BOEING

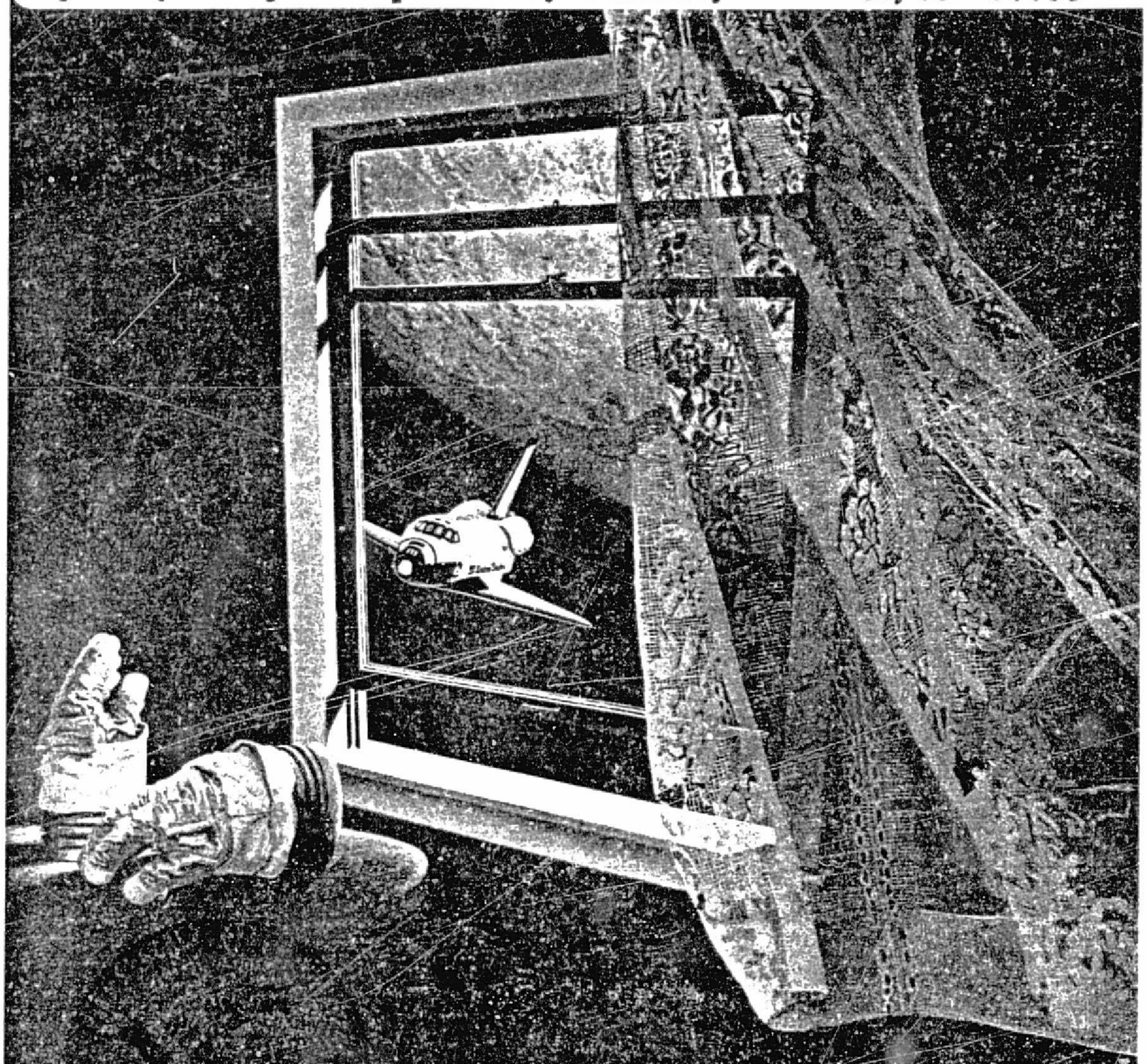
Volume 7-4A
Final Report

7

Data Book
D180-27477-7

Space Station Needs, Attributes, and Architectural Options Study

(NASA-CR-173686) SPACE STATION NEEDS, ATTRIBUTES AND ARCHITECTURAL OPTIONS STUDY. VOLUME 7-4A: DATA BOOK, ARCHITECTURE, TECHNOLOGY AND PROGRAMMATICS, PART A Final Report (Boeing Aerospace Co., Seattle, G3/18 N84-27799 Unclas 00806



Arthur D. Little, Inc. Battelle Life Systems, Inc. HAMILTON STANDARD Division of UNITED TECHNOLOGIES RCA

RESEARCH INSTITUTE OF MICHIGAN INTERMETRICS Microgravity Research Associates, Inc. NBS Econ

Space Station
Needs, Attributes and Architectural Options Study

Contract NASW-3680

D180-27477-7

Final Report

Volume 7 - 4A

Data Book

Architecture, Technology, and Programmatics - Part A

April 21, 1983

for

National Aeronautics and Space Administration

Headquarters

Washington, D. C.

Approved by Gordon Woodcock

Gordon Woodcock,
Study Manager

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BOEING

FOREWORD

The Space Station Needs, Attributes and Architectural Options Study (Contract NASW-3680) was initiated in August of 1982 and completed in April of 1983. This was one of eight parallel studies conducted by aerospace contractors for NASA Headquarters. The Contracting Officer's Representative and Study Technical Manager was Brian Pritchard. The Boeing study manager was Gordon R. Woodcock.

The study was conducted by Boeing Aerospace Company and its team of subcontractors:

Arthur D. Little, Inc. (ADL)	Materials Processing in Space
Battelle Columbus Laboratories	Materials Processing in Space
ECON, Inc.	Pricing Policies and Economic Benefits
Environmental Research Institute of Michigan (ERIM)	Earth Observation Missions
Hamilton Standard	Environmental Control and Life Support Equipment
Intermetrics, Inc.	Software
Life Systems, Inc. (LSI)	Environmental Control and Life Support Equipment
Microgravity Research Associates (MRA)	Materials Processing in Space
National Behavioral Systems (NBS)	Crew Accommodations and Architectural Influences
RCA Astro-Electronics	Communications Spacecraft
Science Applications, Inc. (SAI)	Space Science

This document is one of seven final report documents:

D180-27477-1	Volume 1, Executive Summary
D180-27477-2	Volume 2, Mission Analysis
D180-27477-3	Volume 3, Requirements
D180-27477-4	Volume 4, Architectural Options, Subsystems, Technology, and Programmatics
D180-27477-5-1	Volume 5-1, National Defense Missions and Space Station Architectural Options Final Report (SECRET)
D180-27477-5-2	Volume 5-2, National Defense Missions and Space Station Architectural Options, Final Briefing (SECRET)
D180-27477-6	Volume 6, Final Briefing

D180-27477-7-1	Volume 7-1, Science and Applications Missions Data Book
D180-27477-7-2	Volume 7-2, Commerical Missions Data Book
D180-27477-7-3	Volume 7-3, Technology Demonstration Missions Data Book
D180-27477-7-4	Volume 7-4, Architectural Options, Technology, and Programmatics Data Book
D180-27477-7-5	Volume 7-5, Mission Analysis Data Book

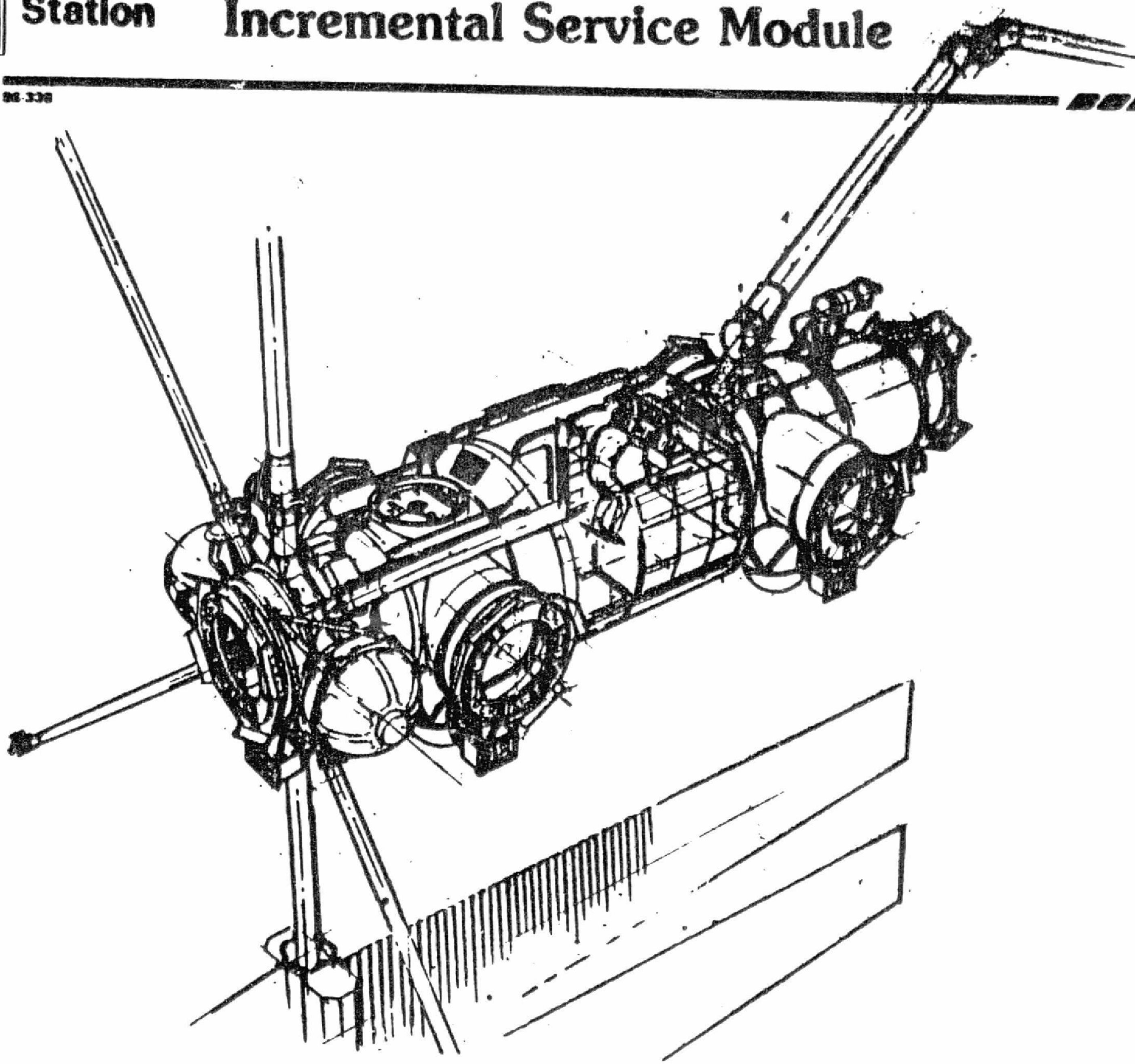
Note: The volume 7 data books will be distributed to a limited number of requestors.

The study task descriptions and a final report typical cross reference guide are found in Appendix 1.

The Boeing and subcontractor team member are listed in Appendix 2.

Acronyms and abbreviations are listed in Appendix 3.

Incremental Service Module



VOLUME 7-4A
DATA BOOK

Architecture, Technology, and Programmatics

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Architecture, Technology, and Programmatics Part A

Architecture, Technology, and Programmatics Part B

7.4.1 Mass Statements

VAX/VMS GRW6809 SERVMOD 18-MAR-1983 13:09 LPA 18-MAR-1983 13:11 KSC103:[CRW.TJV]SERV...PRT;2
VAX/VMS GRW6809 SERVMOD 18-MAR-1983 13:09 LPA0 18-MAR-1983 13:11 KSC1C3:[CRW.TJV]SERVMOD.PRT;2
VAX/VMS GRW6809 SERVMOD 18-MAR-1983 13:09 LPA0: 18-MAR-1983 13:11 KSC1C3:[CRW.TJV]SERVMOD.PRT;2

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
1	1	1.1.1	SP STA SER MOD	16312	4.0	0.0	-0.1	SUM
				(35961	13.1	0.0	-0.3)	
2	2	1.1.1.1	STRUCTURES	3562	4.8	0.0	-0.1	SUM
				(7852	15.8	0.0	-0.2)	
3	3	1.1.1.1.1	CABIN ASSY	3104	5.0	0.0	0.0	SUM
				(6843	16.4	0.0	0.1)	
4	4	1.1.1.1.1.1	LARGE CYL	605	5.0	0.0	0.0	2.3 M LENGTH; 3.048 M. O.D.; 2219 ALUM; 2697 KG/M2; 2% FOR WELD LANDS & TOLERANCES
				(1333	16.4	0.0	0.0)	
5	4	1.1.1.1.1.2	STIFF RINGS	252	5.0	0.0	0.0	25 CM2 X-SEC; 2219 AL; AVG DIA 2.98; 4 RINGS
				(555	16.4	0.0	0.0)	
6	4	1.1.1.1.1.3	LARGE CONE #1	202	3.6	0.0	0.0	CONE FRUSTRUM FROM 3.048D TO 2.159 D; WALL 0.01; L 0.444; STIFFENERS AT 105 KG
				(445	11.9	0.0	0.0)	
7	4	1.1.1.1.1.4	LARGE CONE #2	202	6.1	0.0	0.0	SAME AS ABOVE
				(445	20.1	0.0	0.0)	
8	4	1.1.1.1.1.5	SMALL CYL #1	267	2.5	0.0	0.0	2.159 DIA X 1.804 LG; 0.01 WALL; 2 - 1.46D CUTOUTS; 2% FOR WELD LANDS & TOL.; 10% FOR STIFFENERS
				(588	8.2	0.0	0.0)	
9	4	1.1.1.1.1.6	SMALL CYL #2	267	7.5	0.0	0.0	SAME
				(588	24.6	0.0	0.0)	
10	4	1.1.1.1.1.7	SMALL CONE #1	43	1.5	0.0	0.0	CONE FRUSTRUM FROM 2.159

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
								D TC 1.626 C; WALL 0.01; L=C.267; NO STIFFENERS; 2% FOR WELDS
11	4	1.1.1.1.1.8	SMALL CONE #2	43	8.5	C.C	C.0	SAME
				(94	28.0	C.C	C.C)	
12	4	1.1.1.1.1.9	DOCKING CYL #1	184	0.7	C.C	C.C	1.626 DIA X 1.333 LONG; 0.01 CM WALL; 2% FOR WELDS & TOLERANCES
				(405	2.2	C.0	C.C)	
13	4	1.1.1.1.1.10	DOCKING CYL #2	184	9.3	C.C	C.C	SAME
				(405	30.6	C.C	C.C)	
14	4	1.1.1.1.1.11	DOCK ADAPT #1	39	C.C	C.C	C.C	MACHINED PART WITH CALC VOL. .01447 M3
				(85	0.0	C.C	0.C)	
15	4	1.1.1.1.1.12	DOCK PORT ADAPT	39	9.9	C.C	C.C	SAME
				(85	32.5	C.C	C.C)	
16	4	1.1.1.1.1.13	HATCH SUPPORT	21	3.E	C.C	C.C	MACHINED PART VOL. CALC. 0.00765
17	4	1.1.1.1.1.14	INT HATCH	38	3.8	C.C	C.C	1.1 DIA X C.C35 TBAR + 1C KG FOR HINGES & LATCHES
				(83	12.5	0.C	C.C)	
18	4	1.1.1.1.1.15	BERTH PORT CYL #	157	2.5	1.C	C.0	1.53 DIA X C.9 LONG CYL, 0.01 WALL; ADAPTERS 39 KG; 2% FOR WELDS
19	4	1.1.1.1.1.16	BERTH PORT CYL#2	157	2.5	-1.C	C.C	SAME
				(346	8.2	-3.3	C.C)	
20	4	1.1.1.1.1.17	BERTH PORT CYL#3	157	7.5	1.C	C.C	SAME

INDEX #	INDENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(346	24.6	3.3	0.0)	
21	4	1.1.1.1.1.18	BERTH PORT CYL#4	157	7.5	-1.0	0.0	SAME
				(346	24.6	-3.3	0.0)	
22	4	1.1.1.1.1.19	CABIN WINDOWS	90	6.3	0.0	1.0	3 WINDOWS 0.2 M2 EACH AT 150 KG/M2
23	3	1.1.1.1.2	INTERIOR STRUCTU	318	5.0	0.0	-1.0	SUM
				(701	16.4	0.0	-3.2)	
24	4	1.1.1.1.2.1	FLOOR	100	5.0	0.0	-1.0	2.4 X 3.4 M AT TBAR OF 12 KG/M2
				(220	16.4	0.0	-3.3)	
25	4	1.1.1.1.2.2	CEILING	48	5.0	0.0	1.0	2.4 X 2.5 M AT TBAR OF 8 KG/M2
26	4	1.1.1.1.2.3	BLKD BELOW FLOOR	20	5.0	0.0	-1.5	ROUGH ESTIMATE
				(44	16.4	0.0	-4.9)	
27	4	1.1.1.1.2.4	EQUIP SUPT RAILS	150	5.0	0.0	-1.5	3 RAILS FOR HEAVY EC/LSS EQUIPMENT
28	3	1.1.1.1.3	S/ARRAY MASTS	140	0.5	0.0	0.0	18 M LENGTH; 0.3 M DIA; TBAR 0.25 CM; GPFF AT 1660 KG/M2; DOUBLED FOR JOINTS & MECHANISMS
				(308	1.6	0.0	0.0)	
29	2	1.1.1.2	MECHANISMS	546	5.5	0.0	0.0	SUM
				(1203	18.0	0.0	0.0)	
30	3	1.1.1.2.1	BERTHING PORT #1	82	0.0	0.0	0.0	60% OF DOCKING PORT
				(180	0.0	0.0	0.0)	
31	3	1.1.1.2.2	BERTHING PORT #2	82	2.5	-1.7	0.0	60% OF DOCKING PORT
				(180	8.2	-5.6	0.0)	
32	3	1.1.1.2.3	BERTHING PORT #3	82	2.5	1.7	0.0	60% OF DOCKING PORT

INDEX #	IDENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(180	8.2	5.6	0.0)	
33	3	1.1.1.2.4	BERTHING PORT #4	82	7.5	-1.7	0.0	60% OF DOCKING PORT
				(180	24.6	-5.6	0.0)	
34	3	1.1.1.2.5	BERTHING PORT #5	82	7.5	1.7	0.0	SOC EST
				(180	24.6	5.6	0.0)	
35	3	1.1.1.2.6	DOCKING PORT #1	136	10.0	0.0	0.0	SOC EST
				(299	32.8	0.0	0.0)	
36	2	1.1.1.3	THERMAL CONTROL	684	1.7	-0.1	-3.8	SUM
				(1507	5.6	-0.3	-12.3)	
37	3	1.1.1.3.1	RADIATOR	392	0.3	0.0	-5.7	SUM
				(864	1.1	0.0	-18.7)	
38	4	1.1.1.3.1.1	RADIATOR WING #1	98	4.2	0.0	-5.1	25% SOC RADITOR MASS EST
39	4	1.1.1.3.1.2	RADIATOR WING #2	98	-3.5	0.0	-5.1	25% SOC RADIATOR MASS EST
				(216	-11.5	0.0	-16.8)	
40	4	1.1.1.3.1.3	RADIATOR WING #3	98	4.2	0.0	-6.3	25% SOC RADIATOR MASS EST
				(216	13.8	0.0	-20.8)	
41	4	1.1.1.3.1.4	RADIATOR WING #4	98	-3.5	0.0	-6.3	25% SOC RADIATOR MASS EST
				(216	-11.5	0.0	-20.8)	
42	3	1.1.1.3.2	PLUMBING	31	2.5	0.0	1.2	EQUIV OF 52 M OF 2 CM DIAM X 1MM WALL CRES TUBING; 20% MARGIN FOR FITTINGS
				(68	8.2	0.0	3.9)	
43	3	1.1.1.3.3	FLUIDS	23	2.5	0.0	1.2	FLUID FILL FOR PLUMBING; FREON AT 1458 KG/M3
44	3	1.1.1.3.4	WATER-FREON HX	10	3.8	0.0	-1.7	HAM STD EST

IN-DEX #	IN-DENT #	WBS	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(22	12.5	C.C	-5.6)	
45	3	1.1.1.3.5	WATER-TO-WATER H	10	3.8	C.C	-1.4	HAM STD EST
				(22	12.5	C.C	-4.6)	
46	3	1.1.1.3.6	COLD PLATES	32	5.0	C.C	C.C	5 COLD PLATES @ 6.36 KG
				(70	16.4	C.C	C.C)	EA (HAM STD EST)
47	3	1.1.1.3.7	LATENT HX	59	4.6	-1.C	-C.8	HAM STD EST
				(130	14.9	-3.3	-2.6)	
48	3	1.1.1.3.8	FREON COOLANT PU	20	3.6	C.C	-1.7	HAM STD EST
				(44	11.8	C.C	-5.6)	
49	3	1.1.1.3.9	WTR COOLANT PUMP	13	3.6	C.C	-1.4	HAM STD EST
				(28	11.8	C.C	-4.6)	
50	3	1.1.1.3.1C	HEAT PIPE HX	25	C.6	C.C	-5.7	SOC EST
				(55	2.1	C.C	-18.8)	
51	3	1.1.1.3.11	MISC THERM ITEMS	23	5.0	C.C	C.C	SOC EST
				(50	16.4	C.C	C.C)	
52	3	1.1.1.3.12	TANKS & PRESS	23	5.C	C.C	C.C	SOC EST
				(50	16.4	C.C	0.C)	
53	3	1.1.1.3.13	THERMAL COATINGS	23	0.6	C.C	-5.7	SOC EST
				(5C	2.1	C.C	-18.8)	
54	2	1.1.1.4	PRIMARY PROPULSI	0	0.0	C.C	C.C	NO PRIMARY PROP
				(0	C.0	C.C	C.C)	
55	2	1.1.1.5	AUXILIARY PROPUL	919	3.5	C.C	-C.7	SUM
				(2C26	11.4	C.C	-2.2)	
56	3	1.1.1.5.1	MAST #1	78	0.5	3.4	3.4	COMPOSITE; 8 M LONG X 2C CM DIA @ 8 KG/M2; 15 KG DRIVE MECH; 8 KG FOR

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(171	1.6	11.2	-11.2)	
58	3	1.1.1.5.3	MAST # 3	78	0.5	-3.4	-3.4	SAME AS ABOVE
				(171	1.6	-11.2	-11.2)	
59	3	1.1.1.5.4	MAST # 4	78	0.5	-3.4	3.4	SAME AS ABOVE
				(171	1.6	-11.2	11.2)	
60	3	1.1.1.5.5	WATER TKS & PLUM	607	5.0	0.0	-1.0	SUM
				(1338	16.4	0.0	-3.3)	
61	4	1.1.1.5.5.1	TANKS & PLUMB	166	5.0	0.0	-1.0	6 SHUTTLE TANKS AT 23 KG PLUS 20% FOR PLUMBING AND INSTALLATION
62	4	1.1.1.5.5.2	WATER	441	5.0	0.0	-1.0	FILL FOR SIX TANKS AT 73.5 KG EACH
				(972	16.4	0.0	-3.3)	
63	2	1.1.1.6	ORDNANCE	12	9.0	0.0	0.0	SUM
				(26	29.5	0.0	0.0)	
64	3	1.1.1.6.1	MAST RELEASES	12	9.0	0.0	0.0	6 UNITS AT 2 KG EACH
				(26	29.5	0.0	0.0)	
65	2	1.1.1.7	ELECTRICAL POWER	2609	3.0	0.0	0.1	SUM
				(5751	9.8	0.0	0.2)	
66	3	1.1.1.7.1	SOLAR ARRAYS	900	0.4	0.0	0.0	SUM
				(1984	1.5	0.0	0.0)	
67	4	1.1.1.7.1.1	SOLAR ARRAY #1	333	0.6	0.0	21.9	13.88 KG/KW; 298 M2/2 = 149 M2; 162W/M2; 24 KW ARRAY
				(734	2.1	0.0	71.8)	
68	4	1.1.1.7.1.2	POWER COND # 1	117	0.0	0.0	0.0	50% OF SIC SILVERMAN SCC ESTIMATE (WAS TWICE THE POWER)

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
								W/M2; 24 KW ARRAY
70	4	1.1.1.7.1.4	POWER COND #2	117	0.0	0.0	0.0	50% OF SCC SILVERMAN EST FOR SCC
71	3	1.1.1.7.2	REGEN FUEL CELL	1213 (2674	4.6 15.1	0.0 0.0	0.1 0.4)	SUM
72	4	1.1.1.7.2.1	REGEN FUEL CELL	607 (1338	4.5 14.7	-1.4 -4.5	0.1 0.4)	SUM
73	5	1.1.1.7.2.1.1	POWER/ELEC BOX	117 (257	2.0 6.6	0.0 0.0	1.3 4.3)	50% OF SCC POWER COND MASS
74	5	1.1.1.7.2.1.2	ELECTROLYZER BOX	50 (110	4.2 13.8	-1.7 -5.6	0.5 1.6)	FACTORED FROM SID GROSS DATA
75	5	1.1.1.7.2.1.3	FUEL CELL BOX	92 (202	4.2 13.8	-1.7 -5.6	-0.5 -1.6)	FACTORED FROM SID GROSS DATA
76	5	1.1.1.7.2.1.4	H2 TANK #1	73 (160	5.5 18.0	-1.7 -5.6	0.5 1.6)	SUM
77	6	1.1.1.7.2.1.4.1	TANK	65 (143	5.5 18.0	-1.7 -5.6	0.5 1.6)	ESTIMATED BASED ON 500 PSI KEVLAR OVERWRAPPED TANK 0.51 M3
78	6	1.1.1.7.2.1.4.2	H2	8 (17	5.5 18.0	-1.7 -5.6	0.5 1.6)	.51 M3
79	5	1.1.1.7.2.1.5	H2 TANK #2	73 (160	5.5 18.0	-1.8 -5.9	0.0 0.0)	SUM
80	6	1.1.1.2.2.1.5.1	TANK	65 (143	5.5 18.0	-1.8 -5.9	0.0 0.0)	SAME AS ABOVE TANK
81	6	1.1.1.7.2.1.5.2	H2	8	5.5	-1.8	0.0	.51 M3

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(17	18.0	-5.9	0.0)	
82	5	1.1.1.7.2.1.6	O2 TANK	185	5.5	-1.7	-0.5	SUM
				(407	18.0	-5.6	-1.6)	
83	6	1.1.1.7.2.1.6.1	TANK	65	5.5	-1.7	-0.5	SAME AS ABOVE TANK
				(143	18.0	-5.6	-1.6)	
84	6	1.1.1.7.2.1.6.2	O2	120	5.5	-1.7	-0.5	.51 M3
				(264	18.0	-5.6	-1.6)	
85	5	1.1.1.7.2.1.7	VALVES & PLUMBIN	17	4.5	-1.7	0.0	10% OF OTHER HARDWARE
				(37	14.8	-5.6	0.0)	
86	4	1.1.1.7.2.2	REGEN FUEL CELL	606	4.7	1.4	0.1	SUM
				(1335	15.4	4.5	0.4)	
87	5	1.1.1.7.2.2.1	POWER/ELEC BOX	117	3.0	0.0	1.3	50% OF SOC POWER COND
				(257	9.8	0.0	4.3)	MASS
88	5	1.1.1.7.2.2.2	ELECTROLYZER BOX	49	4.2	1.7	0.5	FACTORED FROM SID GROSS
				(108	13.6	5.6	1.6)	DATA
89	5	1.1.1.7.2.2.3	FUEL CELL BOX	92	4.2	1.7	-0.5	FACTORED FROM SID GROSS
				(202	13.6	5.6	-1.6)	DATA
90	5	1.1.1.7.2.2.4	H2 TANK #1	73	5.5	1.7	0.5	SUM
				(160	18.0	5.6	1.6)	
91	6	1.1.1.7.2.2.4.1	TANK	65	5.5	1.7	0.5	SAME AS ABOVE TANK
				(143	18.0	5.6	1.6)	
92	6	1.1.1.7.2.2.4.2	H2	8	5.5	1.7	0.5	.51 M3
				(17	18.0	5.6	1.6)	
93	5	1.1.1.7.2.2.5	H2 TANK #2	73	5.5	1.8	0.0	SUM
				(160	18.0	5.9	0.0)	

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(17	18.0	5.9	0.0)	
96	5	1.1.1.7.2.2.6	O2 TANK	185	5.5	1.7	-0.5	SUM
				(407	18.0	5.6	-1.6)	
97	6	1.1.1.7.2.2.6.1	TANK	65	5.5	1.7	-0.5	SAME AS ABOVE TANK
				(143	18.0	5.6	-1.6)	
98	6	1.1.1.7.2.2.6.2	O2	120	5.5	1.7	-0.5	.51 M3
				(264	18.0	5.6	-1.6)	
99	5	1.1.1.7.2.2.7	VALVES & PLUMBIN	17	4.5	1.7	0.0	10% OF OTHER HARDWARE
				(37	14.8	5.6	0.0)	
100	3	1.1.1.7.3	CABLES & EQUIP	496	3.6	0.0	0.0	SUM
				(1093	12.0	0.0	0.0)	
101	4	1.1.1.7.3.1	MAST POWER CABLE	116	0.5	0.0	0.0	SCALED FROM SOC (18M VS 26M LENGTH)
				(255	1.6	0.0	0.0)	
102	4	1.1.1.7.3.2	BUSSING & CABLE	300	5.0	0.0	0.0	SCALED FROM SOC
				(661	16.4	0.0	0.0)	
103	4	1.1.1.7.3.3	INTERNAL LIGHTS	30	5.0	0.0	0.0	SCALED FROM SOC
				(66	16.4	0.0	0.0)	
104	4	1.1.1.7.3.4	EMERG BATTERY	50	2.0	0.0	0.0	SAME AS SOC
				(110	6.6	0.0	0.0)	
105	2	1.1.1.8	GN&C	720	0.7	0.0	0.1	SUM
				(1587	2.3	0.0	0.4)	
106	3	1.1.1.8.1	CMG'S	600	0.7	0.0	0.0	SUM
				(1322	2.3	0.0	0.0)	
107	4	1.1.1.8.1.1	CMG #1	300	0.7	-1.5	0.0	SOC EST
				(661	2.3	-4.9	0.0)	

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(970	9.1	C.C	6.7)	
111	3	1.1.1.9.1	RF EQUIPO	357	3.0	C.C	2.2	SUM
				(787	9.7	C.C	7.3)	
112	4	1.1.1.9.1.1	KU AMPS	47	2.5	C.0	1.3	SOC EST
				(103	8.2	C.C	4.3)	
113	4	1.1.1.9.1.2	S-BAND AMPS	110	2.5	C.0	1.3	SOC EST
				(242	8.2	C.C	4.3)	
114	4	1.1.1.9.1.3	SURV RADAR	65	9.0	C.C	-1.4	SOC EST
				(143	29.5	C.C	-4.6)	
115	4	1.1.1.9.1.4	HI-GAIN ANTENNA	34	0.6	C.C	7.C	SOC EST
				(74	2.1	C.C	23.C)	
116	4	1.1.1.9.1.5	MAST & DRIV	20	0.6	C.C	7.C	SOC EST
				(44	2.1	C.C	23.C)	
117	4	1.1.1.9.1.6	CLS ANTENNA	8	0.6	C.C	6.5	SOC EST
				(17	2.1	C.0	21.3)	
118	4	1.1.1.9.1.7	L-BAND ANTENNA	4	0.6	C.C	6.C	SOC EST
				(8	2.1	C.C	19.7)	
119	4	1.1.1.9.1.8	UHF ANTENNA	9	0.6	C.C	5.5	SOC EST
				(19	2.1	C.C	18.C)	
120	4	1.1.1.9.1.9	HORNS & DRIVE	10	0.6	C.C	5.5	SOC EST
				(22	2.1	C.C	18.C)	
121	4	1.1.1.9.1.10	RF CABLING	50	0.6	C.C	2.5	SOC EST
				(110	2.1	C.C	8.2)	
122	3	1.1.1.9.2	INTERCOMM SYSTEM	25	5.0	C.C	C.C	SUM
				(55	16.4	C.C	C.C)	

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(44	2.1	0.0	13.1)	
127	4	1.1.1.9.3.2	DIGITAL PROCESS	23	0.6	0.0	1.0	SOC EST
				(50	2.1	0.0	3.3)	
128	4	1.1.1.9.3.3	AUDIO/DATA CABLI	15	0.6	0.0	0.0	SOC EST
				(33	2.1	0.0	0.0)	
129	2	1.1.1.10	DATA MGMT	175	5.9	0.6	0.6	SUM
				(385	19.5	2.0	2.0)	
130	3	1.1.1.10.1	CONT & DISPLAY P	25	6.5	0.6	0.6	SOC EST
				(55	21.3	2.0	2.0)	
131	3	1.1.1.10.2	CRT'S	40	6.5	0.6	0.6	SOC EST
				(88	21.3	2.0	2.0)	
132	3	1.1.1.10.3	KB & DIGITAL DIS	20	6.5	0.6	0.6	SOC EST
				(44	21.3	2.0	2.0)	
133	3	1.1.1.10.4	REMOTE TERMINALS	40	4.0	0.6	0.6	SOC EST
				(88	13.1	2.0	2.0)	
134	3	1.1.1.10.5	WIRING & DATA BU	50	6.5	0.6	0.6	SOC EST
				(110	21.3	2.0	2.0)	
135	2	1.1.1.11	INSTRUMENTATION	100	5.5	0.0	0.0	COVERS INSTRUMENTATION
				(220	18.0	0.0	0.0)	NOT PART OF SPECIFIC SUBSYSTEMS (SOC EST).
136	2	1.1.1.12	CREW ACCOMM	0	0.0	0.0	0.0	NONE REQ'D
				(0	0.0	0.0	0.0)	
137	2	1.1.1.13	ECLSS	829	4.8	-0.1	-0.7	SUM
				(1827	15.9	-0.4	-2.2)	
138	3	1.1.1.13.1	O2/N2 CONTROL UN	20	4.3	-0.5	-1.4	HAM STD EST

IN- DEX #	IN- DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(141	18.7	3.4	-2.3)	
142	3	1.1.1.13.5	ATMOS REVIT SYS	128	5.0	-C.2	-C.5	SUM
				(282	16.3	-0.7	-3.0)	
143	4	1.1.1.13.5.1	DEHUMIDFIER&FAN	39	5.1	-C.5	-1.2	HAM STD EST
				(85	16.7	-1.6	-3.9)	
144	4	1.1.1.13.5.2	CONTAM. CONTROL	30	5.5	C.3	-C.3	HAM STD EST
				(66	18.0	1.1	-1.1)	
145	4	1.1.1.13.5.3	ODOR CONTROL	9	5.9	-C.4	C.C	HAM STD EST
				(19	19.4	-1.5	C.C)	
146	4	1.1.1.13.5.4	CO2 REMOVAL (SAW	50	4.4	-C.3	-1.2	HAM STD EST
				(110	14.4	-1.C	-3.9)	
147	3	1.1.1.13.6	CABN DMP&RELIEF	5	5.0	C.C	-1.3	EST
				(11	16.4	C.C	-4.3)	
148	3	1.1.1.13.7	EMERG N2 SUPPLY	360	5.2	-C.2	-0.5	SUM
				(793	17.1	-C.7	-1.6)	
149	4	1.1.1.13.7.1	EMERG N2 TANK #1	120	2.C	-0.6	C.C	SUM
				(264	6.6	-2.C	C.C)	
150	5	1.1.1.13.7.1.1	TANK	58	2.0	-C.6	C.C	SIZED TO REPRESS SM PLUS CM ONCE (ENTIRE N2 & O2 TANK SET)
151	5	1.1.1.13.7.1.2	N2	62	2.0	-C.6	C.C	SAME AS ABOVE
				(136	6.6	-2.C	C.C)	
152	4	1.1.1.13.7.2	EMERG N2 TANK #2	120	6.8	-C.6	C.C	SUM
				(264	22.3	-2.C	C.C)	
153	5	1.1.1.13.7.2.1	TANK	58	6.8	-C.6	C.0	SAME AS ABOVE

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(127	22.3	2.C	-4.9)	
157	5	1.1.1.13.7.3.2	N2	62	6.8	C.6	-1.5	SAME AS ABCVE
				(136	22.3	2.C	-4.9)	
158	3	1.1.1.13.8	EMERG C2 SUPPLY	144	3.1	C.C	-C.8	SEE LINE #15C
				(317	10.2	C.C	-2.5)	
159	4	1.1.1.13.8.1	EMERG C2 TANK #1	72	3.1.	-C.6	C.C	SAME AS ABCVE
				(158	10.2	-2.C	C.C)	
160	5	1.1.1.13.8.1.1	TANK	32	3.1	-C.6	C.C	SAME AS ABCVE
				(70	10.2	-2.C	C.C)	
161	5	1.1.1.13.8.1.2	02	40	3.1	-C.6	C.C	SAME AS ABCVE
				(88	10.2	-2.0	C.C)	
162	4	1.1.1.13.8.2	EMERG C2 TANK #2	72	3.1	C.6	-1.5	SAME AS ABCVE
				(158	10.2	2.C	-4.9)	
163	5	1.1.1.13.8.2.1.	TANK	32	3.1	C.6	-1.5	SAME AS ABCV
				(70	10.2	2.1	-4.8)	
164	5	1.1.1.3.8.2.2	02	40	3.1	C.6	-1.5	SAME AS ABCVE
				(88	10.2	2.C	-4.9)	
165	2	1.1.1.17	MISSION ECUIPMEN	3026	4.8	C.C	C.5	SUM
				(6671	15.8	C.C	1.7)	
166	3	1.1.1.17.1	MANIPULATOR	524	7.5	C.C	3.C	RMS MASS
				(1155	24.6	C.C	9.8)	
167	3	1.1.1.17.2	SPARES	644	5.0	C.C	C.C	SOC EST
				(1419	16.4	C.C	0.C)	
168	3	1.1.1.17.3	MISC STORES	400	5.0	C.C	C.C	EST
				(881	16.4	C.C	C.C)	

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(194	16.4	0.0	0.0)	
172	3	1.1.1.17.7	CONSUMABLES	478	1.1	0.0	0.0	SUM
				(1053	3.5	0.0	0.0)	
173	4	1.1.1.17.7.1	ATMOSPHERE	103	5.0	0.0	0.0	PRESSURE VOLUME
				(227	16.4	0.0	0.0)	
174	4	1.1.1.17.7.2	FOOD	375	0.0	0.0	0.0	FACTORED FROM SCC DATA
				(826	0.0	0.0	0.0)	(3/8)
175	3	1.1.1.17.8	SUPPLIES	362	5.0	0.0	0.0	SAME AS ABOVE
				(798	16.4	0.0	0.0)	
176	3	1.1.1.17.8.1	HYGIENE	95	5.0	0.0	0.0	SAME AS ABOVE
				(209	16.4	0.0	0.0)	
177	3	1.1.1.17.8.2	ECLSS SUPPLIES	113	5.0	0.0	0.0	SAME AS ABOVE
				(249	16.4	0.0	0.0)	
178	3	1.1.1.17.8.2	EVA SUPPLIES	135	5.0	0.0	0.0	SA
				(297	16.4	0.0	0.0)	
179	2	1.1.1.18	GROWTH	2690	4.0	0.0	-0.1	33% OF IDENTIFIED MASS
				(5930	13.1	0.0	-0.3)	EXCLUSIVE OF PRESSURE SHELL AND CONSUMABLES.

IN-DEX	IN-DENT	WBS & TITLE	PASS	SHAPE & ORIENT	IXX	IYY	IZZ	IYX =IXY	IXZ =IZX	IYZ =IZY
1	1	1.1.1	16312	COMPOSITE SHAPE	405919.	449795.	145784.	279.	8913.	-836.
		SF STA SER POD	35961	-- -- --	9632295.	10673419.	3459387.	6612.	211494.	-19827.
2	2	1.1.1.1	3562	COMPOSITE SHAPE	9109.	23664.	27589.	0.	78.	0.
		STRUCTURES	7852	-- -- --	216161.	561533.	654665.	0.	1839.	0.
3	3	1.1.1.1.1	3104	COMPOSITE SHAPE	4544.	20284.	20683.	0.	118.	0.
		CABIN ASSY	6543	-- -- --	107820.	481327.	490795.	0.	2789.	0.
4	4	1.1.1.1.1.1	605	CYLINDER SHELL	1405.	703.	703.	0.	0.	0.
		LARGE CYL	1333	1.00 0.00 0.00	33344.	16672.	16672.	0.	0.	0.
5	4	1.1.1.1.1.2	252	CYLINDER SHELL	567.	395.	395.	0.	0.	0.
		STIFF RINGS	559	1.00 0.00 0.00	13455.	9363.	9363.	0.	0.	0.
6	4	1.1.1.1.1.3	202	CYLINDER SHELL	316.	161.	161.	0.	0.	0.
		LARGE CONE #1	445	1.00 0.00 0.00	7490.	3824.	3824.	0.	0.	0.
7	4	1.1.1.1.1.4	202	CYLINDER SHELL	316.	161.	161.	0.	0.	0.
		LARGE CONE #2	445	1.00 0.00 0.00	7490.	3824.	3824.	0.	0.	0.
8	4	1.1.1.1.1.5	267	CYLINDER SHELL	311.	156.	156.	0.	0.	0.
		SMALL CYL #1	589	1.00 0.00 0.00	7383.	3692.	3692.	0.	0.	0.
9	4	1.1.1.1.1.6	267	CYLINDER SHELL	311.	156.	156.	0.	0.	0.
		SMALL CYL #2	588	1.00 0.00 0.00	7383.	3692.	3692.	0.	0.	0.
10	4	1.1.1.1.1.7	43	CYLINDER SHELL	39.	20.	20.	0.	0.	0.
		SMALL CONE #1	94	1.00 0.00 0.00	921.	467.	467.	0.	0.	0.
11	4	1.1.1.1.1.8	43	CYLINDER SHELL	39.	20.	20.	0.	0.	0.
		SMALL CONE #2	94	1.00 0.00 0.00	921.	467.	467.	0.	0.	0.
12	4	1.1.1.1.1.9	184	CYLINDER SHELL	122.	61.	61.	0.	0.	0.
		DOCKING CYL #1	405	1.00 0.00 0.00	2886.	1443.	1443.	0.	0.	0.
13	4	1.1.1.1.1.10	164	CYLINDER SHELL	122.	61.	61.	0.	0.	0.
		DOCKING CYL #2	405	1.00 0.00 0.00	2886.	1443.	1443.	0.	0.	0.
14	4	1.1.1.1.1.11	39	CYLINDER SHELL	22.	11.	11.	0.	0.	0.
		DOCK ADAPT #1	85	1.00 0.00 0.00	521.	263.	263.	0.	0.	0.
15	4	1.1.1.1.1.12	39	CYLINDER SHELL	22.	11.	11.	0.	0.	0.
		DOCK PORT ADAPT	85	1.00 0.00 0.00	521.	263.	263.	0.	0.	0.
16	4	1.1.1.1.1.13	21	CYLINDER SHELL	6.	3.	3.	0.	0.	0.
		HATCH SUPPORT	46	1.00 0.00 0.00	151.	76.	76.	0.	0.	0.
17	4	1.1.1.1.1.14	30	DISK	6.	3.	3.	0.	0.	0.
		[illegible] HATCH	[illegible]	1.00 0.00 0.00	136.	68.	68.	0.	0.	0.

