flowmeter, limb plethysmograph, plethysmograph transducer, gas flowmeter, power conditioning equipment, physiological kit, video monitor, oscilloscope, physiological gas analyzer, experiment console, signal conditioner couplers, multichannel recorder, recording paper, electrophysiological receiver and camera controller. Included also are: receiver, voice recorder, event timer, linear measurement kit, medical physical examination kit, electrophysiological backpack, sonocardiogram, plotter/printer (DMS) and waste stowage device.

The biomedical activities unit also includes radiobiology research equipment such as radiation source, badges and detectors as well as a sound meter and other assorted meters.

4.3.4.7 Fluid Sample Analysis Unit

This unit includes a work station, chemicals and equipment for performing fluid sample analysis work. A chemical analysis kit, chemical storage cabinet, mass spectrometer analyzer, AOTS meter, pH meter and staining system are provided. Included also are a GEMSAEC analyzer which can provide 30 to 35 individual analyses on each sample, a refrigerated centrifuge, and gas supplies.

4.3.4.8 Specimen Preservation Unit

This unit provides the researchers with the equipment and the refrigerated storage spaces necessary for the collection, conditioning and storage of specimens. Included in this unit are a solids compactor, tool sterilizer, steam autoclave, two specimen mass measurement devices, general tool kit, clean-up kit, and waste storage device. The refrigerated spaces provided in this unit include a cryogenic freezer at -200°F, a low temperature freezer at -95°F and a refrigerator at 40°F.

4.3.5 Cost Estimates

A work breakdown structure (WBS) for the Life Sciences Spacelab is shown in Figure 4-17. The LSSL equipment cost was calculated at the component level (level 7), then added up to the assembly, subsystem and system levels. System level (level 4) cost elements were then included to arrive at the total LSSL project level (level 3) cost. A discussion of the various cost estimates, starting with the laboratory equipment cost, is given in the following paragraphs. Cost items are provided in non-recurring design and development, recurring production and recurring operations.

4.3.5.1 Laboratory Equipment Cost

Laboratory equipment total cost has been divided into equipment unit costs and is presented in detail in Table 4-12. Component costs have been obtained primarily from References 4.3-1 through 4.3-3. The equipment cost presented includes the recurring production and non-recurring cost of the components. The cost of equipment integration and installation is presented in the following paragraph.

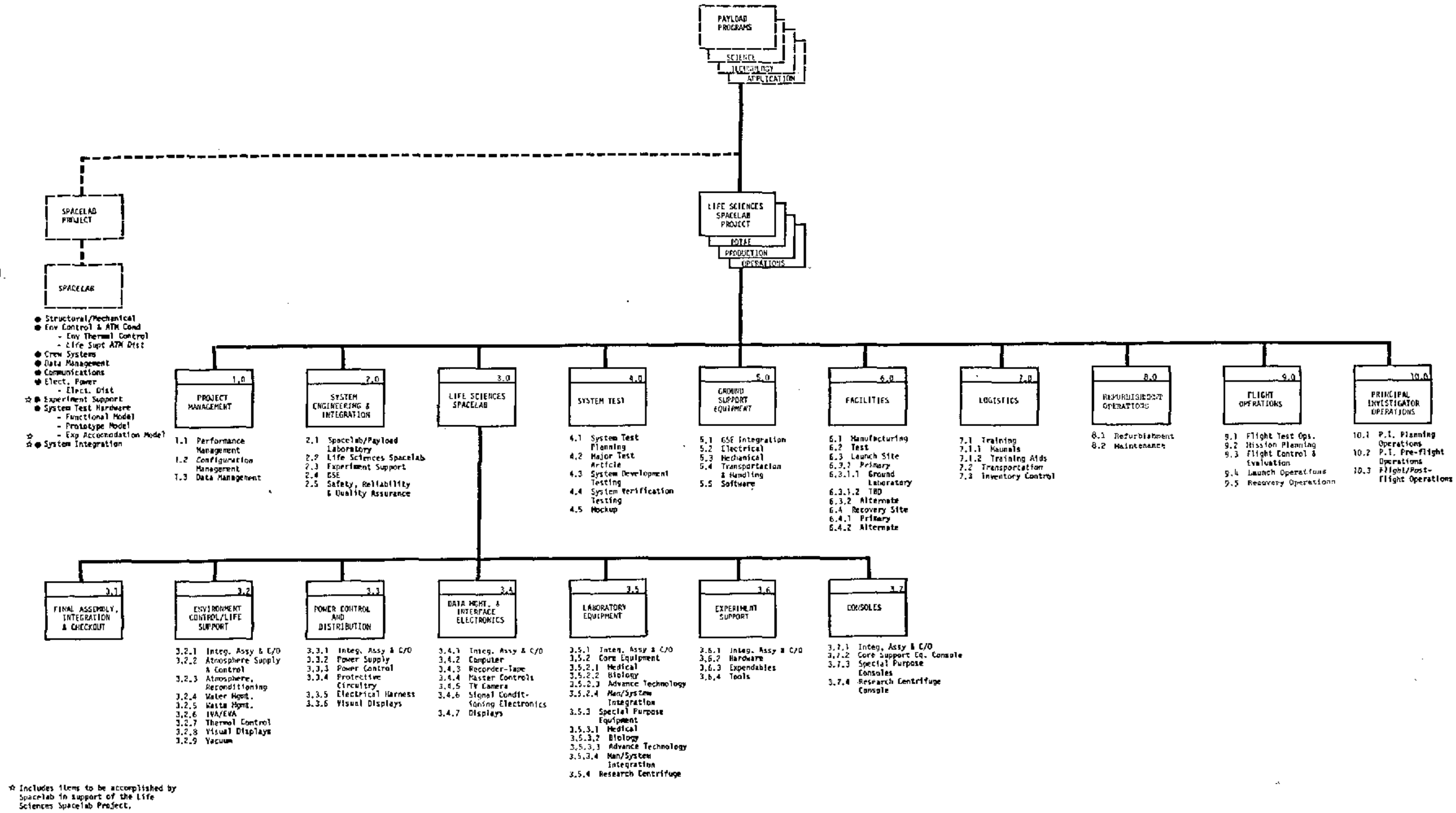

Figure 4-17. Life Sciences Spacelab - Work Breakdown Structure

Table 4-12

COST OF LIFE SCIENCES SPACELAB EQUIPMENT

Component	Quantity	Development Cost x 1000 Dollars	Unit Cost, x 1000 Dollars
1. Crew Station and Storage Unit			
Crew work station	1	20	20
Vacuum cleaner	1	46	2
Betadine wipes (250 wipes)	1	2.4	2
Organism holding unit	1	13	1.1
Veterinary kit	1	35	5
Film vault			
2. Cells and Tissue Holding Unit			
Incubator	2	47	118
Sealable colony chamber	2	200	5
Accelerometer	1	1	1
Accelerometer coupler	1	1	1
Prepared media	2	5.8	.5
Air particle sampler	1	28	4
Assorted antennas	1	20	0.5
Waste storage device	1	1	0.5
Receiver	2	21	5
3. Visual and Microscopic Examination Unit			
Compound microscope	1	0.5	3.5
Dissecting microscope	1	10	5
Microscope accessory kit	1	10	4
TV/microscope adapter	1	0	0.5
Microdissection kit	1	40	5
Microbiology kit	1	40	5

Table 4-12

COST OF LIFE SCIENCES SPACELAB EQUIPMENT (Continued)

Component	Quantity	Development Cost x 1000 Dollars	Unit Cost, x 1000 Dollars
3. Visual and Microscopic Examination Unit (Continued)			
Histology kit	1	20	3
Hematology kit	1	7	1
Log books	11	-	-
Color video camera	1	0	100
B&W video camera	2	10	14
Movie camera	2	10	6
Still camera	2	20	5
Polaroid camera	1	0.5	0.5
Crew work station	1	20	20
Waste storage device	1	20	0.5
4. Primate and Small Vertebrate Holding Units			
EC/LSS for primates and small vertebrates (includes crew LiOH canisters)	1	2,310	785
Rat/hamster cage	8	224	3.2
Water dispenser	8	included in holding unit cost	
Food dispenser	8	included in holding unit cost	
Water flowmeter	9	10	1
Flowmeter coupler	9	20	2
Small vertebrate holding unit	1	1,544	55
Signal conditioner couplers	14	10	1
Accelerometer	2	1.5	0.5
Accelerometer coupler	2	0.5	0.1
Unrestrained monkey cage	2	177	62
Waste management system	2	442	29

Table 4-12

COST OF LIFE SCIENCES SPACELAB EQUIPMENT (Continued)

Component	Quantity	Development Cost x 1000 Dollars	Unit Cost, x 1000 Dollars
4. Primate and Small Vertebrate Holding Units (Continued)			
Food dispenser	2	54	13.3
Water dispenser	2	94	22.6
Photographic supplies	2	22	8
Instrumentation and controls	-	93	23
5. Display Control Console and Data Management Unit			
(Spacelab supplied)			
6. Biomedical Activities Unit			
Limb plethysmograph	1	37	1
Gas flowmeter	6	13	0.8
Power conditioning equipment	1	147	124
Physiological kit	1	19	2
Video monitor	1	12	2
Oscilloscope	1	150	20
Physiological gas analyzer	1	0	50
Experiment console	1	233	97
Signal conditioning couplers	32	40	4.6
Multichannel recorder	1	200	100
Electrophysiology receiver	1	100	15
Receiver	1	200	10
Voice recorder	1	35	15
Event timer	2	0	0.2
Linear measurement kit	1	1	0.1

Table 4-12

COST OF LIFE SCIENCES SPACELAB EQUIPMENT (Continued)

Component	Quantity	Development Cost x 1000 Dollars	Unit Cost, x 1000 Dollars
6. Biomedical Activities Unit (Continued)			
Medical/phys. examination kit	1	40	5
Electrophysiological backpack	1	25	5.6
Psychogalvanometer	1	-	GFE
Doppler flowmeter	2	10	0.4
Sonocardiogram	1	200	30
Plotter/printer	1	20	0.5
Waste storage device	1	20	0.5
Sound level meter	1	10	6
Multimeter	1	22	4
Assorted meters	4	4	1
Radiation source	1	150	50
Dosimeter	1	0	2
Radiation detector, general	1	350	50
7. Fluid Sample Analysis Unit			
Chemicals		0	6
Chemical storage cabinet	1	22	12
Mass spectrometer gas analyzer	2	100	100
Temperature block	2	5	1
AOTS meter	1	0.5	0.5
Volumetric measurement kit	1	50	5
Staining system	1	0	13
Gas supplies	6	50	5.3
GEMSAEC	1	0	75
pH meter	1	90	26.5
Crew work station	1	20	20
Chemical analysis kit	1	100	10
Refrigerated centrifuge	1	124	7

Table 4-12

COST OF LIFE SCIENCES SPACELAB EQUIPMENT (Continued)

Component	Quantity	Development Cost x 1000 Dollars	Unit Cost, x 1000 Dollars
8. Specimen Preservation Unit			
Compactor for solids	1	5	1
Plastic bags (250 bags)	-	3.4	3.8
Clean-up kit	1	40	4
Tool sterilizer	1	5	1
General tool kit	1	16	1.4
Steam autoclave	1	25	2
Specimen mass measurement device (Macro)	1	0	5
Specimen mass measurement device (Micro)	1	0	8
Low temperature freezer	1	150	30
Cryogenic freezer	1	250	50
Refrigerator	1	65	5
Radioactive chemicals	1	2.4	0.5
Glove box liners (30)	1	5	0.1
Waste storage device	1	20	0.5
9. Additional Equipment			
Work and surgical bench	1	100	10
Portable display/keyboard	1	50	60
Body mass measurement device	1	20	20
Physiological exercise equipment and metabolic analyzer	1	20	100
Rotating litter chair	1	20	100
Lower body negative pressure device	1	20	100

4.3.5.2 LSSL System Level Costs

The LSSL system level costs are summarized as presented in the following paragraphs:

4.3.5.2.1 Laboratory Equipment

The laboratory equipment cost obtained from the summation of the data in Table 4-12 is given as:

Laboratory equipment non-recurring cost	=	$9,007,000
Laboratory equipment recurring production cost (per flight unit)	=	$3,212,000

4.3.5.2.2 Experiment Support System

This cost item includes experiment interfaces and structural support, photographic equipment and the refrigeration system. The structural support includes all mechanical and structural interfaces needed for holding units, cages and experiment hardware. Photographic equipment includes cameras, controllers and drive mechanisms to support all experiment areas. Invididual cameras are included in each animal and specimen cage or holding unit and each major biomedical experiment area. The refrigeration system provides a common 5°F refrigerant loop to all the cold storage compartments in the LSSL. Additional heat sinks, such as cryogenic refrigerants, are added to secondary loops circulating in freezer compartments to obtain extremely low temperatures of -95°F and -200°F. Experiment support costs are summarized as follows:

Item	Non-Recurring Cost	Recurring Production Cost
Structural support	$ 307,000	$ 25,000
Photographic support	698,000	221,400
Refrigeration system	528,780	91,110
Total	$ 1,554,780	$ 312,510

4.3.5.2.3 Power Control and Distribution System

The power control and distribution system comprises the controls and distribution equipment to supply and manage electrical power to the experiment hardware.

Included also are the oxygen and nitrogen tank sets chargeable to payload, but not the fuel cells which constitute a part of the orbiter's baseline system. Power control and distribution system cost is summarized as follows:

Non-recurring cost	=	$ 280,000
Recurring production cost	=	$ 160,000
Recurring operations cost	=	$1,100,000

4.3.5.2.4 Data Management and Interface Electronic System

The data management and interface electronic system comprises all the monitoring instrumentation required by the experiments, as well as data acquisition, processing, control and storage. Experimental animals are considered to be fully instrumented and provided with implanted electrodes and the matched signal conditioners for the transducers which need amplification prior to be input to multiplexers. Full use is made of the equipment and capabilities supplied by the Spacelab. The Spacelab computers will process, display, store and/or telemeter the data, as required. The data management and interface electronic system cost includes the signal conditioners and other experiment electronic interface equipment, as well as procuring and installing physiological and environmental instrumentation. The total system cost is given as follows:

Data Management and interface electronic system
non-recurring cost = $940,000

Data management and interface electronics
recurring production cost = $370,000

Data management and interface electronics
recurring operations cost = $390,000

4.3.5.2.5 Consoles

The cost of the LSSL consoles includes the integration, assembly and checkout of the consoles including the panel assemblies, instrumentation and displays. The cost of the consoles is given as follows:

Consoles non-recurring cost	=	$1,320,000
Consoles recurring production cost	=	$ 380,000

4.3.5.2.6 Environmental Control and Life Support System

The cost of the environmental control and life support system is considered to be a part of the basic vehicle cost and not chargeable to the LSSL. Expendables for the EC/LS to extend the mission from 7 days to 30 days include oxygen and LiOH filters. The oxygen for normal use is supplied at no cost from excess oxygen available to the orbiter and delivered to the Spacelab and is thus not chargeable to LSSL. The cost of the LiOH filters is included in the laboratory equipment cost, together with the cost of the primates' EC/LS system, under paragraph 4.3.5.1.

4.3.5.2.7 Final Assembly, Integration and Checkout

This task includes the integration of the experiment assemblies in the LSSL and providing the necessary interfaces with the basic Spacelab vehicle subsystems. Final system checkouts, including ground support system and interfaces, are also included in this task. The cost of this task is as follows:

Final assembly, integration and checkout
non-recurring cost = $3,350,000

4.3.5.3 LSSL Laboratory Cost

The LSSL laboratory cost is obtained by adding up all the level 4 items listed above, resulting in the following:

LSSL laboratory non-recurring cost	=	$16,452,000
LSSL laboratory recurring production cost	=	$ 7,647,000
LSSL laboratory recurring operations cost	=	$ 3,432,000

4.3.5.4 LSSL Project Cost Estimates

The LSSL project cost is obtained from the summation of system level (level 4) cost items which include, in addition to the LSSL laboratory cost, project management, system engineering and integration, system test, ground support equipment, facilities, logistics, ground and flight operations and principal investigator costs. The cost of the LSSL project is presented in Table 4-13, listed by system level cost item and divided into design and development, production and operations phases. A graphical representation of the cost data is also shown on a WBS diagram in Figure 4-18.