19	4	1.[illegible] .1.16 BERTH PORT CYL#2	157 CYLINDER SHELL 346 C.CC 1.CC C.CO	57. 1342.	 2.	57. 1342.	C. C.	C. C.	C. C.
20	4	1.1.1.1.1.17 BERTH PORT CYL#3	157 CYLINDER SHELL 346 C.CC 1.00 C.CO	57. 1342.	92. 218C.	57. 1342.	C. C.	0. 0.	C. 0.
21	4	1.1.1.1.1.18 BERTH PORT CYL#4	157 CYLINDER SHELL 346 C.CC 1.C0 0.CO	57. 1342.	92. 218C.	57. 1342.	C. C.	0. 0.	C. C.
22	4	1.1.1.1.1.19 CABIN WINDOWS	90 MASSPOINT 198 0.0C 0.CC C.C0	0. 0.	C. C.	C. C.	C. C.	0. 0.	C. C.
23	3	1.1.1.1.2 INTERIOR STRUCTU	318 MASSPOINT 701 C.0C 0.0C C.00	500. 11863.	377. 8545.	409. 9701.	C. C.	0. 0.	0. 0.
24	4	1.1.1.1.2.1 FLOOR	100 RECTANGULAR PLATE 220 0.0C 0.CC 1.CC	96. 2286.	48. 1135.	144. 3425.	C. C.	0. 0.	C. 0.
25	4	1.1.1.1.2.2 CEILING	48 RECTANGULAR PLATE 105 C.0C C.0C 1.C0	25. 593.	23. 547.	48. 114C.	C. C.	0. 0.	C. C.
26	4	1.1.1.1.2.3 BLKD BELOW FLOOR	20 MASSPOINT 44 C.0C 0.CC C.C0	0. 0.	C. C.	C. C.	C. C.	0. 0.	C. C.
27	4	1.1.1.1.2.4 EQUIP SUPT RAILS	150 RECTANGULAR PLATE 330 0.0C 0.C0 1.CC	145. 3429.	72. 1705.	217. 5137.	C. C.	C. 0.	C. C.
28	3	1.1.1.1.3 S/ARRAY MASTS	140 REC 308 C.CO 1.00 C.00	3780. 89658.	C. C.	378C. 89658.	C. C.	0. C.	0. C.
29	2	1.1.1.2 MECHANISMS	546 COMPOSITE SHAPE 1203 -- -- --	948. 22454.	736C. 174803.	8314. 197257.	C. C.	0. 0.	C. C.
30	3	1.1.1.2.1 BERTHING PORT #1	82 MASSPOINT 180 C.0C 0.0C C.C0	0. 0.	C. C.	C. C.	C. C.	0. 0.	0. C.
31	3	1.1.1.2.2 BERTHING PORT #2	82 MASSPOINT 180 0.0C 0.CC C.C0	0. 0.	C. C.	C. C.	C. C.	0. 0.	C. 0.
32	3	1.1.1.2.3 BERTHING PORT #3	82 MASSPOINT 180 0.0C 0.CC C.C0	0. 0.	C. C.	C. C.	C. C.	0. 0.	C. C.
33	3	1.1.1.2.4 BERTHING PORT #4	82 MASSPOINT 180 C.0C 0.CC C.C0	C. 0.	C. C.	C. C.	C. C.	0. 0.	C. C.
34	3	1.1.1.2.5 BERTHING PORT #5	82 MASSPOINT 180 0.0C 0.CC C.CC	0. 0.	C. C.	C. C.	C. C.	0. 0.	C. C.
35	3	1.1.1.2.6 DOCKING PORT #1	135 MASSPOINT 299 0.0C C.CC C.C0	0. 0.	C. C.	C. C.	C. C.	C. C.	C. C.
36	2	1.1.1.3 THERMAL CONTROL	684 COMPOSITE SHAPE 1507 -- -- --	5055. 119943.	13171. 312542.	8224. 195158.	-172. -4072.	3047. 72304.	-175. -4148.
37	3	1.1.1.3.1 RADIATOR	352 COMPOSITE SHAPE 864 -- -- --	141. 3349.	5952. 141227.	5810. 137878.	C. C.	C. C.	C. C.
38	4	1.1.1.3.1.1 [illegible]	[illegible] MASSPOINT [illegible]	C. [illegible]	C. C.	C. C.	C. C.	C. C.	C. C.

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39	4	1.1.1.3.1.2	98	MASSPOINT			0.		0.	0.	0.	0.
		RADIATOR WING #2	216	0.00	0.00	0.00	0.		0.	0.	0.	0.
40	4	1.1.1.3.1.3	98	MASSPOINT			0.	0.	0.	0.	0.	0.
		RADIATOR WING #3	216	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
41	4	1.1.1.3.1.4	98	MASSPOINT			0.	0.	0.	0.	0.	0.
		RADIATOR WING #4	216	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
42	3	1.1.1.3.2	31	MASSPOINT			0.	0.	0.	0.	0.	0.
		PLUMBING	68	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
43	3	1.1.1.3.3	23	MASSPOINT			0.	0.	0.	0.	0.	0.
		FLUIDS	50	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
44	3	1.1.1.3.4	10	MASSPOINT			0.	0.	0.	0.	0.	0.
		WATER-FREON HX	22	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
45	3	1.1.1.3.5	10	MASSPOINT			0.	0.	0.	0.	0.	0.
		WATER-TO-WATER H	22	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
46	3	1.1.1.3.6	32	MASSPOINT			0.	0.	0.	0.	0.	0.
		COLD PLATES	70	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
47	3	1.1.1.3.7	59	MASSPOINT			0.	0.	0.	0.	0.	0.
		LATENT HX	130	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
48	3	1.1.1.3.8	20	MASSPOINT			0.	0.	0.	0.	0.	0.
		FREON COOLANT PU	44	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
49	3	1.1.1.3.9	13	MASSPOINT			0.	0.	0.	0.	0.	0.
		WTR COOLANT PUMP	28	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
50	3	1.1.1.3.10	25	MASSPOINT			0.	0.	0.	0.	0.	0.
		HEAT PIPE HX	55	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
51	3	1.1.1.3.11	23	MASSPOINT			0.	0.	0.	0.	0.	0.
		MISC THERM ITEMS	50	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
52	3	1.1.1.3.12	23	MASSPOINT			0.	0.	0.	0.	0.	0.
		TANKS & PRESS	50	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
53	3	1.1.1.3.13	23	MASSPOINT			0.	0.	0.	0.	0.	0.
		THERMAL COATINGS	50	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
54	2	1.1.1.4	0	MASSPOINT			0.	0.	0.	0.	0.	0.
		PRIMARY PROPULSI	0	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
55	2	1.1.1.5	919	COMPOSITE SHAPE			9084.	8961.	8465.	0.	-927.	-820.
		AUXILIARY PROPUL	2026	--	--	--	215547.	212832.	200984.	0.	-22005.	-19449.
56	3	1.1.1.5.1	78	RCD			416.	244.	172.	0.	0.	-205.
		PAST #1	171	0.00	0.76	0.76	9872.	5783.	4089.	0.	0.	-4863.
57	3	1.1.1.5.2	78	RCD			416.	244.	172.	0.	0.	-205.
		PAST # 2	171	0.00	-0.76	0.76	9872.	5783.	4085.	0.	0.	-4863.
58	3	1.1.1.5.3	78	RCD			416.	244.	172.	0.	0.	-205.
		[illegible]	171	[illegible]	[illegible]	0.76	9872.	5783.	4085.	0.	0.	-4863.

	[illegible] 4	171	0.00 -0.76 0.76	5972.	57[illegible]	4065.	0.	0.	-4863.
60	3 1.1.1.[illegible]	507	COMPOSITE SHAPE	0.	[illegible]	0.	0.	0.	0.
	WATER TKS & PLUM	1338	-- -- --	0.	0.	0.	0.	0.	0.
61	4 1.1.1.5.5.1	166	MASSPOINT	0.	0.	0.	0.	0.	0.
	TANKS & PLUMB	365	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
62	4 1.1.1.5.5.2	441	MASSPOINT	0.	0.	0.	0.	0.	0.
	WATER	972	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
63	2 1.1.1.6	12	COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
	ORDNANCE	26	-- -- --	0.	0.	0.	0.	0.	0.
64	3 1.1.1.6.1	12	MASSPOINT	0.	0.	0.	0.	0.	0.
	MAST RELEASES	26	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
65	2 1.1.1.7	2609	COMPOSITE SHAPE	359624.	335055.	50119.	-2.	-480.	-1.
	ELECTRICAL POWER	5751	-- -- --	8533709.	7950681.	1189296.	-49.	-11353.	-18.
66	3 1.1.1.7.1	909	COMPOSITE SHAPE	353025.	321756.	31354.	0.	0.	0.
	SOLAR ARRAYS	1984	-- -- --	8377117.	7635103.	744567.	0.	0.	0.
67	4 1.1.1.7.1.1	333	RECTANGULAR PLATE	16803.	1137.	15666.	0.	0.	0.
	SOLAR ARRAY #1	734	1.00 0.00 0.00	398716.	26972.	371744.	0.	0.	0.
68	4 1.1.1.7.1.2	117	MASSPOINT	0.	0.	0.	0.	0.	0.
	POWER COND # 1	257	1.00 0.00 0.00	0.	0.	0.	0.	0.	0.
69	4 1.1.1.7.1.3	333	RECTANGULAR PLATE	16803.	1137.	15666.	0.	0.	0.
	SOLAR ARRAY #2	734	1.00 0.00 0.00	398716.	26972.	371744.	0.	0.	0.
70	4 1.1.1.7.1.4	117	MASSPOINT	0.	0.	0.	0.	0.	0.
	POWER COND #2	257	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
71	3 1.1.1.7.2	1213	COMPOSITE SHAPE	3457.	2245.	4553.	1.	-721.	-1.
	REGEN FUEL CELL	2674	-- -- --	82036.	53365.	100030.	18.	-17112.	-15.
72	4 1.1.1.7.2.1	607	COMPOSITE SHAPE	567.	1363.	1353.	-503.	-429.	235.
	REGEN FUEL CELL	1338	-- -- --	13450.	32354.	32115.	-11942.	-10190.	5573.
73	5 1.1.1.7.2.1.1	117	MASSPOINT	0.	0.	0.	0.	0.	0.
	POWER/FUEL BOX	257	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
74	5 1.1.1.7.2.1.2	50	MASSPOINT	0.	0.	0.	0.	0.	0.
	ELECTROLYZER BOX	110	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
75	5 1.1.1.7.2.1.3	92	MASSPOINT	0.	0.	0.	0.	0.	0.
	FUEL CELL BOX	202	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
76	5 1.1.1.7.2.1.4	73	COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
	H2 TANK #1	160	-- -- --	0.	0.	0.	0.	0.	0.
77	6 1.1.1.7.2.1.4.1	65	MASSPOINT	0.	0.	0.	0.	0.	0.
	TANK	143	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
78	6 1.1.1.7.2.1.4.2	4	MASSPOINT	0.	0.	0.	0.	0.	0.
	H2	17	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.

80	6	1 [illegible] .2.1.5.1	65	MASSPOINT	0.		C.	C.	C.	0.
		TANK	143	C.OC 0.CC C.CO	0.	[illegible]	C.	C.	0.	C.
81	6	1.1.1.7.2.1.5.2	8	MASSPOINT	0.	C.	C.	C.	0.	C.
		H2	17	C.OC C.CO C.00	0.	C.	C.	C.	0.	C.
82	5	1.1.1.7.2.1.6	185	CCMPCSITE SHAPE	0.	C.	C.	C.	0.	0.
		O2 TANK	4C7	-- -- --	0.	C.	0.	C.	0.	0.
83	6	1.1.1.7.2.1.6.1	65	MASSPOINT	0.	C.	C.	C.	0.	C.
		TANK	143	C.OC 0.CC C.CO	0.	C.	0.	C.	0.	0.
84	6	1.1.1.7.2.1.6.2	120	MASSPCINT	0.	C.	C.	C.	0.	0.
		O2	264	C.OC 0.CC C.CO	0.	C.	C.	C.	0.	0.
85	5	1.1.1.7.2.1.7	17	MASSPOINT	0.	C.	C.	C.	0.	C.
		VALVES & PLUMBIN	37	0.0C 0.CC C.CO	0.	C.	C.	C.	0.	0.
86	4	1.1.1.7.2.2	606	CCMPCSITE SHAPE	567.	874.	864.	341.	-292.	-235.
		REGEN FUEL CELL	1335	-- -- --	13445.	20742.	20504.	8102.	-6920.	-5576.
87	5	1.1.1.7.2.2.1	117	MASSPOINT	0.	C.	C.	C.	0.	C.
		POWER/ELEC BOX	257	C.CC 0.CC C.CO	0.	C.	C.	C.	0.	C.
88	5	1.1.1.7.2.2.2	49	MASSPCINT	0.	C.	C.	C.	0.	C.
		ELECTROLYZER BOX	108	C.OC 0.CC C.CC	0.	C.	C.	C.	0.	0.
89	5	1.1.1.7.2.2.3	92	MASSPOINT	0.	C.	0.	C.	0.	0.
		FUEL CELL BOX	202	C.0C 0.CC C.CO	0.	C.	C.	C.	0.	0.
90	5	1.1.1.7.2.2.4	73	CCMPCSITE SHAPE	0.	C.	C.	C.	0.	C.
		H2 TANK #1	160	-- -- --	0.	C.	C.	C.	0.	C.
91	6	1.1.1.7.2.2.4.1	65	MASSPCINT	0.	C.	C.	C.	0.	C.
		TANK	143	C.OC C.CC C.CO	0.	C.	C.	C.	0.	C.
92	6	1.1.1.7.2.2.4.2	8	MASSPOINT	0.	C.	C.	C.	0.	C.
		H2	17	C.0C 0.CC C.CO	0.	C.	C.	C.	0.	0.
93	5	1.1.1.7.2.2.5	73	CCMPCSITE SHAPE	0.	C.	C.	C.	0.	C.
		H2 TANK #2	160	-- -- --	0.	C.	C.	C.	0.	C.
94	6	1.1.1.7.2.2.5.1	65	MASSPCINT	0.	C.	C.	C.	C.	C.
		TANK	143	0.0C 0.CC C.CO	0.	C.	C.	C.	0.	0.
95	6	1.1.1.7.2.2.5.2	8	MASSPCINT	C.	C.	C.	C.	0.	C.
		H2	17	C.CC C.CC C.CO	0.	C.	C.	C.	0.	C.
96	5	1.1.1.7.2.2.6	185	CCMPCSITE SHAPE	C.	C.	C.	C.	C.	C.
		O2 TANK	4C7	-- -- --	C.	C.	C.	C.	0.	C.
97	6	1.1.1.7.2.2.6.1	65	MASSPCINT	C.	C.	C.	C.	C.	C.
		TANK	143	C.CC C.CC C.CO	C.	C.	C.	C.	0.	C.
98	6	1.1.1.7.2.2.6.2	120	MASSPCINT	C.	C.	C.	C.	0.	C.
		O2	264	C.CC C.CC C.CC	C.	C.	C.	C.	0.	C.
99	5	1.1.1.7.2.2.7	17	MASSPCINT	C.	C.	C.	C.	C.	C.
		[illegible]	[illegible]	[illegible]						

100	4	1.1.1.7.3	455 COMPOSITE SHAPE		3132.	1856.	5021.	C.	C.	C.
		CA[illegible] & EQUIP	1093 -- -- --		74321.	44[illegible]	119135.	C.	0.	C.
101	4	1.1.1.7.3.1	116 RCC		3132.	C.	3132.	C.	0.	C.
		MAST POWER CABLE	255 C.CC 1.CC C.00		74321.	C.	74321.	C.	0.	0.
102	4	1.1.1.7.3.2	300 MASSPOINT		0.	C.	C.	C.	0.	C.
		BUSSING & CABLE	661 0.0C 0.CC C.CO		0.	C.	C.	C.	0.	0.
103	4	1.1.1.7.3.3	30 MASSPOINT		0.	C.	C.	C.	0.	C.
		INTERNAL LIGHTS	66 C.0C C.CC C.CO		0.	C.	0.	C.	0.	0.
104	4	1.1.1.7.3.4	50 MASSPOINT		0.	C.	C.	C.	0.	C.
		EMERG BATTERY	110 C.0C 0.CC C.CO		0.	C.	C.	C.	0.	0.
105	2	1.1.1.8	720 COMPOSITE SHAPE		1399.	49.	135C.	C.	0.	C.
		GN&C	1587 -- -- --		33198.	1163.	32035.	C.	0.	0.
106	3	1.1.1.8.1	600 COMPOSITE SHAPE		1350.	C.	135C.	C.	0.	C.
		CMG'S	1322 -- -- --		32035.	C.	32035.	C.	0.	C.
107	4	1.1.1.8.1.1	300 MASSPOINT		0.	C.	C.	C.	0.	C.
		CMG #1	661 C.0C 0.CC C.CO		0.	C.	C.	C.	0.	C.
108	4	1.1.1.8.1.2	300 MASSPOINT		0.	C.	C.	C.	0.	C.
		CMG #2	661 0.0C 0.CC C.CO		0.	C.	0.	C.	0.	0.
109	3	1.1.1.8.2	120 MASSPOINT		0.	C.	C.	C.	0.	C.
		COMPUTER & SUPPC	264 C.CC 0.CC C.CC		0.	C.	C.	C.	0.	C.
110	2	1.1.1.9	440 COMPOSITE SHAPE		2912.	6479.	3567.	C.	-2328.	C.
		TRACKING & COMM	970 -- -- --		69053.	153747.	84653.	C.	-55236.	C.
111	3	1.1.1.9.1	357 COMPOSITE SHAPE		2630.	5787.	3156.	C.	-2261.	C.
		RF EQUIPC	787 -- -- --		6242C.	13732C.	749CC.	C.	-53642.	C.
112	4	1.1.1.9.1.1	47 MASSPOINT		0.	C.	C.	C.	0.	C.
		KU AMPS	1C3 C.CC 0.CC C.CO		0.	C.	C.	C.	0.	C.
113	4	1.1.1.9.1.2	110 MASSPOINT		0.	C.	0.	C.	0.	0.
		S-BAND AMPS	242 C.0C C.CC C.CO		0.	C.	C.	C.	0.	C.
114	4	1.1.1.9.1.3	65 MASSPOINT		0.	C.	C.	C.	0.	C.
		SURV RADAR	143 C.0C C.CC C.CO		0.	C.	C.	C.	0.	C.
115	4	1.1.1.9.1.4	34 MASSPOINT		0.	C.	C.	C.	0.	C.
		HI-GAIN ANTENNA	74 C.0C 0.CC C.CO		0.	C.	C.	C.	0.	C.
116	4	1.1.1.9.1.5	20 MASSPOINT		0.	C.	C.	C.	0.	C.
		MAST & DRIV	44 C.0C C.CC C.CC		0.	C.	C.	C.	0.	C.
117	4	1.1.1.9.1.6	8 MASSPOINT		0.	C.	C.	C.	0.	C.
		CLS ANTENNA	17 0.0C 0.CC C.CO		0.	C.	C.	C.	0.	C.
118	4	1.1.1.9.1.7	4 MASSPOINT		0.	C.	C.	C.	0.	C.
		L-BAND ANTENNA	8 C.0C C.CC C.CO		0.	C.	C.	C.	0.	C.
119	4	1.1.1.9.1.8	[illegible] MASSPOINT		0.	C.	C.	C.	C.	C.
		[illegible] ANTENNA	[illegible] [illegible] [illegible] C.CO		0.	C.	C.	C.	C.	C.

		H[illegible] & DRIVE	22	C.0C C.CC C.CC	0.	C.	C.	C.	C.	C.
121	4	1.1. .1.1C	50	MASSPOINT	C.	.	C.	C.	0.	C.
		RF CABLING	110	C.0C 0.CC C.CC	0.	C.	C.	C.	0.	C.
122	3	1.1.1.9.2	25	COMPOSITE SHAPE	0.	C.	C.	C.	0.	0.
		INTERCOMM SYSTEM	55	-- -- --	0.	C.	C.	C.	0.	C.
123	4	1.1.1.9.2.1	5	MASSPOINT	0.	C.	C.	C.	0.	C.
		VOICE TERMINALS	11	C.0C 0.CC C.CC	0.	C.	C.	C.	0.	C.
124	4	1.1.1.9.2.2	20	MASSPOINT	0.	C.	C.	C.	0.	C.
		C&W EQUIP	44	C.0C C.CC C.C0	0.	C.	C.	C.	0.	C.
125	3	1.1.1.9.3	58	COMPOSITE SHAPE	160.	16C.	C.	C.	0.	C.
		COMM & TRNG SUPP	127	-- -- --	3759.	3795.	C.	C.	0.	C.
126	4	1.1.1.9.3.1	20	MASSPOINT	0.	C.	0.	C.	0.	0.
		TV CAMERAS	44	C.0C 0.CC C.C0	0.	C.	C.	C.	0.	C.
127	4	1.1.1.9.3.2	23	MASSPOINT	0.	C.	C.	C.	0.	C.
		DIGITAL PROCESS	51	0.0C 0.CC C.00	0.	C.	C.	C.	0.	C.
128	4	1.1.1.9.3.3	15	MASSPOINT	0.	C.	C.	C.	0.	C.
		AUDIO/DATA CABLI	33	C.0C 0.CC C.00	0.	C.	C.	C.	0.	C.
129	2	1.1.1.10	175	COMPOSITE SHAPE	0.	193.	193.	C.	0.	C.
		DATA MGMT	385	-- -- --	0.	4576.	4576.	C.	0.	C.
130	3	1.1.1.10.1	25	MASSPOINT	0.	C.	C.	C.	0.	C.
		CONT & DISPLAY F	55	C.0C 0.0C C.C0	0.	C.	C.	C.	0.	0.
131	3	1.1.1.10.2	40	MASSPOINT	0.	C.	C.	C.	C.	0.
		CRT'S	88	C.0C 0.CC C.C0	0.	C.	C.	C.	0.	C.
132	3	1.1.1.10.3	20	MASSPOINT	0.	C.	C.	C.	0.	0.
		KB & DIGITAL DIS	44	C.0C 0.CC C.00	0.	C.	C.	C.	0.	C.
133	3	1.1.1.10.4	40	MASSPOINT	0.	C.	C.	C.	0.	C.
		REMOTE TERMINALS	88	0.0C C.CC C.CC	C.	C.	C.	C.	0.	0.
134	3	1.1.1.10.5	50	MASSPOINT	0.	C.	C.	C.	0.	C.
		WIRING & DATA BU	110	C.0C 0.CC C.C0	0.	C.	C.	C.	0.	C.
135	2	1.1.1.11	100	MASSPOINT	0.	C.	C.	C.	0.	0.
		INSTRUMENTATION	220	C.0C 0.CC C.CC	0.	C.	C.	C.	0.	0.
136	2	1.1.1.12	0	MASSPOINT	0.	C.	C.	C.	0.	C.
		CREW ACCOM	0	C.0C C.CC C.C0	0.	C.	C.	C.	0.	C.
137	2	1.1.1.13	829	COMPOSITE SHAPE	684.	2794.	2839.	197.	-229.	-188.
		ECLSS	1827	-- -- --	16240.	66293.	67375.	4666.	-5432.	-4467.
138	3	1.1.1.13.1	20	MASSPOINT	C.	C.	C.	C.	0.	C.
		O2/N2 CONTROL UN	44	C.0C C.CC C.00	C.	C.	C.	C.	C.	C.
139	3	1.1.1.13.2	28	MASSPOINT	C.	C.	C.	C.	C.	C.
		SENSIBLE HEAT EX	61	C.0C C.CC C.C0	C.	C.	C.	C.	C.	C.

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141	3	1.[illegible]3.4 CO2 [illegible]UIFIER	64 MASSPOINT 141 0.00 0.00 0.00	0. 0.		0. 0.	0. 0.	0. 0.	0. 0.
142	3	1.1.1.13.5 ATMOS REVIT SYS	128 COMPOSITE SHAPE 282 -- -- --	38. 859.	59. 1405.	45. 1065.	8. 181.	24. 572.	12. 294.
143	4	1.1.1.13.5.1 DEHUMIDFIER&FAN	39 MASSPOINT 85 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
144	4	1.1.1.13.5.2 CONTAM. CONTROL	30 MASSPOINT 66 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
145	4	1.1.1.13.5.3 DOCK CONTROL	9 MASSPOINT 19 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
146	4	1.1.1.13.5.4 CO2 REMOVAL (SAW	50 MASSPOINT 110 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
147	3	1.1.1.13.6 CABN EMPG&RELIEF	5 MASSPOINT 11 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
148	3	1.1.1.13.7 EMERG N2 SUPPLY	360 COMPOSITE SHAPE 793 -- -- --	295. 7005.	2023. 48010.	1958. 46472.	230. 5467.	-288. -6834.	-144. -3417.
149	4	1.1.1.13.7.1 EMERG N2 TANK #1	120 COMPOSITE SHAPE 264 -- -- --	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
150	5	1.1.1.13.7.1.1 TANK	58 MASSPOINT 127 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
151	5	1.1.1.13.7.1.2 N2	62 MASSPOINT 136 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
152	4	1.1.1.13.7.2 EMERG N2 TANK #2	120 COMPOSITE SHAPE 264 -- -- --	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
153	5	1.1.1.13.7.2.1 TANK	58 MASSPOINT 127 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
154	5	1.1.1.13.7.2.2 N2	62 MASSPOINT 136 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
155	4	1.1.1.13.7.3 EMER N2 TANK #3	120 COMPOSITE SHAPE 264 -- -- --	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
156	5	1.1.1.13.7.3.1 TANK	58 MASSPOINT 127 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
157	5	1.1.1.13.7.3.2 N2	62 MASSPOINT 135 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
158	3	1.1.1.13.8 EMERG O2 SUPPLY	144 MASSPOINT 317 0.00 0.00 0.00	133. 3152.	81. 1922.	52. 1230.	0. 0.	0. 0.	-65. -1538.
159	4	1.1.1.13.8.1 EMERG O2 TANK #1	72 MASSPOINT 15? 0.00 0.00 0.00	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.	0. 0.
160	5	1.1.1.13.8.1.1	?? MASSPOINT	0.	0.	0.	0.	0.	0.

ORIGINAL PAGE IS OF POOR QUALITY

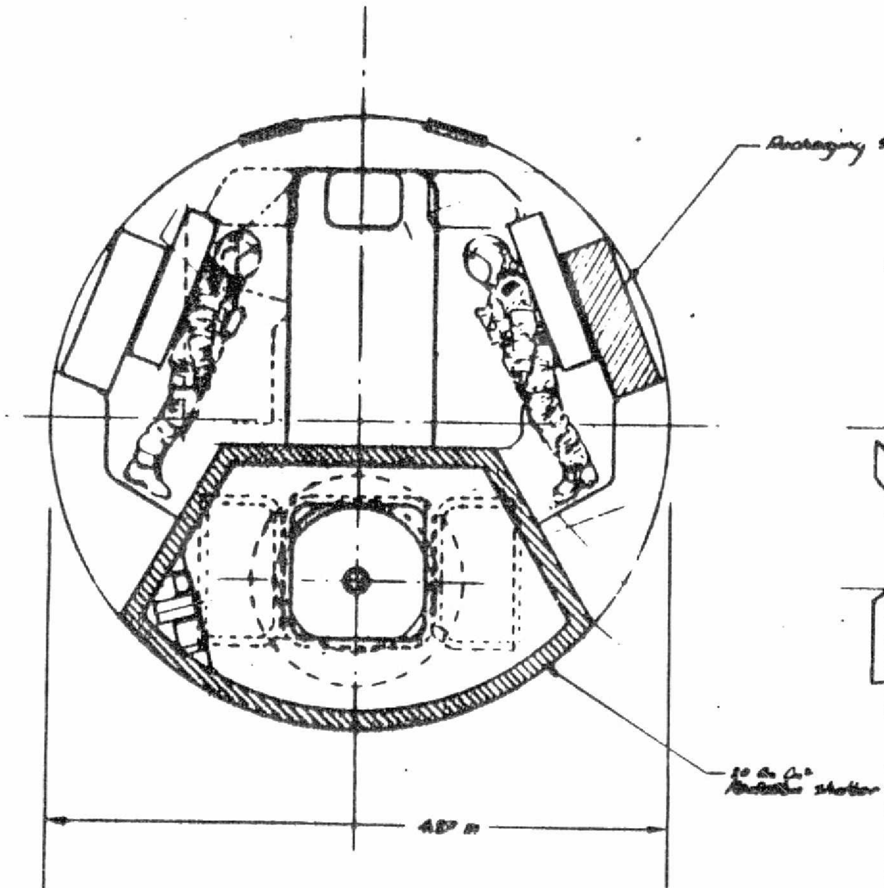
161	5	1.[illegible]1.13.8.1.2	40	MASSPOINT			0.	0.	0.	0.	0.	0.
		O2	88	0.00	0.00	0.00	0.	[illegible]	0.	0.	0.	0.
162	4	1.1.1.13.8.2	72	MASSPOINT			0.	0.	0.	0.	0.	0.
		EMERG O2 TANK #2	158	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
163	5	1.1.1.13.8.2.1.	32	MASSPOINT			0.	0.	0.	0.	0.	0.
		TANK	70	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
164	5	1.1.1.3.8.2.2	40	MASSPOINT			0.	0.	0.	0.	0.	0.
		O2	88	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
165	2	1.1.1.17	3026	COMPOSITE SHAPE			3899.	16444.	12545.	0.	4224.	0.
		MISSION EQUIPMEN	6671	--	--	--	92530.	390205.	297675.	0.	100222.	0.
166	3	1.1.1.17.1	524	MASSPOINT			0.	0.	0.	0.	0.	0.
		MANIPULATOR	1155	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
167	3	1.1.1.17.2	644	MASSPOINT			0.	0.	0.	0.	0.	0.
		SPARES	1419	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
168	3	1.1.1.17.3	400	MASSPOINT			0.	0.	0.	0.	0.	0.
		MISC STORES	881	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
169	3	1.1.1.17.4	112	MASSPOINT			0.	0.	0.	0.	0.	0.
		CREW PERSONAL EF	246	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
170	3	1.1.1.17.5	75	MASSPOINT			0.	0.	0.	0.	0.	0.
		MANUALS	165	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
171	3	1.1.1.17.6	88	MASSPOINT			0.	0.	0.	0.	0.	0.
		UTENSILS & TOOLS	194	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
172	3	1.1.1.17.7	479	COMPOSITE SHAPE			0.	2020.	2020.	0.	0.	0.
		CONSUMABLES	1053	--	--	--	0.	47937.	47937.	0.	0.	0.
173	4	1.1.1.17.7.1	103	MASSPOINT			0.	0.	0.	0.	0.	0.
		ATMOSPHERE	227	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
174	4	1.1.1.17.7.2	375	MASSPOINT			0.	0.	0.	0.	0.	0.
		FOOD	826	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
175	3	1.1.1.17.8	362	MASSPOINT			0.	0.	0.	0.	0.	0.
		SUPPLIES	798	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
176	3	1.1.1.17.8.1	95	MASSPOINT			0.	0.	0.	0.	0.	0.
		HYGIENE	209	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
177	3	1.1.1.17.8.2	113	MASSPOINT			0.	0.	0.	0.	0.	0.
		ECLSS SUPPLIES	249	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
178	3	1.1.1.17.8.2	135	MASSPOINT			0.	0.	0.	0.	0.	0.
		EVA SUPPLIES	297	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.
179	2	1.1.1.18	2650	MASSPOINT			0.	0.	0.	0.	0.	0.
		GROWTH	5839	0.00	0.00	0.00	0.	0.	0.	0.	0.	0.

Space Station

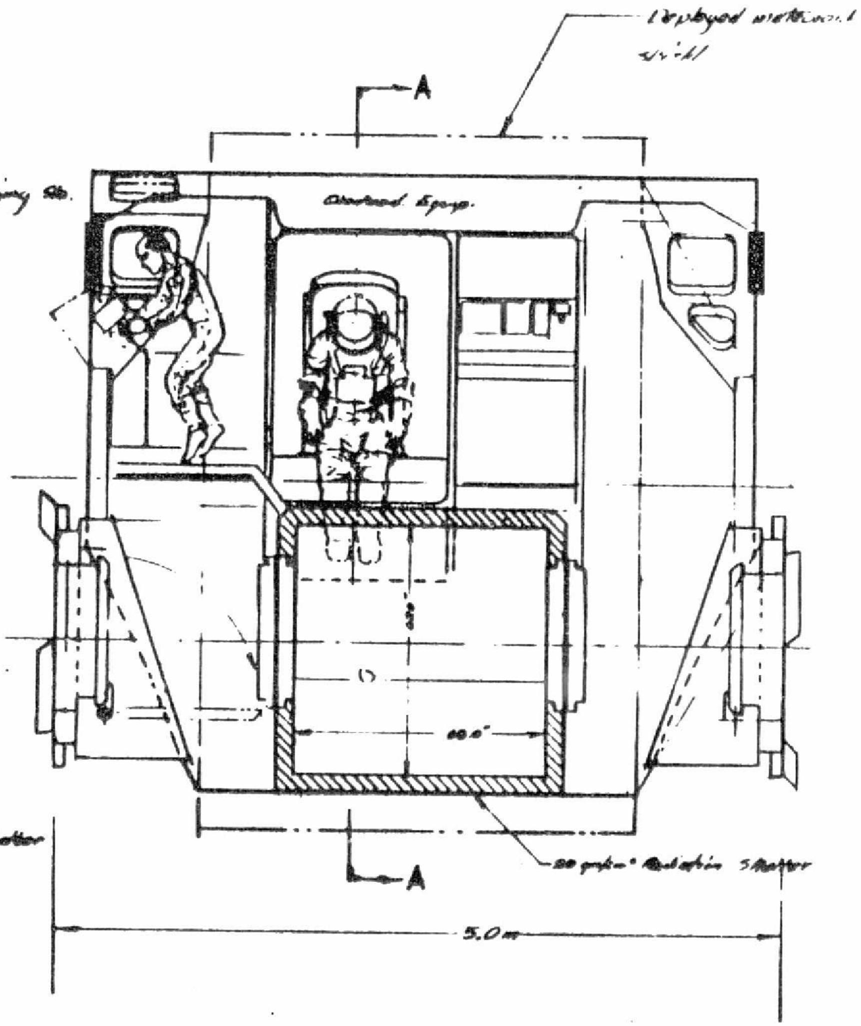
NASA

Command & Control Module
Preliminary Interior Arrangement

BOEING



Section A A



DEX #	DENT #		TITLE	KG(LB)	X	Y	Z	FOR ESTIMATE
1	1	1.1.2	SP STA C/M	8982	2.4	0.2	0.8	SUM
				(19801	7.9	0.5	2.5)	
2	2	1.1.2.1	STRUCTURES	2981	2.5	0.0	0.4	SUM
				(6571	8.2	0.0	1.3)	
3	3	1.1.2.1.1	CABIN ASSY	2142	2.5	0.0	0.5	SUM
				(4722	8.2	0.0	1.5)	
4	4	1.1.2.1.1.1	LARGE CYL	964	2.5	0.0	0.0	4.27 OD X 2.5 M LENGTH X 0.01 WALL + 60 KG STIFFENER RINGS
5	4	1.1.2.1.1.2	LARGE CONE #1	173	0.5	0.0	0.0	4.27 D TO 1.46 OD 0.75 M LONG & 0.01 WALL
				(381	1.6	0.0	0.0)	
6	4	1.1.2.1.1.2	LARGE CONE #2	173	4.5	0.0	0.0	SAME AS ABOVE
				(381	14.8	0.0	0.0)	
7	4	1.1.2.1.1.3	WINDOW FRAME #1	305	0.5	0.0	2.0	20% OF CONE FOR SHELL + 6 WINDOWS 0.3 M2 EACH AT 150 KG/M2
				(672	1.6	0.0	6.6)	
8	4	1.1.2.1.1.4	WINDOW FRAME #2	305	4.5	0.0	2.0	SAME AS ABOVE
				(672	14.8	0.0	6.6)	
9	4	1.1.2.1.1.5	BERTH PT CYL#1	111	0.5	0.0	-1.0	SCALED FROM SERVICE MODULE UNIT
				(244	1.6	0.0	-3.3)	
10	4	1.1.2.1.1.6	BERTH PT CYL#2	111	4.5	0.0	-1.0	SAME AS ABOVE
				(244	14.8	0.0	-3.3)	
11	3	1.1.2.1.2	INTERNAL STRUCT	839	2.5	0.0	0.2	SUM
				(1849	8.2	0.0	0.7)	
12	4	1.1.2.1.2.1	FLOOR	243	2.5	0.0	0.0	4.5 M SQ AT 12 KG/M2
				(535	8.2	0.0	0.0)	
13	4	1.1.2.1.2.2	CEILING	144	2.5	0.0	2.0	4 X 4.5 M AT 8 KG/M2

IN-DEX #	IN-DENT #	#	TITLE	MASS KG(LB)	SETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(317	8.2	0.0	6.6)	
14	4	1.1.2.1.2.3	INTERNAL BLK#1	101	1.5	0.0	0.0	4 M DIA AT 8 KG/M2
				(222	4.9	0.0	0.0)	
15	4	1.1.2.1.2.4	INTERIOR BLK#2	101	3.5	0.0	0.0	SAME AS ABOVE
				(222	11.5	0.0	0.0)	
16	4	1.1.2.1.2.5	LOWER EQPT SUP R	150	2.5	0.0	-2.0	4 X 4.5 M AT 8 KG/M2
				(330	8.2	0.0	-6.6)	
17	4	1.1.2.1.2.6	UPPER EQPT SUP R	100	2.5	0.0	2.0	3 X 4.5 M PLATE AT 8 KG/M2
				(220	8.2	0.0	6.6)	
18	2	1.1.2.2	MECHANISMS	164	2.5	0.0	0.0	SUM
				(361	8.2	0.0	0.0)	
19	3	1.1.2.2.1	BERTHING PORT #1	82	0.0	0.0	0.0	SOC EST; 60% OF DOCKING PORT
				(180	0.0	0.0	0.0)	
20	3	1.1.2.2.2	BERTHING PORT #2	82	5.0	0.0	0.0	SOC EST; 60% OF DOCKING PORT
				(180	16.4	0.0	0.0)	
21	2	1.1.2.3	THERMAL CONTROL	831	2.4	0.0	0.9	SUM
				(1832	7.9	0.0	2.9)	
22	3	1.1.2.3.1	RADIATOR SKIN	370	2.5	0.0	1.0	D=4.8M; L=2.9M; T=0.3 CM (FOR COLLISION SHIELDING); S=43.73 M2; ALUMINUM 2% FACTOR FOR OVERLAP
23	3	1.1.2.3.2	RADIATOR TUBES	53	2.5	0.0	1.0	12MM ID; T=1MM; 2219 AL; WT=.1197 KG/M; SPACING=0.1 M; 80% COVERAGE; 10% FOR FLEX CONNECTORS

IN-DEX #	L DE.. #	WBS #	TITLE	MASS KG(LB)	OFFSETS, M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
24	3	1.1.2.3.3.	TUBE PEDESTALS	108	2.5	0.0	1.0	X-SEC AREA 0.97 CM2;
				(238	8.2	0.0	3.3)	TOTAL LENGTH = 4.57M; ALUMINUM
25	3	1.1.2.3.4	FREON COOLANT	101	2.5	0.0	1.0	TUBE ID 12 MM; TUBE
				(222	8.2	0.0	3.3)	LENGTH 457 M; DENSITY 1458 KG/M3
26	3	1.1.2.3.5	STANDOFF SUPT SY	51	2.5	0.0	1.0	EST INCLUDES STRUTS,
				(112	8.2	0.0	3.3)	HINGES, BRACKETS, SPRINGS, ETC.
27	3	1.1.2.3.6	MULTI-LAYER INSU	23	2.5	0.0	1.0	30 LAYERS; .15 MIL
				(50	8.2	0.0	3.3)	MYLAR, SKIN AREA 53.2 M2, 0.34 KG/M2, 25% FACTOR FOR INSTL.
28	3	1.1.2.3.7	COLD PLATES	32	2.5	0.0	1.0	5 COLD PLATES 6.36 KG EA (HAM STD EST)
29	3	1.1.2.3.8	MISC FREON LOOP	50	2.5	0.0	1.0	HTX'S, INSTRUMENTS,
				(110	8.2	0.0	3.3)	DUCTS, ETC.
30	3	1.1.2.3.9	COOLNT WTR PUMP	13	1.0	0.0	-1.0	HAM STD EST
				(28	3.3	0.0	-3.3)	
31	3	1.1.2.3.10	WATER-TO-FREON H	10	1.0	0.0	-1.3	HAM STD EST
				(22	3.3	0.0	-4.3)	
32	3	1.1.2.3.11	FREON PUMP PACK	20	1.0	0.0	-1.3	HAM STD EST
				(44	3.3	0.0	-4.3)	
33	2	1.1.2.4	PRIMARY PROPULSI	0	0.0	0.0	0.0	(NO PRIME PROP)

IN-DEX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(0	0.0	0.0	0.0)	
34	2	1.1.2.5	AUXILIARY PROPUL	0	0.0	0.0	0.0	(NO AUX. PROP)
				(0	0.0	0.0	0.0)	
35	2	1.1.2.6	ORDNANCE	32	2.5	0.0	1.0	32 PIN PULLERS ON OUTER WALL AT 1 KG EA (SOC EST)
				(70	8.2	0.0	3.3)	
36	2	1.1.2.7	ELECTRICAL POWER	270	2.5	0.0	1.0	SUM
				(595	8.2	0.0	3.3)	
37	3	1.1.2.7.1	BUSSING	9	2.5	0.0	1.0	FACTORED FROM SOC HAB MOD; FACTOR = 5/14
				(19	8.2	0.0	3.3)	
38	3	1.1.2.7.2	HARNESSES	179	2.5	0.0	1.0	SAME
				(394	8.2	0.0	3.3)	
39	3	1.1.2.7.3	MISC EQUIP	18	2.5	0.0	1.0	SAME
				(39	8.2	0.0	3.3)	
40	3	1.1.2.7.4	INTERIOR LIGHTS	14	2.5	0.0	1.0	SAME
				(30	8.2	0.0	3.3)	
41	3	1.1.2.7.5	EMER BATTERY	50	2.5	0.0	1.0	SOC EST
				(110	8.2	0.0	3.3)	
42	2	1.1.2.8	GN&C	100	0.5	1.0	1.7	BACKUP COMPUTER IN CONT. STATION; MAIN GN&C COMP IN SERVICE MOD
43	2	1.1.2.9	TRACKING & COMM	248	1.3	1.4	0.2	SUM
				(546	4.3	4.4	0.5)	
44	3	1.1.2.9.1	RF EQUIP	167	1.1	1.6	0.0	SUM
				(368	3.6	5.2	0.0)	
45	4	1.1.2.9.1.1	SIGNAL PROC	22	1.1	1.6	0.0	SOC EST
				(48	3.6	5.2	0.0)	
46	4	1.1.2.9.1.2	DIGITAL PROC	22	1.1	1.6	0.0	SOC EST

IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
			(48	3.6	5.2	0.0)	
4	1.1.2.9.1.3	SWITCHING NETWOR	20	1.1	1.6	0.0	SOC EST
			(44	3.6	5.2	0.0)	
4	1.1.2.9.1.4	MODUL & PREAMP	40	1.1	1.6	0.0	SOC EST
			(88	3.6	5.2	0.0)	
4	1.1.2.9.1.5	GPS RCVR & PROC	23	1.1	1.6	0.0	SOC EST
			(50	3.6	5.2	0.0)	
4	1.1.2.9.1.6	EVA RCVR/XMTR	20	1.1	1.6	0.0	SOC EST
			(44	3.6	5.2	0.0)	
4	1.1.2.9.1.7	RADAR PROC	20	1.1	1.6	0.0	SOC EST
			(44	3.6	5.2	0.0)	
3	1.1.2.9.2	INTER COMM SYSTE	25	1.4	1.3	0.2	SUM
			(55	4.5	4.2	0.7)	
4	1.1.2.9.2.1	VOICE TERMINALS	5	2.5	0.0	1.0	5 AT 1 KG EA
			(11	8.2	0.0	3.3)	
4	1.1.2.9.2.2	C & W EQUIP	20	1.1	1.6	0.0	SUM EST
			(44	3.6	5.2	0.0)	
3	1.1.2.9.3	COMM & TKG SUPPO	56	1.9	0.7	0.6	SUM
			(123	6.3	2.2	1.9)	
4	1.1.2.9.3.1	TV CAMERA	20	2.5	0.0	1.0	4 AT 5 KG
			(44	8.2	0.0	3.3)	
4	1.1.2.9.3.2	DIGITAL PROC	23	1.1	1.6	0.0	SOC EST
			(50	3.6	5.2	0.0)	
4	1.1.2.9.3.3	CABLE HARNESSES	13	2.5	0.0	1.0	FACTORED FROM SOC EST
			(28	8.2	0.0	3.3)	(5/14)
2	1.1.2.10	DATA MGMT]	568	1.4	-0.5	1.4	SUM
			(1252	4.7	-1.6	4.6)	
3	1.1.2.10.1	D&C PANEL	108	0.3	0.0	2.0	SOC EST
			([illegible]	[illegible]	[illegible]	[illegible]	