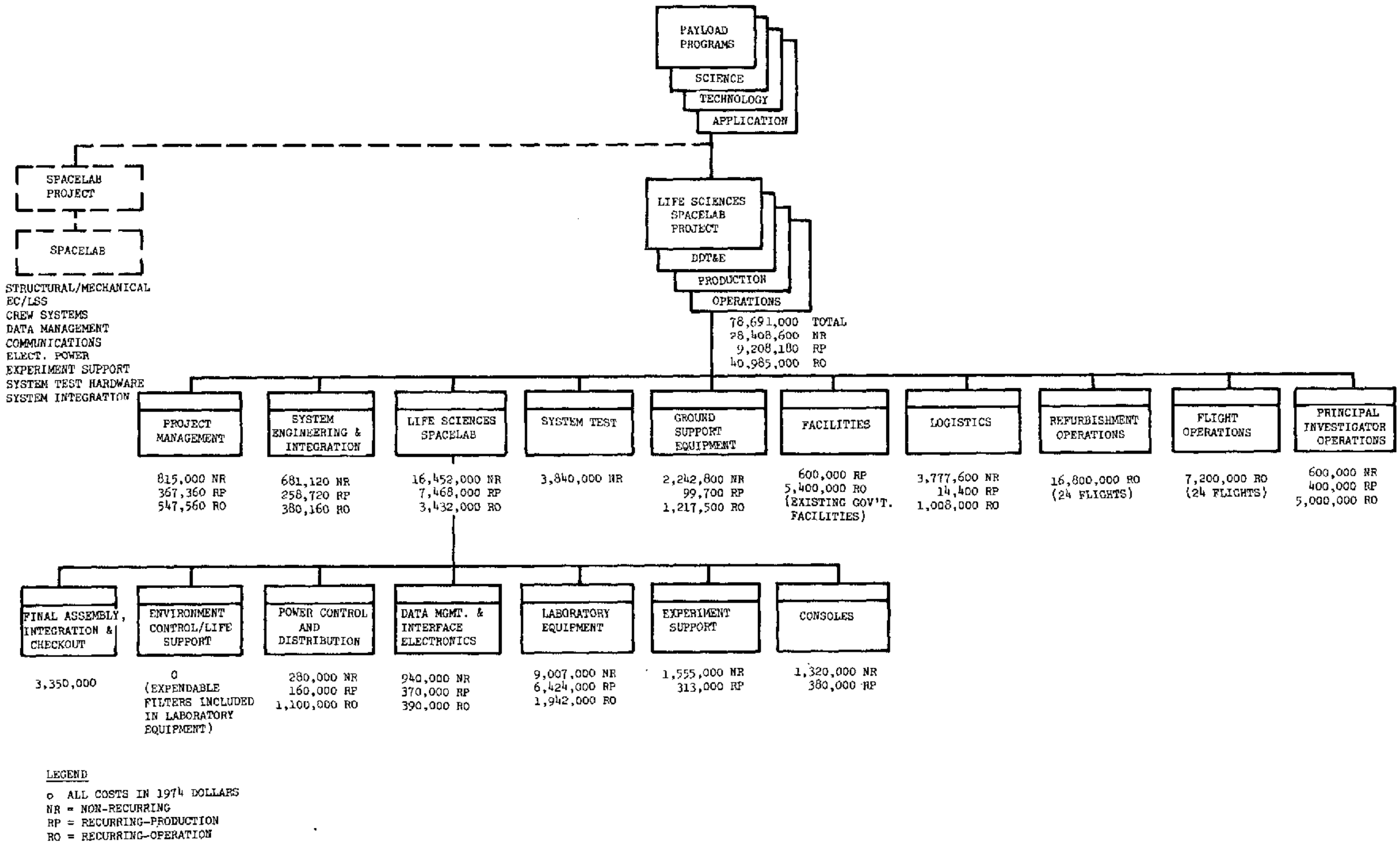

Figure 4-18. Life Sciences Spacelab - Cost and Work Breakdown Structure

4.3.6 References

4.3-1 Life Sciences Payload Definition and Integration Study (Task C&D) Volume III, General Dynamics Report No. CASD-NAS 73-003, Contract No. NAS8-29150, August 1973.

4.3-2 Life Sciences Payload Definition and Integration Study, Volume IV, General Dynamics Report No. CASD-NAS 74-046, Contract No. NAS8-30288, August 1974.

4.3-3. McDonnell Douglas Astronautics Company Cost Data Bank.

Table 4-13

LSSL PROJECT COST ESTIMATE

Cost Item	Cost in 1974 Dollars			
	Design and Development	Production	Operations	Total
Project Management	815,080	367,360	457,560	1,630,000
System Engineering and Integration	681,120	258,720	380,160	1,320,000
Life Sciences Spacelab	16,452,000	7,647,000	3,432,000	27,531,000
System Test	3,840,000	0	0	3,840,000
Ground Support Equipment	2,242,800	99,700	1,217,500	3,560,000
Facilities	0	600,000	5,400,000	6,000,000
Logistics	3,777,600	14,400	1,008,000	4,800,000
Flight Operations	0	0	7,200,000	7,200,000
Refurbishment	0	0	16,800,000	16,800,000
Principal Investigators	600,000	400,000	5,000,000	6,000,000
Totals	28,408,600	9,387,180	40,895,220	78,691,000
Project Total				78,691,000

4.4 RESEARCH CENTRIFUGE EXPERIMENT

4.4.1 Objective

The life sciences research centrifuge will provide a 1g control environment and a variable g (0.5 to 2.0 g) research environment for research test subjects, e.g., small vertebrates, other man-surrogates or basic research organisms. The centrifuge will be normally flown on a combined payload with the Life Sciences Spacelab on medical or space biology emphasis missions.

4.4.2 Design Requirements

The design requirements for the life sciences research centrifuge are the following:

Force at rim of centrifuge		1.5 to 2.0 g
Centrifuge radius		5.75 FT
Rotational Velocity,	at 1.0 g	22.6 RPM
	at 1.5 g	28 RPM
	at 2.0 g	32 RPM
Duration of centrifugation, continuous		30 days
Specimen life support,	temperature	70 ± 5°F
	humidity	50 ± 10%
	food per cage	0.17 LBS/DAY
	water per cage	1.0 LB/DAY
	waste management	As Required
Urine and waste samples		Freezer Storage (To be supplied by Spacelab)

4.4.3 System Description

A preliminary design of a centrifuge to meet the above requirements was conducted and is presented in the following paragraphs. The concept used in the centrifuge design includes a continuous rotating centrifuge primary structure which houses the animal cages in its outer rim and a load-retrieving turntable. The turntable may be spun up to the speed of the primary rotating structure. A mechanism incorporated in the turntable is then made to load or retrieve animal cages from the primary structure. The animal cages, including cameras, environmental control and data management equipment are considered to be part of the biological specimen holding facility and are not considered in this section.

The life sciences research centrifuge, shown in Figure 4-19, is comprised of the following basic structural elements:

A. Support Housing: The support housing is attached to the main structure of the Spacelab interior. The support housing has a cavity that will accept and support a rotating shaft with two support bearings. Attached to the support housing is the motor assembly including an electric motor, gear drive reduction, and a brake unit.

B. Primary Driven Structure: The primary driven structure consists of a circular housing containing eight cage cavities and a hollow support shaft. The hollow support shaft is secured to the support housing by the housing's two bearings. The hollow support shaft has a ring gear attached to the shaft exterior that meshes with the support housing drive motor and gear train.

C. Load-Retrieve Turntable: The load-retrieve turntable is smaller than, and fits within, the primary driven structure. The support shaft of the load-retrieve turntable is supported by two bearings located in the hollow center of the primary driven structure. A clutch is located between the primary driven structure support shaft inside diameter and the turntable support shaft outside diameter. The solid shaft extends throughout the support housing to form the rotating element of the brake assembly. Also attached to the turntable is the cage cavity index detent selector. Each cage cavity has an identifying index detent that the selector will identify and lock up when the RPM is matched with the primary driven structure.

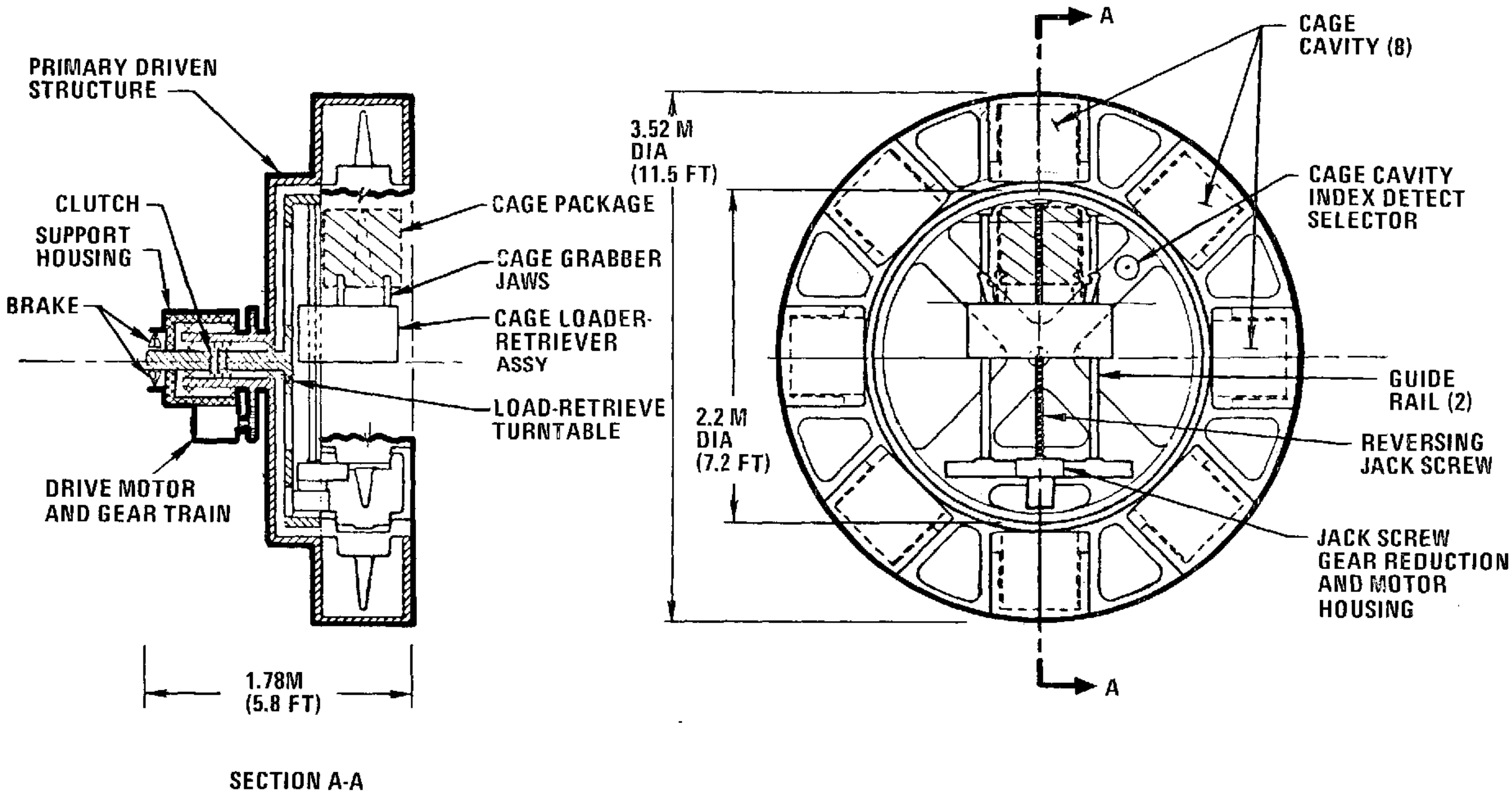

Figure 4-19. Life Sciences Research Centrifuge

D. Cage Loader/Retriever Assembly: The cage loader/retriever assembly has three (3) basic parts: (1) Cage loader/retriever, (2) reversing jack screw and guide rails, and (3) jack screw gear reduction and motor housing. The jack screw gear reduction and motor housing provide the means by which the loader/retriever can propel the cage package into and out of the cage cavity.

4.4.4 System Operation

The primary driven structure will rotate and perform as a centrifuge when power is applied to the motor assembly. The turntable is a free, independent member when the clutch and brake are disengaged. Applciation of the clutch will cause the turntable to rotate at the same RPM as the primary driven structure. The detent selector will line up the turntable cage package with the cage cavity and the cage loader/retriever assembly will insert or retrieve the cage package as required. With the release of the detent selector, release of the clutch, and application of the brake, the turntable will be stopped and the primary driven structure will continue to rotate at the specified RPM. The primary driven structure can be stopped by turning off the power to the drive motor, engagement of the clutch and application of the brake.

4.4.5 Cost Estimates of Research Centrifuge

Cost estimates of the Research Centrifuge experiment were made and are described in this section. Cost estimating relationships were derived for both the design and development (non-recurring) phase and the recurring production phase. Included are the costs of the four major assemblies:

A. motor assembly cost
B. centrifuge structure cost
C. medical support equipment cost
D. instrumentation and controls cost

A description of each of the above-mentioned cost items is presented in the following.

4.4.5.1 Motor Assembly

Commerical type components have been selected for this application. The equipment was assumed to undergo qualification and reliability testing to bring it up to the level of flight qualified hardware. The design and development phase (non-recurring) costs for commercial components are shown in Table 4-14 as compared to a typical flight type hardware expenditure. The qualification and readiness cost of the commercial equipment is shown to be 53% of a comparable flight type equipment.

Table 4-14

DESIGN AND DEVELOPMENT PHASE EXPENDITURE BREAKDOWN
FOR COMMERCIAL VERSUS FLIGHT TYPE EQUIPMENT

Function	Flight Type Hardware	Commercial Equipment Development Cost
Design	17.31	0
General and Administrative	8.94	0
Program Management	1.29	0.65
System Engineering	5.45	1.36
Development, Qualification and Reliability Tests	10.45	6.88
GSE	19.14	19.14
Tooling	4.02	0
Non-Accountable Test Hardeare	1.73	0
Specifications, Vendor Coordination and Procurement Expenses	14.13	7.07
System Integration	8.67	8.67
System Test	8.48	8.48
Minor Subcontracts	0.39	0.39
Total	100%	52.64% of Flight Type Equipment

The motor assembly is comprised of the following major components: 1) motor; 2) gear drive; 3) clutch; 4) brakes; and 5) bearings. Applying the cost estimating relationship (CER) used for non-recurring cost of life support systems yields the following:

Flight type assembly design cost C = 41,922 N + 123,530 dollars, where N = the number of component types in assembly = 5. Then, C = 209,610 + 123,530 = 333, 140 dollars. Applying the percentage values shown in Table 4-14 to the non-recurring flight type assembly design cost yields the values given in Table 4-15. The design and development cost of a comparable flight type motor assembly was found to be = 1,924,550 dollars.

Table 4-15

DESIGN AND DEVELOPMENT PHASE COST BREAKDOWN

OF FLIGHT-QUALIFIED COMMERCIAL MOTOR ASSEMBLY

Function	Cost, Dollars
Program Management	12,510
System Engineering	26,174
Qualification & Reliability Tests	132,410
GSE	368,358
Specifications Vendor Corrdination & Procurement Expenses	136,066
System Integration	166,858
System Test	163,201
Minor Subcontracts	7,506
Total	1,013,083

The cost of the commercial components is then to be added to the non-recurring cost to obtain the total cost of the motor assembly. Approximate costs of the commercial type units are as follows:

A. motor, fan-cooled, explosion-proof = 320 dollars

B. gear drive = 130 dollars

C.	brakes, drum types	=	280 dollars
D.	clutches, friction discs, modified	=	320 dollars
E.	bearings	=	120 dollars
			1,170 dollars

Total cost of flight-qualified motor assembly = 1,013,083 + 1170 = 1,014,253 dollars.

4.4.5.2 Centrifuge Structure

The centrifuge structure, shown in Figure 4-20 is comprised of the following:

1) support housing and primary-driven structure
2) load retrieve turntable
3) drive motor and gear train

The design and development phase (non-recurring) cost of the centrifuge structure, utilizing flight type hardware, is obtained by modifying and utilizing two previously derived relationships. The first, which was originally derived from a spacecraft structural panel, was modified to account for the centrifuge primary structure and turntable and is shown graphically in Figure 4-20. The design, development and test cost of the centrifuge primary structure and turntable, obtained from Figure 4-20, is C_D = \$242,740. The hardware production cost of the structure, estimated at 25% of non-recurring cost is C_P = \$60,685.

The recurring cost of the drive motor and gear train is estimated by using the following relationship based on data obtained from Gemini program cost data:

$$C = 99.7\ P^{0.942} F^{0.1037} + 822\ W_G \qquad \text{dollars}$$

where,

P = power input to motor = 500 watts,
F = operating frequency = 400 Hz, and
W_G = gear train weight = 22 lbs

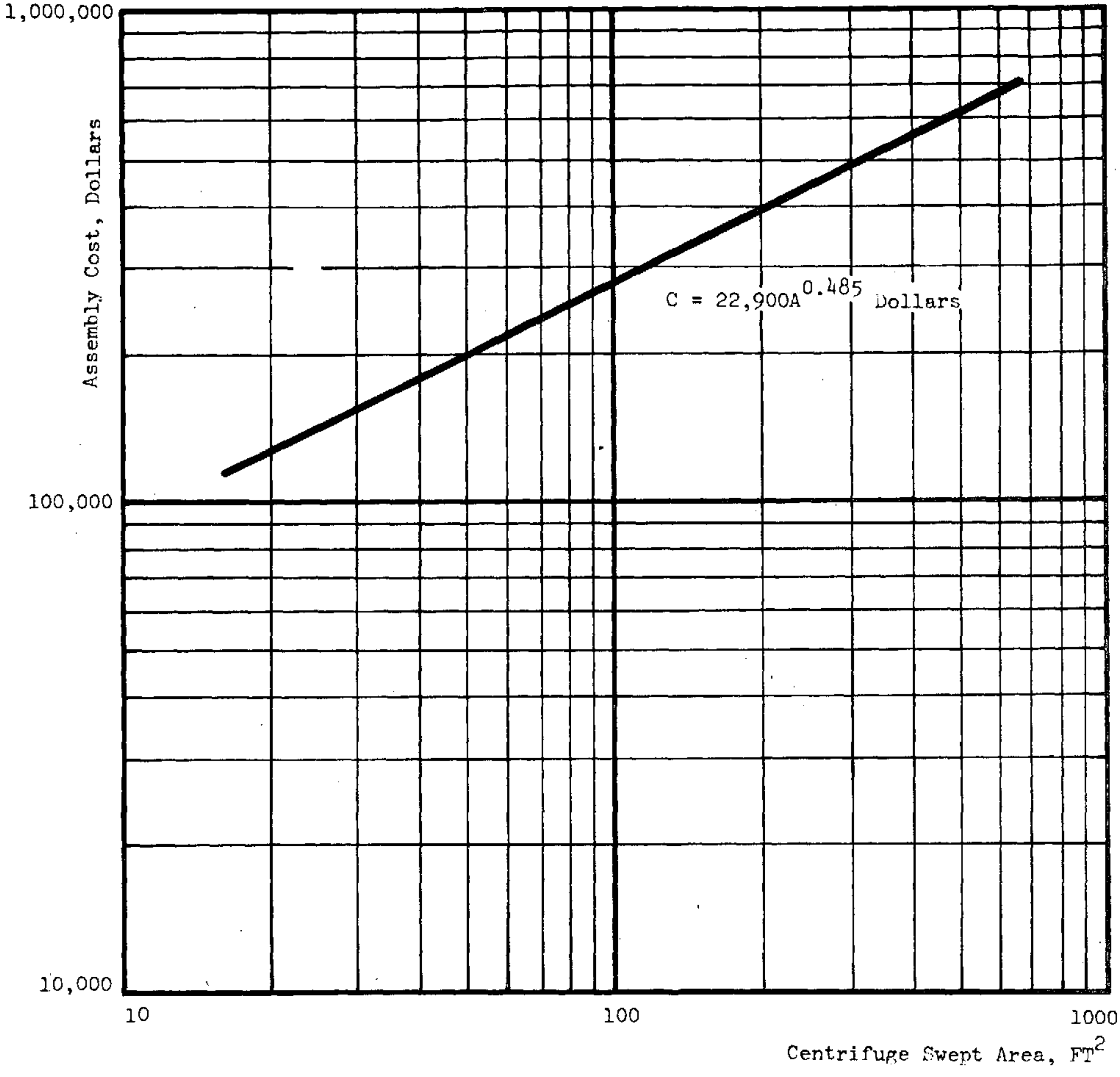

Figure 4-20. Centrifuge Primary Structure and Turntable Cost Estimating Relationship (Design and Development Phase)

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

Drive motor and train non-recurring cost = \$81,072

The hardware production cost of the drive motor and gear train, estimated at 25% of non-recurring cost, is C_P = \$20,268.

The total cost of the centrifuge structure assembly, considering both recurring and non-recurring costs, is then: C = 242,740 + 60,685 + 81,072 + 20,268 = \$404,765.

4.4.5.3 Medical Support Equipment

For the centrifuge experiment, medical instrumentation will be assumed to be supplied with the test animals. Data transmission will also be included as a part of the animal holding unit rather than the centrifuge experiment.

4.4.5.4 Instrumentation and Controls

The assembly consists of centrifuge controls, switches for lighting, cameras and animal holding facility life support functions, and instrumentation for environmental parameters. All the instrumentation and controls considered are minor in nature. The recurring cost estimating relationship is simply the cost per pound of equipment. The hardware production cost of the instrumentation and control equipment is given as:

$$C = 4200\ W_{IC} \qquad \text{dollars}$$

where,

W_{IC} = weight of components = 5.5 lbs

then,

C = \$23,100

The design and development phase cost of the equipment is estimated = \$92,400. The total cost of instrumentation and controls = 23,100 + 92,400 = \$115,500.

4.4.5.5 Centrifuge Total Cost Summary

A total cost summary for the life sciences research centrifuge is presented in Table 4-16. A number of off-the-shelf commerical components, notably the motor assembly parts, were incorporated in the centrifuge. However, it was assumed that no significant hardware modifications were required to bring components up to flight status hardware. The cost of any additional modifications to the centrifuge should be added to the total cost shown in Table 4-16.

Table 4-16

CENTRIFUGE TOTAL COST SUMMARY

Item	Design & Development Phase Cost	Hardware Cost
Motor Assembly*	1,013,083	1,170 (commercial equipment)
Centrifuge Structure	323,812	80,953
Instrumentation and Controls	92,400	23,100 (Skylab-type equipment)
Total	1,429,295	105,223
Total Cost =	$1,534,518	

(*)Note: Commercial equipment used is flight-qualified but no design modifications are included.

4.5 CLOUD PHYSICS EXPERIMENT

4.5.1 Objectives

The Cloud Physics Laboratory (CPL) is a zero-g atmospheric microphysics/cloud physics facility designed to accommodate a large variety of experiments proprosed by the atmospheric physicists. The CPL will provide the scientific community with a general purpose orbital laboratory to complement and supplement cloud physics research. The mission objectives of the CPL are to acquire data currently unachievable in terrestrial laboratories. Research will be concentrated on a range of particles that are affected by gravity but the forces to be studied are gravity independent. These data are essentaial to the verification of existing theories of atmospheric microphysics especially in the areas of weather modification and control.

4.5.2 Cloud Physics Laboratory Description

The Cloud Physics Laboratory is a general purpose facility, available to the scientific community and capable of performing complementary and supplementary research in atmospheric microphysics. As shown in Figure 4-21, the laboratory is a self-contained unit approximately 2.7 m (8.85 ft) long, 2.72 m (8.9 ft) high, and 1.2 m (3.9 ft) maximum depth occupying a volume of $\sim 8.8\ m^3$ ($\sim 310\ ft^3$). A detailed laboratory and subsystem description is presented in Reference 4.5-1. The laboratory will constitute a partial load of the Spacelab mission and will be dependent on usage of the Spacelab resources for: 1) power, 2) heat rejection; 3) scientific crew operation; and 4) limited data management and communications.

The laboratory contains all subsystems required for the conduct of the defined experiment program. All laboratory subsystems are installed within the laboratory console shown in Figure 4-21. The laboratory flown will be modified for each individual experiment mission. Six cloud chambers have been designed for use in the experimental program. One or more chambers will be flown per mission. The six chambers are 1) continuous flow diffusion; 2) static diffusion-liquid; 3) static diffusion-ice; 4) expansion; 5) general; and 6) earth simulation. Twenty-one experiment classes have been identified to encompass the physical processes involved in atmospheric microphysics. Aprimary and an alternate chamber

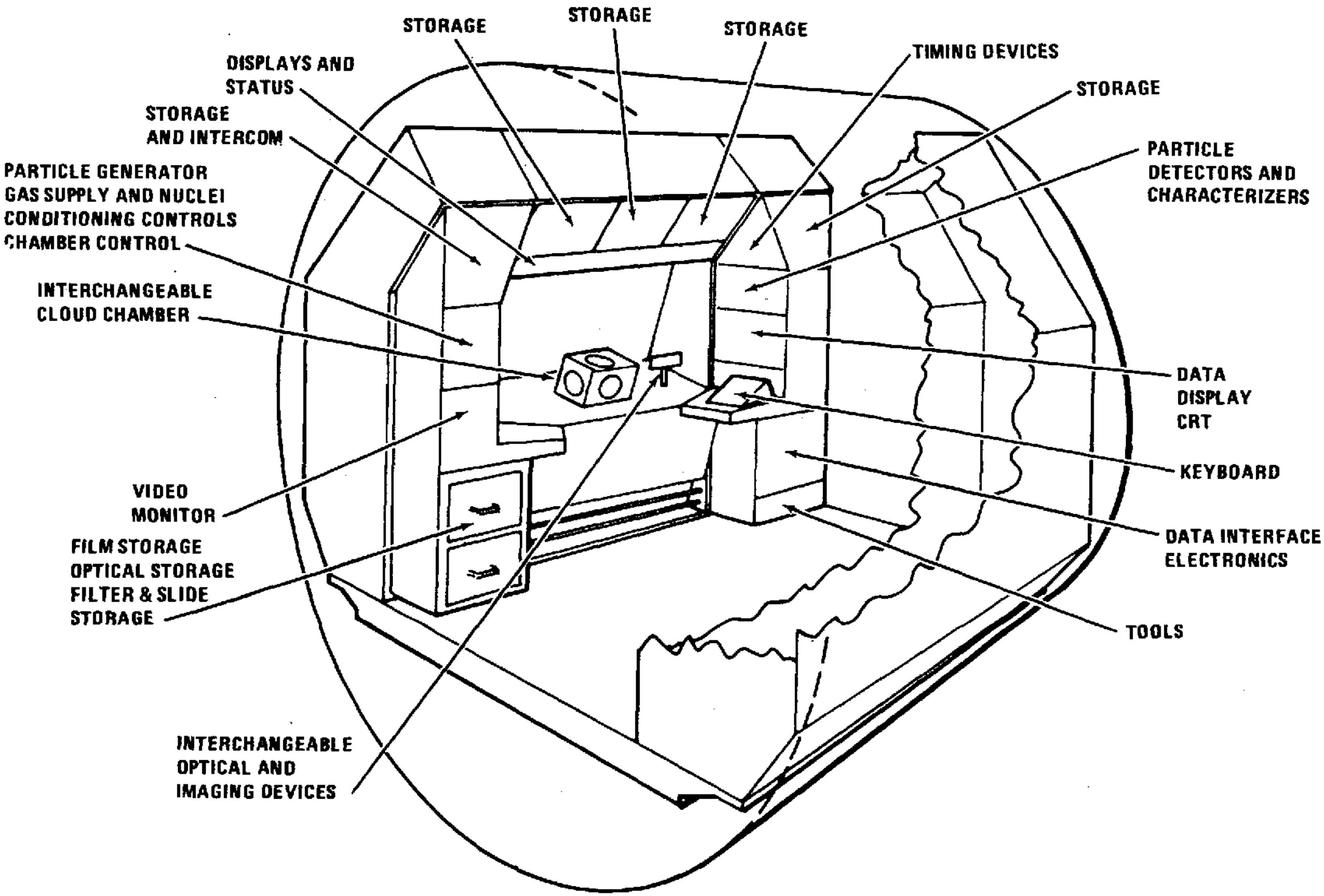

Figure 4-21. Cloud Physics Laboratory Configuration

have been identified, from among the six cloud chambers, in which each of the 21 experiment classes may be conducted. A description of each of the subsystems included in the CPL is given in the following paragraphs.

4.5.2.1 Thermal Control/Expendables Storage and Control System

4.5.2.1.1 Thermal Control Subsystem

Systems will be provided to supply cooling to the cloud chamber thermoelectric modules and to all console-mounted CPL avionic and support equipment.

The cooling assembly will provide the means to transport heat from and maintain temperatures in the cloud chambers. Heat will be removed from the chamber by liquid water coolant that in turn will reject heat to a 7°C Spacelab coldplate through a heat exchanger. The heat exchanger will contain a phase change material that absorbs excess cloud chamber heat during operation at a temperature less than -32°C. The heat removal to achieve -40°C in the cloud chambers will be accomplished by using Thermoelectric (TE) cooling within the cloud chamber.

4.5.2.1.2 Flow, Humidity and Pressure Control Subsystem

Generation of humid gas samples and control of the flow and pressure of the samples during transfer to the cloud chamber will be managed by the Humidification Assembly and the Water Storage and Supply Assembly.

The Humidification Assembly 1) provides a water vapor source; 2) mixes proper proportions of water vapor, air and sample gases; 3) equilibrates the mixture at Spacelab ambient temperature and at the proper pressure and humidity; and 4) is utilized during the purging and cleaning operations between experiments. The assembly will be comprised of a wick evaporator, a valve module and a humidification chamber.

The Water Storage and Supply Assembly (WS/SA) will supply deaerated, sterile water at constant pressure to the Wick Evaporator and, when required, to the cloud chambers.

Water for use in the WS/SA will be stored in an all-metal, positive expulsion type, cylindrically shaped tank. Water capacity will be two (2) liters, which will provide a minimum reserve of 20%. The tank will incorporate a shutoff valve on the water side and a shutoff valve with flow limiter on the gas (air) side. All materials will be corrosion resistant. A long stroke, metal bellows will expel water at a constant 35 kPa to the water distrubution plumbing. The tank will be designed to a limit pressure of 1000 kPa to preclude failure in the event of a malfunctioning 35 kPa regulator valve. The water side of the storage tank will be steam sterilized, evacuated and dried, then purged and filled with dry nitrogen for storage prior to filling with water.

4.5.2.1.3 Expendables Storage Subsystem

Expendables storage will include all equipment (tanks, valves and plumbing) for storing and distributing sample gases and clean air for test and cleansing. The dry air used as an additive to test samples and for cleansing purge will be stored externally to the pressurized Spacelab cabin on the forward cone. The Spacelab-designed tank installation will be used in its entirety, including tanks, valves, rupture discs, plumbing, support structure, and a spare feed through connection to internal CPL plumbing.

The various sample gases used in test gas preparation will be stored in separate 203 mm diameter tanks. The baseline installation will have provisions for five (5) tanks. Preservation of CPL cleanliness will be managed by the use of separate flexible hoses and Q.D.'s to connect to the valve module test port.

4.5.2.1.4 Instrumentation and Display Subsystem

This subsystem includes pressure and temperature transducers used throughout the thermal control and expendables storage and control subsystems to monitor system status and performance.

4.5.2.1.5 Cleaning Purge and Vent Subsystem

The Cleansing Purge and Vent Subsystem (CP/VS) will include: 1) all plumbing, valves, regulators, filters, etc., used to transport dry air from the Dry Air Storage Subassembly interface to the Humidification Chamber and Cloud Chamber Components, and 2) all plumbing and other components used to vent the waste gas samples from the HC and CC components.

4.5.2.2 Particle Generators

Several types of generators are required in the CPL experiments to supply particles varying from hygroscopic NaCl particulates which typify many forms of natural nuclei in the atmosphere to large water droplets or ice crystals to study growth habits or collision breakup. These generators are of fundamental importance to the total experiment program. The particle generators required for the CPL include the following: 1) wire probe retractor, 2) water drop impeller, 3) vibrating orifice, 4) evaporation/condensation aerosol, 5) spray atomization aerosol, and 6) powder dispersion aerosol type generators. The first three generators are for droplets/ice particles in the range of 10 to 250 μm, the last three are for nuclei down to 30Å in size.