IN- DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
			(264	1.0	0.0	6.6)	
3	1.1.2.10.3	KEYBOARDS & DISP	50	0.3	0.0	2.0	SOC EST
			(110	1.0	0.0	6.6)	
3	1.1.2.10.4	REMOTE TERM	120	4.5	0.0	2.0	SOC EST
			(264	14.8	0.0	6.6)	
3	1.1.2.10.5	COMPUTERS	120	1.1	-1.6	0.0	SOC EST
			(264	3.6	-5.2	0.0)	
3	1.1.2.10.6	WIRING & BUSSING	50	1.1	-1.6	0.0	SOC EST
			(110	3.6	-5.2	0.0)	
2	1.1.2.11	INSTRUMENTATION	36	2.5	0.0	1.0	FACTORED FROM SOC EST
			(79	8.2	0.0	3.3)	(5/14)
2	1.1.2.12	CREW ACCOMMODATI	50	2.5	0.0	0.0	SUM
			(110	8.2	0.0	0.0)	
3	1.1.2.12.1	SLEEP RESTRAINTS	20	2.5	0.0	0.0	SOC EST; 2 UNITS IN
			(44	8.2	0.0	0.0)	STORM SHELTER
3	1.1.2.12.2	HEALTH MAINT	20	2.5	0.0	0.0	MEDICAL KITS
			(44	8.2	0.0	0.0)	
3	1.1.2.12.3	PERSONAL STORAGE	10	2.5	0.0	0.0	EST_
			(22	8.2	0.0	0.0)	
2	1.1.2.13	ECLSS	1475	2.8	1.0	1.5	SUM
			(3251	9.2	3.3	4.8)	
3	1.1.2.13.1	O2/N2 CONTROL UN	20	1.2	0.5	3.0	HAM STD EST
			(44	3.9	1.6	9.8)	
3	1.1.2.13.2	SENSIBLE HEAT EX	28	1.2	-0.5	3.0	HAM STD EST
			(61	3.9	-1.6	9.8)	
3	1.1.2.13.3	CONDEN MULTI-FIL	80	3.7	1.0	2.4	HAM STD EST
			(176	12.1	3.3	7.9)	
3	1.1.2.13.4	CO2 LIQUIFIER	64	3.2	-1.0	2.4	HAM STD EST
			[illegible]	[illegible]	[illegible]	[illegible]	

N-EX #	IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
				(282	8.1	0.4	9.8)	
77	4	1.1.2.13.5.1	DEHUMID & FAN	39	2.7	-0.5	3.0	HAM STD EST
				(85	8.9	-1.6	9.8)	
78	4	1.1.2.13.5.2	CONTAM CONT	30	2.7	0.5	3.0	HAM STD EST
				(66	8.9	1.6	9.8)	
79	4	1.1.2.13.5.3	ODOR CONT	9	3.5	-0.5	3.0	HAM STD EST
				(19	11.5	-1.6	9.8)	
80	4	1.1.2.13.5.4	CO2 REMOVAL (SAW	50	2.0	0.5	3.0	HAM STD EST
				(110	6.6	1.6	9.8)	
81	3	1.1.2.13.6	CABN DMP & RELF	5	1.2	0.0	-0.9	EST
				(11	3.9	0.0	-3.0)	
82	3	1.1.2.13.7	EMERG H2O SUPPLY	702	3.1	1.7	1.2	SUM
				(1547	10.2	5.6	3.9)	
83	4	1.1.2.13.7.1	EMER H2O TANK #1	234	3.1	1.7	1.7	SUM
				(515	10.2	5.6	5.6)	
84	5	1.1.2.13.7.1.1	TANK	109	3.1	1.7	1.7	HAM STD EST
				(240	10.2	5.6	5.6)	
85	5	1.1.2.13.7.1.2	H2O	125	3.1	1.7	1.7	4.417 FT 3
				(275	10.2	5.6	5.6)	
86	4	1.1.2.13.7.2	EMER H2O TANK #2	234	3.1	1.7	1.2	SUM
				(515	10.2	5.6	3.9)	
7	5	1.1.2.13.7.2.1	TANK	109	3.1	1.7	1.2	HAM STD EST
				(240	10.2	5.6	3.9)	
8	5	1.1.2.13.7.2.2	H2O	125	3.1	1.7	1.2	4.417 FT 3
				(275	10.2	5.6	3.9)	
9	4	1.1.2.13.7.3	EMERG H2O TANK#3	234	3.1	1.7	0.7	SUM
				(515	10.2	5.6	2.3)	
0	5	1.1.2.13.7.3.1	TANK	109	3.1	1.7	0.7	HAM STD EST

IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
			(220	3.9	0.0	-3.0)	
3	1.1.2.13.9	EMU STRG RECHRG	142	2.0	0.6	1.8	SUM
			(313	6.6	2.0	6.0)	
4	1.1.2.13.9.1	EMU RECHRG STA #	48	2.0	-1.7	2.0	SUM
			(105	6.6	-5.6	6.6)	
5	1.1.2.13.9.1.1	RNTS/BATTERY/02	12	2.0	-1.7	2.0	HAM STD EST
			(26	6.6	-5.6	6.6)	
5	1.1.2.13.9.1.2	CO2 REGEN	36	2.0	-1.7	2.0	HAM STD EST
			(79	6.6	-5.6	6.6)	
4	1.1.2.13.9.2	EMU RECHRG STA #	48	2.0	1.7	2.0	SUM
			(105	6.6	5.6	6.6)	
5	1.1.2.13.9.2.1	RNTS/BATTRY/02 R	12	2.0	1.7	2.0	HAM STD EST
			(26	6.6	5.6	6.6)	
5	1.1.2.13.9.2.2	CO2 REGEN	36	2.0	1.7	2.0	HAM STD EST
			(79	6.6	5.6	6.6)	
4	1.1.2.13.9.3	WRKSTA,TLS,FIX,	46	2.0	1.9	1.5	HAM STD EST
			(101	6.6	6.2	4.9)	
3	1.1.2.13.10	GALLEY	170	3.2	0.6	1.4	SUM
			(374	10.6	2.1	4.6)	
4	1.1.2.13.10.1	REFRIGERATOR	23	2.8	1.0	1.5	HAM STD EST
			(50	9.2	3.3	4.9)	
4	1.1.2.13.10.2	FREEZER	95	3.2	1.0	1.5	HAM STD EST
			(209	10.5	3.3	4.9)	
4	1.1.2.13.10.3	OVEN	18	3.1	1.0	2.3	HAM STD EST
			(39	10.2	3.3	7.5)	
4	1.1.2.13.10.4	FOOD STORAGE	10	3.1	-1.0	2.5	HAM STD EST
			(22	10.2	-3.3	8.2)	
4	1.1.2.13.10.5	HOT WTR SUPPLY	10	3.8	-0.9	-0.8	HAM STD EST
			([illegible]	[illegible]	[illegible]	[illegible])	

IN-DENT #	WBS #	TITLE	MASS KG(LB)	OFFSETS,M(FT) X	Y	Z	RATIONALE FOR ESTIMATE
			(11	13.1	C.C	6.6)	
3	1.1.2.13.11	TRASH COMPACTOR	36	3.7	1.3	1.3	HAM STD EST
			(79	12.1	4.3	4.3)	
2	1.1.2.17	MISSION EQUIPMEN	705	2.4	-0.3	2.C	SUM
			(1554	7.8	-C.9	6.7)	
3	1.1.2.17.1	EMU SUITS	432	2.0	C.C	2.C	SUM
			(952	6.6	C.C	6.6)	
4	1.1.2.17.1.1	EMU SUIT #1	213	2.0	-1.2	2.C	REGENERABLE EMU W/SCL,
			(469	6.6	-3.9	6.6)	APP
4	1.1.2.17.1.2	EMU SUIT #2	213	2.0	1.2	2.0	SAME AS ABCVE
			(469	6.6	3.9	6.6)	
4	1.1.2.17.1.3	LCVG #1	3	2.0	-1.2	2.0	SHUTTLE LCVG
			(6	6.6	-3.9	6.6)	
4	1.1.2.17.1.4	LCVG #2	3	2.0	1.2	2.C	SHUTLE LCVG
			(6	6.6	3.9	6.6)	
3	1.1.2.17.2	CONSUMABLES	273	2.9	-C.7	2.1	SUM
			(601	9.6	-2.4	6.9)	
4	1.1.2.17.2.1	ATMOSPHERE	73	2.5	C.C	1.C	PRESSURE X VCLUME
			(160	8.2	C.0	3.3)	
4	1.1.2.17.2.2	FOOD	200	3.1	-1.C	2.5	EST
			(440	10.2	-3.3	8.2)	
2	1.1.2.18	GROWTH	1522	2.5	C.C	C.C	33% OF IDENTIFIED MASS
			(3355	8.2	C.C	0.0)	LESS PRESSURE SHELL AND MISSION EQUIPMENT.

IN-DEX	IN-DENT	WBS & TITLE	MASS.	SHAPE & ORIENT	IXX	IYY	IZZ	IYX =IYX	IXZ =IZX	IYZ =IZY
1	1	1.1.2	8982	COMPOSITE SHAPE	21107.	24026.	19875.	538.	319.	483.
		SP STA C/M	19801	-- -- --	500868.	570123.	471634.	12770.	7564.	11464.
2	2	1.1.2.1	2981	COMPOSITE SHAPE	10548.	12934.	10243.	0.	0.	0.
		STRUCTURES	6571	-- -- --	250295.	306926.	243061.	0.	0.	0.
3	3	1.1.2.1.1	2142	COMPOSITE SHAPE	7500.	10084.	7887.	0.	0.	0.
		CABIN ASSY	4722	-- -- --	177964.	239291.	187157.	0.	0.	0.
4	4	1.1.2.1.1.1	964	CYLINDER SHELL	4394.	2695.	2695.	0.	0.	0.
		LARGE CYL	2125	1.00 0.00 0.00	104271.	64045.	64045.	0.	0.	0.
5	4	1.1.2.1.1.2	173	CYLINDER SHELL	389.	203.	203.	0.	0.	0.
		LARGE CONE #1	381	1.00 0.00 0.00	9237.	4811.	4811.	0.	0.	0.
6	4	1.1.2.1.1.2	173	CYLINDER SHELL	389.	203.	203.	0.	0.	0.
		LARGE CONE #2	381	1.00 0.00 0.00	9237.	4811.	4811.	0.	0.	0.
7	4	1.1.2.1.1.3	305	MASSPOINT	0.	0.	0.	0.	0.	0.
		WINDOW FRAME #1	672	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
8	4	1.1.2.1.1.4	305	MASSPOINT	0.	0.	0.	0.	0.	0.
		WINDOW FRAME #2	672	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
9	4	1.1.2.1.1.5	111	CYLINDER SHELL	65.	35.	35.	0.	0.	0.
		BERTH PT CYL#1	244	1.00 0.00 0.00	1542.	837.	837.	0.	0.	0.
10	4	1.1.2.1.1.6	111	CYLINDER SHELL	65.	35.	35.	0.	0.	0.
		BERTH PT CYL#2	244	1.00 0.00 0.00	1542.	837.	837.	0.	0.	0.
11	3	1.1.2.1.2	839	MASSPOINT	3013.	2815.	2356.	0.	0.	0.
		INTERNAL STRUCT	1849	0.00 0.00 0.00	71494.	66798.	55904.	0.	0.	0.
12	4	1.1.2.1.2.1	243	RECTANGULAR PLATE	410.	410.	820.	0.	0.	0.
		FLOOR	535	0.00 0.00 1.00	9731.	9731.	19461.	0.	0.	0.
13	4	1.1.2.1.2.2	144	RECTANGULAR PLATE	243.	192.	435.	0.	0.	0.
		CEILING	317	0.00 0.00 1.00	5766.	4556.	10322.	0.	0.	0.
14	4	1.1.2.1.2.3	101	DISK	202.	101.	101.	0.	0.	0.
		INTERNAL BLK#1	222	1.00 0.00 0.00	4793.	2397.	2397.	0.	0.	0.
15	4	1.1.2.1.2.4	101	DISK	202.	101.	101.	0.	0.	0.
		INTERIOR BLK#2	222	1.00 0.00 0.00	4793.	2397.	2397.	0.	0.	0.
16	4	1.1.2.1.2.5	150	RECTANGULAR PLATE	253.	200.	453.	0.	0.	0.
		LOWER EQPT SUP R	330	0.00 0.00 1.00	6007.	4746.	10752.	0.	0.	0.
17	4	1.1.2.1.2.6	10[illegible]	RECTANGULAR PLATE	169.	75.	244.	0.	0.	0.
		UPPER EQPT SUP R	22[illegible]	0.00 0.00 1.00	4004.	1780.	5784.	0.	0.	0.
18	2	1.1.2.2	164	COMPOSITE SHAPE	0.	1025.	1025.	0.	0.	0.
		MECHANISMS	361	-- -- --	0.	24323.	24323.	0.	0.	0.
19	3	1.1.2.2.1	82	MASSPOINT	0.	0.	0.	0.	0.	0.
		BERTHING PORT #1	18[illegible]	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.

20	3	1.1...2.2	82	MASSPCINT	0.	..	C.	C.	0.	0.
		BERTHING PORT #2	180	C.0C 0.CC C.C0	0.	C.	C.	C.	0.	C.
21	2	1.1.2.3	831	CCMPCSITE SHAPE	2C0.	292.	92.	C.	135.	0.
		THERMAL CCNTRCL	1832	-- -- --	4742.	6515.	2177.	C.	32C6.	0.
22	3	1.1.2.3.1	370	MASSPOINT	0.	C.	C.	C.	0.	0.
		RADIATOR SKIN	815	0.0C 0.00 C.C0	0.	C.	0.	C.	0.	0.
23	3	1.1.2.3.2	53	MASSPCINT	0.	C.	C.	C.	0.	0.
		RADIATOR TUBES	116	C.0C 0.0C C.C0	0.	C.	C.	C.	0.	0.
24	3	1.1.2.3.3.	108	MASSPOINT	0.	C.	C.	C.	0.	0.
		TUBE PEDESTALS	238	0.0C 0.0C C.00	0.	C.	C.	C.	0.	0.
25	3	1.1.2.3.4	101	MASSPOINT	0.	C.	C.	C.	0.	0.
		FRECN CCOLANT	222	0.00 0.00 C.00	0.	C.	C.	C.	0.	0.
26	3	1.1.2.3.5	51	MASSPOINT	0.	C.	C.	C.	0.	0.
		STANDOFF SUPT SY	112	0.0C 0.C0 C.00	0.	C.	C.	C.	0.	0.
27	3	1.1.2.3.6	23	MASSPOINT	0.	C.	C.	C.	0.	0.
		MULTI-LAYER INSU	50	0.0C 0.CC C.00	0.	C.	C.	C.	0.	0.
26	3	1.1.2.3.7	32	MASSPOINT	0.	C.	C.	C.	0.	0.
		CCLD PLATES	70	0.0C 0.CC C.00	0.	C.	C.	C.	0.	0.
29	3	1.1.2.3.8	50	MASSPCINT	0.	C.	C.	C.	0.	0.
		MISC FRECN LCCP	110	C.0C 0.CC C.00	0.	C.	0.	C.	0.	0.
30	3	1.1.2.3.9	13	MASSPOINT	0.	C.	0.	C.	0.	0.
		CCCLNT WTR PUMP	29	0.0C 0.0C C.C0	0.	C.	C.	C.	0.	0.
31	3	1.1.2.3.1C	10	MASSPOINT	0.	C.	C.	C.	0.	0.
		WATER-TO-FREON H	22	C.0C 0.CC C.C0	0.	C.	C.	C.	0.	0.
32	3	1.1.2.3.11	20	MASSPOINT	0.	C.	C.	C.	0.	0.
		FRECN PUMP PACK	44	0.0C 0.CC C.00	0.	C.	C.	C.	0.	C.
33	2	1.1.2.4	0	MASSPOINT	0.	C.	0.	C.	0.	0.
		PRIMARY PROPULSI	0	0.0C 0.CC C.00	0.	C.	C.	C.	0.	C.
34	2	1.1.2.5	0	MASSPOINT	0.	C.	C.	C.	0.	0.
		AUXILIARY PROPUL	0	0.0C 0.CC C.00	0.	C.	C.	C.	0.	0.
35	2	1.1.2.6	32	MASSPOINT	0.	C.	C.	C.	0.	0.
		ORDNANCE	70	C.0C 0.CC C.C0	0.	C.	C.	C.	0.	0.
36	2	1.1.2.7	270	CCMPCSITE SHAPE	0.	C.	C.	C.	0.	C.
		ELECTRICAL POWER	595	-- -- --	0.	C.	C.	C.	0.	C.
37	3	1.1.?.7.1	9	MASSPCINT	0.	C.	C.	C.	0.	0.
		BUSSING	19	C.0C C.CC C.C0	0.	C.	C.	C.	0.	0.
38	3	1.1.2.7.2	179	MASSPCINT	0.	C.	C.	C.	C.	0.
		HARNESSES	394	0.0C 0.CC C.C0	0.	C.	C.	C.	0.	0.
39	3	1.1.?.7.3	14	MASSPOINT	0.	C.	C.	C.	C.	C.
		MISC EQUIP	31	0.0C C.CC C.C0	C.	C.	C.	C.	0.	C.
40	3	1.1.?.7.4	14	MASSPCINT	0.	C.	C.	C.	0.	C.

ORIGINAL PAGE IS OF POOR QUALITY

		INTR LIGHTS	30	0.00 0.00 0.00	0.		0.	0.	0.	0.
41	3	1.1.2.7.5	50	MASSPOINT	0.	0.	0.	0.	0.	0.
		EMER BATTERY	110	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
42	2	1.1.2.8	100	MASSPOINT	0.	0.	0.	0.	0.	0.
		GNEC	220	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
43	2	1.1.2.9	248	COMPOSITE SHAPE	115.	95.	145.	-72.	45.	-51.
		TRACKING & COMM	546	-- -- --	2718.	2260.	3451.	-1710.	1069.	-1222.
44	3	1.1.2.9.1	167	COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
		RF EQUIP	368	-- -- --	0.	0.	0.	0.	0.	0.
45	4	1.1.2.9.1.1	22	MASSPOINT	0.	0.	0.	0.	0.	0.
		SIGNAL PROC	48	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
46	4	1.1.2.9.1.2	22	MASSPOINT	0.	0.	0.	0.	0.	0.
		DIGITAL PROC	49	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
47	4	1.1.2.9.1.3	20	MASSPOINT	0.	0.	0.	0.	0.	0.
		SWITCHING NETWOR	44	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
48	4	1.1.2.9.1.4	40	MASSPOINT	0.	0.	0.	0.	0.	0.
		MODUL & PREAMP	88	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
49	4	1.1.2.9.1.5	23	MASSPOINT	0.	0.	0.	0.	0.	0.
		GPS RCVR & PROC	50	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
50	4	1.1.2.9.1.6	20	MASSPOINT	0.	0.	0.	0.	0.	0.
		EVA RCVR/XMTR	44	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
51	4	1.1.2.9.1.7	20	MASSPOINT	0.	0.	0.	0.	0.	0.
		RADAR PROC	44	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
52	3	1.1.2.9.2	25	COMPOSITE SHAPE	14.	12.	18.	-5.	6.	-6.
		INTER COMM SYSTE	55	-- -- --	338.	281.	425.	-213.	133.	-152.
53	4	1.1.2.9.2.1	5	MASSPOINT	0.	0.	0.	0.	0.	0.
		VOICE TERMINALS	11	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
54	4	1.1.2.9.2.2	20	MASSPOINT	0.	0.	0.	0.	0.	0.
		C & W EQUIP	44	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
55	3	1.1.2.9.3	56	COMPOSITE SHAPE	48.	40.	61.	-30.	19.	-22.
		COMM & TRK SUPPO	123	-- -- --	1145.	952.	1454.	-720.	450.	-515.
56	4	1.1.2.9.3.1	20	MASSPOINT	0.	0.	0.	0.	0.	0.
		TV CAMERA	44	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
57	4	1.1.2.9.3.2	23	MASSPOINT	0.	0.	0.	0.	0.	0.
		DIGITAL PROC	50	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
58	4	1.1.2.9.3.3	13	MASSPOINT	0.	0.	0.	0.	0.	0.
		CABLE HARNESSES	28	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
59	2	1.1.2.10	568	COMPOSITE SHAPE	781.	1981.	1809.	65.	111.	381.
		DATA MGMT	1252	-- -- --	18543.	47007.	42937.	2109.	2636.	9045.
60	3	1.1.2.10.1	109	MASSPOINT	0.	0.	0.	0.	0.	0.
		SEC PANEL	[illegible]	0.00 0.00 0.00	0.	0.	0.	0.	0.	0.

61	3	1.1.2.10.2	120	MASSPOINT			0.	C.	C.	C.	0.	0.
		CRT'S	264	0.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
62	3	1.1.2.10.3	50	MASSPCINT			0.	C.	C.	C.	0.	C.
		KEYBOARDS & DISP	110	C.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
63	3	1.1.2.10.4	120	MASSPOINT			0.	C.	C.	C.	0.	0.
		REMOTE TERM	264	C.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
64	3	1.1.2.10.5	120	MASSPOINT			0.	C.	G.	C.	0.	0.
		CCMPUTERS	264	0.0C	0.0C	C.C0	0.	C.	0.	C.	0.	0.
65	3	1.1.2.10.6	50	MASSPOINT			0.	C.	0.	C.	0.	0.
		WIRING & BUSSING	110	0.0C	C.C0	C.00	0.	C.	C.	C.	0.	0.
66	2	1.1.2.11	36	MASSPOINT			0.	C.	C.	C.	0.	0.
		INSTRUMENTATION	79	0.00	0.CC	C.C0	0.	G.	G.	C.	0.	0.
67	2	1.1.2.12	50	CCMPOSITE SHAPE			0.	C.	C.	C.	0.	0.
		CREW ACCOMMODATI	110	--	--	--	0.	C.	C.	C.	0.	C.
68	3	1.1.2.12.1	20	MASSPCINT			0.	C.	C.	C.	0.	0.
		SLEEP RESTRAINTS	44	0.0C	C.CC	C.00	0.	C.	C.	C.	0.	0.
69	3	1.1.2.12.2	20	MASSPCINT			0.	C.	C.	C.	0.	C.
		HEALTH MAINT	44	0.0C	0.GC	C.C0	0.	C.	G.	C.	0.	0.
70	3	1.1.2.12.3	10	MASSPCINT			0.	C.	G.	C.	0.	0.
		PERSONAL STCRAGE	22	0.0C	0.CC	C.C0	0.	C.	0.	C.	0.	0.
71	2	1.1.2.13	1475	CCMPOSITE SHAPE			2873.	2184.	2168.	364.	166.	-247.
		ECLSS	3251	--	--	--	68184.	51834.	51442.	8635.	3933.	-5851.
72	3	1.1.2.13.1	20	MASSPOINT			0.	C.	0.	C.	0.	0.
		C2/N2 CCNTRCL UN	44	0.0C	0.CC	C.00	0.	C.	C.	C.	0.	0.
73	3	1.1.2.13.2	28	MASSPCINT			0.	C.	C.	C.	0.	0.
		SENSIBLE HEAT EX	61	0.0C	0.0C	C.00	0.	C.	G.	C.	0.	0.
74	3	1.1.2.13.3	80	MASSPCINT			0.	C.	C.	C.	0.	0.
		CONDEN MULTI-FIL	176	0.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
75	3	1.1.2.13.4	64	MASSPCINT			0.	C.	C.	C.	0.	0.
		CC2 LIQUIFIER	141	0.0C	0.CC	C.C0	0.	C.	C.	C.	0.	C.
76	3	1.1.2.13.5	123	CCMPOSITE SHAPE			30.	24.	54.	-18.	0.	0.
		ATMOS REVIT SYS	282	--	--	--	712.	575.	1287.	-418.	0.	0.
77	4	1.1.2.13.5.1	39	MASSPOINT			0.	C.	C.	C.	0.	0.
		DEHUMID & FAN	85	C.0C	0.0C	C.C0	0.	C.	C.	C.	0.	0.
78	4	1.1.2.13.5.2	30	MASSPOINT			0.	C.	C.	C.	0.	C.
		CCNTAM CCNT	66	C.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
79	4	1.1.2.13.5.3	9	MASSPOINT			0.	C.	C.	C.	0.	C.
		ODOR CONT	17	C.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
80	4	1.1.2.13.5.4	50	MASSPOINT			0.	C.	C.	C.	G.	C.
		CC2 REMOVAL (SAW	110	C.CC	0.CC	C.C0	G.	C.	C.	C.	0.	C.

81	3	1.1.2.[illegible]	5 MASSPOINT	0.	[illegible]	0.	0.	0.	0.
		CABN EMP & RELF	11 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
82	3	1.1.2.13.7	702 COMPOSITE SHAPE	117.	117.	0.	0.	0.	0.
		EMERG H2O SUPPLY	1547 -- -- --	2776.	2776.	0.	0.	0.	0.
83	4	1.1.2.13.7.1	234 COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
		EMER H2O TANK #1	515 -- -- --	0.	0.	0.	0.	0.	0.
84	5	1.1.2.13.7.1.1	109 MASSPOINT	0.	0.	0.	0.	0.	0.
		TANK	240 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
85	5	1.1.2.13.7.1.2	125 MASSPOINT	0.	0.	0.	0.	0.	0.
		H2O	275 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
86	4	1.1.2.13.7.2	234 COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
		EMER H2O TANK #2	515 -- -- --	0.	0.	0.	0.	0.	0.
87	5	1.1.2.13.7.2.1	109 MASSPOINT	0.	0.	0.	0.	0.	0.
		TANK	240 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
88	5	1.1.2.13.7.2.2	125 MASSPOINT	0.	0.	0.	0.	0.	0.
		H2O	275 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
89	4	1.1.2.13.7.3	234 COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
		EMERG H2O TANK#3	515 -- -- --	0.	0.	0.	0.	0.	0.
90	5	1.1.2.13.7.3.1	109 MASSPOINT	0.	0.	0.	0.	0.	0.
		TANK	240 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
91	5	1.1.2.13.7.3.2	125 MASSPOINT	0.	0.	0.	0.	0.	0.
		H2O	275 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
92	3	1.1.2.13.8	100 MASSPOINT	0.	0.	0.	0.	0.	0.
		AIRLOCK PUMP	220 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
93	3	1.1.2.13.9	142 COMPOSITE SHAPE	357.	6.	390.	0.	0.	-30.
		EMU STRG RECHRG	313 -- -- --	9432.	184.	9248.	0.	0.	-701.
94	4	1.1.2.13.9.1	48 COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
		EMU RECHRG STA #	105 -- -- --	0.	0.	0.	0.	0.	0.
95	5	1.1.2.13.9.1.1	12 MASSPOINT	0.	0.	0.	0.	0.	0.
		RNTS/BATTERY/O2	26 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
96	5	1.1.2.13.9.1.2	36 MASSPOINT	0.	0.	0.	0.	0.	0.
		CO2 REGEN	79 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
97	4	1.1.2.13.9.2	48 COMPOSITE SHAPE	0.	0.	0.	0.	0.	0.
		EMU RECHRG STA #	105 -- -- --	0.	0.	0.	0.	0.	0.
98	5	1.1.2.13.9.2.1	12 MASSPOINT	0.	0.	0.	0.	0.	0.
		RNTS/BATTRY/O2 R	25 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
99	5	1.1.2.13.9.2.2	36 MASSPOINT	0.	0.	0.	0.	0.	0.
		CO2 REGEN	79 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
100	4	1.1.2.13.9.3	46 MASSPOINT	0.	0.	0.	0.	0.	0.
		WRKSTA,TLS,FIX,	101 0.00 0.00 0.00	0.	0.	0.	0.	0.	0.
101	3	1.1.2.13.10	170 COMPOSITE SHAPE	213.	141.	111.	-28.	-34.	54.

ORIGINAL PAGE IS OF POOR QUALITY

No.	Lvl	Code / Name	N									
		GALL .	374	--	--	--	5060.	35...	2636.	-664.	-813.	1293.
102	4	1.1.2.13.10.1	23	MASSPCINT			0.	C.	0.	C.	0.	0.
		REFRIGERATOR	50	C.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
103	4	1.1.2.13.10.2	95	MASSPCINT			0.	C.	C.	C.	0.	C.
		FREEZER	209	C.0C	0.CC	C.00	0.	C.	C.	C.	0.	0.
104	4	1.1.2.13.10.3	18	MASSPCINT			0.	C.	0.	C.	0.	0.
		OVEN	39	C.0C	0.C0	C.00	0.	C.	0.	C.	0.	0.
105	4	1.1.2.13.10.4	10	MASSPOINT			0.	C.	0.	C.	0.	0.
		FOOD STORAGE	22	0.0C	0.0C	C.C0	0.	C.	C.	C.	0.	0.
106	4	1.1.2.13.10.5	10	MASSPOINT			0.	C.	C.	C.	0.	0.
		HOT WTR SUPPLY	22	C.0C	0.0C	C.C0	0.	C.	C.	C.	0.	0.
107	4	1.1.2.13.10.6	9	MASSPOINT			0.	C.	C.	C.	0.	0.
		CCLD WTR SUPPLY	19	0.0C	0.CC	C.00	0.	C.	C.	C.	0.	0.
108	4	1.1.2.13.10.7	5	MASSPOINT			0.	C.	C.	C.	0.	0.
		FCLDING TELE	11	0.0C	0.0C	C.00	0.	C.	C.	C.	0.	0.
109	3	1.1.2.13.11	36	MASSPOINT			0.	C.	C.	C.	0.	0.
		TRASH COMPACTCR	79	0.0C	0.C0	C.00	0.	C.	C.	C.	0.	0.
110	2	1.1.2.17	705	CCMPOSITE SHAPE			887.	289.	932.	-147.	64.	-92.
		MISSICN ECUIPMEN	1554	--	--	--	21055.	6855.	22122.	-3494.	1511.	-2191.
111	3	1.1.2.17.1	432	CCMPOSITE SHAPE			622.	C.	622.	C.	0.	0.
		EMU SUITS	952	--	--	--	14762.	C.	14762.	C.	0.	0.
112	4	1.1.2.17.1.1	213	MASSPOINT			0.	C.	0.	C.	0.	0.
		EMU SUIT #1	469	C.0C	0.00	C.00	0.	C.	0.	C.	0.	C.
113	4	1.1.2.17.1.2	213	MASSPOINT			0.	C.	0.	C.	0.	0.
		EMU SUIT #2	469	0.0C	0.0C	C.00	0.	C.	0.	C.	0.	0.
114	4	1.1.2.17.1.3	3	MASSPOINT			0.	C.	0.	C.	0.	0.
		LCVG #1	6	0.0C	0.CC	C.00	0.	C.	C.	C.	0.	0.
115	4	1.1.2.17.1.4	3	MASSPOINT			0.	C.	C.	C.	0.	0.
		LCVG #2	6	C.0C	0.C0	C.C0	0.	C.	0.	C.	0.	0.
116	3	1.1.2.17.2	273	CCMPOSITE SHAPE			174.	14C.	73.	-32.	48.	-80.
		CCNSUMABLES	601	--	--	--	4124.	3312.	1726.	-761.	1142.	-1904.
117	4	1.1.2.17.2.1	73	MASSPOINT			0.	C.	C.	C.	0.	0.
		ATMCSPHERE	160	0.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.
118	4	1.1.2.17.2.2	200	MASSPCINT			C.	C.	C.	C.	0.	C.
		FCCD	440	0.0C	0.CC	C.C0	0.	C.	C.	C.	C.	C.
119	2	1.1.2.18	1522	MASSPOINT			0.	C.	C.	C.	0.	0.
		GROWTH	3355	0.0C	0.CC	C.C0	0.	C.	C.	C.	0.	0.

7.4.2 Space Station Habitability Report

SPACE STATION HABITABILITY REPORT

THE BOEING AEROSPACE COMPANY

NASW-3680/CC0081

Submitted by
NATIONAL BEHAVIOR SYSTEMS

March 3, 1983

SYNOPSIZED VERSION

(Full report available from Boeing upon request.)

TABLE OF CONTENTS

INTRODUCTION

The purpose of this report is to summarize as concisely as possible the observations, experience, and suggestions of astronauts who have had experience in long duration space flight and other NASA personnel who have been deeply involved in long duration space flight development and operations on issues related to crew habitability, productivity and adaptation. This information will be organized and written for space station design engineers who are working at the very earliest phases of development and conceptualization. Ideas can then be incorporated that will facilitate the efficient operations and habitability of the space station at lower costs yet with much in the way of higher productivity and satisfaction on the part of long duration flight crews. Such early input should also eliminate many expensive design and hardware changes at those points in development when they become difficult and quite costly.

METHODOLOGY

Data included in the following report was compiled from interviews and from NASA technical reports.

Interviews were carried out in conjunction with this contract between October 13, 1982 and January 15, 1983 with Astronauts, Mission Specialists, ex-Astronauts, and others involved with NASA training, habitability, and mission control functions, and others. The following is a breakdown:

I. SKYLAB: 5

II. NASA ASTRONAUTS (Not Skylab): 1

III. MISSION SPECIALISTS: 6

IV. OTHER NASA PERSONNEL: 11
- Biomedical Applications Branch
- Mission Control
- Habitability
- Training Division
- Flight Training Branch
- Inflight Maintenance
- Graphics
- Space Suit
- Systems Integration

V. NOTES FROM MEETING AT JSC WITH SOME STAFF INVOLVED IN HABITABILITY.

VI. ANTARCTIC SOUTH POLE SUPPORT TEAM

VII. INTERVIEW WITH LICENSED MARRIAGE AND FAMILY THERAPIST

Interviews were conducted privately, with a tape recorder. Interviewees were told the material was to be confidential. The procedure was to start and end with open-ended, non-specific questions. The body of the interview was a response to specific questions. These questions were not rigidly administered, and thus, sometimes varied between interviews.

Interviews lasted from 45 minutes to 2 hours and 45 minutes. The average is about 2 hours.

Each interview was completely transcribed and summarized. From these summaries, general areas were identified, digested, and focused. On the basis of these third phase iterations, the following report was compiled.

II. NASA TECHNICAL REPORTS

Data was also compiled for the following NASA Technical Reports:

SKYLAB EXPERIENCE BULLETINS
1,2,4,5,6,7,8,9,10,11,12,13,
14,15,16,18,19,23,26 and 27.

SKYLAB LESSONS LEARNED
Johnson Space Center Report
Marshall Space Flight Center Report

SKYLAB TECHNICAL DE-BRIEFING REPORTS
1/2, 1/3 and 1/4

SKYLAB 1/4 TECHNICAL AIR-TO-GROUND VOICE TRANSCRIPTION

SKYLAB 1/4 ON-BOARD VOICE TRANSCRIPTION

MEDICAL OPERATIONS AND LIFE SCIENCES ACTIVITIES ON SPACE STATION (NASA TM 58248/October 7, 1982)

ORBITER HABITABILITY ASSESSMENT OF OFT FLIGHTS 1 THROUGH 4

WORKSHOP PROCEEDINGS: SPACE HUMAN FACTORS (Aug 24-26, 1982, Leesburg, VA)

RECORD OF MCDONNELL DOUGLAS MDTSCO DISCUSSIONS WITH NASA STAFF MEMBERS (1982)

LIFE SCIENCES CONSIDERATIONS FOR A SPACE STATION

III. GUIDE TO REFERENCE SYSTEM

( ) = Represents the number of astronauts who discussed the topic.

[ ] = Represents the number of NASA personnel who discussed the topic.

(A) = Interview with Antarctic Team members.

(FT) = Interview with Marriage and Family Therapist.

The following symbols are used to indicate some of the materials related to a topic. However, this reference system is neither exhaustive nor complete.

EB = SKYLAB EXPERIENCE BULLETINS

DB = SKYLAB DEBRIEFING REPORTS

LL = SKYLAB LESSONS LEARNED

IV = SKYLAB IV TRANSCRIPTS

MO = MEDICAL OPERATIONS

HF = SPACE HUMAN FACTORS

MD = MCDONNELL DOUGLAS MDTSCO DISCUSSIONS

LS = LIFE SCIENCES CONSIDERATIONS

SH = ORBITER HABITABILITY REPORT

REPORT OUTLINE

GENERAL PRINCIPLES

I. ENVIRONMENT

II. TECHNOLOGY

III. ORGANIZATIONAL SYSTEMS

IV. PERSONALITY SYSTEMS

GENERAL PRINCIPLES:

An overall finding was that the longer a crew spent in space, the more concerned they were with habitability and interpersonal factors.

THE FOLLOWING GENERAL GUIDELINE CONCEPTS CAME OUT OF THE INTERVIEWS:

- FLEXIBILITY
- POTENTIAL FOR GROWTH
- EVOLUTIONARY DEVELOPMENT
- BALANCE
- VARIETY
- AUTONOMY
- PRACTICALITY
- HONEST FEEDBACK
- STANDARDIZATION
- EARLY CREW INPUT INTO DESIGN
- EARLY STAFF INPUT INTO DESIGN
- HABITABILITY CONSIDERATIONS
- DESIGN FOR INFLIGHT MAINTENANCE
- SEE ALL SYSTEMS AS AN INTERRELATED WHOLE
- TAKE FULL ADVANTAGE OF CREW TALENT, SKILL & EXPERIENCE

THE FOLLOWING QUOTATIONS ARE REPRESENTATIVE OF CREW ATTITUDES:

"The more maximum the habitability, the better people will work. Anything you can do in the beginning to make it more habitable, the better satisfied people will be in the long run."

"I think the longer they stay, the more amenities they are going to want -- the more creature comforts."

"The basic message is environment. (In Skylab) we didn't bother to take into account the human needs, and we paid the price...in terms of discomfort and frustration. I just hope we don't have to learn that lesson over again."

"Classically, we don't get involved soon enough."

"Human Factors folks ought to be involved in reviewing whatever the design is before it hits the street -- while it is still on paper."

The more naturalness we can get in our life at zero-g the better."

COMMENTS REPRESENTATIVE OF NASA PERSONNEL ATTITUDES

"Any industrialization taking place in a hostile, remote environment will bring out psychological problems which could have a profound effect on productivity of both the sick and well crewmen."

"Attention to habitability improves and maintains work efficiency."

I. ENVIRONMENT

1.1 General Layout
- 1.1.1 Windows
- 1.1.2 Separation of Work and Living
- 1.1.3 Multi-directionality
- 1.1.4 Hatches
- 1.1.5 Ceilings

1.2 Work Stations
- 1.2.1 Console Work Station
- 1.2.2 General Purpose Laboratory and Work Station
- 1.2.3 Medical Laboratory
- 1.2.4 Airlock
- 1.2.5 Animal Laboratory
- 1.2.6 Plant Facility

1.3 Design for Inflight Maintenance

1.4 Crew Facilities
- 1.4.1 Private Quarters
- 1.4.2 Wardroom
- 1.4.3 Waste Management
  - 1.4.3.1 Shuttle Problems
  - 1.4.3.2 Skylab System
  - 1.4.3.3. General Points
- 1.4.4 Personal Hygiene
- 1.4.5 Shower
- 1.4.6 Exercise Equipment

1.5 Restraint Systems
- 1.5.1 IVA Body
- 1.5.2 IVA Equipment Restraints
- 1.5.3 EVA Restraints

1.6 IVA Mobility

1.7 Lighting

1.8 Stowage

1.9 Decor
- 1.9.1 Color
- 1.9.2 Clothing

1.10 Food
- 1.10.1 Types of Food and Preferences

1.10.2 Food Storage
1.10.3 Food Cleanup

1.11 Contamination

1.12 Smells

1.13 Noise

1.14 Temperature

I. ENVIRONMENT

1.1 GENERAL LAYOUT

All design should keep traffic patterns in mind.

1.1.1 WINDOWS (10) EB DB LL

The single issue raised by all astronauts spontaneously, most frequently, and very forcefully is the need for windows.

There should be:

Many windows,
Looking out in all directions
-- Total window coverage.
A large window in the wardroom.

1.1.2 SEPARATION OF WORK AND LIVING (10) [1] DB

All astronauts thought it important to have distinct separation of work and living facilities.

1.1.3. MULTI-DIRECTIONALITY (5) [2] EB DB LL

Four Skylab crew members indicated a willingness to use walls and ceilings used for stowage,experiments and equipment.

1.1.4 HATCHES (3) EB DB

Large doorways in OWS of Skylab were a good feature for working area.

Avoid heavy doors. There is a danger of getting feet caught.

Avoid small openings near doors and in traffic areas. Fingers can be caught and cut.

Avoid sharp edges.

Things should NOT be stowed behind open hatches.

1.1.5 CEILINGS (1) EB

Ceilings do not need to be 8 feet high. They could be 6 feet high, which provides leverage. Constraining factors are ground based training where fidelity in size is important, and technician access for construction.

Ceilings can be used as well as walls for stowage, equipment, etc.

Ceiling height in private quarters needs to permit easy ingress and egress to and from the sleep restraint.

Ceilings should not be the exclusive source for illumination.

1.2 WORK STATIONS (5) EB DB LL MO JS

All work stations must be designed for the zero-g body posture because any position that is contrary, and requires use of muscles to hold the body in position creates discomfort, fatigue and inefficiency. This means that tables and work surfaces should be about chest high and tilted for best visual access. Foot restraints should be slightly tilted. Stooping, crouching, bending down or sitting are to be avoided. Also, increases in body height and torso length need to be included in design.

1.2.1 CONSOLE WORK STATION (2)

Astronauts looked at the console below. They agreed such a station was most desirable.

Reasons cited were:

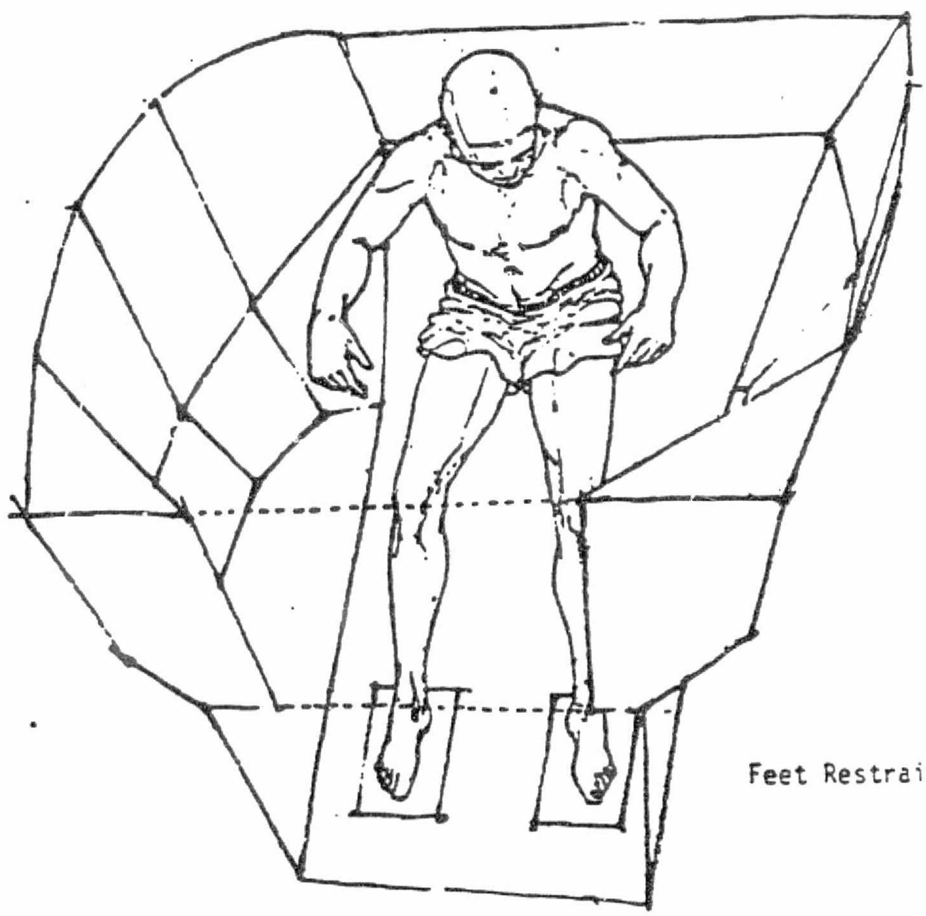
- Easy access
- Access to back of panels

Problems:

- Hard to hold torqued position to use panels near the back. (However this could be solved by having foot restraints swivel or by the use of magnetic foot restraints that could easily be turned on and off.)
- How much would such an extensive system be needed?