4.5.2.3 Particle Detectors and Analyzers

Several types of detectors are required for the CPL experiments. These range from particle size analyzers to nuclei mass monitors. Nuclei are either condensation centers for droplet formation or solidification centers for ice crystal formation. Particles are either water droplets or ice crystals which have grown from nuclei to larger sizes. In order to understand the effects of nuclei in causing condenstation, one must know both the characteristics of the nuclei and the resulting particles under known environmental conditions. Thus, the nuclei measurement devices will provide information about the initial aerosol distribution while the optical particle counter and camera will be required to be taken of the gas samples before they enter the chamber, as well as during the experiment time in the chambers. These detectors are of fundamental importance to the total experiment program. These techniques must be adapted for operation in a low gravity condition and functionally optimized for the specific experiment requirements. The recommended major components of the particle detector and characterized subsystem to be developed for the CPL are the following: 1) optical particle counter, 2) condensation nucleus counter, 3) microporous filter, 4) quartz crystal mass monitor, 5) cascade impactor, 6) electrical aerosol size analyzer, 7) drop size distribution meter, 8) liquid water content meter, 9) optical thermoelectric dew point hygrometer, and 10) electrical dew point hygrometer.

4.5.2.4 Experiment Chambers

Five basic cloud chambers are utilized in microphysics research in the CPL. The continuous flow diffusion, static diffusion liquid and static diffusion ice chambers oeprate on a thermal vapor diffusion principle to provide controlled supersaturated conditions. These chambers require thermally controlled surfaces which are water or ice covered. The expansion and general chambers require thermally controlled surfaces. These chambers are used to define the relative humidity, pressure and temperature environment for the experiments. In addition to the cloud chambers, an Earth Simulation Chamber will simulate certain aspects of planetary and solar convection with its attendant differential rotation.

Table 4-17 presents a summary of the CPL experiment chambers and their characteristics. Included are surface types used, particle sizes, experimental studies to be performed in each chamber and the chamber components required.

4.5.2.5 Console

The CPL modifies a 2.7 m experiment segment of the ERNO configuration Spacelab to include a 1.56 m work station cabinet and a 0.572 m equipment rack cabinet on either side of the work station. Each of the 0.572 m cabinets will provide a storage and accommodation space of 30.32 ft^3. The work station will provide a cabinet volume of 68.64 ft^3. The console is comprised of the following subassemblies: console support structure, power control and distribution, console panels and drawer, overhead storage and floor segment.

Table 4-17

CPL EXPERIMENT CHAMBERS

Chamber	Surface Type	Particle Size	Experimental Areas	Output	Chamber Components
Continuous flow diffusion	liquid	0.01 - 10 μm	condensation nucleation	size distribution	chamber plate subassembly, optical ports, water wicking surfaces, carrier air subassembly, thermal controllers
Static diffusion liquid	liquid	0.01 - 10 μm	condensation nucleation	number	heat pipe, thermoelectric modules, heat exchanger, chamber walls, optical ports, equipment mounting ports, water wicking surface, thermal controllers
Static diffusion ice	ice	1 μm - 1 cm	ice crystals	size, shape	heat pipe, thermoelectric modules, heat exchanger, chamber walls, optical ports, equipment mounting ports, water wicking, electric field, optical conditioning, acoustical subassembly, scatterometer interface equipment, light trap
Expansion	hydrophobic	0.1 μm - 100 μm	cloud simulation	numbers, mean size	chamber wall subassembly, optical ports, mounting ports, electric field, optical heating, acoustical equipment, expansion controller, light traps, scatterometer interface equipment, thermal controller
General	electric fields	>100 μm	large particle interactions	--	wall subassembly, optical ports, mounting ports, electric field, optical heating, acoustical equipment, light traps, scatterometer interface equipment, thermal controller
Earth simulation	two rotating spheres, fluid annulus	--	planetary and solar convection	--	earth simulation model, rotating subassembly, high voltage subassembly, thermal controllers

4.5.2.6 Optical Subsystem

The optical subsystem provides photography of objects in the experiment chambers. Optical access is provided by a double walled viewing port. A set ocoupling optics next to the viewport allows a variable focal zoom to focus on particles in the chamber in the 8 to 30 cm range. A parallel light output of the optics permits a confocal stereo microscope and a film camera to view the particles at the same time through a beam splitter. The experimenter utilizes a small joystick type control to maintain focus on the particles as they shift position.

The optical subsystem is comprised of 1) cine camera; 2) 35 mm still camera; 3) microscope trinocular; 4) 16 mm video camera assembly; 5) light source; 6) anemometer; 7) stereo microscope; 8) IR microscope; and 9) support equipment and expendables.

4.5.2.7 Data Management

The data management subsystem is comprised of the following assemblies: 1) control processor; 2) tape recorder; 3) master control; 4) signal conditioning electronics; 5) instrumentation and display; and 6) cables. The CPL data management subsystem interfaces and utilizes the Spacelab computers via the Spacelab remote acquisition units. Access is also made to the Spacelab low-rate recorder and the video recorder.

4.5.3 Cost Estimates

A work breakdown structure (WBS) for the Cloud Physics Laboratory is shown in Figure 4-22. The CPL equipment cost was calculated at the component level (level 7), then added up to the assembly, subsystem and system levels. System level (level 4) cost elements were then included to arrive at the total CPL project level (level 3) cost. A discussion of the various cost estimates, starting with the laboratory equipment cost, is given in the following paragraphs. Cost items are provided in non-recurring design and development, recurring production and recurring operations.

4.5.3.1 Cloud Physics Laboratory Cost

The CPL detailed cost data were obtained from Reference 4.5-1 and presented in Table 4-18. The laboratory cost items are grouped according to laboratory subsystems. Costs are presented for the design and development, production and opration phases of the program. The costs thus presented include all costs allocated to the laboratory at the subsystem level. A summary of total CPL costs is shown in Table 4-19. Total project cost is presented in the following paragraph.

4.5.3.2 CPL Project Cost

The CPL project cost includes the laboratory cost as well as costs estimated at the system level. In addition to CPL cost, the system level costs include project management, system engineering and integration, system test, ground support, logistics, ground and flight operations and principal investigators. The CPL project cost is presented in Figure 4-22 on the WBS diagram. All facilities have been considered as Government furnished and were thus not included in estimating the CPL project cost. The total CPL project cost estimate was found to be $21.33 million for non-recurring, $6.82 million for recurring production and $16.73 million for recurring operation, for a total of $44,947,000.

4.5.4 <u>References</u>

4.5-1 Zero Gravity Atmospheric Cloud Physics Experiment Laboratory, Contract No. NAS8-30272, Final Report, McDonnell Douglas Astronautics Company, September 1974.

4.6 SPACE PROCESSING FURNACE EQUIPMENT

4.6.1 <u>Objective</u>

The space processing furnace experiment is one of the major payloads planned for NASA's materials sciences and manufacturing in space (MS/MS) program. The overall objectives of the MS/MS program include the utilization of the characteristics of the space environment for the development of materials

Table 4-18

CPL LABORATORY COST ITEMS (Continued)
(in thousands 1974 dollars)

Subsystem/Assembly	Design & Development	Production	Operation
1. Thermal Control/Expendables Storage & Control Subsystem			
a. Thermal control	970.3	244.9	1215.2
b. Flow, humidity & pressure control	919.7	141.8	1061.5
c. Expendables storage	221.2	135.9	357.1
d. Instrumentation & display	22.1	204.9	227.0
e. Cleaning, purge and vent	187.9	37.2	220.1
f. Spares	0	37.3	338.8
g. Integration, assembly and checkout	185.3	61.2	246.5
2. Particle Generators			
a. Wire probe retractor	272.4	38.6	311.0
b. Water drop impeller	73	12.9	85.9
c. Vibrating orifice	273.9	79.6	353.5
d. Evaporation/condensation	91.7	33.0	124.7
e. Spray atomizer	45.6	15.7	61.3
f. Powder dispersion	70.1	11.5	81.6
g. Particle injector	338.2	105.1	443.3
h. Instrumentation & display	53.8	19.5	73.3
i. Spares	0	15.6	140.0
j. Integration, assembly & checkout	172.7	25.3	198.0

Table 4-18

CPL LABORATORY COST ITEMS (Continued)
(in thousands 1974 dollars)

Subsystem/Assembly	Design & Development	Production	Operation
3. Particle Detectors & Characterizers			
a. Optical particle counter	136.5	45.3	0
b. Pulse height analyzer	54.6	15.5	0
c. Condensation nucleus counter	116.9	35.0	0
d. Microporous filter	14.4	9.2	0
e. Quartz crystal mass monitor	641.1	47.9	0
f. Cascade impactor	24.7	11.9	0
g. Electrical aerosol size analyzer	522.8	157.3	0
h. Scatterometer	233.7	59.7	0
i. Liquid water content meter	129.1	51.5	0
j. Droplet size distribution meter	551.6	159.0	0
k. Optical thermoelectric dew point hygrometer	244.2	59.4	0
l. Electrical dew point hygrometer	28.3	6.6	0
m. Instrumentation & display	8.5	32.0	0
n. Spares	0	33.7	303.6
o. Integration, assembly & checkout	276.2	54.8	0

Table 4-18

CPL LABORATORY COST ITEMS (Continued)
(in thousands 1974 dollars)

Subsystem/Assembly	Design & Development	Production	Operation
4. Experiment Chambers			
a. Static diffusion liquid	197.1	98.3	0
b. Static diffusion ice	557.6	232.7	0
c. General	374.7	249.6	0
d. Expansion	470.0	377.0	0
e. Continuous flow diffusion	265.6	131.5	0
f. Earth simulation	349.1	101.9	0
g. Spares	0	65.0	585.3
h. Integration, assembly & checkout	199.4	105.7	0
5. Console			
a. Console support structure	905.5	529.2	0
b. Power control & distribution	147.2	129.1	50.7
c. Console panels & drawers	522.9	69.0	0
d. Instrumentation & display	8.8	6.4	2.5
e. Integration, assembly & checkout	126.7	58.2	0
6. Optical Subsystem			
a. Cine camera	151.8	43.2	0
b. 35 mm still camera	77.4	22.0	0
c. Microscope trinocular	34.7	9.9	0
d. 16 mm video camera	73.4	20.9	0
e. Light source	4.0	2.2	0

Table 4-18

CPL LABORATORY COST ITEMS (Continued)
(in thousands 1974 dollars)

Subsystem/Assembly	Design & Development	Production	Operation
f. Aneomometer	505.5	143.9	0
g. Stereo microscope	65.0	15.2	0
h. IR microscope	1200.6	271.9	0
i. Support equipment & expendables	83.1	11.2	0
j. Displays	15.0	7.3	0
k. Spares	0	26.9	242.5
l. Integration, assembly & checkout	176.9	43.8	0
7. Data Management			
a. Control processor	741.9	184.0	0
b. Tape recorder	0	0	0
c. Master control	203.3	28.4	0
d. Signal conditioning	908.1	245.3	0
e. Instrumentation & display	586.8	180.0	0
f. Expendables	0	0	42.0
g. Cables	24.7	63.1	0
h. Spares	0	34.5	310.4
i. Integration, assembly & checkout	197.2	56.0	0

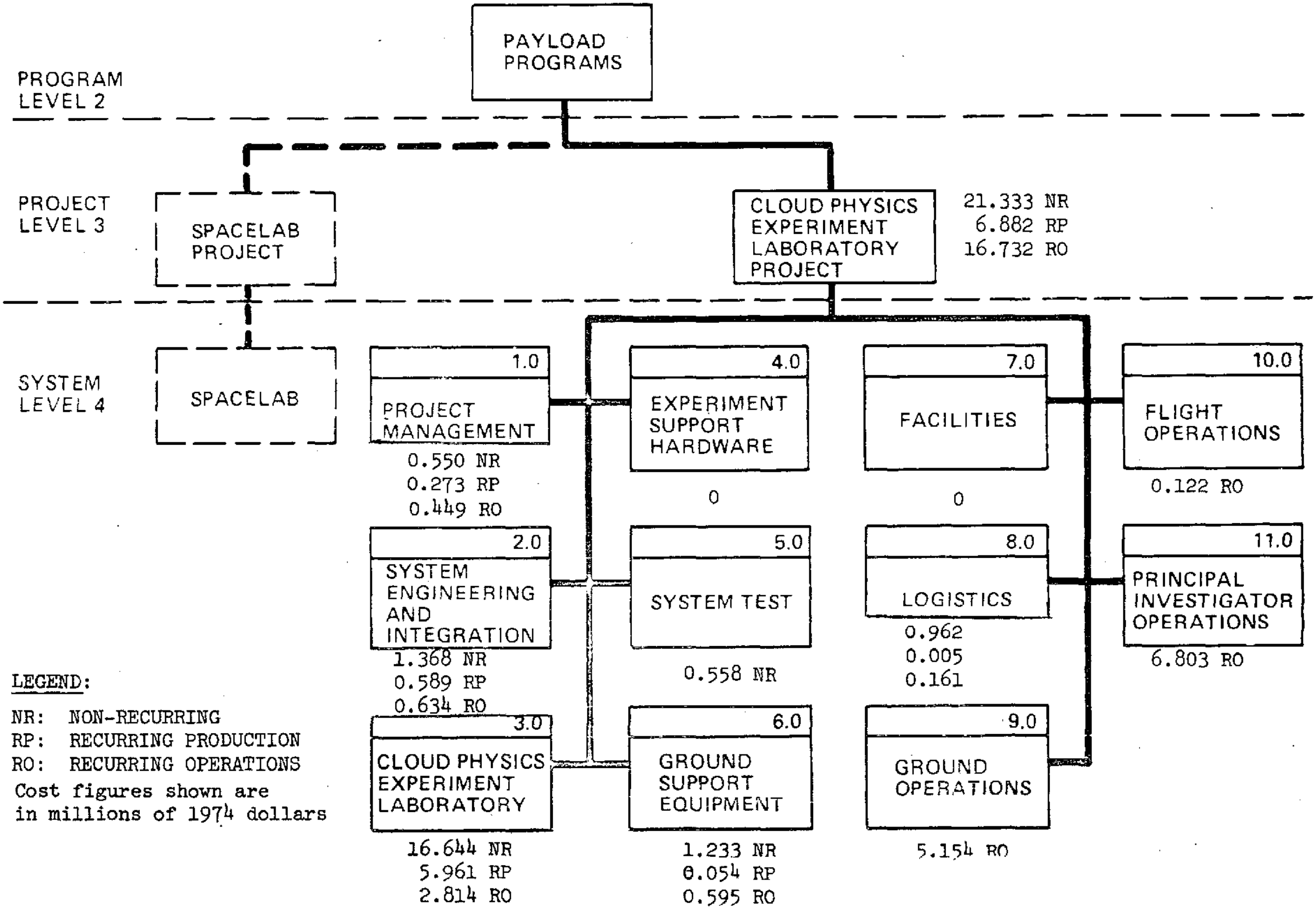

Figure 4-22. CPL Project Cost Breakdown

Table 4-19

CLOUD PHYSICS LABORATORY COST SUMMARY

Cost Item	Costs in Millions of 1974 Dollars			
	DDT&E	Production	Operations	Total
Thermal Control/Expendables Storage and Control	2.501	0.864	0.969	4.334
Particle Generators	1.391	0.357	0.140	1.888
Data Management	2.662	0.791	0.352	3.805
Particle Detectors and Characterizers	2.506	0.774	0.304	3.584
Experiment Chambers	2.693	1.492	0.585	4.770
Console	1.711	0.792	0.053	2.556
Optical Detection and Imaging Devices	2.387	0.618	0.411	3.416
Final Assembly, Integration and Checkout	0.793	0.273	-	1.066
Total	16.644	5.961	2.814	25.419

techniques and processes to advance materials technology and to establish processes to economically manufacture products in space for use on earth. Five equipment assemblies are planned for use in the MS/MS program. Included are the furnace, biological, levitation, general and core equipment assemblies. Different missions will be comprised of different combinations of equipment assemblies. The space processing furnace experiment is comprised of the furnace and core assemblies and will include conducting heat/melt/cool experiments to study the effects of reduced gravity upon material processes. Specific investigations planned for this experiment include the following: 1) study of molten zone crystal growth; 2) study of crystal-pulling-molten zone techniques; 3) study of crystal growth in aqueous solutions and flux; 4) investigation of whisker growth from a vapor; 5) mixing studies of conventional glass preparation; 6) purification of metals by zone refining; 7) solidification of immiscible materials; 8) solidification of particle/fiber reinforced composites; 9) directional solidification of eutectics; and 10) gas phase dispersion in liquid metals.

4.6.2 Experiment Description

The space processing furnace experiment is comprised of two different equipment assemblies. The Furnace assembly is directly used to perform experiments. The second equipment assembly, the Core, includes the information processing, display and fluid supply systems used in supporting the experiments.

The Furnace equipment assembly is basically used for conducting experiments involving high temperature processes, with the material samples encapsulated or held in place by some mechanical support fixtures. Typical experiments include melting, mixing and solidification of composite materials, various selected techniques of crystal growth, directional solidification of eutectc alloys and zone refining of elemental materials, ceramics and alloys. The primary processing equipment for the Furnace assembly will be the heating units, associated power conditioning and control devices and the temperature measurement capability. The Furnace experiment assembly includes the following equipment:

A. Enclosures/Furnaces -- including a general purpose enclosure with a resistance and microwave heater, an 1800°C hot wall furnace, a 1200°C hot wall tube furnace and a gradient furnace.

B. Furnace Accessories -- including mixing and dispersal units, manipulation and displacement units, a sample cooling chamber, a zone refiner and a directional solidification unit.

C. Vacuum System -- including a high vacuum pump, a molecular sieve unit and a vacuum pump power conditioner.

D. Instrumentation and Measurement System -- including temperature measuring pyrometers, vacuum/pressure regulator, vacuum/pressure measuring unit and a residual gas analyzer.

E. Power Conditioning Equipment - including a 10 kw low volt/high amp, 2 KHz-2MHz induction, a 17 kv high voltage and a mixing and dispersal RF induction units.

The Core equipment assembly acts as a service unit for the other equipment assemblies. The heart of the Core is the information processing system which provides for data acquisition and for processing of data for control purposes. The Core equipment assembly comprises the following equipment items:

A. Information Processing System -- including three major subassemblies, the data acquisition units, the data control unit and the analog controller.

B. Display System -- including an oscilloscope and an electro-optical imaging system.

C. Fluid Supply System -- providing inert, oxidizing and reducing gases required for the experiments.

4.6.3 Cost Estimates

A work breakdown structure (WBS) for the Space Processing Application (SPA) project is shown in Fig. 4-23. An estimate of the cost of the SPA project would include all the planned payload configurations and missions, facilities, and ground and flight operations. Included also will be the recurring cost

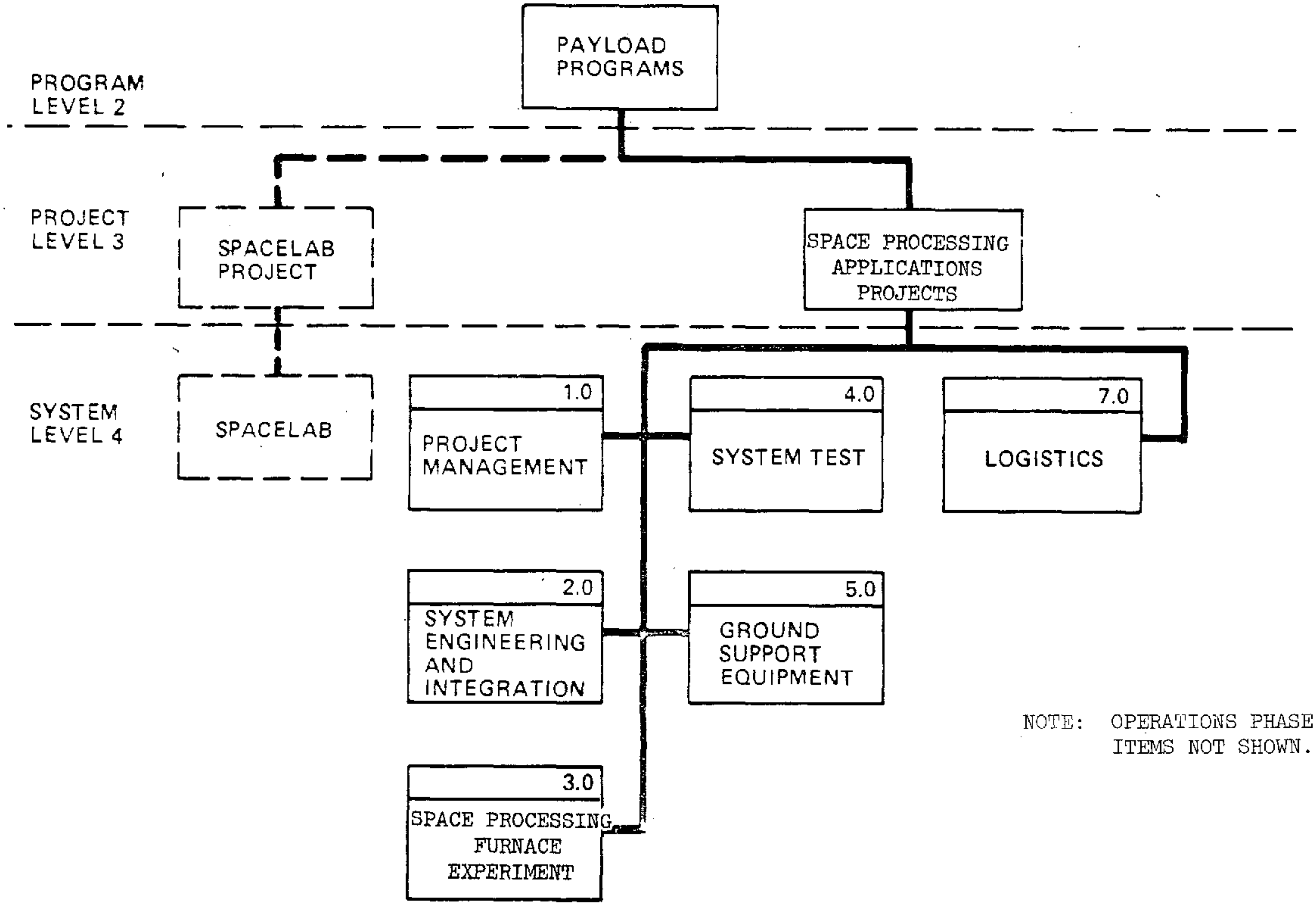

Figure 4-23. Space Processing Applications Work Breakdown Structure

of project management, system engineering and integration, SPA experiments, ground support and logistics functions performed during the operational phase of the program. This study, however, is limited to one payload configuration, that of a Furnace experiment. Cost estimates are given for both the non-recurring design and development and the recurring production phases of the payload. A discussion of the various cost items is presented in the following paragraphs.

4.6.3.1 Laboratory Equipment Cost

Laboratory equipment cost estimates are presented in Table 4-20, which includes component quantities, development status and component development and production costs. The component development status, as well as the cost of many of the commercially available components, have been obtained from the NASA/TRW study report in Reference 4.6-1. The costs of commercially available components, identified by TRW as requiring minimal design changes to be incorporated into the MS/MS payload, were used exactly as provided in the TRW report. The use of a large number of such components in the Furnace experiment resulted in a lower overall experiment cost than obtained in comparable experiments. Estimates of development and production costs of components that are yet to be developed and produced have been obtained from other programs such as the Zero-Gravity Cloud Physics and the Life Sciences Payload Studies. In all cases the cost estimates were kept at a conservative level in keeping with the apparent referenced study philosophy of flying qualified commercial type equipment. The laboratory equipment cost obtained from the summation of data in Table 4-20 is given as follows:

laboratory equipment non-recurring design and development cost = $1,145,000
laboratory equipment recurring production cost, per flight unit = $745,000

4.6.3.2 Data Management and Interface Electronic System

The data management and interface electronic system comprises all the monitoring instrumentation required by the experiments, as well as data acquisition, processing, control and storage. Full use is made of the equipment and capabilities supplied by the Spacelab. The Spacelab computers will process, display, store and/or telemeter the data, as required. The data management

Table 4-20

COST OF SPACE PROCESSING FURNACE EXPERIMENT EQUIPMENT

Component	Quantity	Development Status*	Unit Cost, x1000 Dollars	
			Development	Production
1. Enclosures/Furnaces				
General Purpose Enclosure Chest	1	B	70	50
Resistance Heater	3	B	20	5
Microwave Heater	1	C	250	50
Hot Wall Furnace (1800°C)	1	B	100	30
Hot Wall Tube Furnace (1200°C)	1	B	50	20
Gradient Furnace	1	B	70	40
2. Vacuum System				
High Vacuum Pump	1	A	0	4
Molecular Sieve	1	B	20	20
Vacuum Pump Power Conditioner	1	A	0	2
3. Furnace Accessories				
Acoustic Mixing and Dispersal Unit	1	C	70	30
Electromagnetic Mixing and Dispersal Unit	1	C	50	30

*Legend: (A) item available; may require minimal design change for incorporation in space processing furnace experiment.
(B) item where state of the art is sufficient to permit custom design without further technological development.
(C) item that requires advancement of state of the art or original design item.

Table 4-20

COST OF SPACE PROCESSING FURNACE EXPERIMENT EQUIPMENT (Continued)

Component	Quantity	Development Status*	Unit Cost, x1000 Dollars	
			Development	Production
Mechanical Mixing and Dispersal Unit	1	C	30	15
Three Axis Manipulator	1	A	0	2
Feed and Crystal Holder	1	C	70	25
Piezoelectric Drive	1	B	50	15
Sample Cooling Chamber	1	B	40	10
Zone Refiner	1	B	40	12
Directional Solidification Unit	1	B	50	10
4. Power Conditioning				
Low Volt/High Amp (10 kw)	1	A	0	10
RF Induction (2 KHz-2MHz)	1	A	0	18
High Voltage (17 KV)	1	A	0	4
RF Induction (Mixing and Dispersal)	1	A	0	5

*Legend: (A) item available; may require minimal design change for incorporation in space processing furnace experiment.
(B) item where state of the art is sufficient to permit custom design without further technological development.
(C) item that requires advancement of state of the art or original design item.

Table 4-20

COST OF SPACE PROCESSING FURNACE EXPERIMENT EQUIPMENT (Continued)

Component	Quantity	Development Status*	Unit Cost, x1000 Dollars	
			Development	Production
5. Instrumentation and Measurement				
Two-Color Pyrometer	1	A	0	6
IR Pyrometer	1	A	0	5
Laser Pyrometer	1	C	75	25
Vacuum/Pressure Regulator	1	A	0	1.5
Vacuum/Pressure Measurement	1	A	0	0.8
Residual Gas Analyzer	1	A	0	14
6. Core Equipment				
Digital Clock	1	A	0	1.5
Digital Voltmeter	1	A	0	2.5
Printer (Output)	1	A	0	1.5
Signal Conditioner	1	A	0	1
Set Point Controller	1	A	0	4
Scanner Programmer	1	A	0	3.5

*Legend: (A) item available; may require minimal design change for incorporation in space processing furnace experiment.
(B) item where state of the art is sufficient to permit custom design without further technological development.
(C) item that requires advancement of state of the art or original design item.

Table 4-20

COST OF SPACE PROCESSING FURNACE EXPERIMENT EQUIPMENT (Continued)

Component	Quantity	Development Status*	Unit Cost, x1000 Dollars	
			Development	Production
Multiplexer A/D Converter	1	A	0	4
Processor Unit	1	A	0	7
Input/Output Stage	1	A	0	3
Teleprinter	1	A	0	4
Digital Storage Unit	1	A	0	10
Operator Control Unit	1	A	0	2
Tape Input Unit	1	A	0	6
Storage Peripherals	-	A	0	2
Analog (SCR) Controller	1	A	0	4
Oscilloscope	1	A	0	20
Electro-Optical Imaging System	1	B	20	150
Fluid Supply System	1	B	70	50

*Legend: (A) item available; may require minimal design change for incorporation in space processing furnace experiment.
(B) item where state of the art is sufficient to permit custom design without further technological development.
(C) item that requires advancement of state of the art or original design item.

and interface electronic system cost includes signal conditioners and other experiment electronic interface equipment, as well as procuring and installing environmental instrumentation. The total system cost is given as follows:

data management and interface electronic system non-recurring cost = $940,000

data management and interface electronics recurring production cost = $370,000

4.6.3.3 Power Control and Distribution System

The power control and distribution system comprises the controls and distribution equipment to supply and manage electrical power to the experiment hardware. The cost of the oxygen and hydrogen reactants for the fuel cells are chargeable to the payload but have not been included here since they pertain to the operational phase only.

Power control and distribution system cost is summarized as follows:

Non-recurring cost = $280,000
Recurring production cost = $160,000

4.6.3.4 Consoles

The cost of consoles for the space processing furnace experiment includes the integration, assembly and checkout of the consoles, including the panel assemblies, instrumentation and displays. The cost of the consoles is given as follows:

consoles non-recurring cost = $1,700,000
consoles rucurring production cost = $ 790,000

4.6.3.5 Experiment Support System

This cost item includes provisions for photographic equipment, experiment interfaces and cooling system interfaces. The photographic equipment includes cameras, controllers and drive mechanisms required to support all experiment locations. Equipment interfaces include structural, mechanical and electrical interfaces required between different components. The cooling system inter-interfaces include interfaces and special cooling requirements for the directional solidification unit and the sample cooling chambers. Experiment support costs are as follows:

experiment support design and development cost	= $770,000
experiment support production cost	= $150,000

4.6.3.6 Final Assembly, Integration and Checkout

This cost item includes the integration of experiment assemblies in the Spacelab and providing the necessary interfaces with the vehicle subsystems. Final assembly checkouts, including the checkout of the ground support system and interfaces, are also included in this cost item. A summary of non-recurring and recurring costs is given as follows:

final assembly, integration and checkout non-recurring cost	= $790,000
final assembly, integration and checkout recurring cost	= $270,000

4.6.3.7 Space Processing Furnace Experiment Payload Cost

The cost of the space processing experiment is obtained from the summation of the cost items given in the preceding paragraphs and summarized in Table 4-21. The total cost of the experiment payload is $8,110,000, including $5,625,000 non-recurring and $2,485,000 recurring.

4.6.4 References:

4.6-1. Requirements and concepts for materials science and manufacturing in space payload equipment study, final study report, Volumes IIA through IIE, Contract No. NAS8-28938, TRW Systems Group, Redondo Beach, California, July 1973.

Table 4-21

SPACE PROCESSING EXPERIMENT COST SUMMARY*

Cost Item	Cost in Thousands of 1974 Dollars		
	Design and Development	Production	Total
Payload Equipment	1145	745	1890
Data Management and Interface Electronics	940	370	1310
Power Control and Distribution	280	160	440
Consoles	1700	790	2490
Experiment Support	770	150	920
Final Assembly, Integration and Checkout	790	270	1060
Total	5625	2485	8110

(*) All cost items includes their share of system level cost, including project management, system engineering, system test and ground support.

Section 5

SPACELAB LIFE SUPPORT SUBSYSTEMS

Three life support subsystems applicable to the shuttle Spacelab have been cost analyzed and are presented in this section. Included are 1) cabin thermal control; 2) atmospheric supply and pressurization; and 3) trace contaminants control subsystems. Quantitative analyses of subsystem characteristics, including process flows, performance and physical characteristics, were conducted. Subsystem cost models and cost estimating relationships also were developed. Subsystem schematics were prepared to shown component arrangements and fluid flows. Necessary heat and mass balances were made to determine component sizes and characteristics. Existing component, available from other programs, were utilized whenever possible in order to reduce subsystem cost. Components were then cost analyzed utilizing cost estimating relationships derived in the first phase of the study. Subsystem cost estimates were established from the summation of individual component CER's in a building block fashion. The validity of component CER's was verified when applied to a number of Skylab components and found to agree favorably with actual cost data. A summary of the cost data calcualted for the three life support subsystems evaluated is presented in Table 5-1, which shows at a glance a comparison between different subsystem costs, separated into non-recurring and recurring categories.

In addition to the subsystems presented in this section, cost estimates of 14 types of advanced life support subsystems for Spacelab applications may also be readily made by employing the data derived in the first phase of this study and reported in McDonnell Douglas Reports MDC G-4630 through MDC G-4634, all dated June 1973.