CONSOLE WORK STATION

WORKSTATION DIAGRAM FOR THE
DYNAMIC ZERO-G ENVELOPE



1.2.2 GENERAL PURPOSE LABORATORY AND WORK STATION (5) [3] MD MO LS

Astronauts cited the need for a general purpose laboratory.

Laboratory panels (ATM) should be engineered so the operator knows what he is doing while he is doing it.

Laboratories involving attitude control should use a joy stick system for small pointing maneuvers.

Skylab recommendations for inclusion in the lab are:

- Volt Meters
- AM Meters
- Microscopes
- Furnace
- Tools and equipment for repair in addition to Skylab inventory:
  - hacksaw
  - epoxy
  - hand drill
  - stone & file
  - power drill
  - rubber mallet
  - metal shears
  - files (rattail and round file)
  - soldering iron
  - crimpers
  - emery cloth
  - oil and polishing cloth
  - dykes
  - strong wire cutters
  - cable cutters
  - electrician's screwdriver
  - screwdrivers
  - wrenches
  - leak detector

All tools should be grouped in one area.

Inventory should include tools that do not have a specific flight use in order to provide a more complete off-the-shelf inventory for contingency tasks.

Adequate spares for hardware items need to be provided.

Standardization for:

- size screws
- bolts (Allen head screws and hexagon head bolt were preferred)
- plumbing and electrical connectors
- switches

circuit breakers
indicator lights
control knobs should be used in spacecraft design.

1.2.3 MEDICAL LABORATORY (2) [1] MO LS

Aim of health maintenance is to maintain work efficiency of crews.

Patients should be able to "sit" or "lie down" for examination or treatment.

Medical conditions are categorized as follows:

1. Usual Medical-Surgical Conditions of Adults
2. Unique to Space Occupations
3. Psychological Factors Related to Remote Hostile Environment

Principle for Health Maintenance Facility: Rapid, easy access.

A Health Maintenance Laboratory (HMF) should have:

Microscope
Centrifuge
Blood drawing supplies
Laminar flow workbench
Medical records
Examination Equipment
Ocular function testing apparatus
Diagnostic imaging
EKG, EEG monitoring with downlink capability
Pulmonary function test apparatus
Tracheostomy tray
Paracentesis, thoracentesis trays
Peritoneal levage tray
Lumbar puncture tray
Woods light, flourescein
Hyperbaric treatment facility
X-ray

The medical team sees this facility being developed in various stages, starting with a First Aid Station and evolving to a mature facility.

Recommends NASA establish a "new, broadly based working group to define and investigate the habitability requirements of a space station."

1.2.4 AIRLOCK [2] EB DB LL

Skylab volume marginal when EVA equipment was in the airlock.

Constant danger of damaging EVA equipment during airlock operations:
From: Lack of foot restraints
Lack of temporary equipment restraints for equipment
Lack of sufficient volume to locate EVA equipment outside the crewman's immediate functioning envelope.
From rush of air during repressurization

Inadequate room for the observer during donning and doffing of suits.

It should not be necessary to gather EVA equipment from all over spacecraft stowage areas to prepare for EVA.

"Locating the airlock as an appendage to the space/craft living/working areas and providing EVA equipment and stowage within or very near the airlock could have alleviated most of these problems."

1.2.5 ANIMAL LABORATORY [1] LS

Animal laboratories will need to accomodate:

- Rats
- Primates
- Frogs
- Cats
- Birds
- Fish
- Mice
- Embryos

Facilities will need to include:

- Cages, etc.
- One-g centrifuge
- Waste collection system
- Laboratory to examine and maintain animals
- Refrigerated storage facility for biological samples
- Mass measurement devices
- Sacrificing and dissecting and analysis equipment
- Extreta collection
- Gas Exchange evaluation
- Computers

1.2.6 PLANT FACILITIES

Plant growth facilities require their own environmental control system with subsystems controlling:

- Light
- Temperature
- Gas Composition
- Water/nutrient delivery

1.3 DESIGN FOR INFLIGHT MAINTENANCE AND REPAIR (5) [3] MD

Given proper tools, worksites, restraints, accessibility, and procedures, man can perform maintenance and tasks (both EVA and IVA) as readily in zero-g as he can on the Earth.

Design for maintainability and easy access in zero-g environment in spite of weight and higher initial cost.

1.4 CREW FACILITIES

1.4.1 PRIVATE QUARTERS (9) [2] (A) EB DB LL IV MO

Crew members cited the importance and need for private and acoustically silent quarters for long duration missions.

General principles for priviate quarters include:

- Acoustical Privacy (no "cloth dividers")
- Flexibility
- The ability to personalize
- The ability to change
- Modularity
- Variety
- Craftsmanship
- Adequate Size

"In future space flight, when man starts staying up for long periods of time, each crewman should have a place to call his own.""

1.4.2 WARDROOM (5) [1] EB DB IV MO

If the Wardroom is to be used for eating, crew members should have easy access to food and accouterments. No one should have to float over the table or crawl over other crew members to get in and out or get things they need.

The Wardroom table should NOT be considered a major work or writing station as it is frequently used heating food and in clean up.

Wardroom floors and ceilings should be easy to clean after food spills.

Crew members desire a place to meet as a group. This should be separate from the work area, and could be in the living quarters. It could be part of the wardroom or a separate recreation area.

The Wardroom can double as a medical facility if rapid access to equipment, etc. is possible.

1.4.3 WASTE MANAGEMENT SYSTEMS (3) [4] EB DB LL MD SH

Current Shuttle WCS is inadequate. However, it has been changed and somewhat improved. It is still a source of difficulties.

1.4.3.1 SHUTTLE PROBLEMS:

- Restraints are not adequate.
  - Seatbelt pulls user back too far causing misalignment with seat
  - Handholds do not help as they are too far forward
  - Foot platform is out of reach for some crew members
  - Foot platform tends to have user "push off" when it is used
- Urinal cannot be used without getting hands wet
  - There is insufficient airflow
  - Urinal takes excessive time (9 minutes is shortest)
- Smells interfere with food preparation. (This seems to have been fixed to some degree).
- Use of same hose to clean up after using WCS and to prepare food could lead to contamination.
- Need more privacy. Doors must be open for use.
- Very Noisy

1.4.3.2 SKYLAB SYSTEM:

- Crews liked the Skylab system
- Room does not have to be that big
- Restraint systems were not completely adequate
- Needed individual thermal controls
- Fecal collector in Earth g position (so you don't look at the floor)
- Adequate lighting to read, clean
- Nooks and crannies were hard to clean
- Wanted hand washer in a bubble to contain splashing (This is planned for Shuttle galley, but one staff member says it may not work.)
- Wanted clear (not brown) biocides for hands

1.4.3.3 GENERAL POINTS

All parts to waste management systems should be easy to clean daily. (Toward end of Skylab II mission electronics module in the head began to smell. At end of IV, the blower smelled like ammonia.)

Should be close to crew quarters (2 astronauts indicated that a WCS in the Logistics Module would be too far away).

WMC facility should have temporary stowage (bungee cords, velcro, etc.).

Hand washer should be separate from waste management booth so both can be used at the same time.

1.4.4 PERSONAL HYGIENE

A galley bubble hand washer is planned for Shuttle, but some people in Flight Operations think it may not work as planned.

On Skylab the washcloth squeezer became a source of odor because it was hard to clean.

Need easy way to clean out razor blades.

Need temporary stowage (bungee cords, velcro, etc.).

Need good provision for rinsing washcloths and wringing them out.

1.4.5 SHOWER (7) [3] EB DE IV

Shower is desirable.

It should:
- Be quick and easy to use
- Have hot and cold running water
- Have a mixer valve
- Use airflow system to remove water (vs vacuum)
- Permit washing of hair and scalp
- Heated, with heated dressing area

Two astronauts did not think it was terribly important.

1.4.6 EXERCISE EQUIPMENT (5) DB MO

Exercise equipment should include:
- Treadmill
- Friction Based Exerciser and/or Bicycle Ergometer

The Shuttle treadmill is very noisy.

1.5 RESTRAINT SYSTEMS (6) [6] EB DB LL IV SH

Restraint is an important habitability factor and different types of restraints are needed for different jobs.

Activation, de-activation of restraints, or work done with restraints should not involve sitting, bending, stooping or crouching because of the fatigue and discomfort that results.

There are two major kinds of restraint: Body and Equipment.

There are two restraint situations: IVA and EVA.

1.5.1 IVA BODY RESTRAINTS:

Foot restraint is best as it leaves the hands free.

Foot restraints are needed for delicate work, or when leverage is needed.

1.5.1.1 SKYLAB SYSTEMS

Skylab crews liked triangle shoes and recommend them for future use.

Skylab crews recommend triangle grid all over the space station.

Foot loops are considered adequate for some jobs, but are generally unacceptable because they require the crewmen to concentrate on remaining restrained. (Footloops are being placed by crews on orbit in Shuttle.)

1.5.2 IVA EQUIPMENT RESTRAINTS:

Velcro and gray tape work well and are highly recommended.
A problem with gray tape is that nuts or small items are easily knocked off by someone moving around.
Velcro and gray tape are poorly suited to paper.

Gray Tape Pad:
One astronaut recommended making pads of gray tape that could be used to hold small items while working or moving things about. As a page becomes dirty, it can be discarded and a new one started. Other crew members liked this idea.

Paper like Yellow 3M sticky back (with sticky back on two edges so it won't curl) might be good. Restraining small pieces of paper is a problem.

A writing table needs restraints for papers, books, and small items

Paper in files is difficult to manage. Pulling out one sheet tends to disturb all the others and they float away.

Restraining small nuts, bolts, and small debris is a problem. They float out of pockets and trash bags.

Large plastic transparent bags would be useful in restraining small items while transporting. Since things can be seen, it would be easier to retrieve them without everything else coming out.

Need bungee cords or restraint systems on all the lockers to aid transfer of items.

Large items being moved or handled need handles or some part of the structure that can be easily grasped. If larger than about 20x25 inches, the crewman's view of the transfer path and terminal site is blocked. Energy inputs used to initiate transfer must be removed at termination.

All operational equipment restraints should be standardized and should be simple and easy to use.

Bungee-type restraints attached to stowage lockers, wall, doors, etc. would be good for many situations.

Specific "book" restraints are needed at work sites to retain checklists and hold them open to a specific page.

Lockers and stowage, regardless of size and configuration should have simple latches. Crews prefer a lift handle and magnetic latches.

1.5.3 EVA RESTRAINT SYSTEMS: EB DB LL

It is important to be able to get to any point on the exterior of the spacecraft, and therefore handrails and restraint systems are needed. These can be permanent or facilities for affixing temporary restraints.

Crews preferred double handrails for translation.

Crews liked the universal foot restraint.

Some hand restraint at waist height is needed to aid getting into foot restraints.

It is easy to get turned around and confused. Need chaulk marks to show where equipment should be placed.

1.6 IVA MOBILITY (1) [1] EB LL

Normal translation routes should not interfere with the working, eating, sleeping, or relaxing crewmen.

"Compartment size and layout governed the preferred body orientation."

The PLTs position in the Wardroom required translation over the table and another crewman had to move. Passage was inconvenient and was also "a hazard from the 'foot-in-the-food tray' point of view."

Skylab crewmen impacted the OWS dome sufficiently in route to the dome hatch to leave dents in the ceiling.

The crew members often bruised their legs as a result of multiple hatch negotiations and immediate attitude reorientations during the day.

Very few items of hardware, operational or experimental, are exempt from inadvertent collisions by personnel or from occasional use as a mobility aid or a temporary restraint device. Design practices must account for these probabilities.

Inadvertent control actuation was a continuing problem on Skylab, with switches and circuit breakers the most vulnerable items when located along a primary locomotion path or by inadvertent kicking done in attempting restraint.

All sharp edges and/or pointed items must be eliminated or covered, especially along traffic paths.

1.7 LIGHTING (1) [1] EB LL SH

Lighting in Skylab was insufficient.

Ceiling lights were not adequate to do personal grooming and to clean. Flashlights had to be used.

Interior light scattering made the telescope very difficult to use.

Convenient portable lighting is needed. It should be completely portable and flexible with respect to use by individual crewmen.

1.8 STOWAGE (2) [3] EB LL IV

Stowage on Skylab was a problem. One crew member, and Skylab Reports recommend colorful graphics to indicate storage areas that can be easily recognized from any position, at a distance, and without the need to use logs to find types of items. (Though numerical identification can still be used).

Graphics may be helpful in stowage identification.
Colorful symbols or pictures of the contents
Such graphic systems could become an irritant over a long stay.

There is a need for a practical and streamlined inventory management system.

The biggest stowage problem is re-stowage -- crew members replacing items incorrectly and not making any record.

All like items should be stowed together and in the same area on the spacecraft.

Crew data should be output in the exact format to be used by the crew and should be compatible with the real-time uplink for presentation on board.

Information should be alphabetical and with as many cross categories as is possible.

There should be standard terms for items. Words are preferred to numbers, and each item should have but one name.

1.9 DECOR

1.9.1 COLOR (6) [4] EB DB IV MO

Variety and pleasantness are seen as important by crew members for long duration flights. They do not like "battleship gray or dormitory green."

1.9.2 CLOTHING (4) [1] EB DB IV SH

Two astronauts indicated that variety and color is important in clothing. One wanted to use personal items as much as possible. Two were opposed to the constant use of "uniforms."

Skylab Reports state the need for variety in color and types of materials for clothing for long flights. Crews suggested use of "jogging" suits and other comfortable and colorful materials.

Zippers should have pull tabs.

Crews prefer two-piece garments as opposed to coveralls. They are more sensitive to fit, adjustable, and more convenient for personal hygiene.

Pocket placement and design needs careful study. zero-g conditions are different than one-g. Styling should not be important on this point.

Crew members would like good watches with night light dials and good timers.

1.10 FOOD (6) [4] EB DB LL IV MO SH

Food should be easy and quick to prepare, eat and cleanup.

1.10.1 TYPES OF FOOD AND PREFERENCES

Good food is very important. Crews want variety, spices and the ability to "raid the pantry." (Food tends to taste bland in space.)

It is important to eliminate disliked foods prior to flight because "something that can squeek by here will probably tend to bug you."

Food was broken into the following types:

- Frozen
- Irridated
- Thermostabilized
- Rehydratable
- Natural Form
- Beverages

Crews preferred frozen foods the most, and like irridated foods.

"The whole crew should not be used as medical test subjects." [This could be a source of conflict as the Medical Operations Group seem to assume they will continue to test the crews as they did in Skylab.]

Crews also like to take one meal as a group, usually dinner, where they can talk over the day's activities, etc. This was an important morale factor. "Eating together was one of the nicest times of the day."

1.10.2 FOOD STORAGE

Crews would like food stored in a pantry style with all items of a kind kept together.

Food transfer took a lot of time as each can or package had to be carried individually. Crews recommended that some type of transfer receptacle be developed.

1.10.3 FOOD CLEANUP

There is a need for sufficient trash disposal for each crewmember.

The food disposal area did not lend itself to cleaning because of the nooks and crannies. This was the only area in the wardroom that created undesirable odors.

1.11 CONTAMINATION (1) [3] EB SH

There are five major interior areas of contamination:

- The Waste Management System
- Food System
- Trash Disposal
- Exchanger Screens
- Windows

All contamination is exacerbated by nooks and crannies that are difficult to clean, or equipment that is difficult to take apart for frequent cleaning.

It was thought that the Skylab was very clean, and that was due to the low humidity. There was little moisture or condensation. Higher humidity would have "caused additional fungus and bacteria growth. We would have smelled more."

Trash should be separated into biologically active and inactive materials. Biologically active material should be disposed of daily. Trash should be stowed in an area "external" to the habitable volume of the spacecraft.

Food containers make up the bulk of the trash, and should be designed to consume minimum volume when discarded. A trash compactor (or two) is recommended.

1.12 SMELLS (3) EB DB IV SH

Absence of smells is frustrating. Crews would enjoy good smells in shaving lotions, creams, cooking, etc. Skylab crews enjoyed smelling the "Joy" soap used to de-fog helmets.

Unpleasant smells are to be avoided. The WCS on the Shuttle has been the source of major unpleasant odors, and still has a minor problem. A member of the Flight Operations staff thinks that as this system is used over longer periods of time, odors would become a major problem because material would dry and flake and probably collect down near the airflow system.

1.13 NOISE (3) [2] EB DB IV SH

Noise is a factor that significantly interferes with adequate rest and sleep. This is currently a problem on Shuttle, and was a problem on Skylab. Crews feel it is very important to have acoustically private quarters.

Shuttle noise is an adverse habitability factor. The 7 fans have not been adequately dampened so that crews must use the intercom. The WCS is also very noisy as is the tread mill exerciser.

Flight deck: 55-60 db
Middeck: 65-70 db

Sounds that interfere with sleep are:

RCS primary thrusters (exceptionally noisy)
WCS use
Teleprinter operation

Acoustic blankets used on Shuttle dropped sound approximately 3 db and were abandoned because of limited effectiveness.

Shuttle bunks are in the middeck area close to the WCS and food preparation systems, and there is concern about the ability of crews to sleep adequately while on a three shift system.

1.14 TEMPERATURE EB SH

Temperature on the Shuttle varied.

Flight deck: 70-75 degrees fahrenheit
Middeck: 60-70°

Crews preferred to sleep on the flight deck.

Temperature varied on the middeck with some areas slightly warmer, especially around electrical equipment.

Tail to the Sun caused the flight deck to cool and the crew wore jackets or turned on the lights to increase the thermal load.

During periods of temperature buildup, the crew powered down and used shades to cool the vehicle.

II. TECHNOLOGY

2.1 Information and Communication Systems

2.1.1 Computers

2.1.2 Television Systems

2.1.2.1 Two Way Television

2.1.2.2 Video Tape Machine

2.1.3. IVA Communication

2.1.4 Air-to-Ground Communication

2.1.5 Microfiche

2.2 Space Suit

2.2.1 Pre-breathe

2.2.2 Gloves

2.2.3 Drying

II. TECHNOLOGY

There should be standardization in the design of displays, controls, switches, tools, hardware, and equipment used by the flight crew.

2.1 INFORMATION AND COMMUNICATION SYSTEMS (10) [2] EB DB LL MD MO

All communication systems should have a method for signaling receipt of information and system use state. A light should show when ground is transmitting and when the spacecraft is transmitting.

Communication systems should be designed so that the operator can follow the flow of information.

Some hardware, like intercom systems, should be flexible and moveable. A duplex portable wireless intercom system should be used in future communication systems.

Consideration should be given to the use of fiber optics for use in communication and data systems.

2.1.1 COMPUTERS (10) [2] LL MD MO

There is no question that the crew members favor the ample use of computers on future space stations.

Crew members would like to have the following kinds of hardware:

- Keyboard Terminals
- Printers
- Disk Drives
- Color CRTs
- Thermal printers for graphics
- Light pens
- Plotters
- Joy Sticks

The crew generally favor the use of the best available technology. They have had little experience with voice activated computers and thus were hesitant to request them.

The computer should have a unified bus structure (UNIBUS), where one bus would talk to several computers. This time shared bus would avoid many buses being routed all over the space station.

Data links for this computer should be designed to be built into the space station as the part of the structure during construction which would result in more reliability.

There is general agreement on the need for "user-friendly" software.

Skylab Lessons suggest a total integrated design effort should consider sensors with data compression capabilities, on-board processing systems that will only transmit key parameters and analyzed results, information systems with decision making capabilities as to what constitutes valid data for transmission, and on-board data compression techniques.

Skylab has shown that a redundant general purpose computer, reprogrammable from the ground and backed up by an extremely versatile group of support personnel using a variety of simulations made it possible to meet every contingency situation which arose.

Crews prefer graphic readouts in color instead of lists of numbers. For instance, one crew member said it would be good to have temperatures in various colors on a system diagram. Red would indicate a problem, etc.

Crew should be able to access "nice-to-have" information when requested, but it should be culled out of displays.

Caution and Warning Systems should also be in color graphics that unambiguously identify the actual cause of an alarm.

On-board experiment data readout and assessment capability should be displayable to the crew in real time.

In the Shuttle, not all displays and systems are standardized, thus increasing the problem of learning and using the Shuttle computers. Display systems in primary systems are different than those in backup systems.

2.1.2 TELEVISION SYSTEMS

2.1.2.1 TWO-WAY TELEVISION (9) [2] (A) LL MO

Crew members were very enthusiastic about two-way television systems.

A representative of Mission Control considered it mandatory.

They would like the systems to be in color.

ADVANTAGES:

Be able to see the people you are talking to
Help maintain good rapport with ground
Show charts and information in real time for science and operations
Troubleshooting and repair enabled
Show details of hardware to be repaired
Observe repair procedures
Enable maintenance
Use for training
Facilitate problem solving
Facilitate briefings and conferences with ground
Facilitate communication with family and friends
Uplink news real time and perhaps some sports highlights

There was general approval of a helmet mounted system. However one crew member pointed out that maintenance manuals rarely cover all problems or cover them accurately. He also noted that two dimensional views can be hard to understand. However, he added that one picture was still worth a thousand words.

2.1.2.2 VIDEO TAPE MACHINES (9) [2] MO

This system was seen as very valuable. High speed dump systems would permit the transfer of large amounts of information to be used later, and added to the station library.

2.1.3 IVA COMMUNICATION EB LL IV SH

Provide circuitry to disable speakers which could couple into a microphone whenever the microphone is keyed.

Intercom switches should be designed to be looked at from any angle.

Headsets should be lightweight and wireless.

Shuttle Headsets tend to leave the ears sore.

Noise on the Shuttle created by the cooling fans makes IVA communication difficult without head sets. Fans should have noise dampeners.

2.1.4 AIR-TO-GROUND COMMUNICATION (10) [3] (A) EB LL IV MD MO SH

Up-link conversations to astronauts need to be filtered and screened. Some astronauts would like communication down scheduled. Others would like to initiate it as needed and as is possible.

Crew members would like dedicated communication links with PIs.

There should be a provision for private communications for mission management. "The restrictions against such private communications in Skylab prevented the exchange of information with the crew on the subjects of scheduling of activities or workload." This reluctance came from the fear of being mis-quoted or misunderstood by the press. "If a person is on guard, you're not really going to get the information transferred as quickly and accurately as you would if you were free to say something completely open."

Some crew members do not like having private conversations recorded.

Crew members do not want news, etc. censored.

On-board recording should not be capable of being dumped by the ground while in use. The crew recommend separate tape recorders with a central dumping unit. When a tape is full or they are finished, they take it out of one tape recorder and put it in the dump.

There is need to develop a reliable tape recording system (there have been many problems with the Shuttle one).

Crews like to be able to talk privately to their families a couple of times a week. "More would be better." "That's one of the nicest things on a day-to-day basis you have that helps you feel like you're not too far away."

Communication should remain human. "We shouldn't let ourselves get buried in jargon, procedures, and systems and forget to be humans and understand the human factors of what we are doing."

Paper is a continuing problem with teleprinters.

2.1.5 MICROFICHE (2) [2]

Mission Control has recommended that some data on station systems, maintenance, repair manuals, books, etc. could be stored on microfiche. This would save space and weight. However, again, the need for hard copy is a problem if the information is needed at a remote location away from a reader.

This method is not recommended for any repair related systems or procedures.

2.2 SPACE SUIT (9) [3] EB IV DB

Usefulness and difficulties with the suit depend on what you are doing and task design.

2.2.1 PRE-BREATHE

Pre-breathe is an unacceptable operation for the space station.

This will have to be brought about by using an 8psi Suit, or bringing the pressure of the station down to about 11psi (which would be very awkward with a 14 psi Shuttle, an 11psi station, and a 4psi Suit).

2.2.2 GLOVES

The major fatigue causing factor on the suit is the gloves.

Ways to work-around this would be to:

- Use power tools
- Use end-effectors
- Use cherry pickers

End-effectors would not require restraints for tools.

End-effectors could provide for built-in, or easily replaceable tools.

End-effectors would have the hand entirely in a pressurized container.

Sizes of handles on tools should be related to glove characteristics.

2.2.3 DRYING

Vacuum could be used to dry suits.

This problem can be solved by improving suit dryers and is not a major problem.

Suit dryer motors should be set to turn off automatically.

2.3 ATTITUDE CONTROL

TACS should have check valves in the Nitrogen System. Loose one tank, and you lose the whole system.

TACS should be servicable from the inside and the outside.

TACS can interfere with sleep.

III. ORGANIZATIONAL SYSTEMS

- 3.1 Program Structure
  - 3.1.1 Autonomy
  - 3.1.2 Scheduling
    - 3.1.2.1 Mission Length
    - 3.1.2.2 Work Day Length
    - 3.1.2.3 EVA Length
    - 3.1.2.4 Leisure Time
    - 3.1.2.5 Exercise Time
    - 3.1.2.6 Sleep Time
    - 3.1.2.7 Job Rotation
- 3.2 Role Relationships
  - 3.2.1 Family & Friends
  - 3.2.2 Mission Control
  - 3.3.3 Professional
- 3.3. Training and Simulation
  - 3.3.1 Ground Training
  - 3.3.2 On-board Training

III. ORGANIZATIONAL SYSTEMS

3.1 PROGRAM STRUCTURE

3.1.1 AUTONOMY (7) [3] (A) DB LL MD

Support for autonomy by the crew is high, however, there is considerable concern about what "autonomy" means and what the costs and consequences may be.

3.1.2 SCHEDULING (8) [2] EB DB LL IV

Crews would like to make up their own schedules based on general programs and checklists set in the computer and related to ground devised objectives. Many of the concerns about autonomy relate to concerns about scheduling.

Schedules will vary with the tasks that need to be done.

One staff member recommends a flexible approach in the beginning to permit changes and to see how the situation develops.

Some Mission Specialists think that there will be a lot of free time between moments of intense activity and they would like to take advantage of that time to do experiments, inflight maintenance, repair, etc.

Crew members do not want ground control planning the daily schedule. They generally prefer the ground to set goals and do "global planning" while the crew establish daily and weekly on-board schedules.

Crews do not want "super-planning".

Reasons given are that things change, things take longer than expected, and there are larger crews. It would be a "nightmare" to have to constantly readjust those schedules on a daily, hourly, and minute-by-minute basis.

3.1.2.1 MISSION LENGTH

4 - 6 months (2)
3 months on orbit, 3 months off for 5 years (1)
2 months seems like a lot (1)

Mission length depends on crew members having worthwhile things to do.

3.1.2.2 WORK DAY LENGTH

8 hours (1)
12 hours (2)
16 hours (1) this included meals, breaks, and exercise.

Discussion of schedule times is imprecise because it was not clear if meal times, exercise and breaks were included in the times suggested.

Crew members preferred to have exercise times scheduled.

Crews seem to see this as a matter to be set in general, but where the crew will basically make the day-to-day decisions.

3.1.2.3 EVA LENGTH (8) [2]

All astronauts who discussed EVA made the point that EVA is VERY HARD WORK.

4 hours (1)
6 hours (3)
7 hours (1)
Every other day (2) (This depends on the work to be done and the continuity required.)

3.1.2.4 LEISURE TIME (10) [2] (A) EB MO IV SL

As missions become longer, leisure time becomes more important. Crew members thought that one day out of seven should be free, and one crew member thought that 2 to 3 hours each day should be free time.

3.1.2.5 SHIFTS

There is considerable variation among crew members about using shifts. Depending on the facilities and the work to be done, many still prefer 8 or 16 hour shifts with everyone sleeping at the same time. Others think 24 hour shifts will be necessary.

3.1.2.6 EXERCISE TIME (5) MO

One to one-and-a-half hours of hard exercise is needed each day. The Soviets require two to two-and-a-half hours 6 days a week.]

Exercise time should be scheduled.

3.1.2.7 SLEEP TIME (3) (A)

The crew would like to decide when to get up, when to go to sleep, and when and if they want to adjust sleep cycles.

Inadequate sleep leads to fatigue and more mistakes.

Crews say they need about 7 hours of sleep.

3.1.2.8 JOB ROTATION (8) [1] DB IV

All crew members preferred cross training and job rotation for operations.

"You don't want somebody solely responsible for the housekeeping chores. That can drive you crazy after a while."

"You just got to be jerked out of the routine every once in a while. Even if you want to keep doing it, you have to be jerked out of the routine."

Scientists should be more dedicated to science functions.
Reason given:
The character of the work

Crew members often remarked on their preference for "shopping lists" which gave them the option of doing a variety of work.

Not all crew members need to be trained to do EVA. With larger crews there probably would not be enough suits.

However, it was generally thought that all permanent crew members would want to be able to do EVA activities for variety. Those unable to do so might feel deprived in an isolated and confined environment. One crew member thought EVA was very risky and would prefer not going out. There was not much consensus on this point, and specific crew members were not really sure what their position was.

3.3 ROLE RELATIONSHIPS

3.3.1 FAMILY AND FRIENDS (5) (A) EB DB IV

Communication with family and friends was an important area to crew members and often arose spontaneously. It had high priority.

The communication link should be reliable.

They feel a need to maintain contact with both family and friends in order to fulfill the important role functions of father, husband, friend, etc. "You feel like you aren't too far away."

Privacy is necessary, with little interference from the ground. This could take place in private quarters or in a private communication "shack."

Two-way television is preferred if possible.

Crew members varied in methods of initiating down-links. Some wanted this scheduled, others wanted the freedom to initiate links at will, if the communication lines were free.

Morale was cited as a reason for communication with family and friends.

3.3.2 MISSION CONTROL (3) [2] (A) EB DB IV

Good rapport with Mission Control and cap coms is important.

3.4 TRAINING AND SIMULATIONS (7) [2] DB MD MO

3.4.1 GROUND TRAINING

Crew members thought that training was a necessary but not sufficient prelude to success in working in zero gravity. "It doesn't matter how much you train at things. When you get up there and get in a new environment, you are not going to do it fast; you are going to do it step-by-step as slowly as if you had never seen it before in your life."

Tasks with no training took 1 1/2 to 2 times longer.

There are saturation points in training.

Fidelity in training does not need to be so perfect if extremely uncomfortable.

Training would be greatly facilitated if computer software were standardized and crew members did not have to learn so many "failure" responses.

Many sims were simply a matter of "going through the motions". The big thing was the time line and "learning to go through the days activity." One crew recommended sims where "we ought to go through the total day's activity and make sure of every small step you have to carry out."

It helps in sims when the instructor throws in malfunctions.

3.4.2 ONBOARD TRAINING

Staying away from a system for a long period hurts your ability and familiarity with it.

Small sub-sets of crew members could spend time at the station exclusively involved in training (ground simulations are NEVER adequate).

IV. PERSONALITY SYSTEMS

4.1 Productivity and Morale

4.2 Group Management Skills

4.3 Selection Procedures

IV. PERSONALITY SYSTEMS MO HF SL

"To protect the health of the crew, both physiological and psychologial problems that are caused by isolation in space must be anticipated and countered. Methods for maintaining both physical and mental health are often intertwined."

Areas related to psychological problems and health in space are listed as follows:

Work environment
Work design
Schedule design
Station organization
Role relationships
Interior layout
Interior decor
Food
Nutrition
Sleep
Recreation and Leisure
Communication
Mobility
Restraint
Personal Hygiene
Housekeeping
Clothing
Training
Maintenance
Adequate tools and supplies
Health
Safety
Clothing
Management
Personality factors
Cultural factors
Change or lack of it

4.1 PRODUCTIVITY AND MORALE (9) [4] (A) EB DB LL IV MO HF SL

"Attention to habitability improves and maintains work efficiency."

"If the station is inhospitable, NASA will find morale suffering followed by decreased productivity as the time on-orbit increases."

"Methods for maintaining both physical and mental health are intertwined."

"The possibility of acrimony or unprofessional-like activities among crewmembers may increase, as the Antarctic expeditions verify, when increasingly technical personnel are selected at the expense of physiologial and psychological traits."

4.2 GROUP MANAGEMENT SKILLS (2) MO

Crew members thought there was a need for learning management skills and conflict management skills and were open to such programs.

One crew member recommended having a Behavioral Scientist as a member of the crew as well as a member of the training and planning program.

"Crew members should be trained to deal with the stress of the long stay in the isolation and close quarters of a space station (e.g., training in social support techniques)."

4.3 SELECTION PROCEDURES

There is a need to develop means of evaluating crew personality traits for long term flights.

The question of selection relative to personality traits needs attention. The longer the flight, the more small things can become frustrating.

7.4.3 Data Management System

DATA MANAGEMENT SYSTEM
INTRODUCTION

A space station data management system must respond to a wide range of needs to be successful. It must have flexibility, adaptability, growth capability, and provide a wide range of features. The main attributes needed are: (1) Capability for throughput and mathematics intensive operations like flight control and image processing; (2) Ability to manage large data bases, such as for flight plans and maintenance procedures; (3) User-friendly man-machine interface characteristics for crew and user interaction; (4) Simplicity of access and use for one-time users; (5) Similarities to intelligence, e.g., for subsystems management under varying conditions and for a range of subsystem states including degraded modes or while elements of a subsystem are down for maintenance.

At the same time, the system must be affordable and able to evolve with time as the space station grows and its uses change. It must be amenable to achieving initial operational capability in a reasonable time. It must be designed to be safe under all conditions and able to operate with a range of crew participation in decison-making, and subsytem control and monitoring.

Finally, the system must be verifiable, while also permitting software as well as hardware upgrades on orbit.

These needs clearly indicate that the space station data management system will be unlike any data processing system yet flown on a spacecraft. It will perhaps have more similarities to systems now in use and being developed for aircraft, and will certainly exhibit some features of large ground-based networks. We can anticipate: a range of processor capabilities from small micros dedicated to controlling a particular piece of equipment to mainframe-class for high-speed processing and large data base management functions. There will likely be more than one language used, although standardization should be applied to the extent practicable. Subsystems management should be applied to the extent practicable. Subsystems management may make use of expert system technology, thus implying use of special machine architectures and languages.

The individual processors will be interconnected by a data bus network to facilitate exchange of information between subsystems, control and display systems, data bases, and the ground. The bus network needs to be growable and failure-tolerant, thus implying an architecture with some of the features of packet switching.

Making the entire system failure-tolerant, repairable, and capable of practical operation with crew participation will lead to architectural features that resemble Earth-based systems. There are a number of philosophies for achieving failure-tolerance. That practiced on Shuttle involves redundancy and voting at the main processor level. Other concepts include fault detection and reconfiguration internal to each processor, use of error-correcting codes to detect and correct soft upsets, and job reassignment in internetted systems. All of these must be traded and examined to select the preferred approaches for a space station.

Significant cost and schedule advantages can accrue to the selection of processor families and languages that are widely used and supported. If the space station program selects a specialized processor set or language not widely used in other applications, then all of the cost of maintaining the processors and language will be borne by the program. Alternatively, selection of systems widely-used commercially would offer a base of support that would only have to be supplemented by the space station program. Although commercially-based equipment would require space qualification and the implementation of a parts program, early breadboards and testbeds could use the commercial equipment with expectation that the software and techniques developed would be directly transportable to the space-qualified equipment.

DMS ARCHITECTURE

The space station data mangement system is a data processing system that consists of a collection of processing elements, mass memory elements and communication links. It provides for central processing and data base management and for subsystem control and status monitoring. Definition of the system requires selection of the processing architecture, the data transmission scheme, the processors and mass memory devices.

In developing a data processing system, the first question that must be addressed is whether the system should be centralized or distributed. Since processors are becoming faster, smaller, lighter and less expensive, a distributed system is the preferred approach except when there is a large amount of processing that is required and there are relatively few sources of data. The space station system has numerous sources of data and required points of control where local processing and control is the desired approach. The local processors then have lesser amounts of data for interprocessor communication.

The interconnect topology can take various forms that fall into two general categories—bus structures and graph structures. The simplest system is a global bus (fig. 2-1). All processing nodes are connected to a single bus (dual or triple redundant). All transmissions occur over the same path. The advantage is the simplicity of the interface (each device interfaces one place and the interface is standard). The disadvantage is the limitation on the amount of data that can be transmitted.

In order to provide additional data transmission capability, a multiple bus scheme may be used (fig. 2-2). In this case processing elements that communicate with one another are connected together on one bus (dual or triple redundant). Communication between buses is accomplished through one of the processing nodes. A topology of this type is usually established with some form of hierarchy.

For high data requirements between processing elements, some form of graph (mesh) structure is required. The general graph structure is a point-to-point connection schedule (fig. 2-3). Processing elements that need to communicate are connected directly. This provides the maximum system communication capability. The disadvantages of this system are nonstandardization of interfaces and inflexibility for expansion.

A subset of general graph is a tree in which processing elements are connected in a hierarchical structure (fig. 2-4). This structure reduces the number of communication paths to key paths at the expense of susceptability to faults. If a processing element in one lower limb needs to communicate with one in another branch, the data must be tranmitted up through a higher node. Failure of the higher node eliminates the ability to communicate.

A modification to the tree to increase fault tolerance and data communication is the threaded tree (fig. 2-5). In this case, selected lower level processing nodes are interconnected. This permits continued communication when a higher level node fails.

A somewhat different approach is the star structure (fig. 2-6). With a star structure, all processing elements are interconnected through a central switching element. This structure is very tolerant of failures of processing elements but very susceptible to failures of the central switching. In addition, the communication rate of the system is limited by the central switch.

Another approach is a ring structure (fig. 2-7) in which each processing element communicates with the next. This provides for simple interface design and expandability but long communication paths and susceptibility to failures.

A modification of the ring structure is the chordal ring (fig. 2-8) where each processing element communicates in one direction with the next and in the opposite direction with alternate processing elements. Here communication paths are shortened, and the length is unaffected by failures of a processing element. This is at the expense of a more complicated interface and communication routing scheme.

Table 2-1 provides a general comparison of the various distributed processing architectures. Selection of the specific topology depends on the number of processing nodes, the intercommunication requirements and the fault tolerance requirements. In the case of some systems such as the ECLS, the fault tolerance of the architecture is very important.

DMS SELECTION PROCESS

In establishing the data management system architecture, the following issues must be addressed:

- Topology
- Communication
  - Characteristics
  - Protocol
  - Media
- Processors
- Mass Memory
- Controls and Displays

Selection of the topology first requires definition of the processing and communication requirements. The first step is to identify the number of processing nodes and the location of each. Typically these will correspond to the various subsystems, plus a control processor for human interface to the automation system. The next task is to identify the communication requirements. This may be compiled using a matrix as shown in Figure 5-1. Entries indicate the amount of data required per unit time and the direction of data flow. Entries may also contain additional information such as burst vs. average, video data, etc. The next requirement is to define how the data rates change as a function of time, mission, mission phase, application, etc.

As a separate input to the topology development, the fault tolerance requirements must be defined for various processing nodes and for the system.

Because of the complexity of the communication requirement and the severity of the fault tolerance requirement, it is necessary to model the communication of the most promising topologies, making assumptions about the failure rate of processing nodes, communication protocol and mission scenarios. This would then allow analysis of the communication statistics and fault tolerance for each candidate over significant operating periods. The analyses of the topology alternatives may need to be iterated as various communication characteristics/protocols and processors are defined in response to topology selections.

An additional criterion that must be considered in the topology selection is identification and accommodation of physical interfaces in the space station. It is desirable to minimize the number of communication links that cross each physical disconnect interface. This reduces connection complexity and susceptability to faults.

For the communication links various candidate standard, proposed standard, modified standard and special approaches should be identified. For each of these, the various characteristics need to be defined: speed, electrical characteristics, noise immunity, data limitations, overhead, limitations on transmission media, limitations on protocol, etc. These then need to be compared to the requirements defined for the topology to determine suitability for each of the various alternatives.

Standard communication approaches are preferred, especially when the system is to use elements already developed or in development, or is expected to use elements which are interchangeable with another system.

Communication protocol can be defined and developed separately for various architecture topologies to the extent that various communication approaches permit. For each of the various protocols (collision detection, time slots, token passing, round robin, etc.), the various features need to be defined: efficiency, simplicity, fault tolerance, data integrity and support of synchronous and asynchronous transmissions.

The various protocols need to be traded with respect to the candidate topologies to determine system communication capability and susceptibility to faults. As part of the evaluation of the protocols and the topologies it is necessary to evaluate various system control procedures. These control the flow of data as a function of the processing requirements and the switching of communication links in response to failures. The system control procedures will reflect the simplicity, modularity, expandability and fault tolerance of the topology and the data transmission characteristics and protocol.

Selection of the transmission media is somewhat a function of the communication scheme selected. Standard communication schemes most often specify either directly or indirectly the transmission media. There is an option to modify the standard to the extent necessary to allow another medium. Selection of the medium involves analysis of the options with respect to weight, transmission length, durability, security, etc. The results of this analysis may effect the topology or communcation scheme selection.

Selection of the processors involves analysis of the processing requirements at each processing node (subsystem). This includes processing load (operations per second for a specific processing task, i.e., instruction mix) memory requirements, interface to the automation system and subsystem unique interfaces for data collection control and status monitoring. Also, any unique fault tolerance requirements for the subsystem such as a doubly or triply redundant processor for the ECLS subsystem. Additional criteria to be considered include standardardization among various subsystems, use of standard processor instruction sets, availability of programming languages, modularity of processor components, fault tolerance, and test and maintenance capability.

Selection of the system mass memory is somewhat independent of the above considerations except to the extent that location of the devices affects data communications and hence the topology and communication scheme. To define the mass memory requirements involves listing the various blocks of data, their size, where the data is generated and/or used, whether the required access is read only, write only or read/write, and any memory protection requirements. With this information, various combinations of device type and locations of devices can be traded off in conjunction with the topology selection and the communication scheme.

In all of the above, development facilities could be comprised of state-of-the-art computing equipment such as microprocessors which are not necessarily space qualified. But the commercially available equipment could be space qualified for the operational missions during the development phase of the Space Station Program.

Display selection for the Space Station control stations will depend on the state of hardware development at the time of selection. Currently, the only displays capable of providing high resolution and full color are CRT's. CRT's are readily available in a variety of sizes. New models of color tubes now provide flight qualified packages with the high brightness needed for cockpit applications. The CRT packages, however, are still bulky and heavy, particularly in the larger sizes. The high voltage requirements and safety hazard of the large vacuum bottle represent additional potential difficulties with the CRT.

Flat panel displays such as LED's, liquid crystal displays, electroluminescent and plasma displays have offered a greatly increased number of options in small and medium panel sizes (up to 6" diagonal) in the last few years. Plasma panels are now available in large screen sizes (up to 1m diagonal). Currently, none of these displays offers full color although several manufacturers (i.e., Lucitron, Sony) are working on full color plasma displays. The flat panel displays offer advantages of a lower volume package for the same area, lower operating voltage, and more rugged construction. Thin film electroluminescent (TFEL) displays are one of the better prospects for a potential Space Station flat panel display. These displays can be made in relatively large sizes and are completely solid state. Current work being conducted by the Army is directed toward development of a color TFEL display with a moderate screen size (12" diagonal). Figure 5-2 shows a currently available flat panel TFEL display mode by Sharp. This display uses a single color 240 x 320 pixel array with a 6 inch diagonal screen size.

For the Space Station, and hence for the ECLSS, the display selection methodology should consider the use of flat panel displays where the system requirements permit. For those areas currently requiring CRT's, the driving hardware should be designed to permit the installation of flat panel displays as their technology advances. Displays should be capable of operating in a multifunction basis to minimize hardware required for each system. Figure 5-3 shows some of the available display options and characteristics for both flat panel and CRT displays.

CREW INTERACTION, AUTOMATION

We expect the crew to have several levels of participation in subsystems management. During the space station development and shakedown periods, the crew and especially the ground, will be involved in detailed assessment of systems and subsystems performance and robustness. As the system matures, routine intervention in the automated processes will occur less and less frequently, with crew involvement mainly in troubleshooting, maintenance, and repair.

As a safety goal, we should like to be able to disable all the data busses and still have a system that operates safely, perhaps requiring a substantial level of crew involvement in monitoring and control. This means that at least two levels of crew interaction must be provided: a routine level that will probably be through a centralized controls and displays system that communicates with the individual subsystems through the data bus network, and an emergency level in which the crew will interact with either the ECLSS subsystem as a whole directly, or perhaps even with individual elements of the ECLSS subsystem such as the various units comprising the air revitalization section.

Crew interaction with the ECLSS should be minimal in keeping with the concept of automatic operation of the system. The crew should be presented with only the information they request or need to know. This information would be concerned with the following areas:

1) System status indication
2) Caution and warning indications
3) Data necessary for performance of crew repair and/or resupply of the ECLSS.
4) Selection of alternate automatic operating modes.

Much of the usefulness of the information available to the operator depends on the manner in which it is presented. In general, well designed graphic display formats can be more easily understood by the crew member than presentations of tabular data. Tabular data may be necessary, however, for establishing precise system parameter values during malfunctions, repairs or resupply operations. In these cases, the tabular data might be an operator callable option.

The desirability of minimizing the amount of display and control hardware leads to the concept of a multifunction display and control station capable of accessing a number of systems in the Space Station. Figure 3-1 shows one of a number of possible configurations for such a system. The block labeled host could be either a particular processor or an access to a Space Station data bus network. The controller processor and memory use a software operating system and data base to operate displays and a multifunction keyboard. Multifunction keyboards contain switches with computer controlled programmable legends. The legends on the switches are associated with particular commands which are implemented upon switch activation. Because the legends are programmable, a relatively small number of switches can control a large number of functions. Access to a particular function will, as a result, often involve several switch actions. Only those switch actions commanding a system response are actually sent to the host, thus minimizing the I/O load on the host. Figure 3-2 shows a typical logic tree format for function access.

The graphics and checklist displays shown in Figure 3-1 would be used to portray high resolution formats such as schematic diagrams associated with a particular system or subsystem. The checklist display would typically be a lower resolution display for alphanumeric (and limited graphics) communication between the system and the operator. For example, checklists of maintenance or repair procedures might appear on this display and be checked off as accomplished by crew personnel. Similarly, text messages as to the status of the system would be displayed on this tabular display. The number of keyboards and displays associated with a particular crew station would depend on the desired level of redundancy and on the number of systems for which simultaneous operation is necessary.

Using such a system for the control of the ECLSS would result in a number of operator interactions as outlined in the four modes mentioned earlier.

The system status indication would be part of an overall checkout of Space Station systems. This type of display could simply show the systems as color coded blocks on a display where color coding indicates the operating condition of the system. Under normal automatic operation, this might be the only system indicator.

Caution and warning indications from the ECLSS would be integrated into the overall Space Station caution and warning system. By integrating this system, the most important alerts can be determined and presented to the crew in order of criticality. In addition, the faults can be logically ordered with respect to probable cause so that secondary or tertiary faults do not obscure the basic problem. Given a caution or warning indication, a crew member could decide whether or not to initiate corrective action. If corrective action was chosen, it could involve a range of possible options to be undertaken automatically or semi-automatically. Alternatively the crew member would be able to call up information or system repair and historical trends in system parameters as an aid in analyzing the problem.

The questions of degree of automation, with respect to checkout, maintenance, fault isolation and fault tolerant corrective action will depend on the amount of supervisory command control which the crew is willing to delegate to the automatic system. The crew should be able to call up any of the data upon which the system bases the initiative of a corrective or preventive action. Whether the crew would want veto power over some or all of these actions would depend on the history of operating experience with the ECLSS. As more experience is obtained and the operation of the automatic features are verified, a greater portion of the off-nominal operation could be relinquished by the crew. The goal of system design and operations should be to provide automatic fault correction or bypass, with concurrent notification or current status to the crew, for the most common faults. The correction of less common faults might be left to the crew depending on the costs in time and funding necessary to automate these corrections.

EXPERT SYSTEMS

The following paragraphs discuss the selection of applications for expert systems and the advantages of expert systems from the standpoint of a man-machine interface.

Expert systems are best suited for applications with the following characteristics:

a) There must be at least one human expert acknowledged to perform the task well.
b) The primary source of the expert's exceptional performance must be special knowledge, judgement, and experience.
c) The expert must be able to explain the special knowledge and experience and the methods used to apply them to particular problems.
d) The task must have a well-bounded domain of application.

Some tasks which have proven to have these characteristics include the following:

a) equipment fault diagnosis
b) medical diagnosis
c) signal interpretation
d) robotics
e) planning
f) system control
g) system monitoring

In general, expert systems are well suited as replacements for specialists whose skills are in short supply. For example, on a space station, it is unlikely a small crew would be able to master all the skills necessary to respond to all possible contingencies. Expert system diagnostic and repair advisors are desirable for subsystems whose failure is immediately life-threatening. Expert systems would be developed on an evolutionary basis. They would be used on the ground first, possibly in parallel with but not in line with any real-time system and evolve from the ground to the Space Station and off-line to on-line as mission experience and confidence grows.

Expert systems can generally be provided with natural language interfaces. Such interfaces provide several benefits. For example, expert system advisors can be designed to explain the rationale for their advice. Since the expert system is designed to mimic a human expert, the explanation is generally comprehensible to a naive user. The explanation also provides the user with a basis for evaluating the credibility of the advice. This is a significant advantage over other approaches to decision aids.

Natural language input also provides several significant advantages. For restricted domains of discourse, a remarkable job of understanding text input is possible. In addition, such systems can be designed to respond to abbreviations, to detect and correct spellings, to respond to jargon, to correctly interpret anaphora, and to track current context. Using such devices permit a natural language interface to approach the input speed of a specialized computer command language without requiring training. In addition, we would expect a crew member to be less likely to forget his or her native tongue during times of stress that a specialized computer language. Natural language input can be combined with other approaches such as menus.

Languages for expert systems are discussed separately under Software Languages.

EXPERT SYSTEM CONTROLLER DEVELOPMENT

The following paragraphs describe (1) some ideas of how expert systems might apply to controller design and (2) how expert controllers might be developed.

Types of Controllers

For purposes of this discussion, four classes of controller are envisioned:

Analytic controller. These are controllers such as those based on linear control theory.

Expert system controller. These are controllers based on expert system techniques. In particular, they provide automatic control by mimicking the behavior of an operation in a manually controlled system.

Fuzzy controller. These are controllers based on fuzzy set theory techniques. They are similar to expert system controllers in that they mimic a human operator, but they attempt to reproduce the motor capabilities of a human rather than the reasoning capabilities. Fuzzy controllers have been used in commercial products. For example, a Danish firm markets a cement kiln controller that uses approximately 50 rules. Fuzzy controllers have been used to control processes that have not been successfully automated before.

Hybrid controller. These are controllers that combine two or more of the preceding types of controller. For example, an expert system controller might be capable of controlling a system a large percentage of the time using a few heuristics. If these heuristics also cover the limitations of the expert system, then the latter could transfer control to an analytic controller when necessary. Such an approach would be advantageous if the analytic controller is computationally expensive. A hybrid controller has been proposed for a power systems controller.

Hierarchy of Controllers

We envision the total control problem being broken down into a hierarchy such as the one shown below:

Level I would consist of an expert system controller. It would perform a primarily managerial function. It will monitor overall system activity as well as establishing the system parameters it is controlling, such as the temperature range within the habitable portion of the space station. In addition, it would interface with the crew.

Level II would consist primarily of expert system and fuzzy controllers. Its function would primarily be to control interactions between the various subsystems. It would also report status information to Level I, respond to parameter changes directed by Level I, and permit direct crew intervention.

Level III would consist primarily of hybrid and analytic controllers. It would be primarily concerned with the proper functioning of specific subsystems. It would provide status information to Level II, respond to setpoint changes dictated by Level II, and permit direct crew intervention.

Controller Development

The following discussion assumes that those portions of the overall system for which analytic controllers are suitable have been identified and that development techniques for such controllers are well understood. It is further assumed that analytic controllers are not suitable for the entire system because we are dealing with a new type of system which is not well understood and for which no analytic model exists. The final assumption is that it would be possible for a sufficient number of human operators to control the system manually. To simplify the following discussion, we will assume that one operator is adequate.

The first step is to develop a simulator and set of manual controls for the system. For our purposes here, it is not important whether this is done in hardware or software.

The second step is to create a suite of scenarios of various conditions to which the system would be subjected. Ideally, the suite should cover all conditions including normal conditions and crisis conditions.

The third step is to train the operator to respond to the suite in an acceptable manner. The goal should be to satisfy rather than optimize. The expert systems approach is particularly well suited to subsequent modification as experience is gained; thus, it is easy to observe the dictum that "premature optimization is the root of all evil."

The fourth step is, once the operator is performing satisfactorily, to identify those operator functions not well suited for automation. These functions should be incorporated into the level one controller. The remaining functions should be analyzed to determine what type of controller is best for each function.

The fifth step is to design the controllers by eliciting the rules from the operator.

The sixth step is to validate the controllers using the suite of scenarios. If the controllers are satisfactory, the development process is complete.

The seventh step is to debug the rules in conjunction with the operator. This step will almost certainly occur several times because picking the brain of the operator is an errorful process. Expert system architectures are generally designed to facilitate iterative development. Repeat step six after debugging the rules.

The following figure illustrates this process.

A secondary advantage of this approach is that the development facility can also serve as a crew trainer on how to handle the system should manual intervention be required.

SOFTWARE LANGUAGES

Selection of processor and language technology is very important. Demonstration that the chosen system can meet the diverse needs of space station systems is essential. The key issue is reduction in software costs without loss of system flexibility. Data management systems are now dominated by software cost as illustrated in Figure 10-1. While hardware costs have decreased by orders of magnitude, software costs have decreased only modestly.

A key to lower software cost is use of high order language (HOL). Many space programs have embarked on this path, finally resorting to assembler language to conserve memory. Newer processors offer large addressing ranges, improving the outlook for successful use of high order language. Example candidate languages are compared in Table 10-1.

Striving for software cost reduction has stimulated innovative approaches to system design, redefining the traditional interfaces between hardware and software. If successful, these will lead to major software cost reductions, e.g., by hardware architecture that parallels a particular high-order language, with features now provided as systems software. Potential cost advantages are too great to ignore, but risks must be quantified and understood. Most high level languages do not provide all of the functions attainable with assembler language. If no assembler exists, as is proposed for the Intel 432, late discovery of a necessary function not inherent in the language design would require a costly hardware or architecture change.

Software must be an integral part of system technology advancement. Problems will occur if hardware design is finalized while software design is immature. Accordingly, our trades will consider hardware, software, architecture, and communications as an integral package.

Much can be said for selection and standardization upon a single software language for use on all system and subsystem processors. Although this appears very desirable on surface, it may not be practicable in actuality. Further study and evaluation in this area is necessary before any firm decisions are made. Certainly, commonality and standardization should be a firm goal. The diverse application of the data management system, the subsystems, and processor chips on LRUs may indicate selection of more than one high order language (HOL) depending upon the application. HOLs or assemblers may not be available for some processors. Likewise, the desirability of using artificial intelligence ("expert systems") for some systems needs to be evaluated in more detail. Interface with the human element also is a factor such as use of expert systems. Likewise for scientific experiments where the on-board scientist has software developed in industry or academic environments in language other than the real time operational software. Hence, there is the possibility of more than one language on-board the space station.

The above does not preclude the use of standards, good programming techniques, etc. The software still must be maintainable, easily modifiable, expandable, user friendly, and be able to grow and evolve as the space station grows and evolves not only in the expected and planned modular fashion but also to reflect changing mission and operational requirements.

FORTRAN, COBOL, ALGOL, and JOVIAL languages appeared about 1960. All but ALGOL are still much in use. Strangely, ALGOL (as such) was not used much for large system development. But the principles of ALGOL were well based and have pervaded later language development. ALGOL might be said to be the ancestor of all (at least most) modern programming languages, such as PL/I, Pascal or ADA.

PL/I is an interesting case. Appearing in the mid-1960's in association with the new IBM SYSTEM/360 line and the new Operating System, it was heralded to be the future universal language. Indeed, its embodiment of parts of FORTRAN, COBOL and ALGOL (it is, in fact, an 'ALGOL-like' language) plus its own unique features seemed to be the answer to every programmer's problem. Unfortunately, this was not to be! Why was PL/I not more successful? One often hears reference to early compilers which were truly bad, with errors and inefficient code; but that was long ago and that accusation doesn't hold now. Probably a more significant reason was the lack of backing by the computing community, in general, and the US Department of Defense, in particular.

Now let's take the case of ADA. The first ADA was a lady, the Countess of Lovelace, daughter of the poet Lord Byron, and colleague of mathematician Charles Babbage. Her namesake is a new programming language. She appears to be a good language, and her use could benefit the defense software development business.

Ada has been designated (DOD Instruction #5000.31) as the single programming language for future DOD-funded embedded systems (such as a C^3 or avionics system). Similar designations will probably be made by European ministries of defense. All of this means that any new American or European military system will probably be implemented in Ada.

How this came about is presented in the following historical excerpt from the article, "An Overview of Ada," by J. G. P. Barnes, which appeared in Software Practice and Experiences, Vol. 10, 1980, published by John Wiley & Son, Ltd.

> In the early 1970s, the United States Department of Defense perceived that it needed to take action to stem the tide of rising software costs. In 1973 for instance, it is reputed that software cost the DoD some $3000M of which 56 per cent was incurred by the embedded systems sector. By comparsion, data processing took 19 percent and scientific programming 5 percent with indirect costs accounting for the remainder.
>
> Big savings were clearly possible by concentrating on the embedded systems sector which embraces applications such as tactical weapon systems, communications, command and control and so on. A survey of programming languages in use revealed that whereas data processing and scientific programming were catered for by the standard languages COBOL and FORTRAN respectively, the scene for embedded systems was confused. Languages in use included several variants of JOVIAL, CMS-2, TACPOL, SPL/1 plus many many more.
>
> It was therefore concluded that it would be of major benefit if some degree of standardization could be brought into the embedded systems area. This led to the setting up of the U.S. DoD High Order Language project with two goals. The first, short-term, goal was to introduce a list of approved interim languages. The second, long-term goal was to identify or procure a single language for embedded systems.

These activities, well described by Barnes, were followed by a refinement of the language, resulting in its present form.

A parallel effort was the determination of requirements of a software environment to be associated with Ada. After all, language is not the only problem encountered in software development. APSE (Ada Programming Support Environment--see Attachment #2) is intended to be a flexible, extensible tool set that caters to all phases of the life cycle of systems developed in Ada. APSE contains provisions for requirements specification and tracking, software and project management, coding, testing and documentation.

HAL also is a high order language which was used for space shuttle on-board shuttle software. Data on how much HAL vs. assembly language usage on the space shuttle as well as the technical pros and cons would need to be evaluated. One limitation is its limited usage; i.e., NASA space shuttle. There is little if any use in industry, commercial, military, and other applications.

The preferred language for AI program development, LISP, differs more significantly from other languages such as FORTRAN, COBOL, BASIC, ALGOL, JOVIAL, PASCAL, and ADA than the latter do among themselves. For this reason, the following discussion will emphasize AI programming issues and trades rather than a point by point comparison of LISP with other programming languages. Expert systems will serve as a paradigm for AI programs.

Almost all AI programming is done in LISP. Several attempts have been made to develop other AI languages, including PLANNER, CONNIVER QLISP, POP-2, SAIL, FUZZY, and PROLOG. None of the latter have achieved widespread use. Since LISP is the second oldest programming language in general use, numerous software development tools are available, including tools for developing expert systems. Also, all AI students learn LISP. In addition, LSIP interpreters and compilers are available for a variety of computer systems. Finally, hardware is currently becoming available that specifically supports LISP programming. At the current time, LISP is the only choice for an AI-oriented programming language.

The following paragraphs describe current approaches to expert systems development.

a) Development directly in language other than LISP

This approach is feasible in theory, but, in practice, no significant expert system has been developed this way.

b) Develop directly in LISP

Numerous expert systems have been developed directly in LISP. However, the use of expert system development aids is probably more cost effective.

c) Use expert system development aid

Several expert system development aids are available such as OPS-5, ROSIE, and EXPERT. Commercially viable expert systems have been developed using this approach. One of the more sophisticated aids, ROSIE, is reported to permit development at approximately twice the rate of other approaches. These aids are generally written in LISP; but one, OPS-5, is also available in a BLISS version, and another, EXPERT, is written in FORTRAN.

The BLISS-based version of OPS-5 is not as flexible as the LISP-based version. EXPERT is only suitable for developing diagnostic systems. This is the preferred approach provided that adequate computational resources are available to support the final system.

d) Retarget to another language

If insufficient computational resources are available to support a LISP-based expert system, it is possible to translate the system into a more efficient programming language. This approach has been taken with at least one expert system, the final language being BASIC. This approach may result in a somewhat less flexible final system, i.e., less easy to change in response to a changing environment.

The following paragraphs describe some of the more important characteristics of LISP.

Functional style. LISP programs consist of function definitions rather than a sequence of steps.

Uniformity of data and programs. Both programs and data are represented using the same data structure. In fact, the list is the only data structure available in LISP. Since programs are represented the same way as data, it is possible for a LISP program to process itself or another program. This opens up the possibility for a program to explain its behavior by inspecting itself or to learn, i.e., modify itself in response to changes in the environment.

Single data structure. The single data type, although offering many significant advantages as described above, makes type checking impossible, and, hence, debugging is more difficult. Some dialects of LISP do offer types as an extension.

Simple syntax. The syntax of LISP is extremely simple, consisting of nested lists of items enclosed in parentheses. This simplicity unfortunately results in programs that are difficult to read. However, no proposed improvement of the syntax has ever caught on, suggesting that the advantages of syntactic simplicity outweigh the disadvantages.

Ease of learning. Students who know other programming languages frequently have trouble learning LISP. On the other hand, novices with a mathematical background find LISP an easy language to learn. This is because LISP represents a qualitatively different approach to software development, and one should not expect software development methodologies developed for other languages to work for LISP.

Inefficiency. LISP is a computational resource intensive language. It frequently runs very slowly and requires enormous amounts of memory. This problem stems from several factors. First, the original LISP implementations were interpreters. Although interpreters are still best for development purposes, compilers are now available for production systems. Second, standard computer architectures provide poor support for LISP. The recent introduction of special LISP architectures has done much to correct this problem. Third, LISP does not use a predetermined fixed amount of memory, but dynamically varies its memory requirements during execution. In some cases, the memory requirements can grow to be very large. This problem has been ameliorated by the introduction of LISP oriented memory management systems and the falling price of semiconductor memory.

Control structure. The important control structures in LISP are the conditional and recursion as opposed to the conditional and iteration in most other programming languages.

Lack of standards. There is no LISP standard. This has resulted in two important and largely incompatible dialects - MACLISP and INTERLISP. A careful trade study should precede the choice of one of these dialects.

HARDWARE/SOFTWARE STANDARDS

Introduction

The current state of data processing and software technology contrasts markedly with that available at the beginning of the Shuttle program. In the early seventies only two computers were under development which were conceived capable of the Shuttle task - the IBM AP-101 and the Singer-Kearfott SKC-2000 and both would require extensive modification and tailoring. The maximum memory available, within power, cooling and weight constraints was 64K - 32 bit words. Integrated circuit technology was deemed too immature for use initially - this ban was grudgingly relaxed eventually in cases where volume limitations absolutely prevented the use of existing technology. Data bus technology was emerging but because no applicable standards were available, a unique system was developed. No higher order software language, tailored for an avionics application, was available, therefore NASA contracted for the development of HAL/S and imposed it on the program.

In this atmosphere, the hardware, software, development tools, laboratories etc. all had to be developed in parallel, and consequently a certain amount of bootstrapping was necessary before a mature system evolved. For instance, the initial memory sizing proved to be inadequate when the total set of software requirements emerged and, after several costly requirements scrubs, the memory size was increased to 105K words.

In contrast, today the state of technology is advanced well beyond that required for the Space Station data processing task - a task which is in many ways, less demanding, with fewer critical aspects than the Shuttle. The question is not "Can technology support the Space Station task?" but, "Which of the many possible approaches should be chosen?" Processes, at least as complicated, are in operation in the government and private industry and a number of hardware and software standards have evolved or are evolving which are directly applicable to the Space Station Data Management System. Integrated circuit technology is so advanced that size, weight, and power requirements place only minor secondary constraints on system capability. Memory limitations should no longer constrain the size of software programs but rather the expected program size should dictate (within reasonable limits) the memory size. Although the current NASA language standard (HAL/S) could be used for the Space Station program, the state-of-the-art features and capabilities of the emerging DoD standard (Ada)*, with its integrated software development environment, make it an attractive candidate. Finally, the technology of interconnecting processors and system components has progressed to the point where a number of approaches are available.

*Ada is a registered trademark of the U.S. Government.

System Architectural Considerations

The data processing capability on-board the space station will be distributed among the various modules to allow for redundancy and growth. Within this context, however, options remain for selection of the Data Management System architecture. At one extreme, the system could be made up of a number of identical processors, all interconnected with each other and with all the peripheral devices (sensors, effectors, displays, etc.). Such a system would provide the ultimate in software flexibility but would effectively integrate all functions, critical and non-critical. At the other extreme, the system could be configured to distribute all processing requirements as much as possible to the point of use. This approach could maximize the separation of functions but would be difficult to manage and control and would probably result in a large number of kinds of processors. The more likely approach, and the one to be explored in this paper is a hybrid of the two described above. In the hybrid, the functions would be partitioned among processors in compliance with the following criteria:

1. Minimize functional interaction
2. Minimize bus traffic
3. Segregate critical functions
4. Simplify subsystem software development
5. Simplify updates, expansion and associated verification

A system configured under these criteria will be hierarchical in nature, interconnected at the top level for supervisory control, crew interface, and display, but segregated below to afford separation of functions as appropriate. Discrete subsystem level software requirements may be mechanized via embedded micro processor cards provided to or purchased by the individual subsystem. The major consideration derived from this discussion is - a significantly wide range of processor capability will be required - from mini to micro.

Space Station Environment Considerations

The space qualification requirements which have evolved from the Mercury, Gemini, Apollo, and Shuttle programs must be reevaluated and modified as appropriate for the Space Station. The Space Station requirements would appear to be significantly mitigated because operation during ascent and entry is not required. The requirements, for orbital operation only, assuming proper cooling, may simply be those necessary to prevent particle migration in zero gravity and radiation upset of solid state devices. If analysis proves these considerations to be correct, the use of commercial or near-commercial quality devices may be satisfactory and significant cost savings could accrue.

Hardware Standards

As implied above, the data processing hardware available today, from many sources, would appear more than capable of accommodating the Space Station requirements. All three military services are developing standards for applications comparable to that of the Space Station in complexity. The Air Force has invoked a standard 16-bit instruction set architecture (ISA), MIL STD 1750A. By standardizing on an ISA rather than a computer, and allowing any manufacturer to develop and sell complying hardware, the Air Force can retain a competitive situation and yet accrue software programs and software development environment portability benefits not achievable otherwise. Measures are under study to insure that the ISA and associated software can be applied to a spectrum of machine capabilities from mini-class to embedded micros.

The Army is exploiting the same concepts in its 32-bit ISA, MIL-STD-1862, (NEBULA) Military Computer Family (MCF) program. The Nebula program schedule follows that of the Air Force but, as a result, is the first military standard ISA to be developed with the new DoD standard language, Ada, in mind.

The Navy is also standardizing on a new set of shipboard and weapons system computers. These include the AN/UYK-43 standard large shipboard computer and the AN/UYK-44 Militarized Reconfigurable Processor (MRP) series currently under development. The MRP can be configured either as a stand-alone computer or as a card level embedded application, both with a wide range of capabilities. All three of the above military developments are addressing the system interconnect problem and are attempting to provide a building block, easy-to-configure system capability.

In addition to the military, a wide range of capabilities are availble commercially. Several companies market a series of machines, from mini to micro, software and interconnect compatible, which appear adequate for the Space Station task. Some have off-shoots manufactured to MIL-SPEC standards. Most have an extensive library of software and software development tools and are committed to maintain upward system compatibility for new developments. This commitment is particularly attractive for a 20-year program.

A potentially appealing alternative to one of the military standards, especially if program schedules require early provision of DMS hardware, might be an early competition to select a commercial line which qualifies from a performance, capability, and development environment aspect. Then, while the various subsystems use the selected off-the-shelf hardware in their development, to contract for repackaging the hardware, maintaining one-to-one software compatibility, to space environmental qualifications. This alternative is particularly attractive if the Space Station environmental analysis suggested above proves that near-commercial quality is adequate.

Software Standards

The HAL/S language developed for the Shuttle program, and the accompanying development and support environment and the personnel expertise which has accumulated in NASA and associated contractors represents a significant in-place resource which would probably be adequate for the Space Station. The major DoD thrust toward the new language Ada and its integrated support environment is so significant and all-encompassing however, that it makes the retention of HAL/S questionable. Ada incorporates the latest state-of-the-art features and capabilities which, if realized, could reduce the Space Station software life-cycle cost. If the new system is accepted and promoted to the degree which now appears likely, it will be difficult for NASA to retain and maintain HAL/S capability over the 20-year life of the program. The new DoD Software Initiative program, which uses Ada as its cornerstone, should accrue benefits over the next several years which would have direct applicability if the Space Station adopts the Ada system.

The only significant issue pertaining to the Ada/HAL/S selection, other than the cost to NASA of the initial transition, is the question of Ada maturity. If the Space Station schedule precedes the use of Ada by the DoD on a significant program, it may be necessary to begin the program using the existing HAL/S environment and to plan a transition to Ada at the appropriate time. Both Ada and HAL/S should be evaluated to explore methods for making such a transition as simple as possible.

SOFTWARE DEVELOPMENT APPROACH

Introduction

The NASA space programs, from Gemini to the Space Station have been characterized by an ever increasing dependence on software. In consort with this dependence has emerged a pattern of increasing government control of the software development process. In the Gemini program, the software (which served only the guidance and navigation function) was developed by IBM, the computer manufacturer, on a subcontract to MacDonnell Douglas, the spacecraft contractor. This prime/subcontractor relationship made it difficult for NASA to both obtain the desired visibility into and maintain control of the contents of the software program.

In Apollo, the guidance and navigation hardware design and the associated software were the product of the MIT Instrumentation Laboratory (later the C.S. Draper Laboratory). MIT was an associate contractor as were the two spacecraft contractors - Rockwell International and Grumman Aircraft Corporation. During Apollo the concept of increasingly strong control of the software content by NASA emerged in the form of a Software Control Board, chaired by NASA, with representation from all associate contractors.

The concept of close, strong control of software was carried over and strengthened in the Shuttle program with the selection of IBM as the software developer under direct contract to NASA. An additional layer of NASA control and involvement was introduced by the directed use of government furnished in-house development and verification facilities. Again, a strong NASA chaired Software Control Board was utilized to control program content.

The concept of strong NASA control and involvement in the software development process is almost certain to be continued in the Space Station program. The role of software has spread however, from guidance and navigation in Gemini, to virtually every subsystem and function in the Space Station and therefore is much more pervasive in every aspect of the program. Many more contractors will be directly involved and require software services for subsystem operation. As a result, new management and control concepts will be required.

Space Station Development Environment

The Space Station program will begin with a significant legacy from the Shuttle program. The Software Development Laboratory (SDL)/Software Production Facility (SPF), developed at Johnson Space Center for Shuttle contains an extensive suite of hardware, software development tools, and personnel expertise which can serve as a springboard from which to launch the Space Station program. In addition, the in-place team is fresh from the successful development, verification and flight of the shuttle avionics system. This system contains a software package which, in addition to the application modules, includes a sophisticated asynchronous operating system, redundant computer synchronization schemes, redundancy management techniques, memory management features, and crew interface and display processes. Much of this capability is directly applicable to the Space Station program.

There are however, a number of aspects of the Space Station program which have not been encountered previously. The increasing utilization of software for control of systems which relied on mechanical, analog, or manual measures on past programs will pose a new management and control problem. The Shuttle program relied on the use of software requirements documents produced and integrated by the prime spacecraft contractor, as software specifications for the software contractor, who then coded (or integrated) all flight software. The Space Station will probably have a number of associate contractors and subcontractors - many with embedded micros or dedicated standalone processors. In contrast to the Shuttle era, most of these contractors will have acquired credible software expertise, therefore producing all code with one source as in the Shuttle mode may not be appropriate.

Several other aspects of the Space Station program may force differences in the approach to software development. The 20 year program length with certain, but undefined, growth requirements will require development of new techniques for software program evolution, change, and probably some degree of final on-board validation. A much greater degree of space ground interaction can be expected, especially in the experiment process area. Finally, the amount of software to be developed will be so great as to require significant reduction in the cost per software unit if the program is to succeed.

Fortunately, a number of advances in the software development process and in other related processes have occurred in the past decade which hold the promise of increasing production efficiency. Program Design Languages (PDL) are emerging as a useful first step in program design. While intended to support the design process, PDL's can also simplify the transition from requirements to code. Extensive networking is now economically feasible tying computers and users, widely separated geographically, together in an integrated development environment. Relational data base management systems, multi-user time-shared operating systems, and increasingly capable remote terminals are other examples of areas which should be exploited.

Development Process Considerations

As stated above, the software will be utilized by virtually all subsystem and functional processes in the Space Station. The code may reside in a range of processors, from embedded micros to dedicated, isolated standalone computers to general purpose supervisory systems. Functions may have interactive code located in all three classes. The embedded microprocessors, and possibly some of the dedicated machines will probably make use of Programmable Read Only Memory (PROM) for protection of critical functions. The subsystem design process will in many cases, involve much closer hardware/software iteration than was the general case in the Shuttle.

In such an atmosphere, the Shuttle concept of relying on a single software contractor to generate all code in response to written, NASA baselined, requirements would be extremely unwieldly and inefficient. On the other hand, the requirement for central integration and the desire for NASA control of the system would mitigate against a totally decentralized concept in which software was developed independently by each subsystem area and delivered with the system. A hybrid concept, which allows for the necessary iterative subsystem design process, yet provides for the required upward and cross-subsystem integration and NASA visibility and control should be the goal.

One scenario which appears to satisfy most requirements would be a concept in which a central software development, integration, and verification facility would be maintained by NASA (and presumably its software contractor). The facility would house the complete suite of tools included in the selected standard software development environment; a complete data base containing all information pertinent to the software design, integration and verification process (requirements, PDL, source code, wire and instrumentation lists, spacecraft data, display foremats, etc.); and the simulations, emulations and other capabilities required for integration and verification. This central facility would be accessible, via a dedicated network, to all contractors (and appropriate government organizations). The use and interaction with the facility by the various contractors would depend on the nature of the software involved. If the subsystem application required no software interaction external to the subsystem, it might be possible for the contractor to develop the software on a microprocessor development system (MDS) and to use the network only for transmittal of requirements, source code, and other data required in the configuration control process. The embedded microprocessor and the associated MDS would presumably either be government furnished or bought to a NASA-dicated standard.

If the system application warranted a dedicated standalone machine (or machines), possibly with micros embedded in peripheral equipment, i.e., a Guidance and Control (G&C) system, the use of the network would be much more extensive. The G&C contractor would utilize the central data base as the only approved source of pertinent information (structural, aero, venting, instrumentation, display, etc.) and would be responsible for maintaining performance records as appropriate. The G&C software would be developed on "SMART" remote terminals but use the central facility compilation, debug, and other development tools. Integration of the G&C

software with other subsystems and with supervisory systems, and verification of the total package, would be performed in the central facility supported by the G&C and other contractors.

If a subsystem application did not warrant either an embedded micro or a standalone machine, but did require software services residing in the supervisory system, the development process would be similar to the Shuttle, with the software contractor furnishing code based on requirements from the system contractor. Here again, the network would be used for transmittal of requirements and data, and the receipt of resulting code.

The scenario outlined above could have many variations but the main theme should be persued vigorously. That is - to utlize modern techniques for networking, data base management, requirements development (and translation to software design), code production, verification, and configuration and control - to reduce the Space Station software to an affordable level.

VERIFICATION AND VALIDATION

Introduction

The distributed Data Management System concept baselined for the Space Station affords an opportunity to examine new approaches to the Verification and Validation of on-board software. The philosophy on previous manned space programs such as Apollo and Space Shuttle was to prove to the maximum extent possible before flight that the software, and system, would perform the prescribed functions properly, and above all, would not jeopardize the safety of the crew. The approach used was to exhaustively test the software and system in laboratories that emulated the space system and the dynamic environment with as much fidelity as could be devised over a spectrum of conditions which covered all portions of the flight envelope and every conceivable uncertainty, variation of parameter, and mission contingency. This approach to verification, while obviously successful, is extremely expensive and time consuming and may not be feasible in the Space Station Program. While it is not possible to deviate from the philosophy that mission success and crew safety must be assured, the unique character of the Space Station, the mission and the baseline system may allow or even force the use of new approaches. It is the intent of the following paragraphs to explore the Space Station System and mission from the aspects of verification and validation.

System Considerations

In a centralized system, all software functions available at any given time are resident in a single memory load. Even though measures such as memory write protect, etc., can be taken, a software error in any function or module resident in a machine must be considered capable of jeopardizing the operation of the entire system. Therefore the verification and validation approach must address the total software program and all possible module interactions. A change or update to any module must be addressed in the same way. This potential for adverse interaction must be considered regardless of the function or module criticality.

In a distributed system, it is possible to segregate and isolate critical functions and thereby prevent or reduce the possibility of interaction between modules. A critical function such as flight control may be mechanized in a dedicated processor, or group of processors if redundancy is required. Flight control sensors and effectors could be accessed and commanded via a dedicated bus sytem. The flight control software could be contained in read only memory, thus preventing the possibility of inadvertent write overs from the mass memory system. Verification of the flight control software in such a system would be a much simpler task than in a centralized system. With proper isolation, the verification standards applied to non-critical functions could conceivably be relaxed because of the reduced risk of interaction with critical functions.

To realize significant benefits, verification and validation considerations must be given appropriate weight in the Data Management System design trade process. The allocation of functions among processors and the selection of system architecture and data bus network concept are of particular importance. It may be that the classical disciplinary distribution of functions i.e., Guidance and Navigation, Flight Control, Communication, Electrical Power, Displays and Controls, etc., will prove to be inappropriate from the verification aspect and therefore a different allocation algorithm may be required. The desire for functional isolation may drive the system architecture in the hierarchical direction. Although verification/validation attributes have never driven the design process on previous programs, it appears that the potential for recurring cost savings in the verification process is great enough for serious consideration in the Space Station.

Space Station Configuration Considerations

The Space Station configuration and the nature of the operations to be performed also present an opportunity to explore novel, cheaper verification/validation techniques. In a program such as the Space Shuttle, the vehicle configuration and mission operations generated requirements for precise sequencing and extremely fast reaction times. For instance, during ascent and entry phases, an inadvertant flight control actuator hardover could be tolerated for no more than 100 milliseconds or the vehicle would suffer catastrophic structural damage. Therefore the ability of the crew to monitor or override the system was limited, an automatic reaction was required, and the preflight verification/validation process alone had to be relied upon to provide assurance of mission and crew safety.

The Space Station mission operations, in contrast, are generally characterized by relatively slow sequencing and reaction time requirements. Performance should be easily monitorable by the crew and override or other intervention should be possible. Under these conditions, where no catastrophic effects are possible, it may be appropriate to reduce verification vigor on the ground at the risk of finding a bug on board. It is unlikely that such a reduction in rigor could be considered for the initial Space Station configuration however it might be possible for updates, modifications or add-ons after the program matures.

The Flight Control area is one in which such an onboard cut-and-try technique may be the only feasible way to update the system. As the Space Station configuration grows, as modules are added, detached, and moved, and as the structure becomes more complicated it will become increasingly difficult to accurately model the system on the ground for analysis and simulation. At some point it will become more cost effective to make changes, tweak gains, vary filter constants, etc., on board with limited prior ground verification. A scenario could be drawn in which an entirely new flight control software package could be introduced at some point in the program, given limited verification on the ground, and finally verified and validated on board. Presumably, the previous version would be available loaded in a redundant processor ready for instant use in case the new package did not perform properly.

A similar scenario could be used for other systems, driven by the cost of maintaining a high fidelity systems laboratory on the ground. Eventually, it might be possible to make changes on board, or remotely from the ground, given proper safeguards and backup measures.

GROUND LABORATORY COMPLEX

Introduction

NASA's manned space programs have been characterized by a large investment in ground laboratories. In Apollo, facilities capable of simulating and verifying the Guidance, Navigation and Control (GN&C) function were constructed at the MIT Draper Laboratory and at both spacecraft contractors, Rockwell International and Grumman Aircraft Corporation. In the Shuttle program, the first incorporating major software controlled functions other than GN&C, the laboratory investment was even more substantial. At Rockwell International (the spacecraft contractor) the Avionics Development Laboratory (ADL) was utilized for subsystem development and integration. The ADL was later upgraded in capability to become the Flight Systems Laboratory (FSL) which assumed a significant role in final system verification. At Johnson Space Center (JSC) the Shuttle Avionics Integration Laboratory (SAIL) was constructed to conduct final validation of all Shuttle avionics systems - the orbiter, main engine, solid rocket boosters, external tank, remote manipulator, and the Kennedy Space Center (KSC) Launch Processing System (LPS). The SAIL contained a complete production ship set of shuttle avionics including all cables, cable troughs, and secondary structure, located in as close to the correct geometrical relationship as possible. All interfacing non-avionics functions and high fidelity vehicle dynamics were simulated to allow validation of all mission phases, from prelaunch through entry. The Software Development Laboratory (SDL) was also located at JSC, operated and utilized by IBM, the software contractor. The SDL included functional, bit-for-bit, and computer-hardware-in-the-loop capabilities as well as a suite of development and verification tools. It has been upgraded to a Software Production Facility (SPF) geared to the Shuttle operational phase.

The extensive investment in ground laboratory complexes was deemed necessary in the Apollo and Shuttle programs because of several factors. Both programs "pushed" the state-of-the-art and therefore required extensive investigation to ascertain performance. Both programs had critical mission phases during which minimal crew or ground intervention was possible. In the Shuttle, for the first time, ascent was controlled by the spacecraft system and the booster was not man-rated before the first manned flight. These factors, in addition to the economic effects of mission failure led to the drive for extensive, high-fidelity ground complexes.

Space Station Considerations

Several Space Station program characteristics tend to mitigate the stringent requirements for ground laboratory complexes experienced on previous programs. The avionics state-of-the-art is well within that required for the Data Management System (DMS). The DMS design should have few, if any, "high risk" or even "uncertain" features, but rather should utilize proven technology.

The mission environment should be much more benign, with fewer critical aspects than the Shuttle (no ascent or entry phase). Orbital assembly, checkout and final systems validation will be conducted with the Shuttle attached or in the near vicinity, and therefore with minimal crew risk. Few if any mission operations are so time critical, either in sequencing precision or reaction time, as to prevent manual monitoring and intervention if required.

Flight control system requirements will probably be limited to vernier control of a gravity gradient stabilized structure and to orbital make-up translations. The most difficult task will be to accommodate the wide variation in structural characteristics which will occur as modules are added and removed, and as the station expands. The accommodation could take the form of an adaptive system or one which is updated manually or automatically as the configuration changes. In either case, the control authority will be relatively low and the response times slow, and therefore the system will be manually monitorable and overrideable.

While all these considerations tend to reduce to some degree the need for "absolute" proof testing before lift-off, the most overriding factor is cost. The development and operation of a laboratory such as SAIL is extremely expensive. The cost of building and maintaining such a facility for the 20-year Space Station program would be prohibitive. Therefore an alternate approach must be found.

A final consideration, and one which may provide a solution to part of the problem is the Space Station itself. In contrast to previous programs which were characterized by relatively brief missions, each generally containing some new and untried aspect, the Space Station, once placed in orbit will operate continuously for the life of the program. After an operational state is achieved, and especially if the environment proves benign as postulated above, the Station may serve as its own laboratory to a large degree. In any case, its attributes should be considered in any laboratory planning activity.

A Potential Approach

Ground laboratory requirements can be considered from two aspects: the test and validation operations to be performed prior to initial orbital installation; and the operations in support of growth, change and update after the initial configuration becomes operational. The objective is to find an approach which supports the initial phase but which does not result in an investment in ground facilities beyond those required for the operational phase. In this scenario, a software development laboratory (SDL) is assumed to exist, containing actual computer hardware and simulations or emulations of all peripheral devices, and capable of closed-loop simulation of all mission operations.

In the Shuttle, SDL testing was deemed inadequate for final system validation because of the restricted amount of flight hardware, the difficulty in certifying models, and an inability to incorporate actual noise, delays and other effects of actual vehicle wiring. For the Space Station, however, after initial operational capability, each model and simulated aspect of the SDL can be directly correlated with actual flight performance and modified to match if required. If this correlation is conducted properly the SDL should be able to perform most, if not all, the required ground verification and validation tasks for software updates or modifications in the operational phase.

Prior to the initial operational capability however, the SDL must be augmented by higher fidelity hardware and hardware/software integration tests. In previous programs, this integration required an extensive closed-loop simulation capability to adequately exercise and stress the flight hardware in all mission phases. The set up included elaborate schemes for extracting outputs from and inserting inputs into the flight article in a way which did not disturb system integrity. The complexity of this operation and the length of the validation program were such that a dedicated shipset of avionics hardware and an elaborate laboratory complex was required. Much of the complexity however, and most of the time were attributable to the ascent and entry phases. If on-orbit operations only had been involved, the need for such an elaborate validation program and laboratory complex would have been significantly reduced. While the prime requirement for the DMS validation program should be, as always, to ascertain that the system operates correctly with the flight hardware connected in as close to the flight configuration as possible, a much less costly approach might be possible.

One scenario would use actual space station modules connected as in flight to perform the required preflight verification. The modules could be developmental or boilerplate if near enough in fidelity to the flight articles. If not, the actual flight modules could be utilized and the validation scheduled as part of the preflight build and checkout flow. The latter option, of course, would entail the risk of uncovering a fault late in the program and a potential schedule slip. This one time program risk should be traded off against the cost of higher fidelity developmental modules or even against the cost of a SAIL type facility.

The complexity of support equipment required to perform validation using spacecraft modules operating in a static ground environment will depend on the software design and the facility with which peripheral subsystem equipment can be made to simulate in-space activities. The software, subsystems, and the spacecraft modules should be designed to accommodate and simplify the validation task.

In summary, the unique characteristics of the Space Station Program and the mission environment offer the possibility for minimal (by Shuttle standards) investment in large ground laboratory complexes.

SPACE GROUND INTERACTION

Introduction

The previous space programs have been characterized by a common philosophy concerning interaction between the spacecraft and the ground support complex. This philosophy embodied a maximum of telemetry data flow from space to ground and a large contingent of ground personnel to monitor and analyze every aspect of the operation. The ground-space data transfer consisted primarily of pre-canned messages containing state vector updates, maneuver pads, sensor calibration parameters, etc; transmitted at a much slower rate than the downlink and protected by error detecting and correcting codes. The spacecraft crew had available a "block-uplink" switch to prevent unwanted or spurious updates and each message was verified correct via the downlink before acceptance. The ground complex maintained complete control of all aspects of the mission. A different philosophy must evolve for the Space Station with its projected 20-year program life.

Space Station Program Considerations

The Space Station Program, to be viable economically must develop a space/ground responsibility allocation which allows a much smaller, less expensive ground support environment. The mission environment, with its more-or-less constant orbital characteristics, should be relatively stable and amenable to on-board flight planning. Day-to-day operations should be largely concerned with station system monitoring, housekeeping, and experiment servicing. Occasional periods of intense ground interaction may occur when modules are added or replaced or when major configuration changes occur. The norm should be on board control with ground support as required.

The modern network approach proposed for the ground based software development complex should be extended to include the Space Station DMS as a very smart remote terminal. Such a concept, assuming appropriate protection and/or isolation of critical functions would provide the optimum interface between experimenters and their experiments, between ground subsystem personnel and their subsystems, and between ground and on board mission and flight planners.

To accomplish this the ground complex, operational as well as experiment oriented must be compatible with and utilize common software standards. Further, the software standards chosen must be sufficiently flexible to accommodate the unknown, but certainly wide-ranging nature of 20 years of operations.

IN-FLIGHT CHECKOUT AND MONITORING

Introduction

The requirement for in-flight checkout and spacecraft system monitoring has gradually increased with each space program. The Shuttle, with its system management and failure detection and isolation capabilities is the most sophisticated to date. Despite the on-board capability provided, however, the Shuttle operation places heavy reliance on ground monitoring and analysis of telemetry data. This reliance may decrease and gradually transfer on-board as the program matures but it is doubtful whether ground support will ever be reduced to the levels required for Space Station economic viability.