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Table 5-1

LIFE SUPPORT SUBSYSTEMS COMPARISON SUMMARY
(in thousands of 1974 dollars)

Cost Item	Cabin Thermal Control Subsystem	Atmosphere Supply and Pressurization Subsystem	Trace Contaminant Control Subsystem
Non-Recurring Cost			
• Engineering design	585	794	417
• Program management	70	59	31
• General and administrative	302	410	215
• System engineering	240	250	131
• System integration	649	398	209
• Development, qualification and reliability tests	635	480	252
• System test	634	389	204
• Non-accountable test hardware	58	79	42
• Specifications, vendor coordinations and procurement expense	767	648	340
• Minor subcontracts	29	18	9
• Tooling	136	185	97
• GSE	1,433	878	461
Recurring Hardware Cost	425	413	334
Total Subsystem Cost	5,963	5,001	2,742

5.1 THERMAL CONTROL SUBSYSTEM

5.1.1 Spacelab Thermal Control Subsystem Requirements

The Spacelab thermal control subsystem will be assumed to have the following design requirements:

Temperatures	
Atmosphere dry bulb	65 - 80°F
Atmosphere dewpoint (range)	39 - 69°F
Inside Wall (max)	118°F
Forced cooling air (max)	122°F
Payload H/X water outlet	40 ± 5°F
Heat Loads	
Metabolic (nominal)	
total	560 Btu/hr/man
sensible	350 Btu/hr/man
latent	210 Btu/hr/man
Carbon Dioxide Removal Equipment	
total	120 Btu/hr/man
sensible	82 Btu/hr/man
latent	38 Btu/hr/man
Number of Crew (nominal)	3 men
Electrical Power (nominal)	23,890 Btu/hr (7000 watts)
Structural Heat Loss to Orbiter (max)	890 Btu/hr
Orbiter Heat Rejection Capability for Spacelab	29,000 Btu/hr
Added Capability for Peak Cooling (using phase change thermal control)	42,320 Btu/hr (15 min per 3 hr period)
Maximum Module Heat Leak	1,310 Btu/hr

Available Payload Cooling

Module Atmosphere	3,412 Btu/hr (65 - 80°F)
Avionics Bay Atmosphere	10,683 Btu/hr (75-122°F)
Pallet Cold Plates	15,530 Btu/hr (75-109°F)
(when in pallet - only mode)	22,525 Btu/hr (50-90°F)

5.1.2 Subsystem Description

The Spacelab thermal control subsystem (TCS) utilizes a dual water/freon loop for active thermal control and high performance insulation, thermal coatings and thermal isolators for passive thermal control. The Spacelab TCS carries excessive heat from the module and/or pallet-mounted avionics by coolants from the pallets and the module to the orbiter payload heat exchanger. Independent fluid loops are provided for the pallet and module groupings to accommodate the modular capability of the many Spacelab configurations. Water is used as the coolant fluid in the cabin to minimize potential fire or toxicity hazards in the habitable areas. Additionally, the selection of a water loop enables the use of orbiter-type pump and heat exchanger thus eliminating the cost of the design and development of new components.

The separate pallet loop is filled with freon and interfaces with either the module or the orbiter heat exchanger, depending upon the Spacelab configuration.

Each coolant loop incorporates redundant pumps and filtration; each loop also has a positive displacement accumulator, check valves, ground servicing quick disconnects, temperature and pressure instrumentation. The module has inter-loop and orbiter/payload heat exchangers and a thermal capacitor to accommodate thermal transients. Heat enters the loop from the condensing and avionics heat exchangers.

The pallet loop also incorporates pumps, filtration, check valves, instrumentation and an accumulator. Cold plates and avionics heat exchangers provide direct heat transfer into the loop, with thermal capacitor elements incorporated to accommodate local thermal transients. When the Spacelab is operated in the pallets-only mode, a separate water loop is incorporated between the pallet and the orbiter/payload heat exchanger to maintain functional interface identity.

All configurations are provided with ground support equipment to service, sample and operate the independent or combined fluid loops.

Signal conditioning and display equipment has the capability of verifying the measurement accuracy of transducers and to command varying operating modes. Only the Spacelab cabin TCS, utilized in manned Spacelab configurations, is analyzed in this section. The Spacelab cabin TCS consists of three primary loops: (1) the cabin gas loop; (2) the avionics gas loop; and (3) the water loop. The water loop integrates the subsystem by providing heat transport between the gas loops and the pallet and orbiter interfaces. A schematic of the Spacelab cabin TCS, showing tentative arrangement of the TCS components, is presented in Figure 5-1. A brief description of the function of each of the three loops is given as follows.

5.1.2.1 Cabin Gas Loop

In the cabin gas loop, air is drawn from the cabin into a filter/debris trap assembly upstream of redundant cabin fans. Check valves are provided to prevent recirculation through inactive fans. Downstream of the cabin fans, lithium hydroxide canisters are provided for carbon dioxide control. Cabin air cooling and humidity control are provided downstream of the lithium hydroxide canisters by a condensing heat exchanger which interfaces with the water loop. Condensed moisture adheres to the surface of the heat exchanger fins by surface tension. At the outlet of the heat exchanger air passage, a flow of 30 lbs/hr consisting of a mixture of water and air is drawn and routed through the water separator assembly. The water is separated from the air by centrifugal effect and delivered into the condensate storage tank. The dry air is then returned to the cabin. At the water outlet of each separator, fluid check valves are provided to prevent water backflow. The capability is also provided in the condensate collection system for dumping water overboard for long-duration missions and contingency situations. A modulating valve with redundant actuators is provided upstream of the condenser for cabin temperature control. The valve automatically modulates air flow around the condensing heat exchanger depending on return cabin air temperature sensed at the inlet of the cabin TCS.

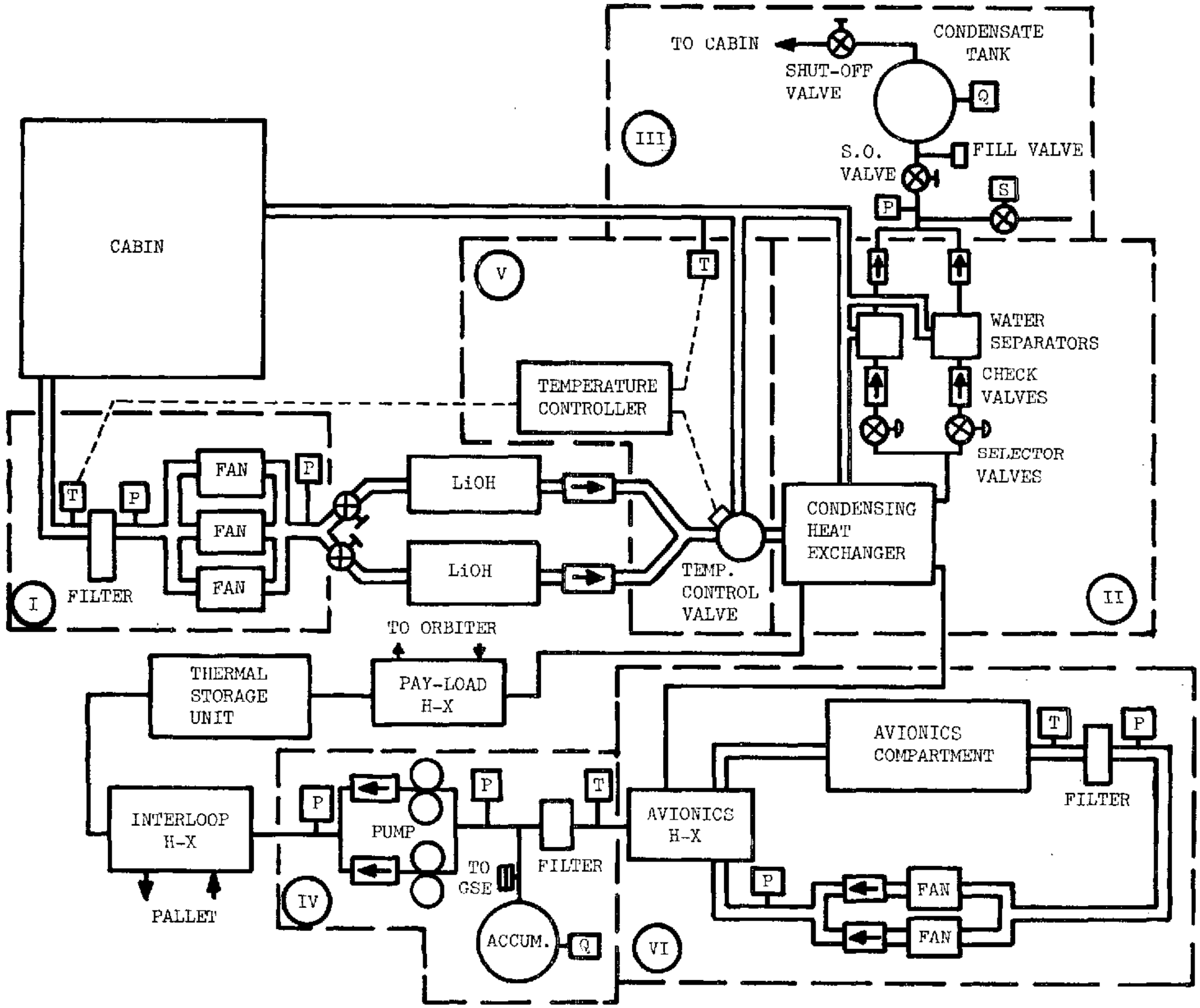

Figure 5-1. Spacelab Cabin Thermal Control Subsystem

5.1.2.2 Avionics Gas Loop

The avionics gas loop provides forced air cooling for avionics equipment located in a compartment isolated from the cabin air. Flow in the loop is provided by the avionics fan assembly, which consists of redundant fans, two check valves and filter for odor and contaminant control. Downstream of the fan assembly, flow is ducted through the avionics heat exchanger interfacing with the water loop. The flow is then delivered to the avionics compartment where it is internally ducted.

5.1.2.3 Water Loop

The water loop collects and transfers heat between equipment in the cabin and the pallet and orbiter interfaces. A separate water loop is provided instead of a single pallet-cabin coolant loop, because of the potential hazard of using fluid other than water within the cabin. The water pump and accumulator assembly is used to direct the water through the interloop heat exchanger, the thermal storage unit, the payload heat exchanger and the condensing heat exchanger. The coolant is then directed to the avionics heat exchanger assembly which is the heat sink for forced air cooled electronics. The interloop heat exchanger transfers heat from the pallet freon loop to the water loop. Downstream the interloop heat exchanger the thermal storage element is provided to accommodate peak loads. The orbiter payload heat exchanger is used to reject a heat load of up to 8.5 KW.

A listing of the cabin thermal control components is given in Table 5-2, which also indicates the weight, power requirements and design status of the assemblies involved.

5.1.3 Cost Estimating Relationships

The components utilized in the cabin TCS have been grouped in six groups, designated I through VI, as shown in the subsystem schematic, Figure 5-1. Cost estimating relationships are developed for each of the component groups and then summed up for a total cost estimate. Components shown in Figure 5-1 but pertaining to CO_2 removal are not included in the analysis. Not included

Table 5-2

SPACELAB CABIN TCS COMPONENTS LIST

Component	Unit Wgt (lbs)	Power (watts)	Design Status
Cabin Fan Assembly			Requalification
Cabin Fan (3)	8.8	450	
Particulate Filter	1.0		
Check Valve (3)	0.4		
Sensor, Temperature	0.3		
Sensor, Pressure (2)	0.4		
Condensing Heat Exchanger/Water Separator			Modified Design
Condensing Heat Exchanger	46.0		
Water Separator (2)	3.5	20	
Temperature Sensor (2)	0.2		
Selector Valve (2)	1.0		
Check Valve, Gas (2)	0.2		
Check Valve, Liquid (2)	0.2		
Condensate Tank Assembly			New Design
Condensate Tank	16.9		
Shutoff Valve, Liquid	1.54		
Shutoff Valve, Gas	0.44		
Pressure Sensor, Liquid	0.44		
Disconnect Valve	0.2		
Quantity Sensor	0.44		
Coolant Pump and Accumulator Assembly			Requalification
Accumulator	3.1		
Pump, Coolant (2)	2.2	50	
Filter	0.2		
Quantity Sensor	0.44		
Pressure Sensor	0.4		
Check Valve, Liquid (2)	0.2		
Disconnect Valve	0.2		
Temperature Controller Assembly			Modified Design
Temperature Controller	2.2		
Temperature Control Valve	4		
Temperature Sensors (2)	0.2		

Table 5-2

SPACELAB CABIN TCS COMPONENTS LIST (Continued)

Component	Unit Wgt (lbs)	Power (watts)	Design Status
<u>Avionics Cooling Assembly</u>			New Design
Fan (2)	6.0	240	
Filter	1.0		
Avionics Heat Exchanger	84.0		
Check Valve (2)	0.4		
Pressure Sensor (2)	0.4		
Temperature Sensor (3)	0.2		

also are the interface thermal control components located outside the manned compartment, which comprise the interloop heat exchanger, the thermal storage unit and the payload heat exchanger.

5.1.3.1 Recurring CER's

A. Cabin Fan Assembly

The cabin fan assembly CER is primarily dependent on electrical power input to the unit and is given by the following relation:

$$\text{Cabin fan assembly cost } C = 45.8\, P^{0.942}\, Q^{0.89} + 2630\, W_{OC} \quad \text{dollars}$$

where,

P = electrical power input to fan = 450 watts

Q = number of fans = 3, and

W_{OC} = weight of associated components, such as filters and valves = 3.28 lbs

Substituting the values of the variables in the above equation results in the following:

Cabin fan assembly cost C = 47,100 dollars

B. Condensing Heat Exchanger/Water Separator Assembly

The CER for the condensing heat exchanger/separator assembly will utilize a heat exchanger CER for the condenser and assume the separator to be part of the associated components, W_{OC}. The condenser/separator cost equation is given as follows:

$$C = 190\ W^{0.267}\ N_P^{1.905} + 3551\ W_{OC} \qquad \text{dollars}$$

where,

W = condenser weight = 46 lbs

N_P = number of ports per condenser = 5

W_{OC} = weight of other components = 11.22 lbs

Substituting the value of variables in the above CER yields:

Condenser/separator assembly cost C = 47,280 dollars

C. Condensate Tank Assembly

The following CER is used to assess the cost of the condensate tank assembly:

$$\text{Condensate tank assembly cost } C = 2302\ V^{0.267} + 3551\ W_{OC} \qquad \text{dollars}$$

where,

V = volume of accumulator, ft^3, and

W_{OC} = weight of other components, lbs

Substituting the value of variables in the above equation, where $V = 1.79\ ft^3$, and $W_{OC} = 3.08$ lbs, yields:

C = cost of condensate tank assembly = 13,626 dollars

D. Coolant Pump and Accumulator Assembly

The coolant pump and accumulator assembly CER combines cost estimates for the pump, accumulator and associated components, comprising valves and sensors, as follows:

$$\text{Coolant pump and accumulator cost } C = 109\, P^{0.942}\, Q^{0.89} + 2302\, V^{0.267} + 3551\, W_{OC} \quad \text{dollars}$$

where,

P = electrical power input to pump = 50 watts

Q = number of pumps used = 2

V = volume of accumulator = 0.05 ft^3, and

W_{OC} = weight of associated equipment = 4.22 lbs

Substituting the values of variables in the above CER yields:

$$\text{Coolant pump and accumulator cost } C = 21{,}882 \quad \text{dollars}$$

E. Temperature Controller Assembly

This assembly comprises a temperature control valve, a temperature controller and sensors. The CER developed for the assembly is based on cost data of similar components in the Gemini and Skylab programs and is given as follows:

$$\text{Temperature controller assembly cost } C = 2304\, W_1 + 5700\, W_2 + 3551\, W_3 \quad \text{dollars}$$

where,

W_1 = weight of temperature control valve = 4.0 lbs

W_2 = weight of temperature controller = 2.2 lbs, and

W_3 = weight of temperature sensors = 0.9 lbs

Substituting the values of variables in the above CER yields:

Cost of temperature controller assembly C = 24,952 dollars

F. Avionics Cooling Assembly

The avionics cooling assembly comprises the avionics condenser, filters, fans, sensors and valves. The following CER is used for the avionics cooling assembly:

$$\text{Avionics cooling assembly cost } C = 159\ W^{0.267}\ N_P^{1.905} + 91\ P^{0.942}\ Q^{0.89} + 2959\ W_{OC} \quad \text{dollars}$$

where,

W = heat exchanger weight = 84 lbs

N_P = number of ports per heat exchanger = 4

P = electrical power input to fan = 240 watts

Q = number of fans = 2, and

W_{OC} = weight of associated components = 3.54 lbs

Substituting the value of variables in the above CER yields:

Cost of avionics cooling assembly C = 56,652 dollars

5.1.3.2 Recurring Cost of Integrated Cabin TCS

The integrated cabin TCS cost is obtained by adding up the recurring costs of individual components and utilizing overall factors for packaging and assembly, resulting in the following:

$$\text{Spacelab cabin TCS recurring cost} = 1.833 \times 11 \times (47{,}100 + 47{,}280 + 13{,}626 + 21{,}882 + 24{,}952 + 56{,}652) = 425{,}098 \quad \text{dollars}$$

5.1.3.3 Non-Recurring Cost of Spacelab Cabin TCS

In establishing the non-recurring costs of the Spacelab TCS, two methods were used: 1) for new design assemblies, the methodology developed in this study for the design and development phase expenditure was applied; and 2) for requalified and modified design assemblies the method used was that of qualifying already developed equipment for use in flight experiments. The cost estimate of management, testing and qualification of previously developed hardware has been developed before in this study and is presented above in paragraph 3.3, Qualification of Commercial Hardware.

The non-recurring cost of new design assemblies is obtained by utilizing a CER developed for engineering design and adding to it the cost of other non-recurring functions on an average percentage basis. The engineering design CER is based on the analysis of a number of cost influencing parameters which indicated that design cost is mainly a function of the number of component types (N) in each system and is given by the following relation:

TCS new assemblies design cost $C_D = 41,922\ N + 123,530$ dollars

A study of Table 5-2 indicates that new design assemblies comprise 11 different component types. Accordingly,

The design cost of condensate tank and avionics cooling assemblies $C_D = 584,672$ dollars

Utilizing the cost breakdown ratios for other non-recurring function,

The total design and development phase cost of the condensate tank and avionics assemblies = 3,377,655 dollars

For the requalified and modified design components, a study of Table 5-2 indicates that they possess 14 different type components. Thus,

The design cost of requalified and modified assemblies $C_D = 710,438$ dollars

Therefore, applying the methodology described above for qualifying already developed components, we obtain:

Total design and development phase costs of requalified and modified assemblies = 2,160,454 dollars

and,

Total non-recurring costs of cabin TCS = 5,538,108 dollars

5.1.3.4 Cabin TCS Total Cost

The total cost of cabin TCS = 5,538,108 + 425,098 = 5,963,206 dollars

5.2 ATMOSPHERIC SUPPLY AND PRESSURIZATION SUBSYSTEM

Atmospheric supply and pressurization subsystem (AS&PS) design requirements and a representative subsystem description, based on the current ERNO Consortium configuration, are presented in the following paragraphs. Included also are the cost estimating relationships and the estimated cost of designing, developing and procuring an AS&PS for the Spacelab.

5.2.1 Atmospheric Supply and Pressurization Subsystem Requirements

The Spacelab AS&PS will be assumed to have the following design requirements:

Atmosphere Total Pressure	14.7 ± 0.25 psia
Oxygen Partial Pressure	3.2 ± 0.25 psia
Atmosphere Relief Pressure	15.04 psi
Atmosphere Leakage, Max.	3 lbs/day
Metabolic Oxygen Consumption	1.8 lbs/man-day
Pressurized Volume:	
Core Segment	1235 ft^3
Experiment Segment	822 ft^3
Experiment Airlock	42 ft^3

Number of Airlock Repressurizations	1/day
Airlock Repressurizing Gas	Dry nitrogen
Flow Rate, Max.	0.5 lbs/min.
Emergency Oxygen	6 man-days

The Spacelab AS&PS consists of two identical high pressure (3000 psi) storage tanks containing 47.1 lbs of oxygen and 34.3 lbs of nitrogen. Storage of emergency oxygen is available in the excess capacity of the oxygen tank. The tanks are equipped with pressure relief valves to protect against overpressurization and with burst discs upstream of the relief valves to avoid leakage.

The total Spacelab gas storage requirements for a representative 7-day mission are given in Table 5-3.

The AS&PS has been designed to provide dry nitrogen for airlock repressurization to prevent condensation on airlock equipment. After the airlock is opened to the cabin, the airlock nitrogen mixes with cabin air. When the airlock is depressurized, some cabin oxygen is also dumped overboard. For worst case

Table 5-3

SPACELAB TOTAL GAS STORAGE REQUIREMENT
FOR A SEVEN-DAY MISSION

Oxygen	
Metabolic Consumption	25.8 lbs
Airlock Repressurization	5.5 lbs
Leakage	4.8 lbs
Emergency Oxygen Available	11.0 lbs
Total GO_2 Storage	47.1 lbs
Nitrogen	
Airlock Repressurization	18.5 lbs
Leakage	15.8 lbs
Total GN_2 Storage	34.3 lbs

conditions, when there is minimum cabin leakage, the resulting oxygen partial pressure may be low and it may be required to compensate for lost oxygen. Thus, the quantities shown for airlock repressurization include gases to provide for this compensation.

5.2.2 Subsystem Description

A schematic of the Spacelab AS&PS is shown in Figure 5-2. The cabin atmosphere composition control is provided by a continuous regulation system used to control the flow and pressure of oxygen and nitrogen. Oxygen and nitrogen are delivered from the gas storage tanks to separate high pressure regulation assemblies each of which contains manually selectable redundant components. Nitrogen is reduced to a pressure of 150 psia and delivered to the inlet of an atmosphere pressure control assembly containing redundant nitrogen solenoid valves. Oxygen is reduced to a pressure of 120 psia and delivered to a point downstream of the atmosphere pressure control assembly. Either oxygen or nitrogen is delivered to the total pressure regulator. The selection of gas to be delivered is made by a flow controller which receives signals from three oxygen partial pressure sensors. When at least two of these sensors indicate that the oxygen partial pressure is at the required level of 3.2 ± 0.25 psi, the oxygen partial pressure controller opens the two redundant nitrogen solenoid valves. The higher nitrogen pressure prevents oxygen flow and only nitrogen is delivered to the total pressure regulator. When the oxygen partial pressure falls below its required level, the nitrogen solenoid valve is closed and only oxygen is delivered. Either one of two redundant total pressure regulators may be manually selected for operation.

The AS&PS contains instrumentation required to monitor and evaluate performance. Parameters required for routine operation of the Spacelab are displayed on the EC/LS monitor. All measurements are telemetered permitting ground station determination of malfunctions at the functional level. Manual crew selection of redundant components restores nominal section performance in the event of equipment failure.

The Spacelab structure is protected against excessive internal pressure by an assembly containing redundant pressure relief valves equipped with manual overrides. The valves are designed to relieve pressure also in the inward

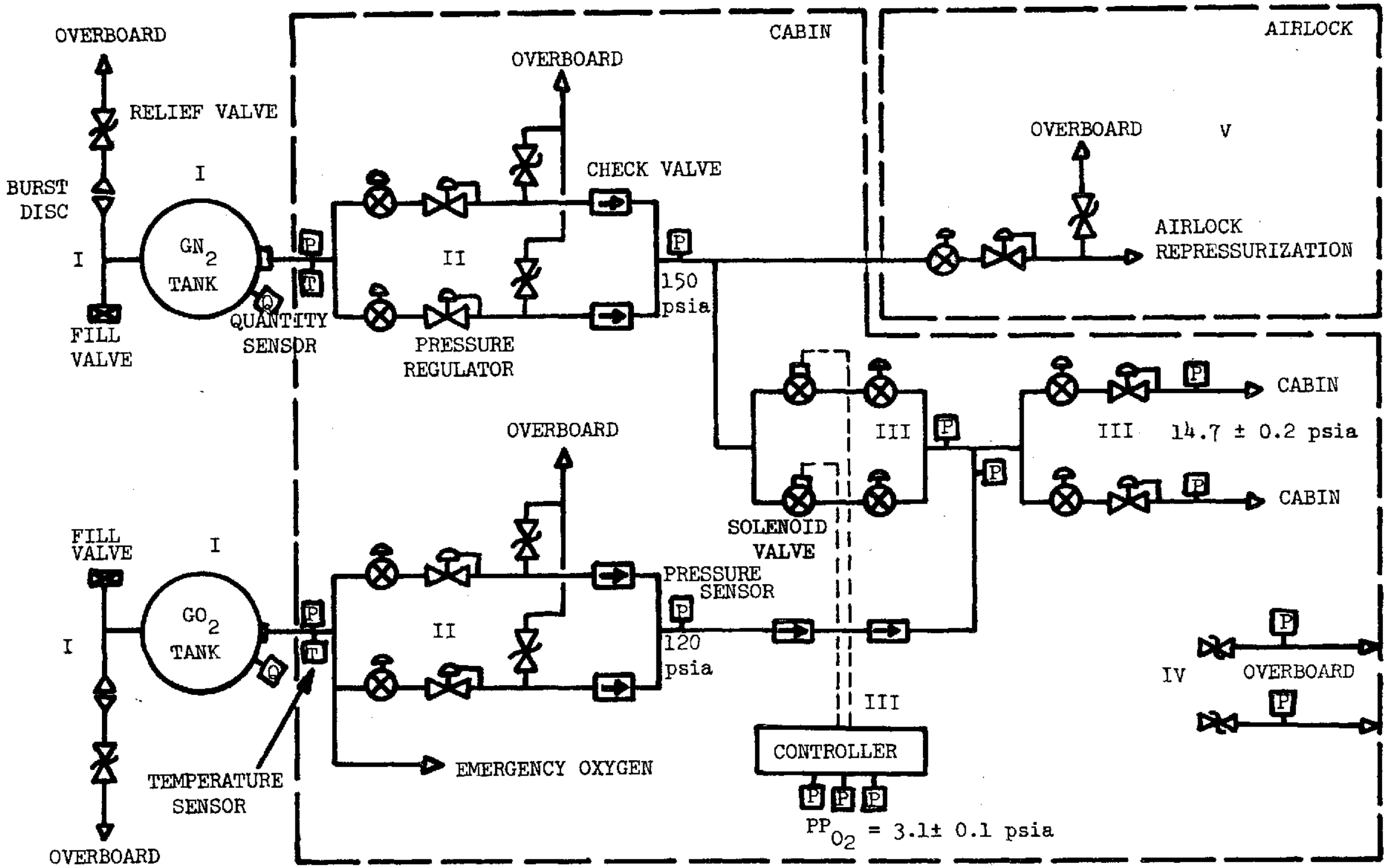

Figure 5-2. Spacelab Atmospheric Supply and Pressurization Subsystem Schematic

direction in the event that a negative pressure differential occurs during descent. They can also be used to manually or remotely depressurize the Spacelab in the event of smoke or fire or accidental release of toxic gases.

A listing of the AS&PS components is given in Table 5-4, which also includes component quantity and weights and nominal power requirements per assembly. Included also in Table 5-4 is the design status of each assembly.

5.2.3 Cost Estimating Relationships

The recurring and non-recurring cost estimating relationships for the Spacelab AS&PS are presented in the following paragraphs. In order to facilitate the calculations, the AS&PS has been divided into five major groups, designated I through V, as shown in the system schematic, Figure 5-2.

5.2.3.1 Recurring CER's

A. Gaseous Atmospheric Supply

The recurring CER's for the GO_2 and the GN_2 tanks are given by the following equation, developed for high pressure gaseous storage tanks:

$$\text{Gaseous tank cost } C = 22{,}361\ V^{0.377}\ Q^{0.89} + 3551\ W_{OC} \qquad \text{dollars}$$

where,

V = volume of tanks = 2.59 ft^3
Q = number of tanks = 2 and
W_{OC} = weight of associated components = 5.98 lbs.

Associated components denote fill and relief valves and other valves and sensors associated with the operation of the tanks. An assembly integration factor is used at the subsystem level to account for necessary piping and packaging. Substituting the values of variables in the above equation yields the following:

$$C = 22{,}361 \times 2.59^{0.377} \times 2^{0.89} + 3551 \times 5.98 = 80{,}550 \qquad \text{dollars}$$

Table 5-4

AS&PS EQUIPMENT LIST

Component	Quantity	Unit Wgt. (lbs)	Nominal Power (watts)	Design Status
Gaseous Atmospheric Supply Assy.	1	143.70	4	New design
Oxygen/Nitrogen Tank	2	60.50		
Pressure Sensor, Tank	2	0.55		
Temperature Sensor, Tank	2	0.02		
Quantity Indicator, Tank	2	0.66		
Oxygen/Nitrogen Fill Valve	2	0.44		
Burst Disc	2	0.66		
Relief Valve	2	0.66		
Regulator Assemblies	1	40	4	Existing
Shutoff Valve	2			
Pressure Regulator, Oxygen	2			
Relief Valve, Oxygen	2			
Check Valve, Oxygen	2			
Pressure Sensor, Oxygen	1			
Shutoff Valve	2			
Pressure Regulator, Nitrogen	2			
Relief Valve, Nitrogen	2			
Check Valve, Nitrogen	2			
Pressure Sensor, Nitrogen	1			
Controller Assembly	1	18.6	24	Existing
Solenoid Valve, Nitrogen	2			
Valve Position Indicator	2			
Shutoff Valve	4			
Flow Indicator, Nitrogen	1			
Check Valve, Oxygen	2			
Flow Indicator, Oxygen	1			
Cabin Pressure Regulator	2			
Pressure Sensor	2			
Controller, Oxygen Partial Pressure	1			
Partial Pressure Sensor, Oxygen	3			

Table 5-4

AS&PS EQUIPMENT LIST (Continued)

Component	Quantity	Unit Wgt. (lbs)	Nominal Power (watts)	Design Status
Cabin Pressure Relief Assy.	1	2.38	12	New design
Cabin Pressure Relief Valve	2			
Flow Indicator, Atmosphere	2			
Repressurization	1	1.77	--	New design
Shutoff Valve	1			
Pressure Regulator	1			
Relief Valve	1			

B. Regulator Assemblies

The cost estimating relationship developed for the regulator assemblies is based on the cost of similar components in the Gemini and Skylab atmospheric control systems and is given by the following:

Regulator assembly cost $C = 4080\ W\ Q^{0.89}$ dollars

where,

W = regulator assembly weight = 9.5 lbs, and

Q = number of regulator assemblies = 2.

Substituting the values of variables in the above equation yields:

$C = 4080 \times 9.6 \times 2^{0.89} = 72{,}660$ dollars

C. Controller Assembly

The controller assembly comprises solenoid and manual shutoff valves, flow and pressure sensors, controllers and oxygen partial pressure sensors. The recurring cost estimating relationship for the controller assembly is given by the following equation, based on a study of currently available component costs. The cost of the oxygen partial pressure sensors is based on the assumption that the Spacelab will utilize the same sensors used on the orbiter with no additional modifications.

Controller assembly cost $C = 3276\ W_V + 3600\ N + 6000\ S$ dollars

where,

W_V = weight of valves and pressure and flow sensors = 6.06 lbs

N = number of controllers = 3, and

S = number of oxygen partial pressure sensors = 3.

Substituting the value of variables in the above equation yields:

$C = 30{,}671$ dollars

D. Cabin Pressure Relief Assembly

The following recurring CER has been derived based on available costs of similar components utilized in the Skylab and other space programs:

Cabin pressure relief assembly cost $C = 7134\ W_R$ dollars

where,

W_R = cabin relief components weight = 2.38 lbs

then,

$C = 16{,}975$ dollars

E. Airlock Repressurization Assembly

The airlock repressurization assembly recurring cost is obtained by utilizing component cost data from the Skylab, Gemini and other space programs. The recurring CER for the airlock repressurization assembly is given by the following:

$$\text{Airlock repressurization assembly cost } C = 2220\ W_A \qquad \text{dollars}$$

where,

$$W_A = \text{airlock repressurization components weight} = 1.77 \text{ lbs}$$

then,

$$C = 3894 \qquad \text{dollars}$$

5.2.3.2 Integrated AS&PS Recurring Cost

The recurring cost of the integrated AS&PS, including the cost of packaging and interface hardware, is obtained from the results of the CER's utilized in this section and resulting in the following:

$$\text{Total AS\&PS recurring cost} = 1.833 \times 1.1 \times (80{,}550 + 72{,}660 + 30{,}671 + 16{,}975 + 3894) = 412{,}836 \qquad \text{dollars}$$

5.2.3.3 Non-Recurring Cost of AS&PS

The non-recurring cost of the AS&PS is obtained by utilizing a CER developed for engineering design and adding to it the cost of other non-recurring functions on a percentage basis, as presented in Section 3 and shown in Table 3-4. The cost breakdown ratios listed in Table 3-4 are average values obtained from analyzing the ECS cost data of the Gemini spacecraft and are assumed representative of cost-effective ECS development. The engineering design CER was based on the analysis of a number of cost influencing parameters which indicated that design cost is mainly a function of the number of component types (N) in each system and is given by the following relation:

$$\text{AS\&PS design cost } C_D = 41{,}922\ N + 123{,}530 \qquad \text{dollars}$$

The AS&PS comprises three new design assemblies, the gaseous atmospheric supply, airlock repressurization and the cabin pressure relief, in addition to two major existing design assemblies, as shown in Table 5-4. The three new design assemblies include 12 component types. An additional four equivalent component types are added to account for the design effort required for incorporating the existing design assemblies. Thus, substituting N = 16 in the above CER yields the following:

AS&PS design cost C_D = 794,282 dollars

Applying the non-recurring cost breakdown shown in Table 3-4 results in the AS&PS design and development phase expenditure breakdown given in Table 5-5.