Space Station Considerations

Several aspects of the Space Station Program will force a new approach to in-flight checkout and monitoring. This will be the first space program in which the mission duration will exceed the mean-time-between-failure (MTBF) of every electronic device on-board. On all previous programs, the missions were short compared to the MTBF of the components. Between each mission the ground checkout operation assessed the readiness of every component, and caused replacement if necessary. Therefore, the reliability clock started anew at lift-off of each mission.

The Space Station Data Management System (DMS) because of this certain MTBF exceedance must be designed, not only to react to observed failures, but to detect potentially latent failures of all components, especially those which are installed to sense and flag dangerous situations. The measures required to detect such failures are not immediately obvious for sensors such as those which may be embedded in a cryogenic tank or an inaccessible part of tne structure. An analogy can be drawn with the common household smoke detector. Observance of the red light may indicate battery health but proper operation can only be assured by blowing smoke into the device. If such direct stimuli cannot be provided for this class of sensors on the Space Station, other measures such as redundancy, periodic replacement, or correlative data may be required.

Another aspect of the Space Station missions will force new and innovative techniques. The normal resupply and/or expansion operation will result in the delivery and attachment of a module which has been essentially inert through ascent and rendevous. Such modules will require activation and check out before use. These operations could be carried out with on board resources only but would be enhanced by the appropriate level of ground involvement.

7.4.4 Communications and Tracking

2.0 SPACE STATION COMMUNICATIONS

Section 2.1 summarizes the communications and tracking requirements for the Space Operations Center (SOC) as defined in NASA Contractor Report No. 160944, Rev. A, Jan. 1982. Section 2.2 summarizes the proposed implementation described in Boeing document D180-26495-3, Rev. A, Jan. 1982, and discusses the degree of compliance with the requirements.

2.1 Review of Requirements

Communications requirements for the SOC are summarized below.

2.1.1 Extra-Vehicular Activity (EVA) Communications

Four simultaneous EVA crew members shall be accommodated at ranges up to 10 KM from SOC. The RF link to each user shall provide the following simultaneous capabilities:

One duplex voice channel to/from SOC

1 KBPS command channel from SOC

50 KBPS telemetry channel to SOC

Ref. 1 indicates that the operating frequency band will be "probably UHF". Ref. 2 mentions TV from EVA to SOC, but this requirement is not identified anywhere else. If this is indeed a requirement, it will have a major impact on EVA communications.

2.1.2 Global Positioning System (GPS)

L-Band navigation signals from GPS satellites at 18,500 KM range shall be received and processed by SOC.

2.1.3 Tracking Radar

Radar coverage for traffic control, rendezvous and docking, and orbital ephemeris generation shall be provided at a millimeter wave frequency. The radar system shall handle up to 12 targets simultaneously, including 4 EVA targets. The radar shall have a long-range mode and a short range mode with the following performance:

Long range mode:	Max range	2000 KM
	Range accuracy	1 KM
	Velocity accuracy	1 m/sec
	Angular resolution	10 millirad
Short range mode:	Max range	1 KM
	Range accuracy	1 M
	Velocity accuracy	0.05 m/sec
	Angular resolution	10 millirad

As a design goal, coverage shall be 100% within ±15° of the orbital plane, and 75% over the remainder of the sphere, except that 100% coverage shall be attained within 8 KM of SOC. The radar shall be capable of target acquisition within 2 minutes at ranges up to 2000 KM using whole-sky sweep. It shall have path prediction capability for multiple-target monitoring.

The shuttle orbiter will respond to the radar through a transponder. Radar enhancement devices (passive) or active transponders will be provided for targets during rendezvous and docking.

2.1.4 SOC-Orbiter Communications

Simultaneous communications between SOC and two shuttle orbiters shall be provided at ranges up to 2000 KM, using S-Band frequencies. The following channels shall be provided while the orbiter is separated.

Two duplex voice channels to/from each orbiter;

Low rate status and payload data readout from orbiter to SOC;

During SOC buildup, commands from orbiter to SOC.

While the orbiter is docked, SOC shall receive payload data from the orbiter. Also, the SOC and orbiter computers must be able to transfer data back and forth. It has not yet been determined whether the docking link shall be hard-line or RF.

During SOC buildup, it will be necessary to track SOC from the orbiter.

2.1.5 SOC-OTV Communications

Simultaneous communications between SOC and four OTV's, two manned and two unmanned, shall be provided at S-Band, Ku-Band or millimeter-wave frequencies. The following channels shall be provided while the OTV is separated:

At ranges up to 400,000 KM:

One duplex voice channel (manned OTV only)
50 KBPS data to SOC

At ranges up to 38,000 KM:

One duplex voice channel (manned OTV only)
50 KBPS telemetry to SOC
1 KBPS commands from SOC

At ranges up to 2000 KM:

Turnaround ranging

At ranges up to 100 KM:

TV from OTV to SOC

Channel bit error rates of 1×10^{-4} are acceptable assuming that command verification is used to prevent false commands.

Communications shall be provided while the OTV is docked, including a computer link for checkout.

2.1.6 SOC-Free Flyer Communications

Simultaneous communications between SOC and five free-flyers shall be provided at S-Band, Ku-Band or millimeter-wave frequencies. The following channels shall be provided:

At ranges up to 2000 KM:

50 KBPS telemetry to SOC
1 KBPS commands from SOC
Turnaround ranging

At ranges up to 100 KM:

TV from free-flyer to SOC

2.1.7 Communications Relay from SOC to Ground

Communications through relay satellites at 38,000 KM range shall be provided at S-Band, Ku-Band or millimeter-wave frequencies. The following channels shall be provided.

Duplex voice to/from SOC
Narrowband and wideband engineering data from SOC
Instrumentation outputs from SOC
Ground commands to SOC

It shall be possible at SOC to patch through to the relay satellite data rates in excess of 50 KBPS from an OTV and TV from a free-flyer.

2.1.8 SOC Direct-to-Ground Communications

Although paragraph 7.555 of Ref. 1 states that communications to ground will be through a relay satellite or directly to ground, no specific requirements are given for a direct-to-ground link.

2.1.9 SOC Internal Communications

The SOC shall provide the following internal communications in all habitable areas of the SOC including EVA airlocks and docking ports:

Duplex voice
Caution and warning signals
Public address
Closed-circuit TV
Wireless voicecomm. for crewmen

Also, SOC shall have the capability, for voice conferencing among 4 EVA crew, manned spacecraft, the ground network and SOC.

Duplex voice access from any pressurized volume on the SOC to ground and to manned spacecraft shall be provided.

A communications and tracking processor/controller shall interface with the integrated entry and display system and provide status monitoring, automatic configuration management, fault isolation and all necessary display/control functions. Also built-in test of subsystem equipment shall be provided.

2.1.10 Other Requirements

SOC attitude constraints shall not be required to maintain acceptable RF link performance margins.

SOC shall be capable of secure communications and operation in RFI environments. Special provisions shall be made for AJ and spoofing protection.

2.2 Communications Design Concept

2.2.1 Subsystem Design Summary

Implementation and performance of the SOC Tracking and Communications Subsystem are summarized herein, based on Boeing Document D180-26495-3, Rev. A, "SOC System Definition Report", Jan. 1982.

2.2.1.1 Extra-Vehicular Activity (EVA) Communications

Four EVA duplex voice links will be provided at UHF, using AM, and with separate frequencies for each EVA user. No encryption or error coding will be used. Data links will also be provided. Maximum range will be 1.6 KM from SOC.

Hardware includes four UHF transceivers, with full redundancy. Two crossed-dipole antennas, one at each end of the boom will provide spherical coverage. Frequencies are offset between the two antennas to prevent interference.

Compliance: Consistent with the requirements, except that the 10 KM range requirement is not met, and TV to SOC is not provided.

2.2.1.2 Global Positioning System (GPS)

SOC will have a GPS receiver and processor, plus a flat spiral antenna to provide upper hemisphere coverage.

Compliance: Meets requirements.

2.2.1.3 Tracking Radar

Two millimeter-wave pulse radars with scanning antennas will provide fore and aft coverage along the SOC velocity vector. Multiple target tracking up to 2000 KM range is a design goal. Approach prediction and collision warning are provided.

Compliance: Although the quoted performance meets the requirements, many of the specified parameter are not addressed. In particular nothing is said in document D180-26495-3 with respect to the following:

Number of targets which can be tracked
Percent coverage
Time to acquire target
Maximum range of short range mode
Accuracy (range, velocity, angular resolution) in short range mode and long-range mode.

2.2.1.4 SOC-Orbiter Communications

SOC will communicate with the orbiter at S-Band using the GSTDN signal mode at ranges up to 600 KM. The following channels will be provided without error coding or encryption:

2 KBPS commands from SOC on 16 KHz subcarrier
16 KBPS telemetry/data to SOC on 1.024 MHz subcarrier
16 KBPS voice from SOC on 70 KHz subcarrier
16 KBPS voice to SOC on 1.7 MHz subcarrier
40 Hz-500 KHz turnaround ranging tones

SOC hardware will include an S-Band transponder which can function as an interrogator, a 30-watt RF power amplifier, two sets of switchable conical log-spiral antennas and a pair of switchable horn antennas, steerable in azimuth. The conical log-spiral antennas provide coverage at shorter ranges and the steerable horns are used at longer ranges.

Compliance: The requirement for operating range of 2000 KM is not met. Only one, instead of two, duplex voice channel is provided for each orbiter.

There is no provision for a command link from orbiter to SOC, as required. The communications interface during docking is not addressed. Also, tracking of SOC from the orbiter is not addressed.

2.2.1.5 SOC-OTV Communications

SOC will communicate with OTV's at S-Band using the TDRSS signal mode at ranges up to 600 KM with no error coding:

16 KBPS data/commands from SOC
64 KBPS data/telemetry to SOC
16 KBPS duplex voice (manned OTV only)
3 MCPS PN turnaround ranging

Encryption is TBD.

SOC hardware will consist of the same antennas used for SOC-orbiter communications. Also an S-Band transponder functioning as an interrogator plus a 30-watt RF power amplifier will be used for each OTV link.

Compliance: None of the operating range requirements (400,000 KM, 38,000 KM and 2,000 KM) are met. TV from OTV to SOC is not provided. Also, the communication interface during docking is not addressed.

2.2.1.6 SOC-Free Flyer Communications

SOC-free flyer communications will have the same capabilities as for either SOC-orbiter or SOC-OTV communications, depending on whether the free-flyer is equipped for GSTDN-mode or TDRSS-mode signal format.

Compliance: The 600-KM operating range does not meet the 2000 KM requirement. Also, TV from the free-flyer to SOC is not provided.

2.2.1.7 Communications Relay From SOC to Ground

SOC will communicate through TDRSS to ground using the TDRSS KSA mode: The following channels will be provided:

- <1 MBPS data/commands to SOC
- <1 MBPS data from SOC
- 16 KBPS duplex voice
- 25-50 MBPS TV from SOC
- 22 MBPS TV to SOC (optional)

Encryption, using the NBS Data Encryption Standard, and error coding will be used on the voice and data links, but not for TV.

SOC hardware will consist of a Ku-Band TDRSS transponder, a 15-watt Ku-Band power amplifier and a pair of 18.4 ft parabolic antennas at opposite ends of the boom. Steering of the antennas can be by command or auto-track.

Compliance: Meets requirements

2.2.1.8 SOC Direct-to-Ground Communications

SOC will communicate with ground at S-Band, using the GSTDN signal mode at ranges up to 2800 KM. The following channels will be provided:

- 4 KBPS data/commands to SOC
- 64 KBPS data/telemetry from SOC on 1.024 MHz subcarrier
- 32 KBPS voice to SOC
- 16 KBPS voice from SOC on 1.7 MHz subcarrier
- 40 Hz - 500 KHz turnaround ranging tones.

Convolutional coding will be used on voice and data channels from SOC. DES encryption will be used on voice and data channels to and from SOC.

Compliance: Meets requirements

2.2.1.9 SOC Internal Communications

SOC will include duplex voice terminals, a control and warning system, TV cameras and monitors, a voice and TV switching network, CR&T terminals, and signal and data processors.

Compliance: The following required services are not mentioned: public address, wireless voicecomm for crewmen, voice access from any pressurized volume in the SOC to ground and to manned spacecraft, communications inside EVA airlocks and docking ports. Also, built-in test of subsystem equipment and fault isolation are not discussed.

2.2.1.10 Other Requirements

DES encryption will be used on some of the RF links to provide communication security. RFI analyses must be performed to verify compatibility.

Compliance: SOC attitude constraints are necessary to some extent to provide adequate antenna coverage. Not all RF links are secure. AJ and spoofing protection are not addressed.

2.2.2 Summary

The communications subsystem design does not meet the specified requirements in the areas discussed below:

The operating range (distance) requirements for EVA communications, SOC-orbiter, SOC-OTV and SOC-free flyer communications are not met.

Television coverage from EVA users, TOV and free-flyers is not provided, as required.

Two duplex voice channels between SOC and orbiter are required (one is provided), a command link for orbiter to SOC is required (not provided). Also communications during docking and tracking of SOC from the orbiter must be provided (neither requirement is addressed).

Anti-jam capability and spoofing protection for communications links are not provided as required.

Communications security (encryption) is provided for some links, but not all.

The following capabilities are required for SOC internal communications but are not discussed in D180-26495-3:

- Public address
- Wireless voicecomm.
- Voice access from all pressurized volumes
- Communications inside airlocks and docking parts
- Built-in test and fault isolation

Further definition of the tracking radar is needed in order to determine if the requirements are being met.

In summary, there are several areas in which the subsystem design does not meet the requirements. These discrepancies must be resolved either by modifying the conceptual design or by changing the requirements, or both. There are several other areas in which further delineation of the design is needed to determine if the requirements can be met.

APPENDIX A

COMMENTS ON REVISED COMMUNICATIONS REQUIREMENTS

This appendix summarizes recent changes to the communications and tracking requirements. Also, how well the proposed implementation meets the new requirements is summarized.

Ref: "NASA Space Station Program Description Document, Systems Requirements and Characteristics, Book 3" First Edition, November 1982.

Major changes in the communications and tracking requirements due to the referenced document are summarized below.

(A) Implementation is defined in three growth increments. By the final increment, all signal processing shall be digital, including voice and video signals, with all links encrypted.

(B) Hardware is required to be modularized, with separate modules for baseband, IF and RF functions.

(C) Duplex TV is required for EVA.

(D) The goal shall be to provide GPS navigation for all interoperating vehicles, with each vehicle continually transmitting its GPS navigation solution to SOC.

(E) Tracking accuracy requirements have been loosened somewhat. The long range accuracy applies to augmented vehicles. Accuracy requirements for docking and rendezvous sensors are given.

(F) The requirements for SOC-OTV communications at ranges of 400 KM and 38,000 KM have been deleted. Only the 2000 KM range is now required. However, return link TV is required at 2000KM range, in addition to the communications channels. (The range for TV was previously 100 KM.)

(G) Duplex TV is required to/from manned OTV's at a range of 2000 KM.

(H) Return link TV is required from free-flyers at a range of 2000 KM.

(I) The following additional types of communications traffic are required through the relay satellite to ground;

Teleprocessing
Text and graphics
Duplex TV
Tracking

Also, separate relay satellite access from the SOC energy section is required, including command, telemetry and tracking.

(J) Reference is made to a tracking and data acquisition satellite (TDAS) which could be available to supersede TDRSS in the mid 1990's.

(K) No requirement for direct-to-ground communications is given.

(L) Bit error rates and signal-to-noise ratios are specified for all internal and external communications.

(M) The frequency bands specified previously for the various communication and tracking functions are no longer called out.

Table A-1 summarizes compliance of the proposed SOC (as defined in NASA Contractor Report No. 160944) relative to the referenced requirements.

TABLE A-1. COMPLIANCE SUMMARY

ITEM	COMPLIANCE
A	The requirement for implementation in three increments is not addressed. All links are digitized, but not all are encrypted.
B	Not compliant.
C	Not compliant.
D	Not compliant.
E	Tracking accuracies are not addressed.
F	Not compliant.
G	Not compliant.
H	Not compliant.
I	Separate relay access from the energy section is not provided.
J	Operation with TDAS is not addressed.
K	Direct-to-ground communications is provided but no longer required.
L	Not addressed.
M	The previously specified band requirements are met, but no longer apply.

7.4.5 ECLSS – Hamilton Standard

VOLUME 7 ETCLS DATA

Hamilton Standard conducted two major tasks in support of the Boeing Aerospace Company Space Station studies. These were:

TASK 1--ETCLS Subsystem Design and Analysis
TASK 2--EVA Analysis Support

TASK 1 ETCLS SUBSYSTEM DESIGN AND ANALYSIS

Subtask 1 Logistics Module As A Safe-Haven

Table 1 presents the ETCLS functions that may be located in the Logistics Module for normal station operation. The table also defines the possible limitations in using these subsystems during safe-haven occupation. In some cases, the failure that created the safe-haven need may preclude using a subsystem unless a redundant source of power, coolant, water, or gas supply is available. Since the Logistics Module will be used for some normal habitable functions (i.e., bathroom), active heat, CO_2, and trace gas removal is required. These functions are best provided by controlled intermixing of air with the Habitability Module.

The ETCLS functions needed to support a safe-haven are listed in Table 2. This table shows which functions are dedicated for safe-haven use and which are normal Logistics Module functions. The location and plumbing of these functions are summarized in the buildup scenario in Subtask 2. The weight, power, and volume of critical ETCLS subsystems are presented in Table 3.

As the Subtask 2 buildup scenario will show, after the fourth buildup launch, sufficient ETCLS redundancy exists that the Logistics Module no longer needs to function as a Safe-Haven.

Subtask 2 ETCLS Buildup

The objective of this Subtask is to define the ETCLS equipment for the Boeing Science and Application Space Station. Elements of this definition are presented in the attached set of figures which include:

1) Equipment schematics for the 6 launch buildup configurations (Figures 1-6)

2) Fluid interfaces for the 6 launch buildup configurations (Figures 7-12)

3) Hardware lists with subsystem weights and packaging dimensions for the Initial and Final Station configurations (Tables 4 and 5)

4) Fluid line sizes (Figures 13 and 14)

There are several design drivers which impact the ETCLS recommendations for the station buildup (see Section 5.5.1 for detailed treatment):

1) The Logistics Module will serve as a Safe Haven in the initial phases.

2) Subsystem functions are designed to be Operational/Fail Operational (or Fail Acceptable)/Fail Safe.

3) The station is occupied by a crew of up to three until the final modules are in place. After this point, the station is capable of supporting a crew of eight.

4) The crew has no water amenities (except handwash) until buildup is complete. Amenities derived from having processed water (shower, clotheswash) are used on an experimental basis until they and the water processing system are qualified.

5) The source of dark side power will be a regenerative fuel cell/electrolysis system.

6) The only gases permitted for venting from the Space Station are H_2 and CH_4.

Table 1

ECLSS Functions Normally Located In Logistics Module

Function	Limitations For Safe-Haven Use
Commode	None
Food Freezer	Oven Needed To Thaw/Cook
Clothes Storage	None
Hand Wash	Reliability/Redundancy
Shower	Reliability/Redundancy
Trash Compactor	None
Trash Storage	None
Water Storage	Reliability/Redundancy
Gas/Cryo Storage	Reliability/Redundancy
Coolant	Reliability/Redundancy

Table 2

ETCLS Functions Needed For Safe-Haven

ETCLS Functions	Available In Logistics Module	Dedicated For Safe-Haven	Comments
• Ventilation • Sensible Heat	X X	X X	Combined Fan/HX Package
• Latent Heat Removal • CO_2 Removal • Odor/Trace Gas Removal		X X X	Combined Functions Performed By HS-C Package Located In Hab. Mod.
• O_2 Makeup • N_2 Makeup		X X	Tanks On Hab. Mod. With Standard 2 Gas Controller In Logistics Module
• H_2O, Food & Drink		X	Hot H_2O Dispenser
• Food		X	Dry Food Kit (Frozen Food Needs Oven)
• Commode	X		Redund. Of Plumbing & Power To Assure Availability
• Trash	X		21 Days Of Used Clothing, Wipes & Food, Containers, etc.
• Clothes	X		Disposable Clothes Storage In Log. Mod. For Early Station
• Hygiene Wipes • Medical Supplies		X X	Kits Moved To Hab. Mod. For Log. Mod. Switch Out & Back To Log. Mod. To Support Safe-haven

Table 3

Subsystem Sizing For Safe-Haven

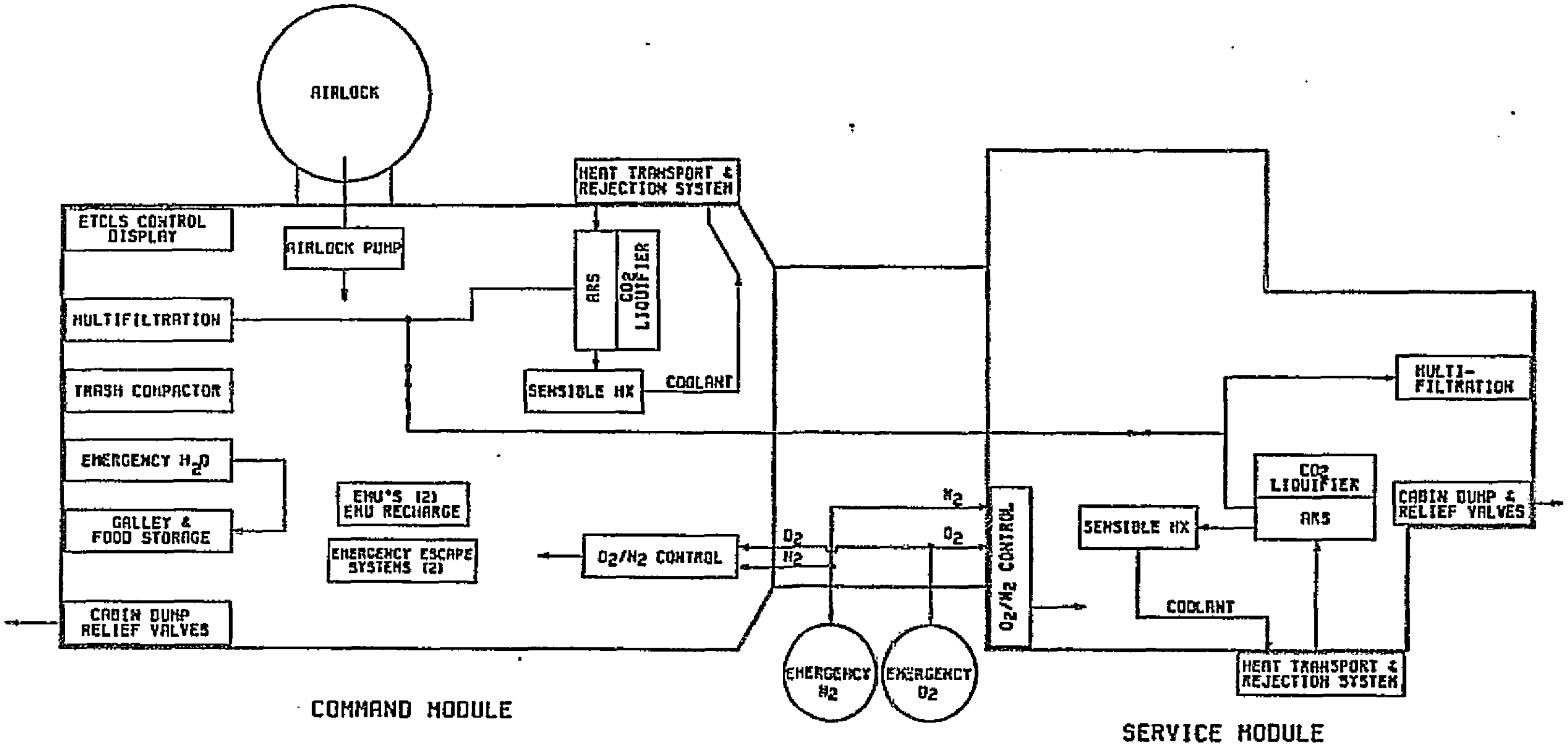
Vehicle Location/Function	Weight (lbm)	Volume (ft^3)	Power (watts)
Logistics Module			
Sensible HX Package	50	2.5	235
O_2/N_2 Control	30	1.5	60
Total Logistics Module	80	4.0	295
Habitability Module			
N_2 Tanks (2)	226	9.5	0
O_2 Tanks (4)	488	18.9	0
H_2O Tanks (3)	638	20.3	0
HS-C Package (1)	143	8.5	80
Total Habitability Module	1495	57.2	80
Total Safe-Haven ETCLS	1575	61.2	375

Figure 1

BOEING SPACE STATION
ETCLS EQUIPMENT
AFTER LAUNCH #1

DHH:2/17/83

NOTES:
1) THIS CONFIGURATION CAN ONLY BE MANNED DURING SHUTTLE TENDED OPERATION
2) REDUNDANT PLUMBING FOR EMERGENCY O_2/N_2 GAS NOT SHOWN



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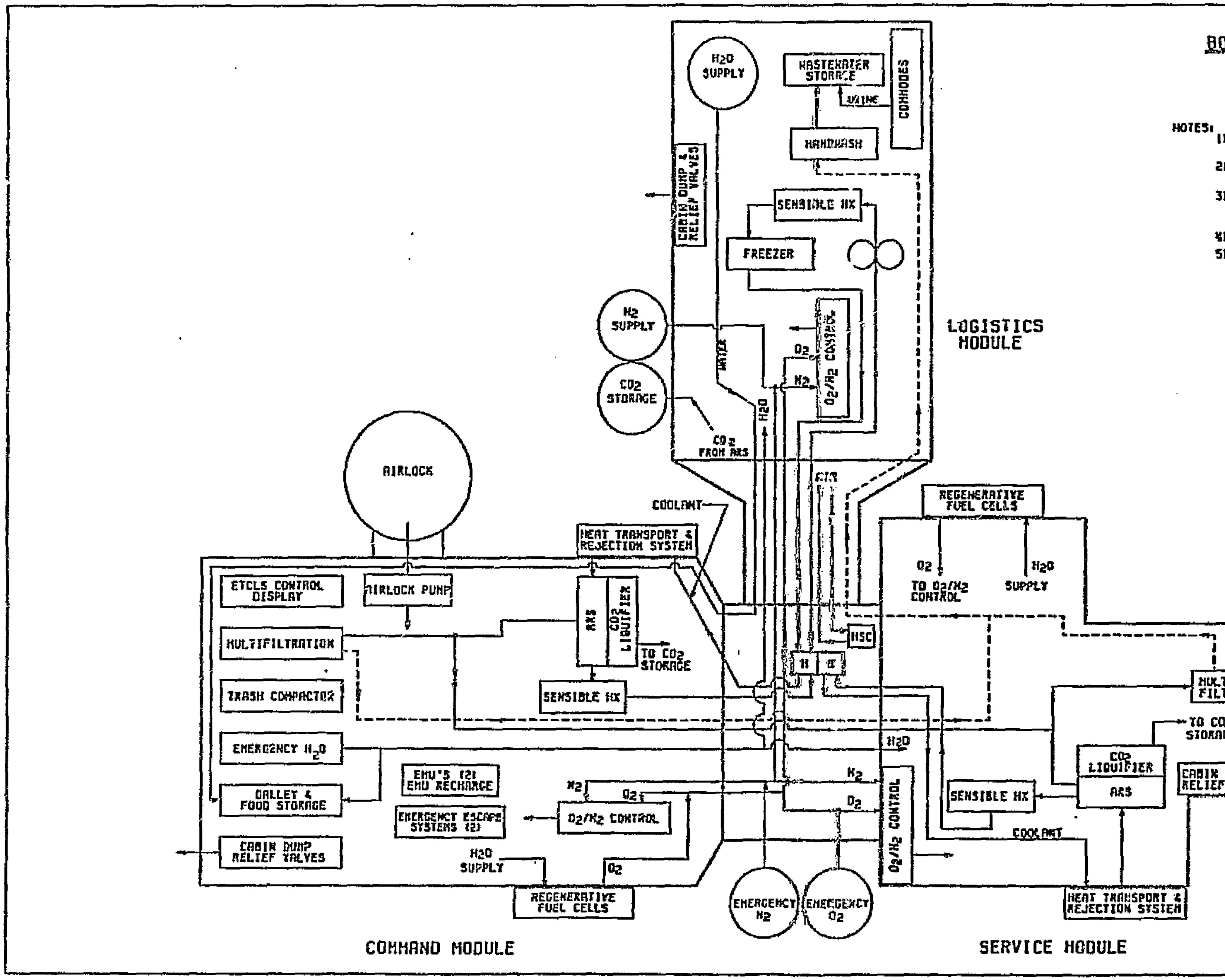


Figure 2

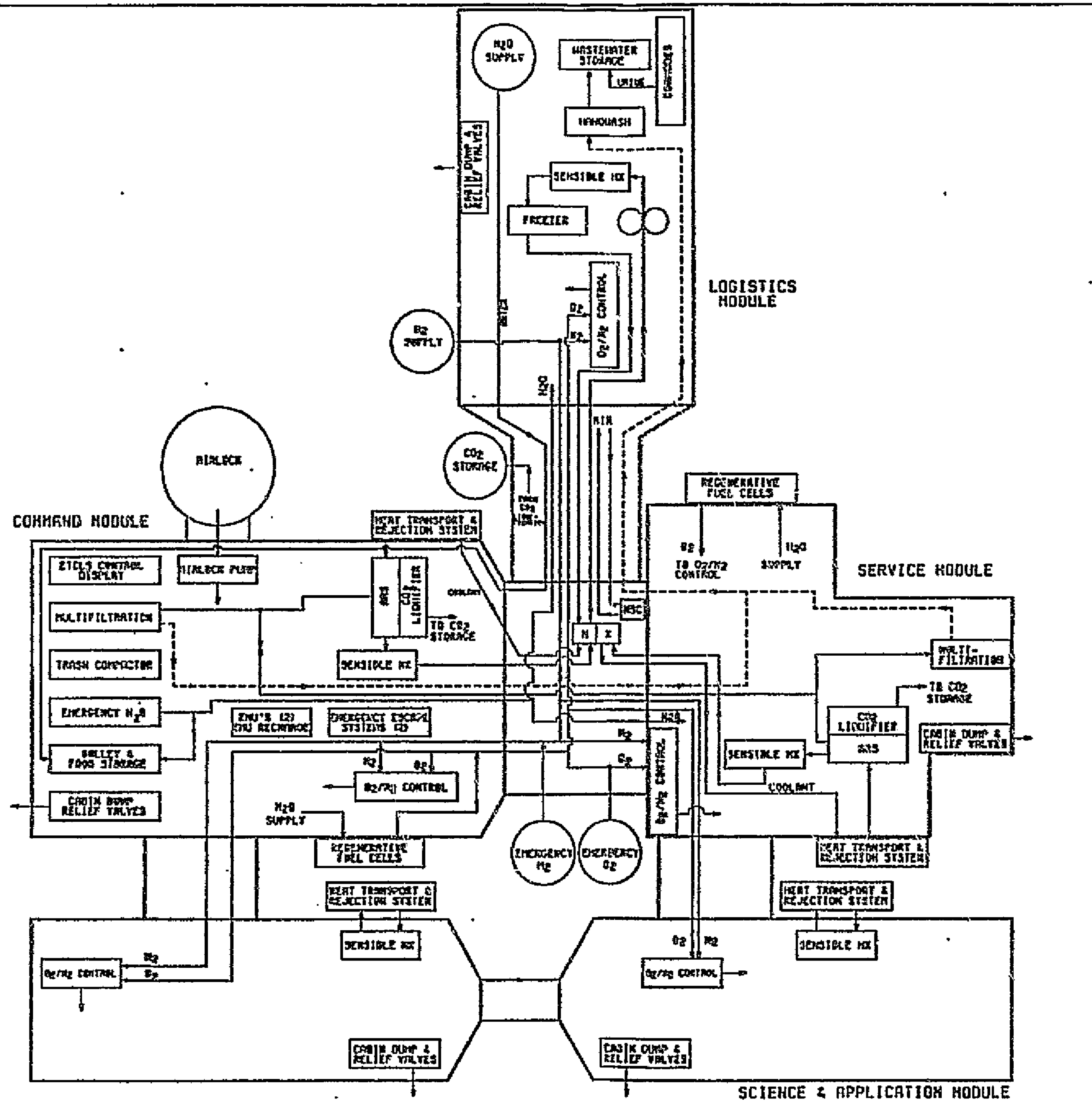
BOEING SPACE STATION
ETCLS EQUIPMENT
AFTER LAUNCH #2

DWW:2/17/83

NOTES:
1) THIS CONFIGURATION CAPABLE OF MANNED FREE FLYER OPERATION
2) REDUNDANT PLUMBING FOR EMERGENCY O_2/N_2 GAS NOT SHOWN
3) LOGISTICS MODULE TO HAVE PASSIVE HEAT REJECTION FOR SAFE HAVEN CAPABILITY
4) CREW SIZE CAPABILITY = 3
5) ---- DENOTES GREY WATER

Figure 3
BOEING SPACE STATION
ECLS EQUIPMENT
AFTER LAUNCH #3
DWL:2/17/83

NOTES:
1) REDUNDENT PLUMBING FOR EMERGENCY O_2/N_2 CRS NOT SHOWN
2) LOGISTICS MODULE TO HAVE PASSIVE HEAT REJECTION FOR SAFE HAVEN CAPABILITY
3) CREW SIZE CAPABILITY = 3
4) ---- DENOTES GREY WATER



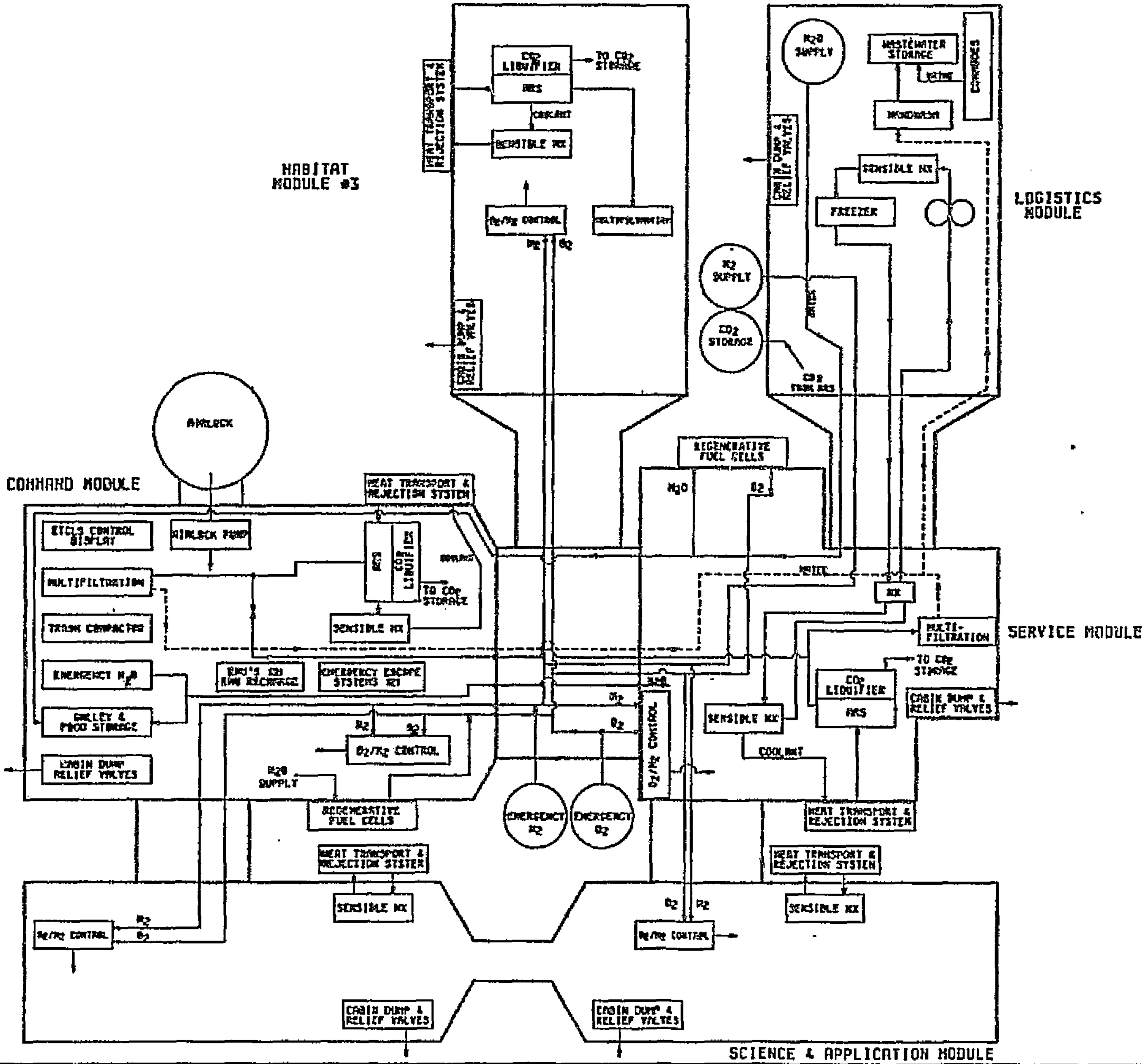


Figure 4
BOEING SPACE STATION
ETCLS EQUIPMENT
AFTER LAUNCH #4
DAM: 2/17/83

NOTES:
1) LOGISTICS MODULE NO LONGER EQUIPPED FOR ... WATER CAPABILITY
2) REDUNDANT PLUMBING FOR EMERGENCY O2/H2 GAS NOT SHOWN
3) CREW SIZE CAPABILITY = 3
4) ---- DENOTES GREY WATER

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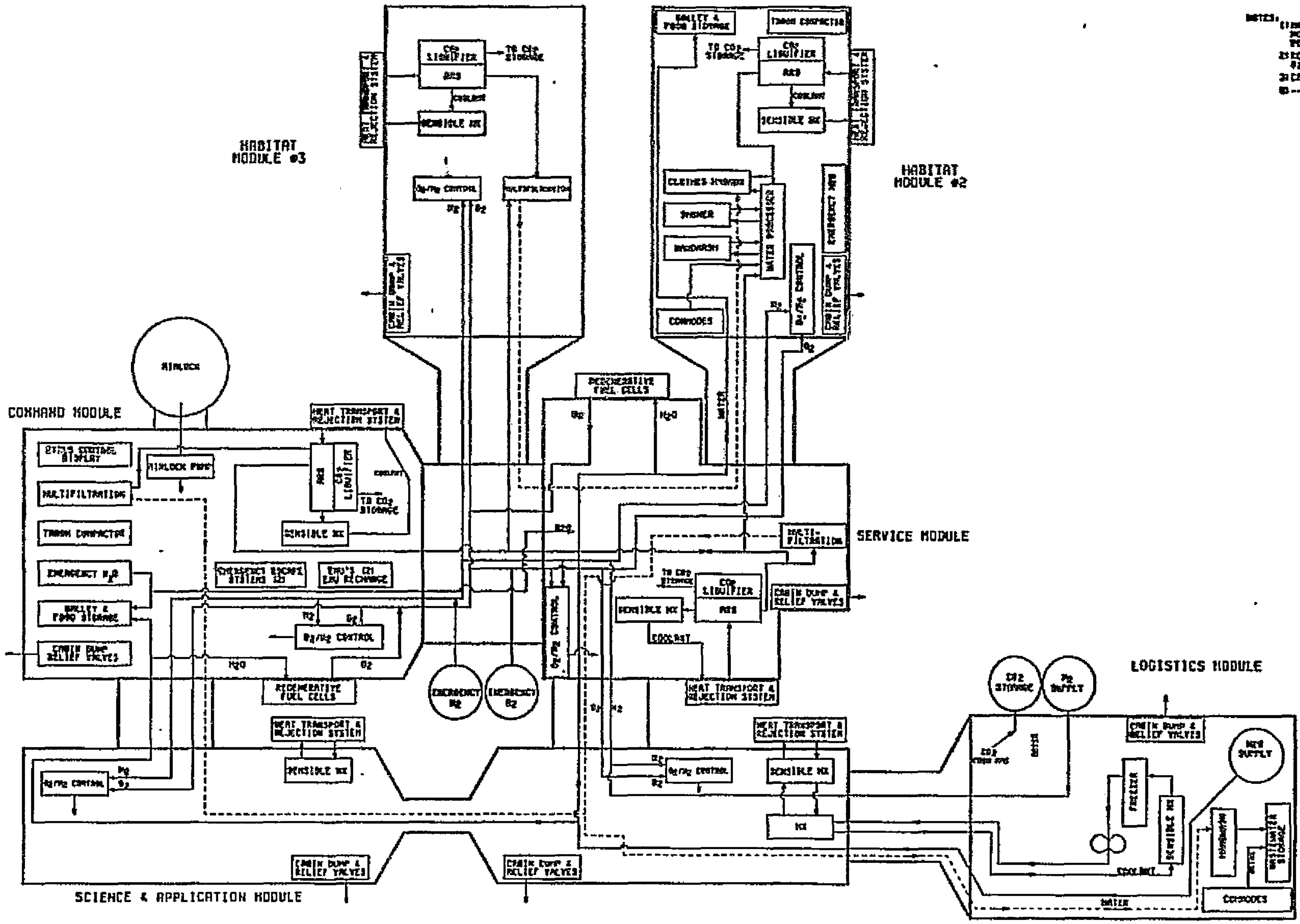
DRAWING = ETCLS #4 USER = SCHMAT
DATE = 3/07/83 TIME = 23.24 SCALE = 0.4092

Figure 5

BOEING SPACE STATION
ETCLS EQUIPMENT
AFTER LAUNCH #5



DRAWING = ETCLS #5 USER = SCHNAT
DATE = 3/08/83 TIME = 09.38 SCALE = 0.3585

Figure 6

BOEING SPACE STATION
ECLS EQUIPMENT
AFTER LAUNCH #6

2/17/83

NOTES:
1) ALL WATER PROCESSED TO POTABLE STANDARDS
2) REDUNDANT PLUMBING FOR EMERGENCY O2/N2 GAS NOT SHOWN
3) CREW SIZE CAPABILITY = 8

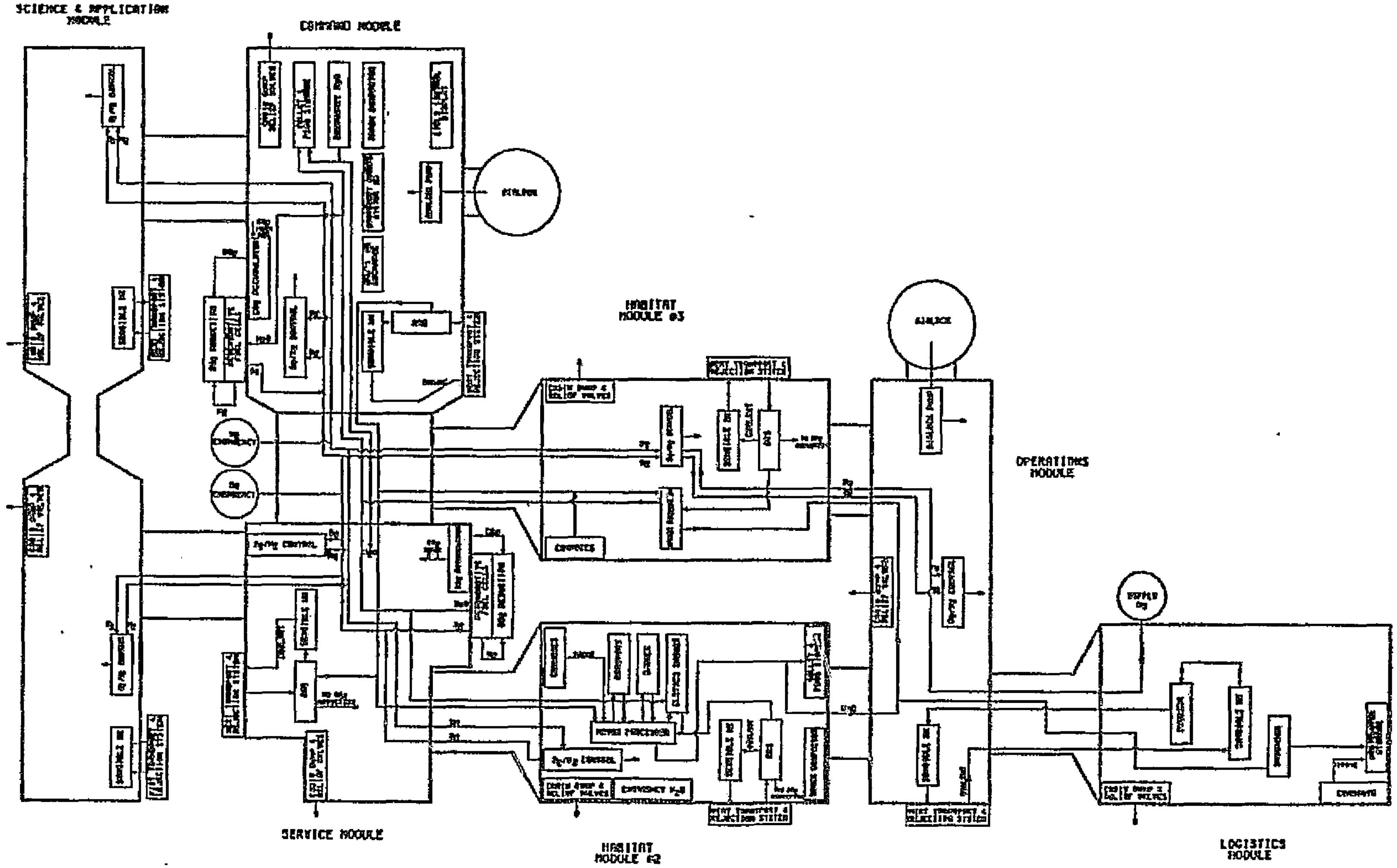


Figure 7

BULKHEAD INTERFACES

AFTER LAUNCH #1

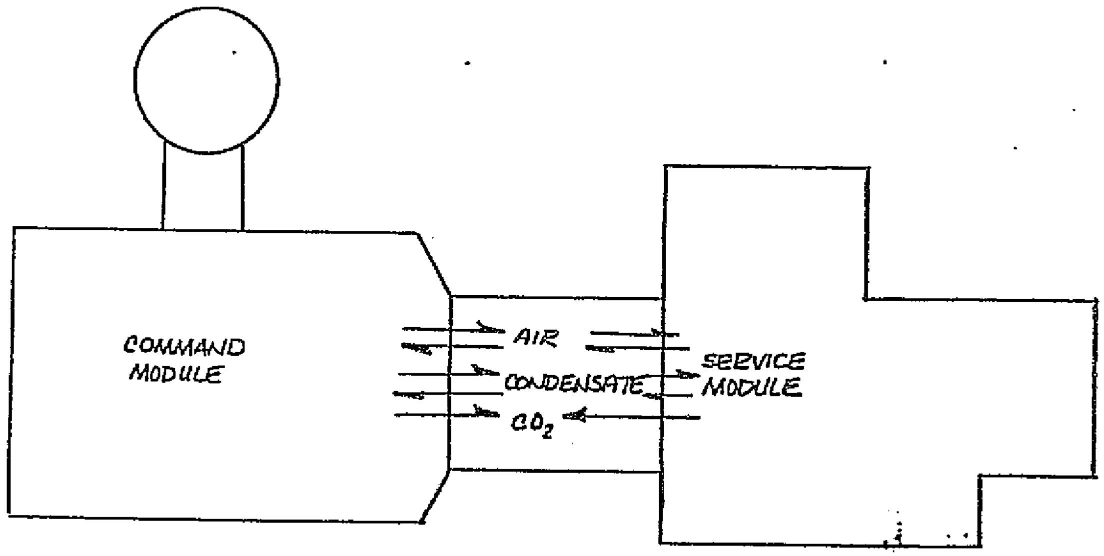


Figure 8

BULKHEAD INTERFACES

AFTER LAUNCH #2

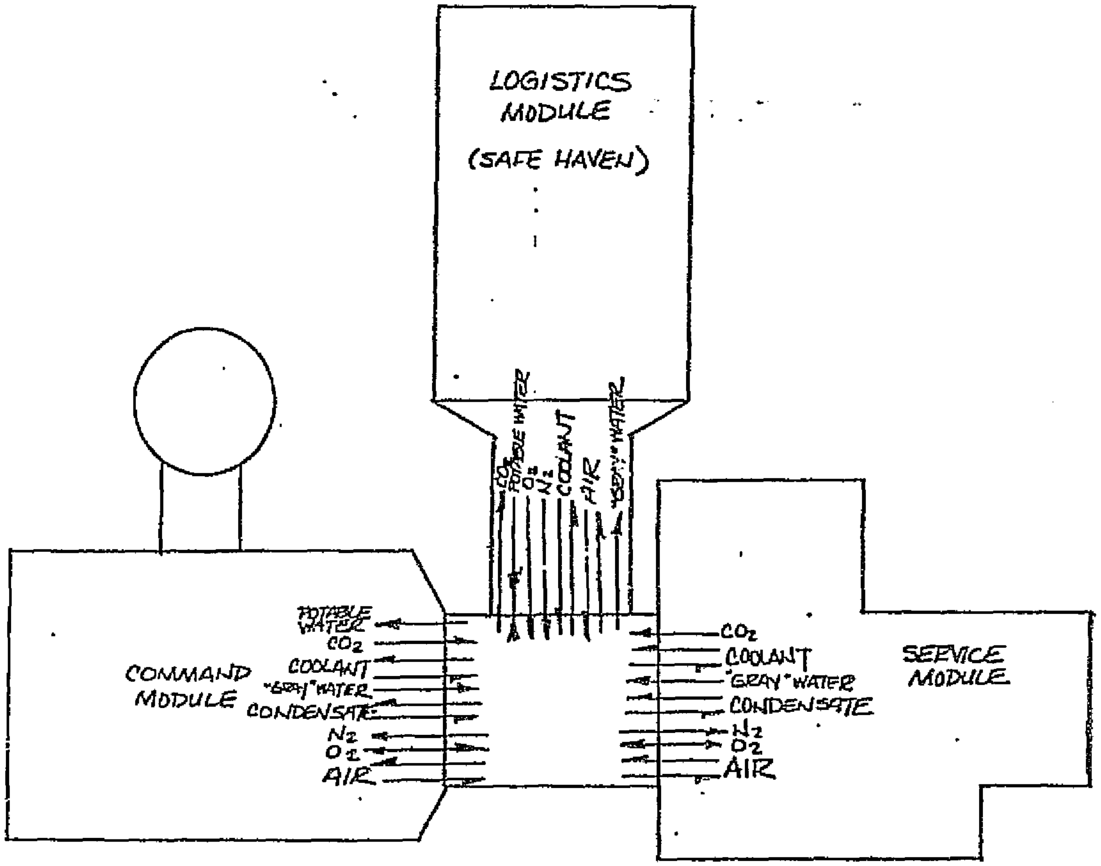


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Figure 9

BULKHEAD INTERFACES

AFTER LAUNCH #3

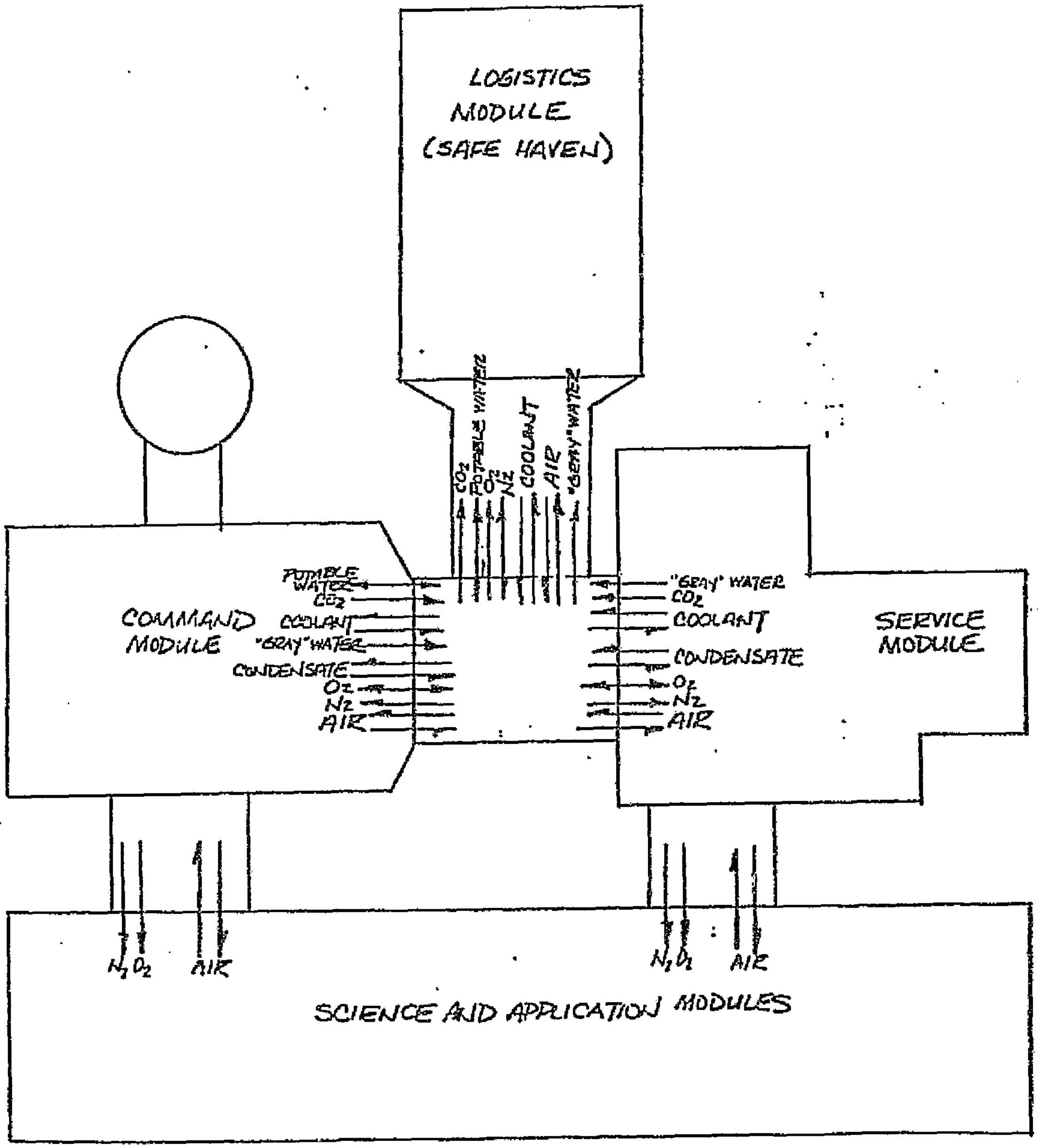

Figure 10

BULKHEAD INTERFACES

AFTER LAUNCH #4

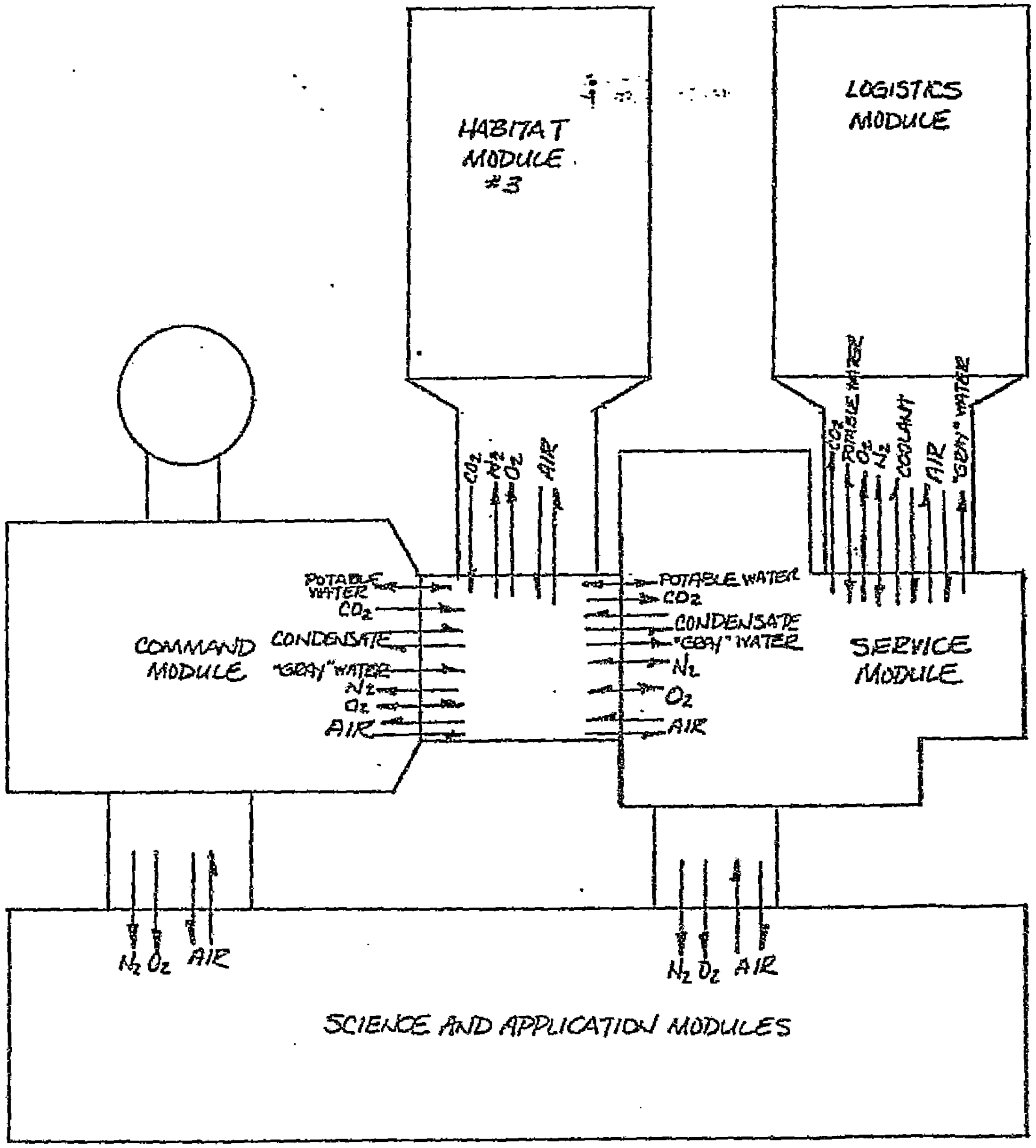

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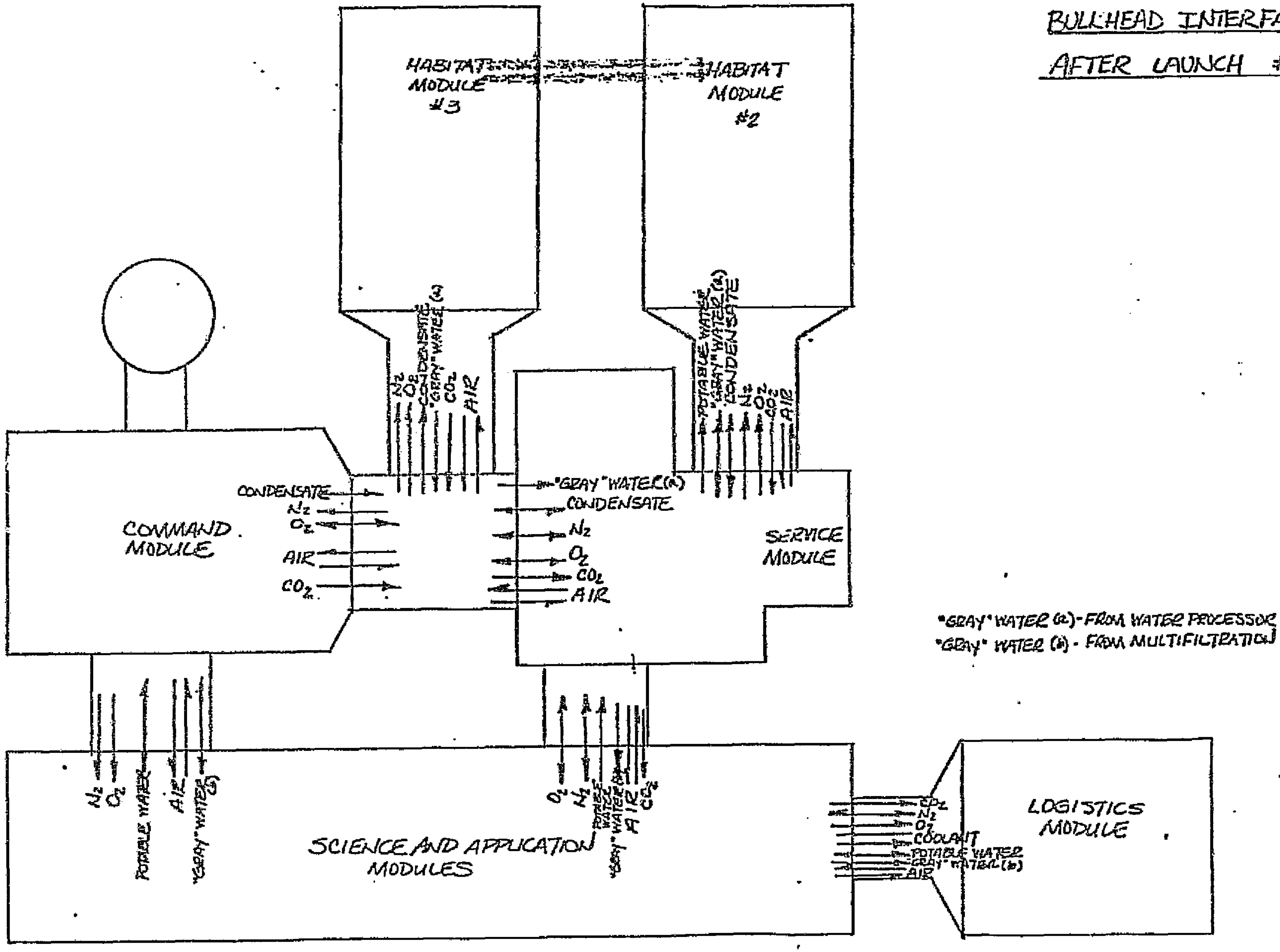
Figure 11

BULLHEAD INTERFACES

AFTER LAUNCH #5



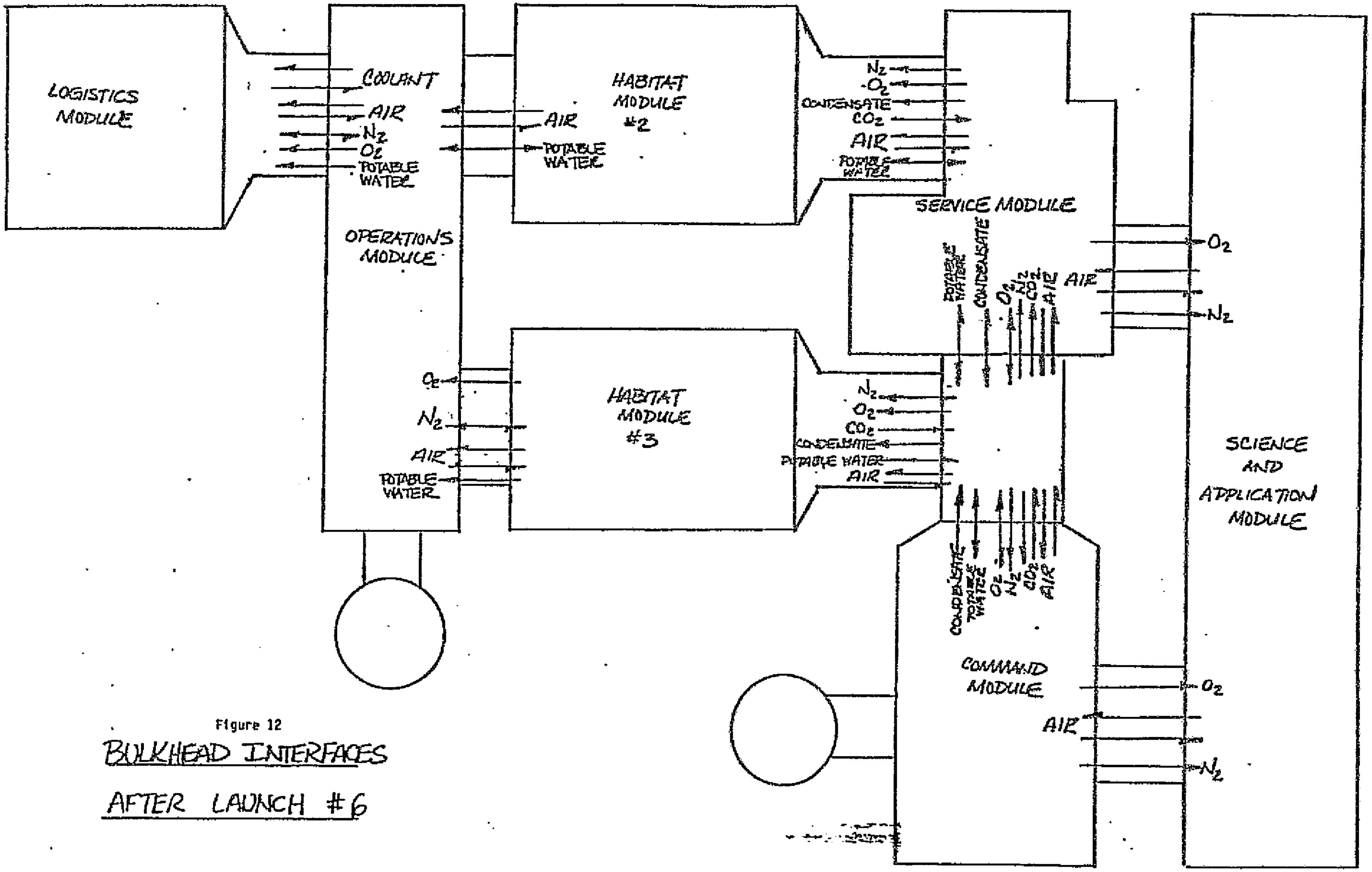


Figure 12

BULKHEAD INTERFACES

AFTER LAUNCH #6

Table 4

Initial Station

Subsystem	Qty./ Shipset	Weight/ Subsystem (lbm)	Subsystem Package Size (ft X ft X ft)
Sensible H/X Package	3	62	1 X 1.5 X 4
Cold Plates	12	14	2 X 2 X 1/12
Latent H/X Package	2	129	1 X 1.5 X 3.5
Emerg. CO_2 Removal	1	143	1 X 2.5 X 3.5
CO_2 Removal (SAWD)	2	110	1 X 2.5 X 2.5
Contaminant Control Ass'y	2	65	1 X 2.5 X 2.5
Atmospheric Monitor	2	77	1 X 1.5 X 1.5
CO_2 Liquefaction System	2	140	1 X 1.5 X 2
Freon Coolant Pump Package	2	45	1 X 1.5 X 2.5
Water Coolant Pump Package	2	28	1 X 1 X 1.5
Freon/Water Interchange H/X	2	21	1 X 1 X 1
Water/Water Interchange H/X	2	21	1 X 1 X 1
Emergency O_2 Storage	2 Tanks	214	3 X 3 X 3
Emergency N_2 Storage	3 Tanks	386	3 X 3 X 3
Normal O_2 Supply (90 Days)	4 Tanks	214	3 X 3 X 3
Normal N_2 Supply (90 Days)	1 Tank	386	3 X 3 X 3
Airlock Pump Ass'y	1	100	1 X 1 X 1.5
O_2/N_2 Control	3	43	1 X 1.5 X 1.5
Condensate Filtration Unit	2	175	1 X 2 X 2
Potable Water Tanks (90 Days)	10	240	1.5 X 1.5 X 3
Emergency Water Tanks	3	240	1.5 X 1.5 X 3
Condensate Storage Tanks	2	70 (empty)	1.5 X 1.5 X 3
**Urine Storage Tanks	3	70 (empty)	1.5 X 1.5 X 3
Gray Water Storage Tanks	2	70 (empty)	1.5 X 1.5 X 3
Hot Water Supply	2	23	1 X 1 X 1.5
Cold Water Supply	1	20	1 X 1 X 1
Handwash	2	25	1.5 X 1.5 X 1.5
Trash Compactor	1	80	1.5 X 2 X 2
Refrigerator	2	50	2 X 2 X 2.5
Freezer	4	210	2 X 2.5 X 2
Oven	1	40	1.3 X 1.3 X 1.5
Waste Collection	2	172	2.3 X 2.3 X 2.3

**Assumes Empty Potable Tanks Are Used For Urine Storage

Table 5
Final Station

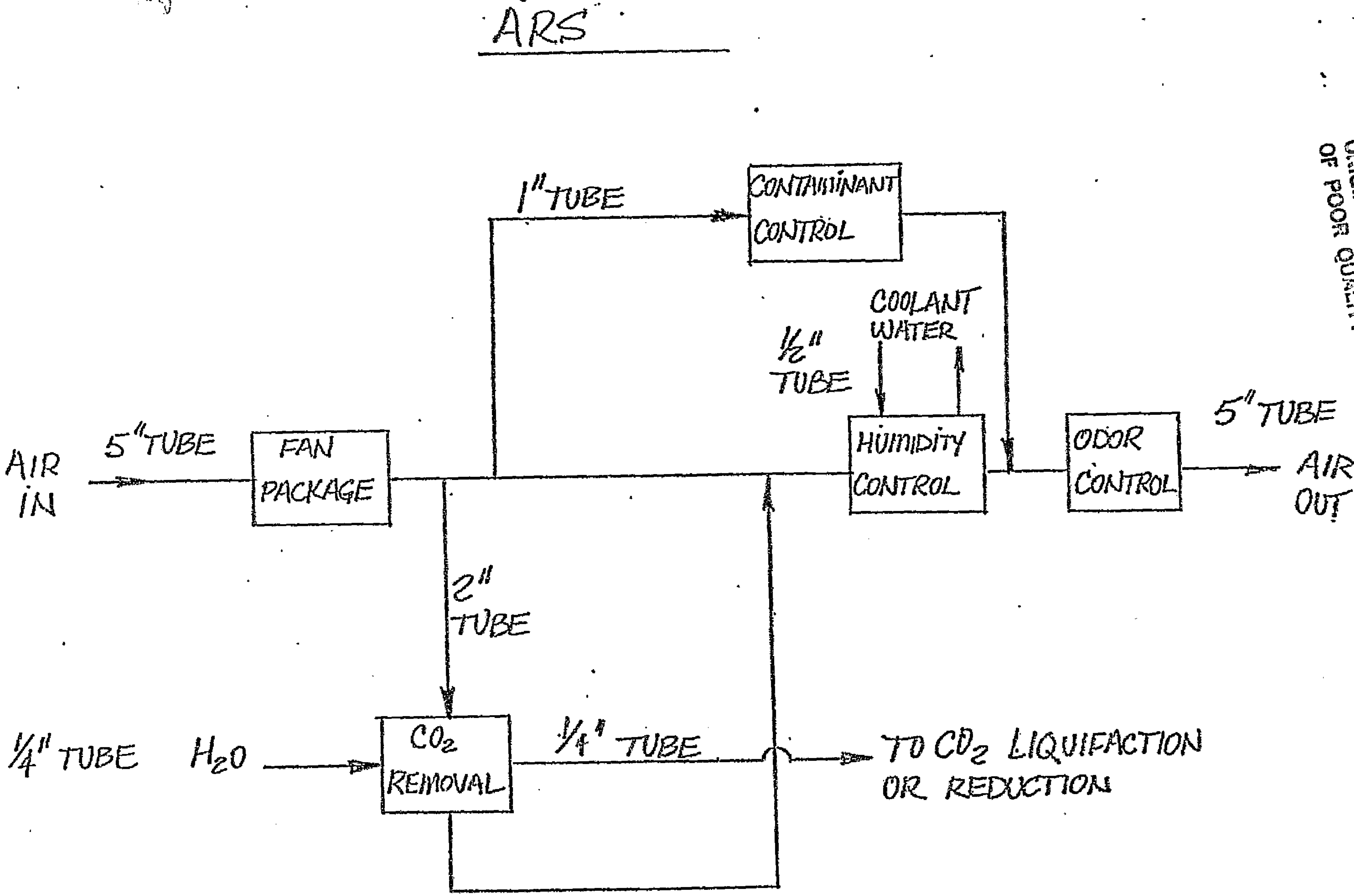
Subsystem	Qty./ Shipset	Weight/ Subsystem (lbm)	Subsystem Package Size (ft X ft X ft)
Sensible H/X Package	8	62	1 X 1.5 X 4
Cold Plates	30	14	2 X 2 X 1/12
Latent H/X Package	4	129	1 X 1.5 X 3.5
CO_2 Removal (SAWD)	4	110	1 X 2.5 X 2.5
CO_2 Reduction Unit	2	84	1.5 X 2.5 X 2.5
Contam. Control Ass'y	4	65	1 X 2.5 X 2.5
Atmospheric Monitor	4	77	1 X 1.5 X 1.5
Freon Coolant Pump Package	7	45	1 X 1.5 X 2.5
Water Coolant Pump Package	7	28	1 X 1 X 1.5
Freon/Water Interchange H/X	7	21	1 X 1 X 1
Water/Water Interchange H/X	5 (min.)	21	1 X 1 X 1
Emergency O_2 Storage	4 Tanks	214	3 X 3 X 3
Emergency N_2 Storage	6 Tanks	386	3 X 3 X 3
Normal N_2 Supply	2 Tanks	386	3 X 3 X 3
Airlock Pump Ass'y	2	100	1 X 1 X 1.5
O_2/N_2 Control	8	43	1 X 1.5 X 1.5
Pretreat/Storage	2 (3 Tanks Each)	70 (Per Tank)	1.5 X 1.5 X 3 (Per Tank)
Water Processing Unit	2	240	2.5 X 2.5 X 6
Potable Water Storage	2 (3 Tanks Each)	70 (Per Tank)	1.5 X 1.5 X 3 (Per Tank)
Emergency Water Tanks	6	240	1.5 X 1.5 X 3
Water Quality Monitor	2	60	1 X 1.5 X 2.5
Hot Water Supply	4	23	1 X 1 X 1.5
Cold Water Supply	2	20	1 X 1 X 1
Handwash	2	25	1.5 X 1.5 X 1.5
Shower	1	105	2.5 X 2.5 X 7
Clothes Wash	1	78	1.5 X 2 X 2
Trash Compactor	2	80	1.5 X 2 X 2
Refrigerator	2	50	2 X 2 X 2.5
Freezer	4	210	2 X 2.5 X 2
Oven	2	40	1.3 X 1.3 X 1.5
Dishwasher	1	78	1.8 X 1.8 X 2.5
Waste Collection	4	172	2.3 X 2.3 X 2.3

Figure 7

FLUID TUBE SIZES

FLUID	TUBE SIZE	
WASTE H_2O	3/8"	
POTABLE H_2O	3/8"	
CONDENSATE	1/4"	
O_2	1/4" - 1/2"	DEPENDING ON CABIN REPRESSURIZATION REQUIREMENTS
N_2	1/4" - 1/2"	DEPENDING ON CABIN REPRESSURIZATION REQUIREMENTS
CO_2	1/4"	
AIR	5"	
COOLANT H_2O	1/2"	
GRAY H_2O	3/8"	

Figure 14


ARS
1" TUBE
CONTAMINANT CONTROL
COOLANT WATER
1/2" TUBE
AIR IN
5" TUBE
FAN PACKAGE
HUMIDITY CONTROL
ODOR CONTROL
5" TUBE
AIR OUT
2" TUBE
1/4" TUBE
H2O
CO2 REMOVAL
1/4" TUBE
TO CO2 LIQUIFACTION OR REDUCTION

TASK 2 EVA ANALYSIS SUPPORT

This task describes the present EMU and outlines how an EMU design is selected, based on mission requirements and objectives, and what impact the EMU system has on the vehicle architecture.

As described in detail in Section 5.5.1, the two major drivers which direct EMU design are vehicle contamination concerns and the forecasted frequency of Extra Vehicular Activity (EVA). The former determines whether venting of cooling water from the EMU Portable Life Support System (PLSS) would be allowed. The latter determines whether the amount of EVA warrents developing systems which minimize resupply weight penalties (regenerative systems) or which minimize crewman preparation time (no prebreathe by using a higher pressure EMU design).

The following text is presented in a question and answer format, to provide a reference for EMU/EVA operations in response to specific questions presented in both correspondence from Mr. Keith H. Miller to Mr. Alfred O. Brouillet dated 19 January 1982 and the Boeing/Hamilton Standard Space Station Study meeting of 17 December 1982 held at Hamilton Standard.

QUESTION 1 EXPENDABLE VS REGENERATIVE COMPARISON

The weight and volume penalties associated with expendables resupply may become prohibitive for a heavy Space Station EVA schedule. What are the trade-offs between using an expendable system EMU versus a regenerative EMU system?

The major areas of expendable replenishment are a) water for thermal control, b) lithium hydroxide (LiOH) for CO_2 control, c) O_2 and d) batteries for power. Whereas the current silver-zinc battery is rechargeable and will probably remain a baseline item for initial Space Station EVA, the current thermal control and CO_2 control subsystems will be traded against regenerative subsystems.

a) H_2O

The current EMU (see Figure 1) utilizes a water sublimation thermal control subsystem, which uses approximately 12 lbs of H_2O per 7 hour EVA. Ten (10) lbs of water must be replaced prior to each EVA. The remaining 2 lbs of water is obtained by condensing crew generated perspiration and respiration.

A current NASA/JSC technology feasibility program will trade-off, design and fabricate a prototype regenerative thermal control unit. This program investigates two thermal control subsystems, one for Shuttle the other for Space Station. The near-term Shuttle non-venting thermal control subsystem consists of a phase change material system (RNTS) which provides four (4) hours of non-venting thermal control. The proposed design for a Space Station unit is a hybrid radiator-thermal storage system; the radiator unit will be capable of providing baseline thermal control with the thermal storage unit handling peak loads, giving the Space Station EMU an 8-hour thermal control capability. This regenerative subsystem will require an initial launch penalty weight of 100 lbs and 1.4 ft^3 per EMU and is additive to the baseline weight of the EMU. However, this one-time launch penalty must be traded against the current EMU penalty of using approximately 10 lbs. of H_2O for each EVA. A secondary reason for using the regenerative system is that it provides non-venting capability (as opposed to the water sublimator which vents H_2O vapor into the environment) for EVA work close to cryogenically cooled sensors and optics. Recharge of the Shuttle thermal control phase change material regenerative subsystem requires 1.5 kW-hr per EVA. Recharge of the Space Station Hybrid Thermal Control Regenerative Subsystem will require 1.8 kW-hr per EVA. The expendable vs regenerative trade is shown in Figure 2.

b) CO_2

The EMU contains a replaceable cartridge for CO_2 control called the Con-aminant Control Cartridge (CCC). This cartridge absorbs CO_2 as well as other trace contaminants produced by the crewmember. The major ingredient of the CCC (the one responsible for CO_2 control) is lithium ydroxide (LiOH) and the CCC replacement weight is 6.4 lbs. per EVA. he contaminated LiOH must be replaced after each EVA (regardless of the EVA time) and cannot be reused on orbit.

Regenerative CO_2 systems have been researched and developed with 3 or 4 concepts showing promise - these being solid amines, membrane systems, electrochemical depolarizer (ECD) systems, and metallic oxides. Due to technology development requirements of certain systems (i.e., metallic oxides) the Space Station EMU regenerative CO_2 subsystem will probably be phased into the program. A 1985 space station EMU (low EVA frequency) would use the current LiOH CO_2 control subsystem; a 1990 space station would use a solid amine CO_2 control subsystem (weight = 60 lb, volume = 1.2 ft^3); and a 1995+ space station EMU would use a metallic oxide CO_2 control subsystem (weight = 50 lbs, volume = 0.6 ft^3). As with the regenerative thermal control system, these regenerative systems have a one-time launch penalty as opposed to using expendables. For CO_2 this involves a 6.4 lb/EVA penalty associated with the expendable LiOH system (also consider the LiOH cartridge storage = one cartridge/EVA, each with a volume of 300 in^3). Preliminary results indicate that the recharge power required for each of these CO_2 system is approximately 1.8 kW-hr. The CO_2 expendable vs regenerative trade is also shown in Figure 2.

c) O_2

An EVA crewmember will use approximately 1.2 lbs of O_2 per 7-hour EVA. However, if these 7 hours were spent within the Space Station 0.5 lb of O_2 would be consumed. Therefore, the on-orbit O_2 penalty for conducting a 7-hour EVA is 0.7 lb of O_2.

d) Batteries

The current EMU silver-zinc battery provides 23.5 amp-hours of power and may be recharged up to 8 times. Each recharge period lasts 16 hours. Each battery weighs 9.6 lbs and has a volume of 120 in^3. Hamilton Standard currently plans to use the silver-zinc batteries as baseline for Space Station. Research into alternate battery types such as lithium batteries has yet to produce a battery which trades favorably to the current EMU battery. However, research continues into alternative battery types such as NiH_2 and the Space Station battery may not be baselined as silver-zinc. The baseline Space Station battery should be capable of many (>50) recharges.

Each of these subsystem evolutions from an expendable to regenerative system may be implemented individually, or cumulatively - which would create, in part, the Hamilton Standard Space Station EMU PLSS. Figures 3 through 6 illustrate the Space Station EMU. Figure 3 provides a Space Station EMU schematic; the major differences over a current EMU being in thermal control (hybrid radiator/phase change material system), CO_2 removal (solid amine system), battery (50+ recharge) and Caution and Warning System (increased memory capability, diagnostic capability). Figure 4 illustrates the dimensions of the Space Station EMU, while Figure 5 demonstrates that the Space Station EMU can meet the requirement of transgression through a 40" hatch. Figures 6a and 6b present a summary of each EMU configuration.

QUESTION 2 ON-ORBIT MAINTF.ANCE

To maintain the high integrity of the EMU, what on-orbit maintenance philosophy is required and what support equipment is required to uphold this maintenance philosophy?

The present EMU is checked out extensively prior to each Shuttle flight. On-ground testing consists of:

- Secondary Oxygen Pack (emergency O_2 system) refill test rig and electrical function test rig.

- Primary Life Support Subsystem oxygen refill test rig and serial data readout rig.

- Liquid Cooling and Ventilation Garment test rig and Space Suit Assembly leakage test rig.

- Lithium Hydroxide refill facility and zero-g stand.

To have this same test capability on-orbit, plus the capability to repair any malfunctions identified during these tests would require a large inventory of test equipment. The current Primary Life Support Subsystem is so finely integrated that on-orbit repair or replacement of components other than expendables remains difficult. This being the case, pre-EVA system status on-orbit checkout of the current EMU is sufficient since repair of faulty subsystems would occur on-ground. The current operating mode requires that most any anomaly found in the EMU require Earth return of the unit.
With this maintenance philosophy in mind, on-orbit checkout operations of the current EMU is limited to:

- Contaminant control cartridge resupply
- H_2O resupply, Battery check/recharge
- Readjust sensors (if necessary)
- Checkout of Primary Life Support Subsystems using the EMU Caution and Warning System
- Leakage check of Space Suit Assembly integrity.

Other Space Station maintenance issues associated with using the urrent EMU include:

a) Cleaning of undergarments (currently crewmen use stericide wipes to clean the inside of the Protective Garment Assembly after each use).

- Liquid Cooling & Ventilation Garment: use on-board washing machine
- Urine Collection Device: throw out after use
- Fecal: diaper, throwout after use
- Drying EMU: stericide wipes, odor, bacteria control

b) Contamination Control: replace LiOH cartridges after each EVA, return canisters to earth for recharging. Contamination of garment by foreign substances (e.g., cryogenics, debris) may be handled by alternative methods, depending upon mission and contaminant.

c) Life, repair: Life of EMU softgoods is 6 years, hardware 15 years. EVA operational life is 180 EVA man-hours when EMU is pressurized at 4.3 $\pm$ 0.1 psig. Repair of the EMU will occur on-ground, with possible spares of gloves and the space suit assembly to allow replacement of these EMU softgoods-on-orbit.

Hamilton Standard has identified a Space Station EMU, which would eliminate current EMU operating characteristics dealing with use of expendables, limited on-orbit maintenance, and prebreathing. The Space Station EMU would operate under the following requirements:

SPACE STATION EMU REQUIREMENTS
PRELIMINARY

1. Each EMU is used for a maximum of one EVA per day.

2. Each EVA dedicated crewmember is provided with own EMU.

3. Two-Man EVA as minimum; 3rd man EVA capability at one time per airlock and recharge facility.

4. 12-hour EMU recharge period.

5. Each EMU is replaced on-orbit every 90 days with EMU spares being stored in the logistics module.

6. Maintainable EMU subsystems/Subassemblies:

   - Hard Upper Torso
   - Primary Life Support System
     - Hi Pressure
     - Lo Pressure
     - Caution & Warning System
     - Communications
     - Sensor Adjustment
   - Secondary Oxygen Pack
   - Displays & Control Module
   - Space Suit Assembly
     - Gloves
     - Joints, Interjoint Sections
     - Leakage Check

7. On-Orbit checkout of EMU accomplished via the Caution & Warning System.

8. EMU uses regenerative thermal control and CO_2 control (Shown in Figure 3).

9. EMU uses >50 recharge battery.

10. No-Prebreathe EMU.

11. Recharge of EMU accomplished through service and cooling umbilical connections.

    - Battery
    - Oxygen
    - Thermal Control

12. A donning station will be incorporated as part of the recharge facility.

13. Storage capability for 3 EMUs shall be configured as an add-on feature of the recharge facility and shall be integrated with the donning station.

14. All EVA related work equipment (MMU, Tools, etc.) stowed on the external shell of Space Station.

15. Planned EVA sorties for up to 8 hours.

16. The EMU shall be capable of passing through internal hatches of 40 inch diameter in both a manned and unmanned mode.

17. Liquid Cooling and Ventilation Garment will be replaced every 90 days. The LCVG may be washed in the space station washing machine; laundered every 6-10 EVA's. A chiffon body stocking will be worn under the LCVG to pick up the majority of waste products (water, hair, skin, etc.) and will be laundered after each use (each body stocking can support up to 10 EVA's, weight 5 oz. each; volume of 10-20 in^3 each).

18. Recharge facility will be capable of simultaneously charging two EMU's; a 3rd EMU will be stored charged.

19. EMU softgoods will be constructed of a single wall laminate bladder to facilitate easy cleaning using a microbial wipe (a quaternary ammonium compound cleaner). A dedicated drying station is not required.

Figures 3 and 4 demonstrate the Space Station EMU. The recharge facility to support this Space Station EMU would function as a joint recharge/donning station and be designated "recharge station". The recharge station schematic layout for power, thermal control, CO_2 and O_2 recharge appears in Figures 7 and 8. Figure 9 demonstrates recharge station equipment quantity, weight, and volume required to support three (3) Space Station EMU's and two (2) recharge stations.

In concepting the recharge station packaging volume, the EMU, donning station, recharge station, support equipment, work bench, spares and operating volume requirements must be considered. Figure 10 illustrates EMU donning volume requirements for a 95th percentile male and Figure 11 lists the recharge station aisle access requirements. On-orbit maintenance of the EMU will require a spares inventory of key EMU subsystem modules, components and undergarments. Figure 12 lists the stowage requirements (volume) for these spares. The EMU stowage, donning, recharge and spares inventory station design should consider the parameters outlined in Figure 13. Figures 14-22 provide recharge station design concepts and Figure 23 shows a potential EMU recharge station hanger.

QUESTION 3a EMU WEIGHT AND VOLUME

What are the weight, volume, and other issues related to use of the EMU?