Table 5-5

AS&PS DESIGN AND DEVELOPMENT PHASE EXPENDITURE BREAKDOWN

Cost Item	Non-Recurring Cost
Engineering design	794,281
Program management	59,193
General and administrative	410,218
System engineering	250,077
System integration	397,829
Development, qualification and reliability tests	479,505
System test	389,110
Non-accountable test hardware	79,382
Specifications, vendor coordinations and procurement expense	648,365
Minor subcontracts	17,895
Tooling	184,460
GSE	878,252
Total	4,588,567

5.2.3.4 Total AS&PS Cost

The total AS&PS cost is obtained by adding up the recurring and non-recurring costs, resulting in the following:

Total AS&PS cost = 412,836 + 4,588,567 = 5,001,403 dollars

5.3 TRACE CONTAMINANTS CONTROL SUBSYSTEM

A complete trace contaminants control subsystem is required for extended duration missions, such as the planned Spacelab 30-Day missions. Gases such as carbon monoxide, that can only be effectively removed by oxidation, may be tolerated in the 7-day missions. However, it is highly recommended that a catalytic oxidizer to remove lower molecular weight contaminants be included for the 30-day missions as the contaminants would build up to objectionable levels in such a long duration. Trade contaminant removal equipment removes or controls atmospheric contaminants sufficiently to limit the concentrations to some acceptable level. Contaminants may be separated into the broad categories of particles and gases. Particles include solids such as dust as well as small liquid droplets. Those gases which have been identified as potential contaminants and those which have been detected in the Mercury and Gemini space vehicles, submarines, Apollo outgassing tests, Earth-based space cabin simulator tests are rather extensive. However, at the present time there exist no adequate criteria for predicting outgassing or generation rates for non-biological contaminants. Reference 5.3-1 has an extensive discussion of these gases and the generation rates have been treated conservatively to establish the required removal rates. These generation rates and maximum allowable concentrations from Reference 5.3-1 provide the basis for designing and sizing the capacity of the trace contaminant removal equipment. The necessary equipment includes particulate filters, activated charcoal, and catalytic oxidizers. A discussion of a trace contaminants control subsystem for the 30-day mission Spacelab is presented in the following paragraphs.

5.3.1 Trace Contaminants Control Subsystem Requirements

The Spacelab trace contaminants control subsystem will be assumed to have the following design requirements:

Atmosphere Total Pressure	14.7 ± 0.25 psia
Oxygen Partial Pressure	3.2 ± 0.25 psia
Atmosphere Leakage, Maximum	3 lbs/day
Trace Contaminant Concentration Levels	See Reference 5.3-1
Pressurized Cabin Volumes:	
Core Segment	1235 ft^3
Experiment Segment	822 ft^3
Experiment Airlock	42 ft^3

5.3.2 Subsystem Description

A schematic diagram of the trace contaminants control subsystem is presented in Figure 5-3. The subsystem comprises a particulate filter, an activated charcoal bed, and a catalytic oxidizer with pre- and post-sorbents. The activated charcoal and particulate filters are located upstream of the cabin fan. The catalytic oxidizer draws its air flow from the downstream side of the fan and returns it for recycling and further absorption through the activated charcoal bed. Trace contaminant control equipment selection and sizing is based on a trade off of oxidizable contaminants removed by charcoal vs. catalytic oxidization. More than a hundred pounds of charcoal would be required to remove all contaminant gases other than H_2, CO, and CH_4. By sizing the catalytic oxidizer to remove essentially all oxidizable gases, non-regenerable sorbents are reduced to a minimum. Expendable sorbent quantities are then limited to that required for ammonia control, some charcoal added to the ammonia sorbent bed for rapid peak odor control, and the pre and post sorbents used in conjunction with the catalytic oxidizer.

Particulate filters include not only a debris filter but also an absolute filter used in conjunction with charcoal. The debris filter traps coarse particles entering the atmosphere purification loop and the absolute filter

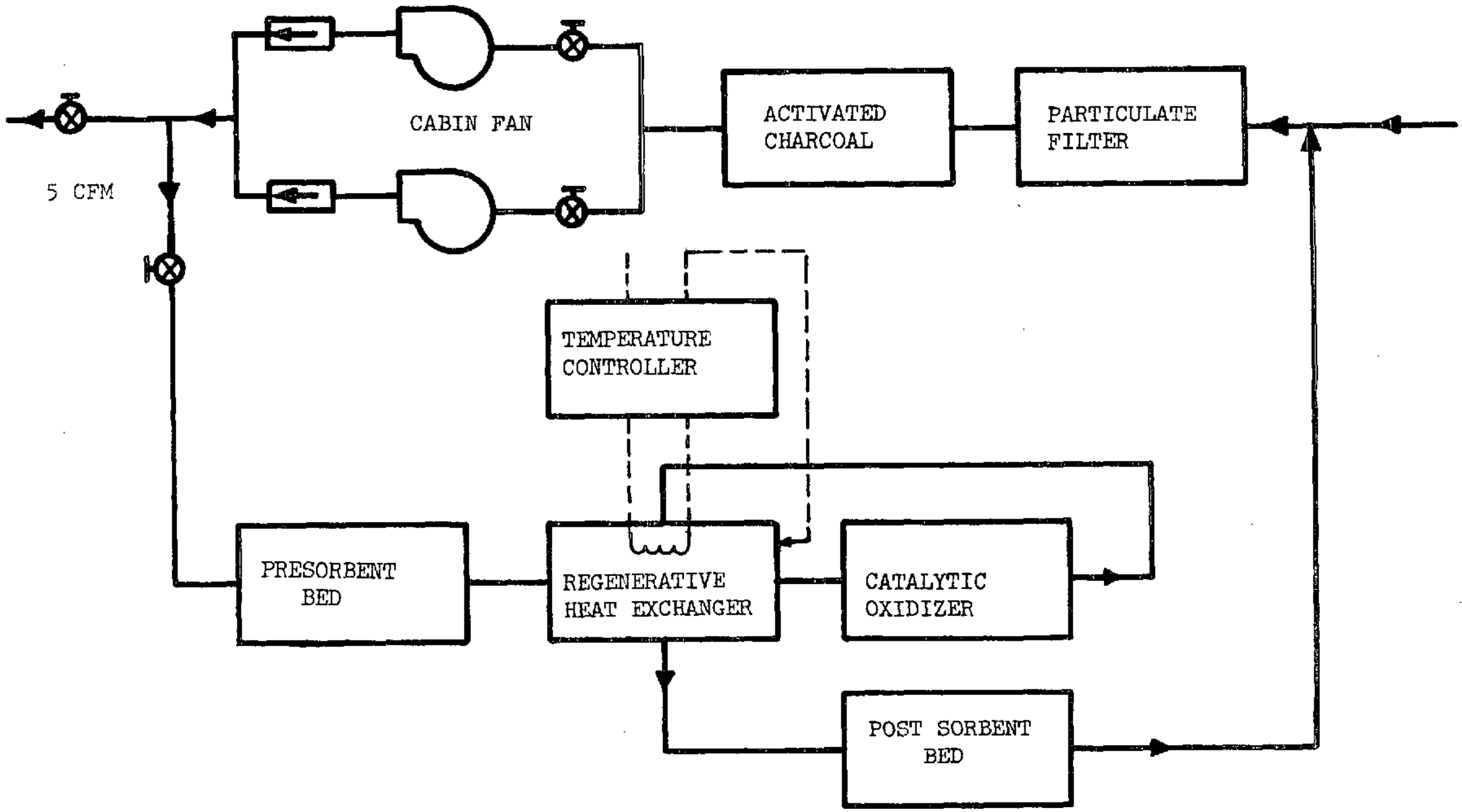

Figure 5-3. Trace Contaminants Control Subsystem

removes particles in size down to 0.3μ. The particulate filters weigh one pound and have a pressure drop of 0.2 in. of water. Activated charcoal is impregnated with phosphoric acid for removal of ammonia and basic (high pH) compounds, but the activated charcoal is primarily to remove contaminant gases having a high molecular weight. The unit is designed to provide a reasonable residence time of approximately 0.2 seconds for contaminant removal.

The catalytic oxidizer comprises a cylindrical unit containing 0.5% palladium catalyst, electrical heaters, and a regenerative heat exchanger, all contained within a vacuum insulated jacket. The pre- and post-sorbent bed filters are connected to the catalytic oxidizer with tubing. The design gas flow through the catalytic oxidizer is 5 cfm which is considered adequate for removal of all oxidizable gases. Carbon monoxide oxidation, which is generally used to size the unit flow, would require only 2 to 2.5 cfm. The catalytic oxidizer oxidizes the various lower molecular weight gases in the cabin atmosphere to CO_2, water vapor, or other compounds. Pre- and post-sorbent beds are included with the catalytic oxidizer to prevent catalyst poisoning and to remove the undesirable oxidation products. These can be acid-impregnated activated charcoal, Linde type 13 Zeolite, and LiOH sorbents. The selected sorbent bed material is usually LiOH. The LiOH is more desirable for during usage the pre-sorbent LiOH will be partially converted to $LiCO_3$ due to CO_2 absorption. The combination LiOH and $LiCO_3$ presorbent will effectively remove such compounds as SO_2, H_2S, HCl, and HF. As a postsorbent, it will remove such acid gases as HCl and HF resulting from the catalytic oxidation processes and will control ammonia and basic (high pH) compounds.

The trace contaminants control subsystem components are listed in Table 5-6, which also includes component quality, weight and nominal power requirements.

5.3.3 Cost Estimating Relationships

The recurring and non-recurring cost estimating relationships for the trace contaminants control subsystem are presented in the following paragraphs.

Table 5-6

TRACE CONTAMINANTS CONTROL SUBSYSTEM COMPONENTS LIST

Component	Quantity	Unit Weight, Lbs.	Power, Watts
Pre/Post Sorbent Bed	2	12.0	-
Particulate Filter	1	1.0	-
Activated Charcoal Bed	1	12.0	-
Catalytic Oxidizer (including heater)	1	5.0	50
Catalytic Oxidizer Heat Exchanger	1	1.5	-
Catalytic Oxidizer Controller	1	4.5	-
Valve, Shut Off Manual	1	0.5	-

5.3.3.1 Recurring Cost Estimates

The recurring cost estimates for each of the trace contaminants control components is given by a CER derived for the component and presented in Table 5-7. The CER derivation is based on cost data for similar components flown in previous space programs and modified to reflect specific component characteristics. The recurring cost of the integrated trace contaminants control subsystem is obtained from solving the individual CER's listed in Table 5-7 and then applying factors that account for the cost of packaging and interface hardware, resulting in the following:

Trace contaminants control subsystem's
total recurring cost = 333,660 dollars

5.3.3.2 Non-Recurring Cost of Trace Contaminants Control Subsystem

Table 5-8 presents a breakdown of the non-recurring costs obtained by utilizing a CER developed for engineering design and adding to it the cost of other non-recurring functions on a percentage basis. The cost breakdown ratios used are average values obtained from analyzing the ECS cost data of the Gemini spacecraft and are assumed representative of cost-effective ECS development. The engineering design CER was based on the analysis of a number

Table 5-7

TRACE CONTAMINANTS CONTROL SUBSYSTEM RECURRING COST ESTIMATES

Component/Subassembly	Cost Estimating Relationships	Notes
Pre/Post Sorbent Bed	Cost = 19,038 $W_{CAN}^{0.267}$ $Q^{0.89}$ + 3551 W_{OC} dollars	W_{CAN} = Average Canister Weight, Lbs. W_{OC} = Other Components Weight, Lbs.
Activated Charcoal Bed	Cost = 19,038 $W_{CAN}^{0.265}$ dollars	
Particulate Filter	Cost = 3000 W_F dollars	W_F = Particulate Filter Weight, Lbs.
Catalytic Oxidizer Heat Exchanger	Cost = 190 $W_{HX}^{0.267}$ $N_p^{1.905}$ + 3551 W_{OC}	W_{HX} = Heat Exchanger Weight, Lbs. N_p = Number of ports per heat exchanger
Catalytic Oxidizer	Cost = 190 (100 $W_C^{0.267}$ + 4 $W_H^{0.265}$)	W_C = Catalytic Oxidizer Weight, Lbs. W_H = Heater Weight, Lbs.
Catalytic Oxidizer Controller	Cost = 5574 W_{CN} dollars	W_{CN} = Controller Weight, Lbs.

Table 5-8

TRACE CONTAMINANTS CONTROL SUBSYSTEM DESIGN AND DEVELOPMENT PHASE EXPENDITURE BREAKDOWN

Cost Item	Non-Recurring Cost
Engineering design	416,983
Program management	31,075
General and administrative	215,357
System engineering	131,286
System integration	208,853
Development, qualification and reliability tests	251,732
System test	204,276
Non-accountable test hardware	41,674
Specifications, vendor coordinations and procurement expense	340,380
Minor subcontracts	9,395
Tooling	96,838
GSE	461,067
Total	2,408,916

of cost influencing parameters which indicated that design cost is mainly a function of the number of component types (N) in each system and is given by the following relation:

Subsystem design cost C_D = 41,922 N + 123,530 dollars

Table 5-6 shows that the number of component types N = 7, resulting in a subsystem design cost = 416,984 dollars. The total subsystem's non-recurring cost is shown in Table 5-8 and = 2,408,916 dollars.

5.3.3.3 Trace Contaminants Control Subsystem's Total Cost

The subsystem's total cost is obtained from the summation of the recurring and non-recurring costs and = 333,660 + 2,408,916 = 2,742,576 dollars.

REFERENCES

5.3-1. Space Station Prototype (SSP), Contaminants Control Subsystem, Hamilton-Standard Division of United Aircraft Corporation, June 1971.

Section 6
CONCLUSIONS AND RECOMMENDATIONS

Cost models have been established and valuable cost estimates were made for selected life sciences experiments and subsystems applicable to the shuttle Spacelab payload. Cost estimates of two non-life sciences experiments, Cloud Physics and Space Processing, were also identified to present a basis of comparison between life sciences and other manned spaceflight experiments where a large part of the cost data was independently collected. The results of comparison showed a generally good consistency. For example, a medical emphasis life sciences Spacelab experiment production cost was estimated at $27 million compared to a Cloud Physics experiment production cost of $21 million. The Cloud Physics experiment is approximately half the size of the medical emphasis LSSL but has relatively higher development cost equipment.

The results of this phase of the study present valuable cost data for the Spacelab experiments and subsystems evaluated which are necessary for planning and allocation of resources. The cost models and estimating relationships may also be used to estimate the cost of comparable Spacelab life sciences experiments and subsystems.

Some of the more pertinent study conclusions include the following:

A. The majority of life sciences experiments and equipment are not defined to a degree commensurate with adequate cost analyses. Preliminary designs had to be performed on all experiments evaluated in this phase of the study.

B. The major cost impact area in life sciences and other experiments is the cost of developing new flight type experiment components.

C. The total project cost for any 10 to 12 year Spacelab project necessitates the allocation of high percentage of cost to the operations phase, sometimes up to 50% of total. A high cost program value is thus inevitable whenever the operations cost is included.

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D. The use of previously developed and flown components provide significant reduction in program costs. This was clearly illustrated in developing cost estimates for the thermal control and atmospheric supply and pressurization subsystems for Spacelab.

E. The cost of flight qualification of commercial hardware, with no major modifications, is approximately 50% of the cost of newly developed flight hardware.

F. Spacelab life sciences experiments require low temperature cooling of magnitudes not available in the basic Spacelab subsystems.

Following are some of the pertinent study recommendations:

A. NASA's supporting research and technology programs should undertake the development of important experiment equipment and components up to flight hardware status.

B. The utilization of flight-qualified components and the qualification of commercial hardware for use in experiments and subsystems should be encouraged in all new programs as an effective cost reduction method.

C. Definition studies and preliminary designs of promising life sciences experiments should be conducted immediately and followed by cost analyses of the experiments, in order to select and develop flight hardware for projected 1980 Spacelab missions.

D. The development of a low temperature refrigeration subsystem for life sciences Spacelab is recommended as an essential support subsystem which may also be used with numerous other Spacelab payloads. The utilization of refrigeration system technology and hardware developed in the Skylab program would greatly reduce development costs of such a subsystem.