A. - The weight and volume of the current EMU -

weight = 241.96 lbs "wet" (charged with O_2, H_2)
weight of EMU "wet" system and support equipment (service and cooling umbilical, oxygen purge assembly, airlock adapter plate) = 277.61 lbs.
volume - crew dependent
volume (stowed) = 16.17 ft^3 (see Figure 5)
recharge power = 50 watts

B. - The weight and volume of the nonvent, advanced joint EMU -

weight = 310 lbs "wet" (charged with O_2, H_2)
weight of EMU "wet" system and support equipment (service and cooling umbilical, oxygen purge assembly, air lock adapter plate) = 347 lbs
- volume (stowed) 17.1 ft^3
- EMU Support Equipment: same as current EMU
- Recharge power = 190 watts

C. - The weight and volume of the Space Station EMU -

weight = 435 lb "wet" (charged with O_2)
weight of EMU "wet" system and support equipment (service and cooling umbilical, oxygen purge assembly, airlock adapter plate) = 469 lb.
volume (stowed) = 22.1 ft^3
recharge power = 440 watts

The Space Station EMU would be maintainable on-orbit and have an inventory of the following spares:

SPACE STATION EMU SPARES

	Weight Each (lbs)	Volume Each (In^3)
PLSS	236.00	8741
LTA	33.80	5508
Arms	8.51	1656
Gloves	2.70	360
LCVG	6.50	1445
UCD	0.56	100 - 120
Body Stocking	0.45	10 - 20
Battery	9.60	300
Helmet	11.12	5202

EMU Sizing: The current EMU must be sized to a specific crewman by utilizing an inventory of space suit assembly elements. The Hard Upper Torso is also fitted to a specific crewman. However, since each crewmember will be required to have his own EMU, on-orbit repair and spares will have to be established accordingly. The NASA research and development program on high pressure suit joints and advanced manufacturing techniques has identified a sizing ring assembly for future suits which can be adjusted at key joint areas (shoulder, elbow, hip, thigh) to allow adjustment of suit lengths. The Space Station EMU Space Suit Assembly will have an operational life of 6,000 EVA hours and will accommodate an on-orbit maintenance philosophy (replacement of joints) which requires only a minimum of spares (this being due to commonality of parts and the use of sizing rings to quickly adjust arm and leg lengths).

QUESTION 3b MODULARIZED VS INTEGRATED PLSS

EMU Primary Life Support Subsystem; should it be integrated or separable from the Hard Upper Torso? Open looped life support or closed loop?

The current Primary Life Support Subsystem is attached and fully integrated into the Hard Upper Torso on-ground. These are not separable on-orbit. A separable Primary Life Support Subsystem would require redesign and additional on-orbit support equipment to verify leakage integrity for each refit. However, as shown in Figure 14-22, the separable PLSS offers benefits in on-orbit stowage and maintenance.

A modularized PLSS in which high and low pressure components are grouped for easy replacement would provide on-orbit maintenance capability for frequent EVA (see requirement #6 Question 2).

An open loop opertion (umbilical) for close proximity Space Station EVA ($<$ 10m) would require only minor adjustments to the EMU (wihin the Display and Control Module, Caution and Warning System). However, the use of an umbilical will not eliminate the need for the Primary Life Support Subsystem, because the umbilical will handle consummable makeup only (there will be no "vent loop" umbilical for safety reasons). Also, the issue of umbilical management while conducting EVA should be weighed heavily when deciding open loop vs closed loop life support. Experience gained during Skylab demonstrated that umbilicals became tangled and cumbersome during EVA.

QUESTION 4 EVA FREQUENCY IMPACT

How will the frequency of EVA affect EMU operations and Space Station design?

The frequency of EVA's (from an EMU perspective) for Space Station are directed by three factors; a) expendables, b) crew physiology and c) on-orbit maintenance. The first item, expendables, can be eliminated if regenerative systems are used. If not, each EVA will consume approximately 18 lbs of expendables, plus the use of an 8-recharge battery (weighing 9.6 lbs - 9.6 lb penalty every 8 EVA's). Maintenance of the EMU on-orbit is a function of EMU soft goods lifetime (current suit 180 EVA hrs) and each EMU should be completely rechecked on-ground every 90 days.

The second item, crew physiology, potentially affects operations in three areas, a) prebreathing, or elimination of "the bends", b) oxygen toxicity over long periods of repeated EVA's, and c) crewmember stamina to conduct a maximum of 5 EVA's per 7 day period.

Prebreathe may be eliminated by selecting a cabin/EMU operating pressure consistent with USAF standards (1.6 ratio cabin N_2 pressure to EMU pressure). A no-prebreathe EMU can be utilized, its operating pressure being finalized once Space Station cabin N_2 pressure levels are designated. The current incidence of bends occurring among crewmembers remains unacceptable and research continues to define optimum cabin/EMU pressure operating levels. Preliminary tests indicate that an 8 psi EMU system would reduce bends occurrence to an acceptable level.

Conclusive data does not exist concerning the subject of oxygen toxicity; yet it may be eliminated by providing a two-gas (O_2 and N_2) EMU system. By utilizing the partial pressure of N_2 which exists within the EMU prior to donning, a crewmember can "precondition" the EMU such that gradual O_2 partial pressure concentration is controlled and oxygen toxicity problems associated with pure O_2 checked. Figure 24 lists P_{EVA} vs P_{cabin} combinations.

Neutral buoyancy facility tests indicate that crewmember stamina is directly related to EMU training experience. As the crewmember became familiar with the EMU, the effort required to conduct a specific task decreased. The level of EVA frequency will be dependent on the individual; additional testing is required to quantify this area.

The third item, on-orbit maintenance, is directly related to the operational life of the Space Station EMU, on-orbit repair capability, and spares inventory. The current EMU operational life is approximately 180 EVA hours. However, the EMU must be completely retested and maintained after 5 EVAs. Consequently, the current EMU may not be capable of supporting a high frequency EVA plan (support of such a plan would require a prohibitively large inventory of EMUs on-board Space Station). Improved SSA joint construction and modularized PLSS subsystems will help facilitate on-orbit maintenance of a singular EMU and allow a high frequency EVA schedule for Space Station.

QUESTION 5 AIRLOCK OPERATION

How are airlock operations affected by the EMU and EVA?

The airlock can serve as a hyperbaric chamber in the emergency condition of rapid decompression and it also provides access to and from the environment of space. Operationally, for the operational Space Station air lock, each EVA requires:

- pump down time: 20-30 minutes
- power: 2KW
- replenishment: 1-2 psi dumped for each EVA

The Shuttle airlock can accommodate two EMU's plus crewmen. The EMU storage, donning, and recharge stations may be placed in a location other than the airlock for projected heavy EVA traffic. For a Space Station where more than 2 crewmembers will conduct EVA simultaneously (current requirement = 2 men EVA as minimum) a second Shuttle-type airlock may be desired. Figure 25 shows a Shuttle airlock layout complete with stowed EMU's.

However, note that the EMU need not be donned within the airlock and airlock design need not be a function of the current EMU donning requirements.

QUESTION 6 EMU OPERATING PRESSURE IMPACT

Besides pressure differentials, what are the operating differences between 4 psi and 8 psi EMU's?

The major differences between the 4 psi EMU and 8 psi EMU lay within construction of the Space Suit Assembly. The range of existing joint mobility as a function of suit pressure is shown in Figure 26.

The 8 psi EMU Space Suit Assembly demonstration program has shown that the technology exists for the construction of an 8 psi EMU. Whereas the current EMU uses tucked fabric joints, the 8 psi EMU will require replacement of certain joints with new joint technologies; specifically, rolling convolute joints, toroidal convolute joints and 4-bearing joints. These utilize a new restraint system which would provide comparable mobility to a 4 psi EMU, yet at 8 psi. Figure 27 illustrates where the new joint technologies would be used

The weight differential between a 4 psi and 8 psi suit is approximately 60 lbs. The increased power requirement as a function of EMU operating pressure is as follows:

P_{EVA}	% Increase in Amp-Hours
4	0
5	5
6	9
7	14
7.5	16

The current silver-zinc battery could provide this increase in power, yet would provide less recharge capability.

Both weight and power trades are demonstrated in Figure 28.

- Safety/early depressurization of the EMU - what are the ramifications for 8 psi EMU?

  NASA established the groundrule for a 4 psi EMU that the Secondary Oxygen Pack would provide, under emergency, pressure maintenance, cooling and oxygen for 30 minutes.

  This groundrule, if used for 8 psi would increase the size and weight of the Secondary Oxygen Pack at least two-fold. However, this groundrule has since changed by requiring that the Secondary Oxygen Pack supply pressure retention for 8 psi and oxygen supply, yet not be required to supply an equal amount of convective cooling as would have been provided by an 4 psi EMU. This change will keep the Secondary Oxygen Pack at current size and keep it operable for 30 minutes.

- Leakage: For a 7 hour EVA capability the comparative leakage is as follows:

  4.3 psi EMU = 30 scc/min
  8.0 psi EMU = <50 scc/min

- Mobility: 8 psi very close to 4 psi. See Figure 29.

- 8 psi EMU Development Program Plan

DEMONSTRATOR SUIT SCHEDULE

Design	Complete
Manufacture	12/31/82
Assembly	2/15/83
Test	2/15/83
Deliver 1st Space Suit Assembly	2/15/83
Deliver 2nd Lower Torso Assembly (LTA) & Arm	3/15/83

8 PSI EMU IMPLEMENTATION

	Option I*	Option II*
Go ahead	January '83	October '84
Design/cert comp	January '85	September '86
First 8 psi flight	July '85	January '87
All 8 psi flights capability	January '87	October '88
Last hardware delivery	April '87	September '89

* Difference Between options purely in start date.

QUESTION 7 EMU VENTING

EMU Outgassing - What does EMU vent?

The current EMU vents water vapor from the sublimator heat rejection system (Nominal heat rejection rate of 1000 Btu/Hr results in steam production rate of 1.68 lb_m/hr); leaks gases and trace organics (0.016 lb_m/hr and 9.5×10^{-6} lb_m/hr respectively); and expels particles from the EMU surfaces (0.5 to 500 micron dust, lint, and metal). If a regenerative system is used the EMU will not vent H_2O and be capable of operation within 3 feet of a cryogenically cooled sensor or optics system (3 feet is current safe limit before EMU venting could contaminate sensor).

QUESTION 8 RECHARGE PENALTIES

What recharge penalties are associated with each mode of EMU operating pressure?

4 psi baseline -	battery recharge	50 watts
	oxygen recharge	1.2 lb
	LiOH recharge	6.4 lb
	H_2O recharge	10.0 lb
8 psi -	battery recharge	58 watts
	oxygen recharge	no greater than 4 psi
	LiOH recharge	no greater than 4 psi
	H_2O recharge	no greater than 4 psi
8 psi non vent - Space Station EMU	battery recharge	65 watts
	oxygen recharge	no greater than 4 psi
	CO_2 recharge	225 watts
	H_2O recharge	150 watts

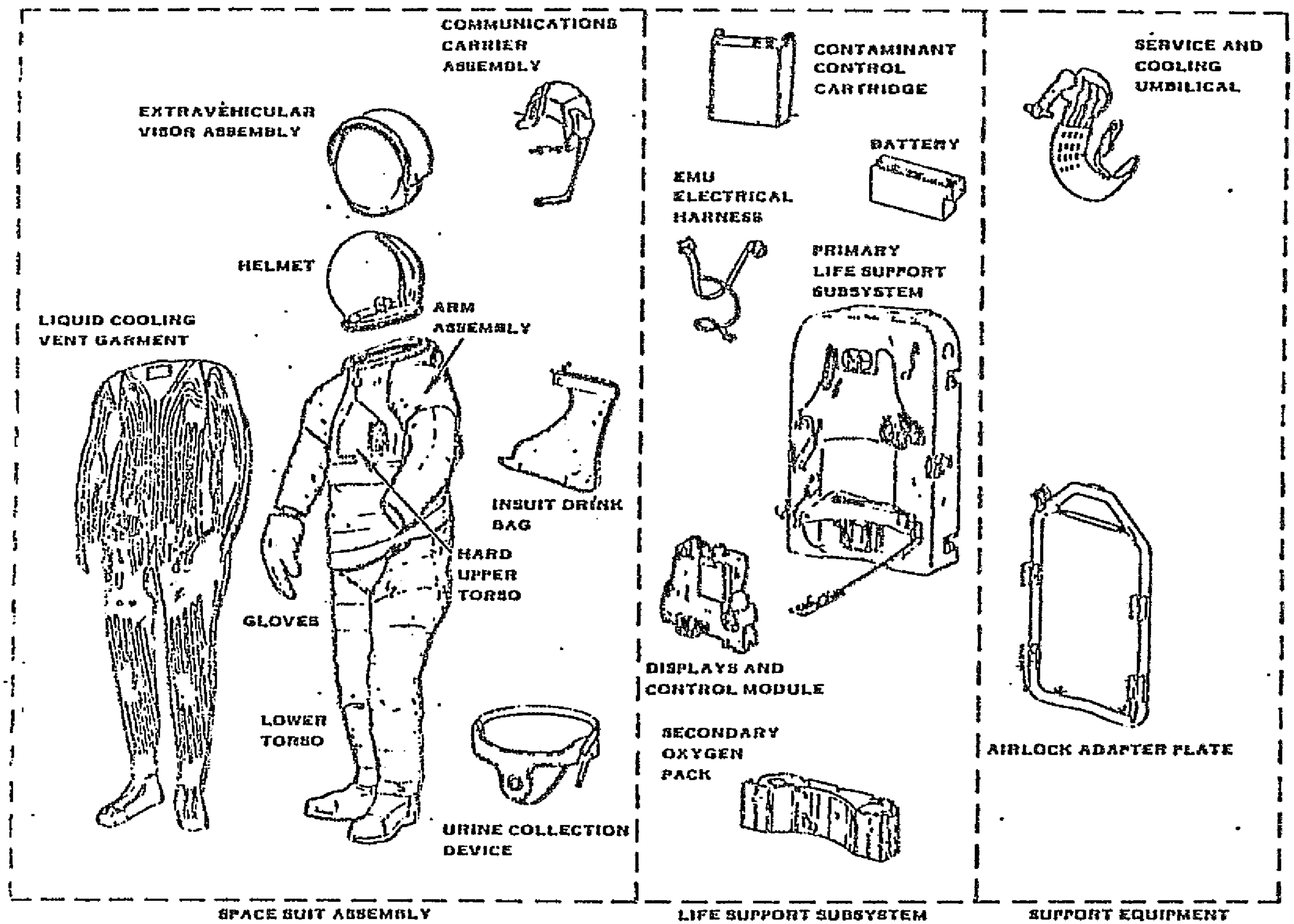


FIGURE 1 SPACE SHUTTLE EMU END ITEMS

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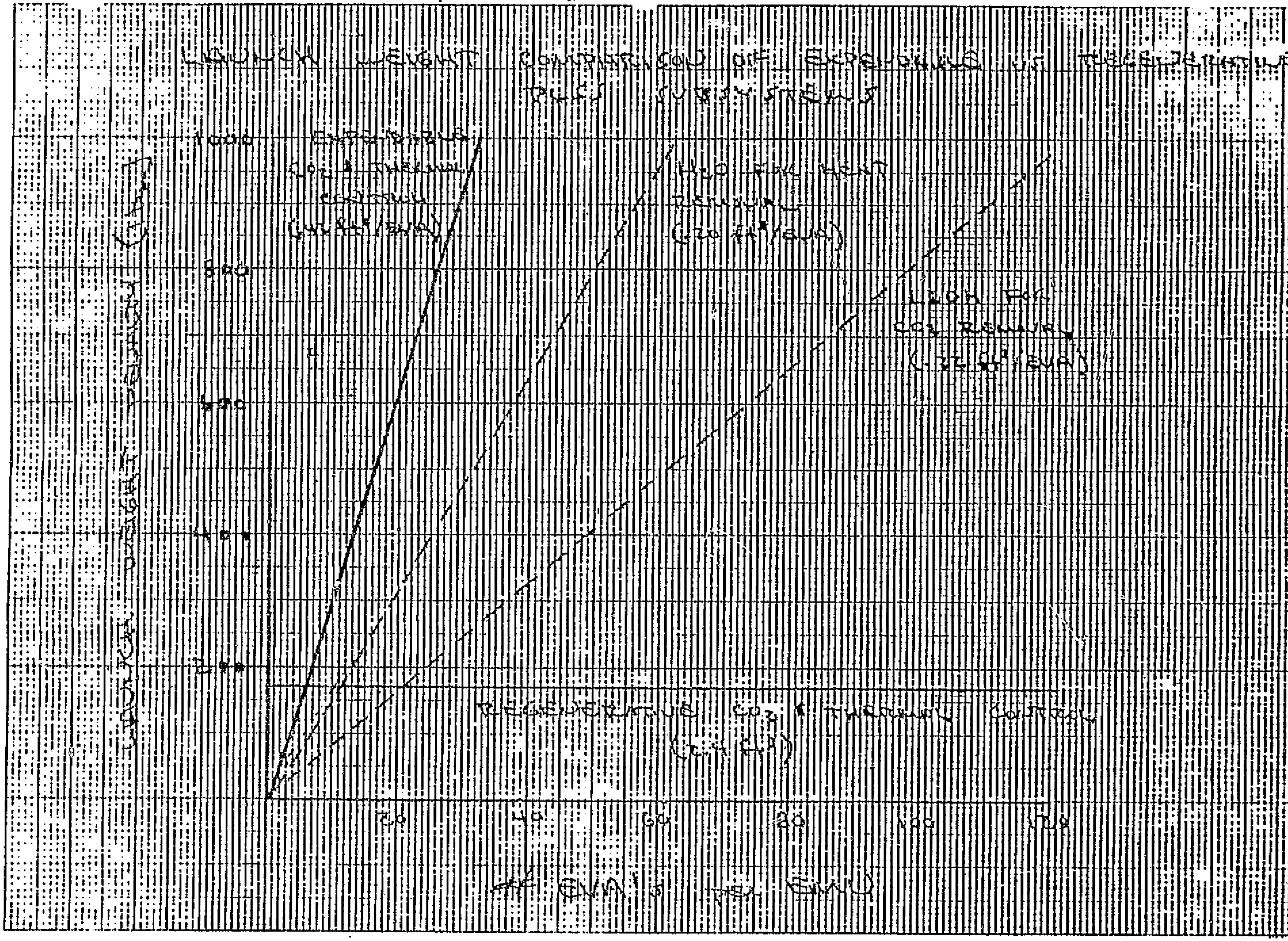
FIGURE



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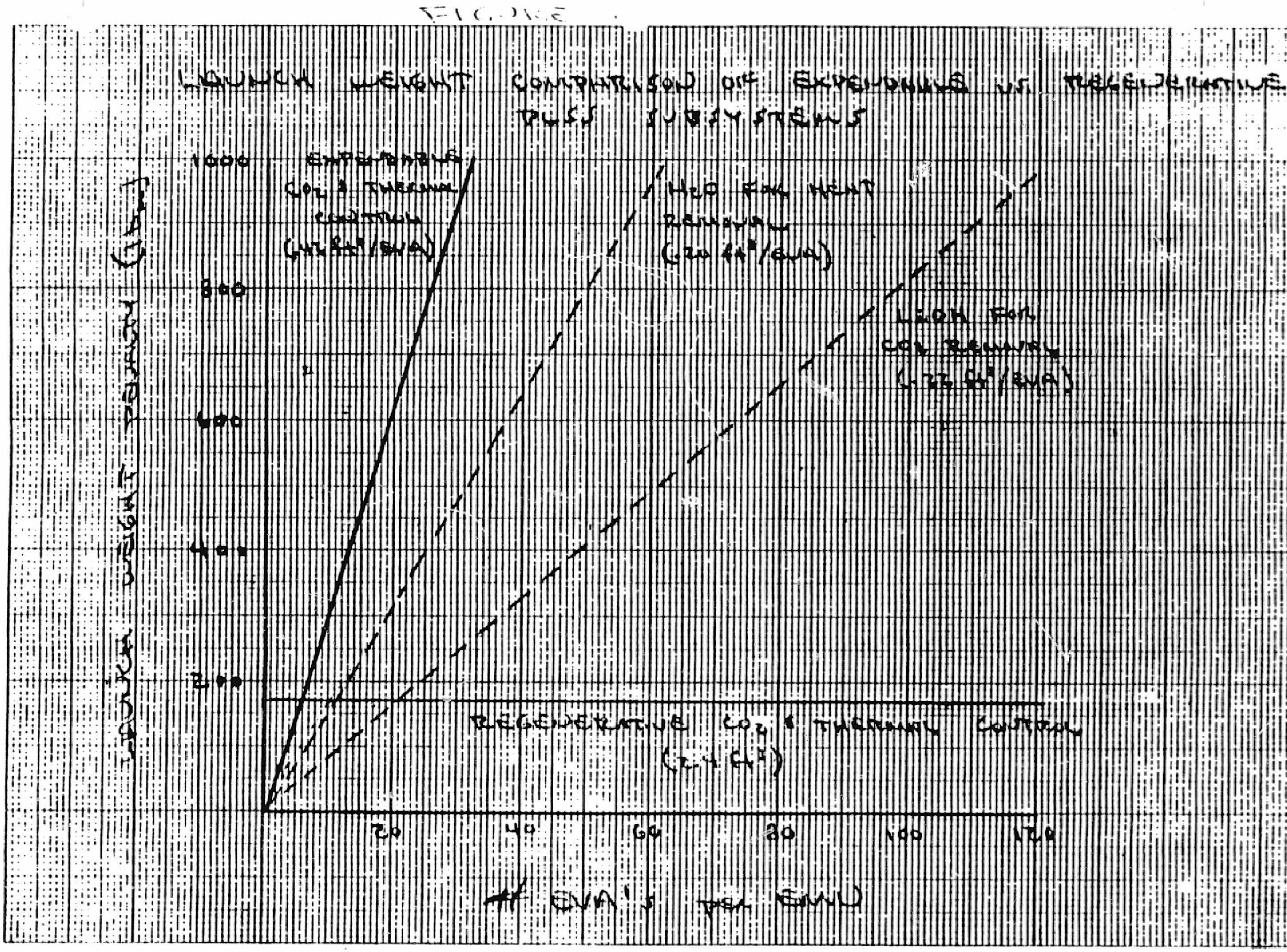
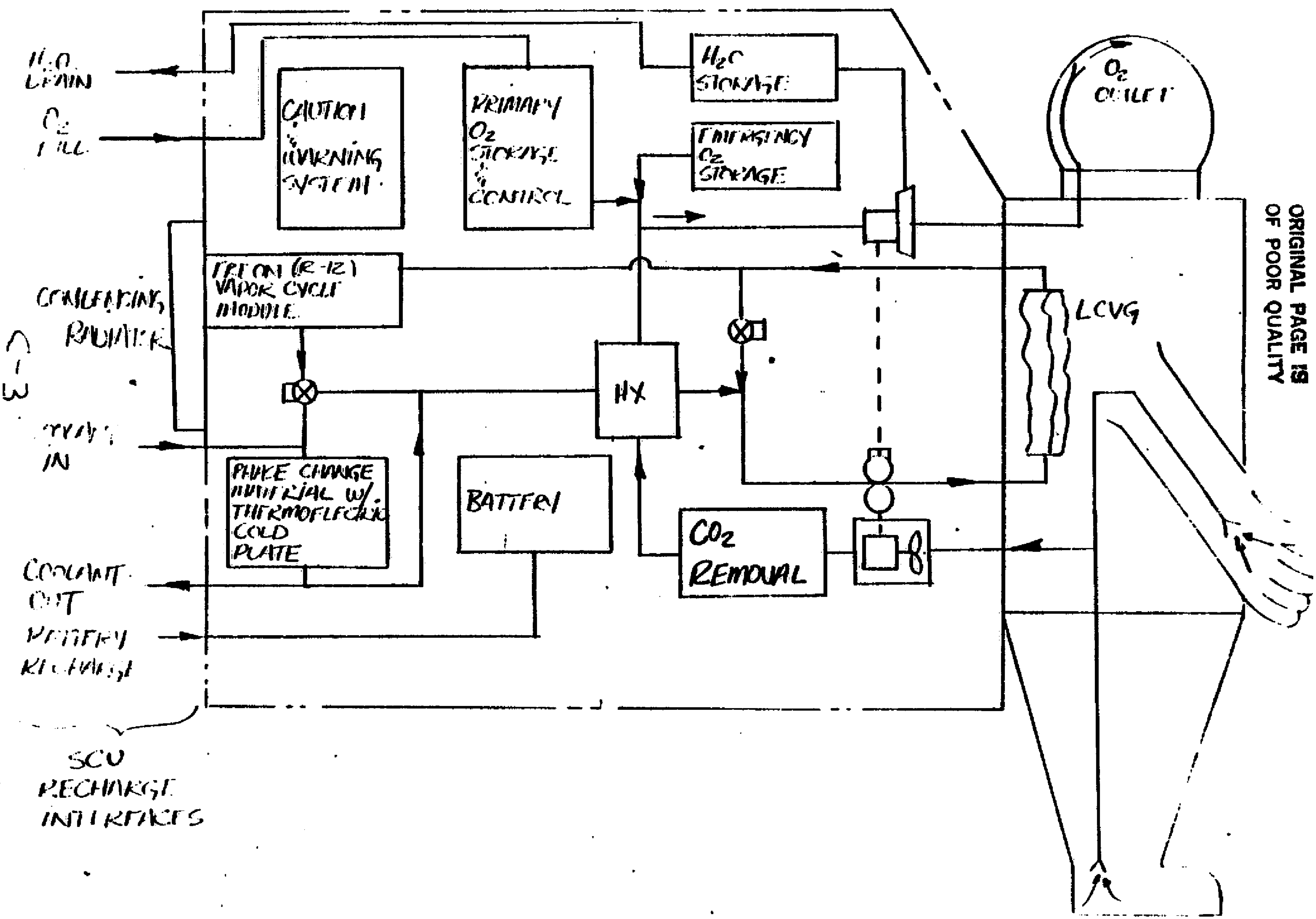
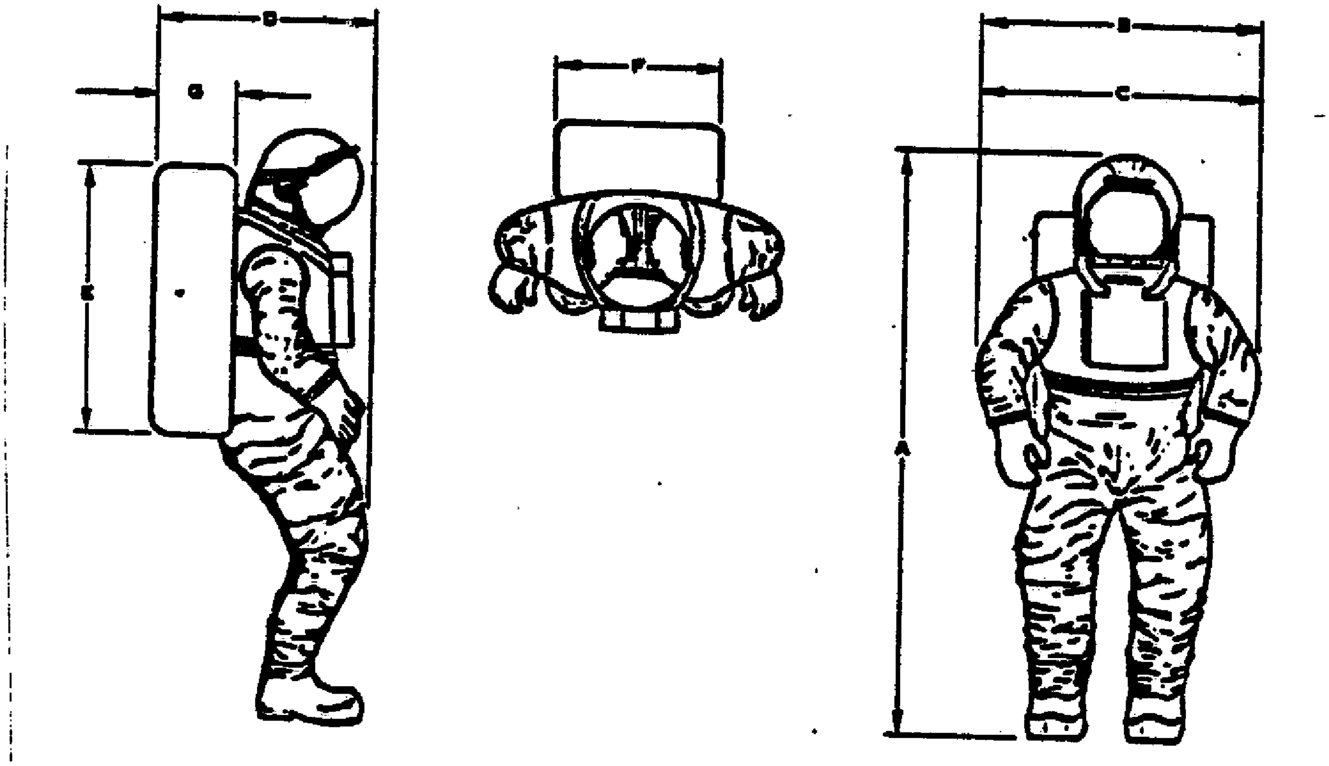

LAUNCH WEIGHT COMPARISON OF EXPENDABLE VS. REGENERATIVE
PLSS SUBSYSTEMS
EXPENDABLE
H2O FOR HEAT
REMOVAL
LiOH FOR
CO2 REMOVAL
REGENERATIVE CO2 & THERMAL CONTROL
1000
800
600
400
200
20
40
60
80
100
120
EVA'S PER EMU

FIGURE 3

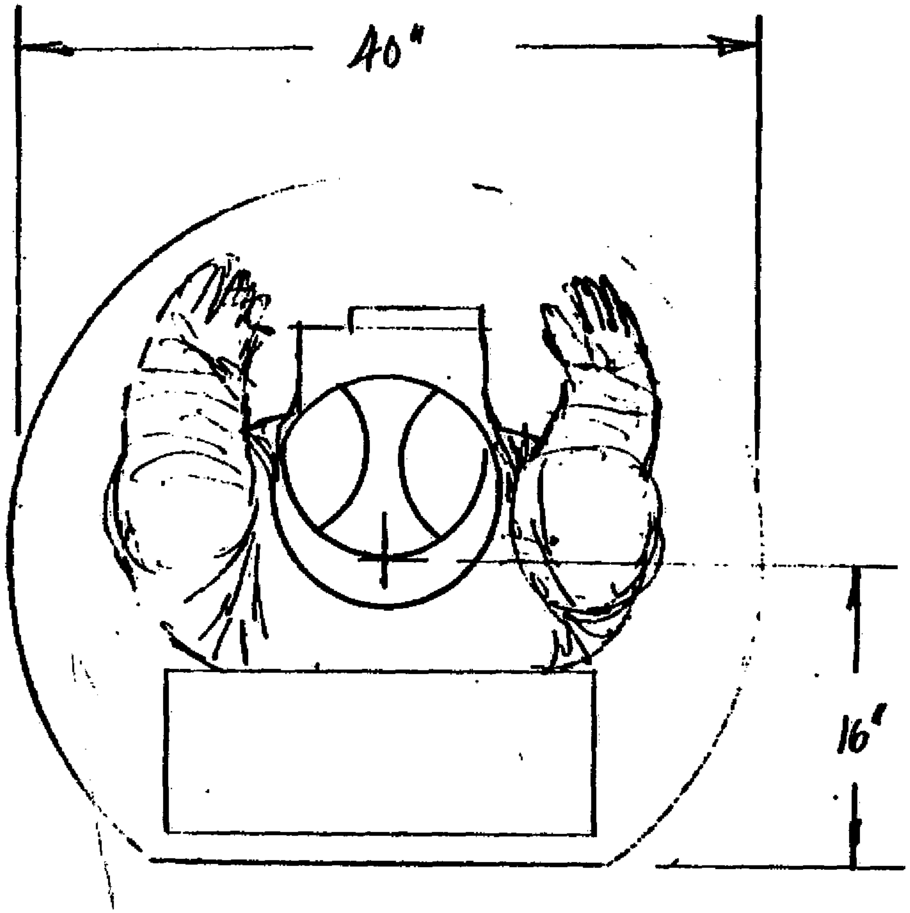
EMU w/ REGENERABLE THERMAL & CO_2 CONTROL





	PERCENTILE MAN			
	5%		95%	
DIMENSION	cm	IN	cm	IN
A	171.5	67.5	192.8	75.5
B (ARMS RELAXED)			74.7	29.4
C (ARMS AT SIDE)			67.1	26.4
D	70.8	27.9	76.9	30.3
	CM (MAX)		IN. (MAX)	
E	108.5		42.7	
F	58.4		23.0	
G	22.6		8.9	

FIGURE 4
EMU ENVELOPE W/ REGENERATIVE
THERMAL SINK & CO_2 REMOVAL



"SHUTTLE" GEOMETRY
HATCH.

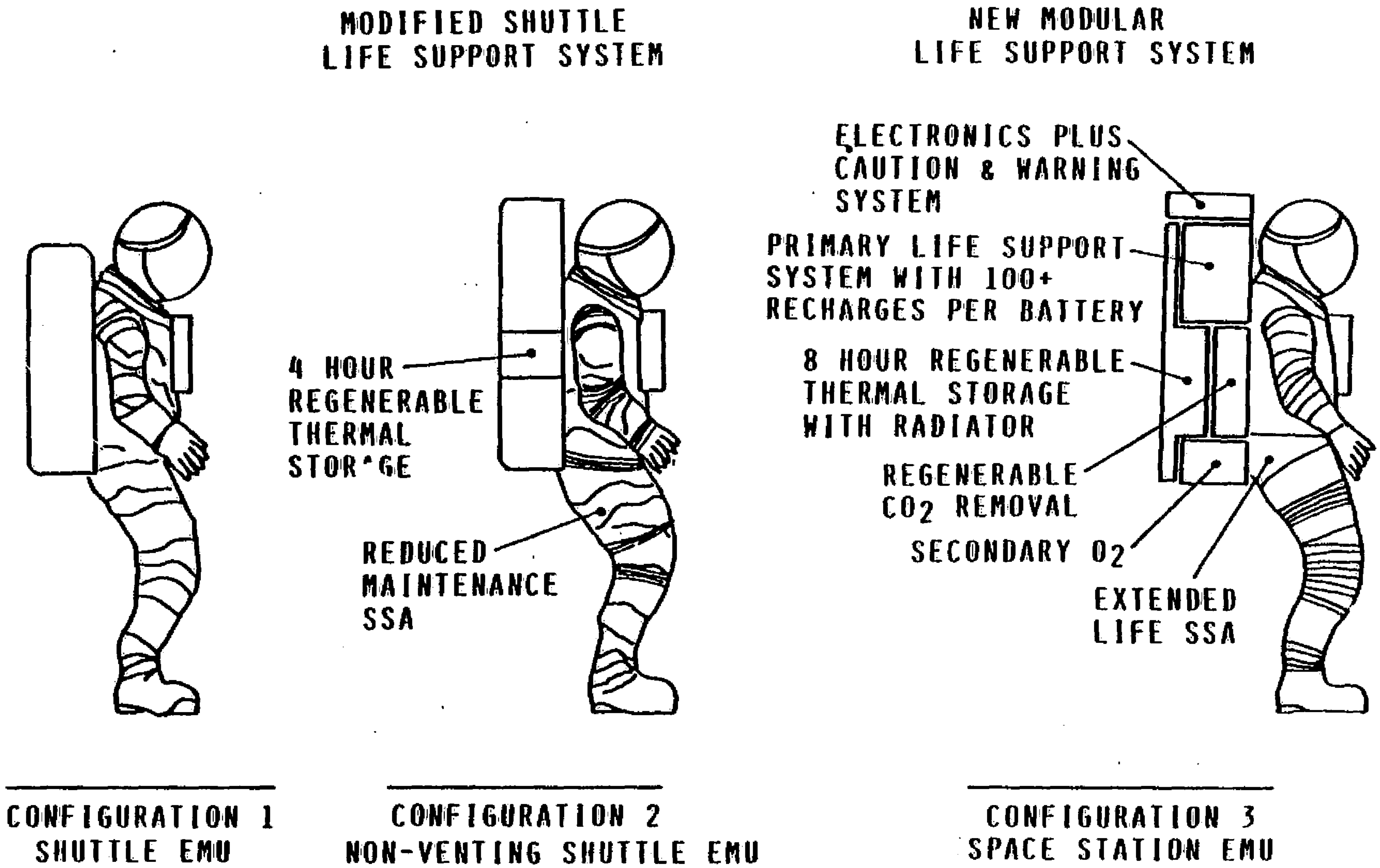
FIGURE 5

IV & EVA 40" DIA HATCH CLEARANCE
w/ REGENERABLE EMU

1/10 SCALE

EMU EVOLUTION

FIGURE 6a



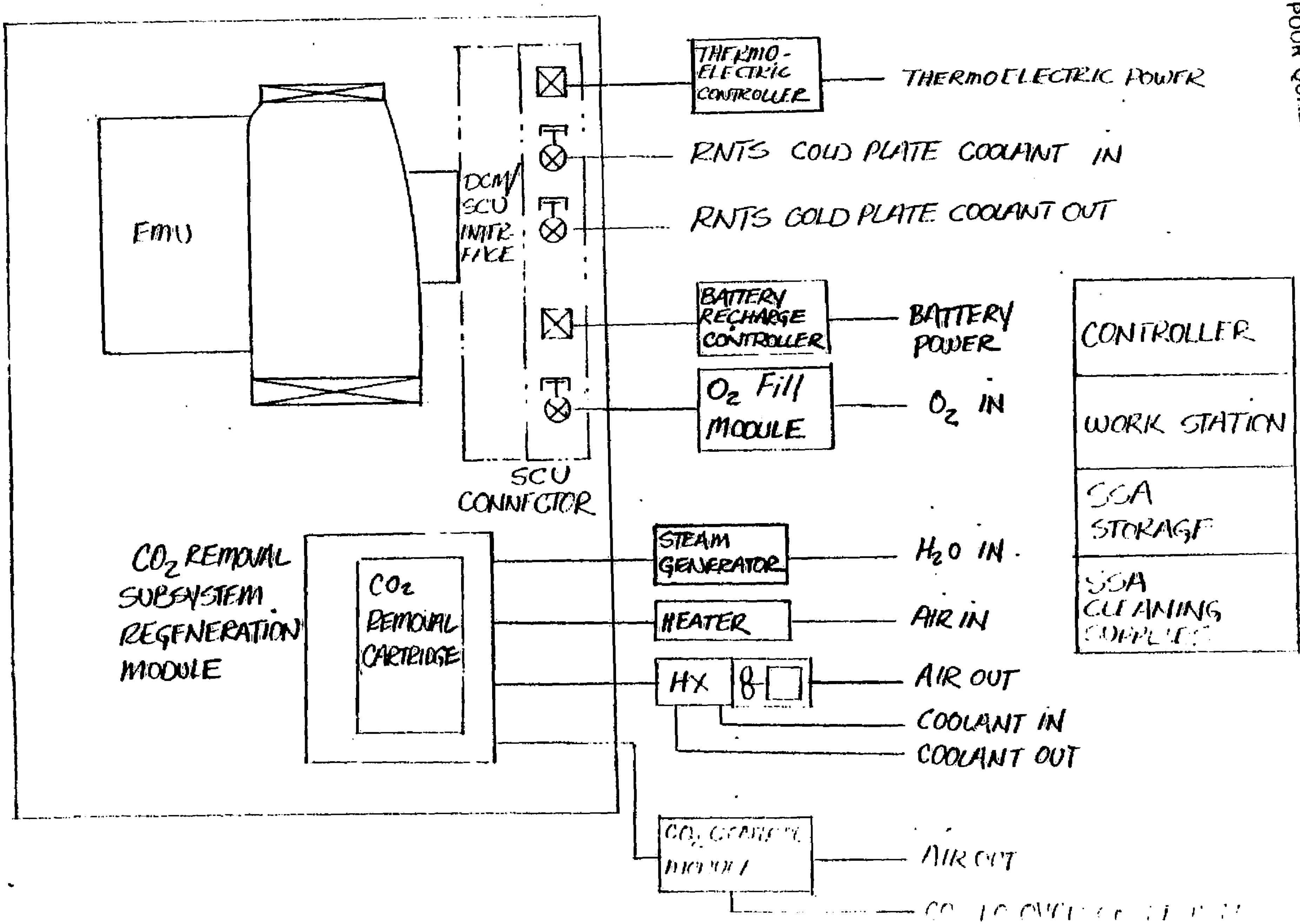
CONFIGURATION COMPARISONS

FIGURE 6b

CONFIGURATION	1	2	3
TECHNOLOGY AVAILABILITY	PRESENT	1985-1990	1990-1995
WEIGHT (LB) (CHARGED)	242	310	435
EXPENDABLE PENALTY PER EVA (LB/EVA)	25.1	15.4	1.0
VOLUME (STOWED)	16.2	17.1	22
REGENERATION POWER (WATTS)	50	190	440
EVA's BETWEEN REFURBISHMENT	5	15	65
TOTAL LIFE (EVA's)	30	30	750

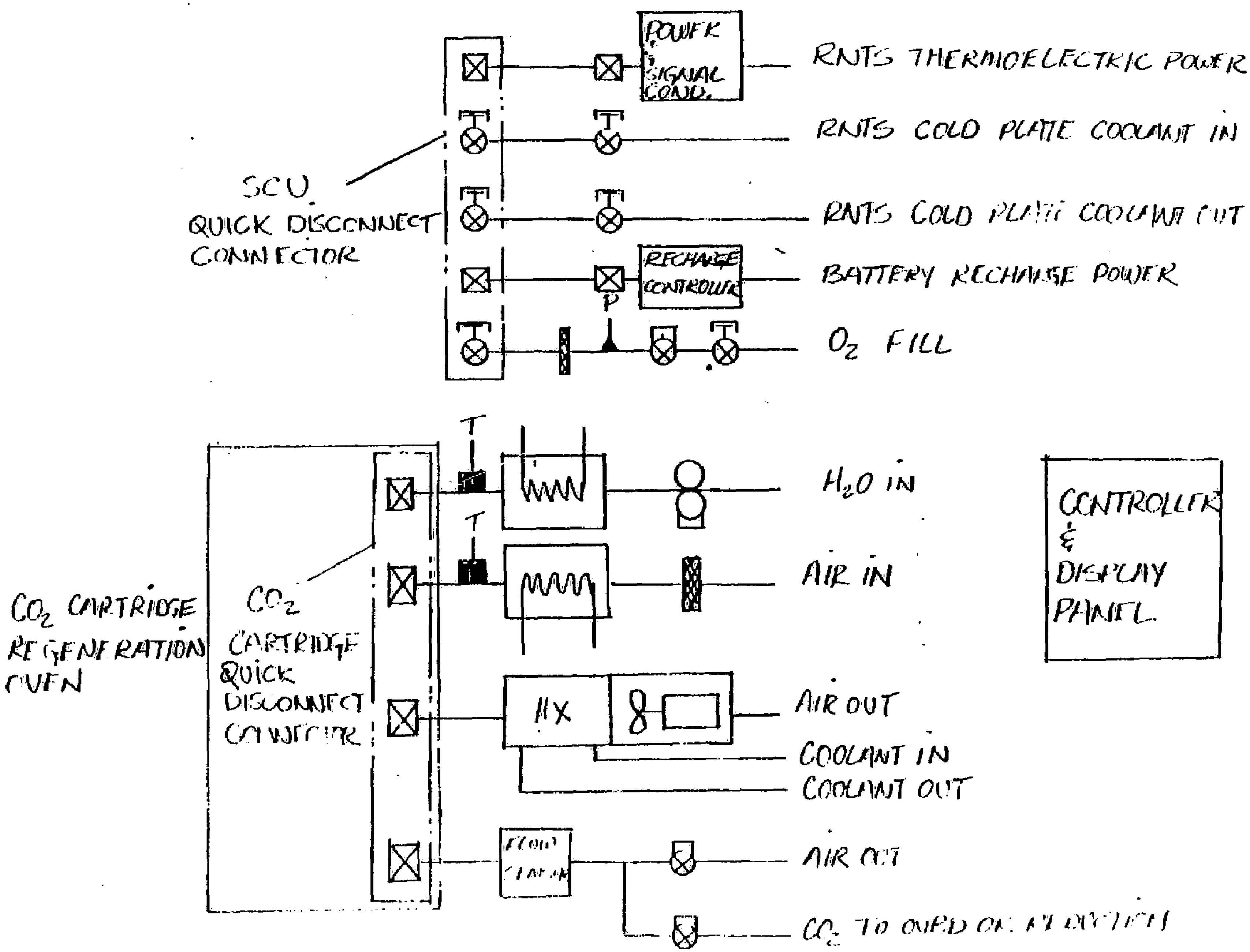
RECHARGE STATION

FIGURE 7



RECHARGE STATION SCHEMATIC

FIGURE 8

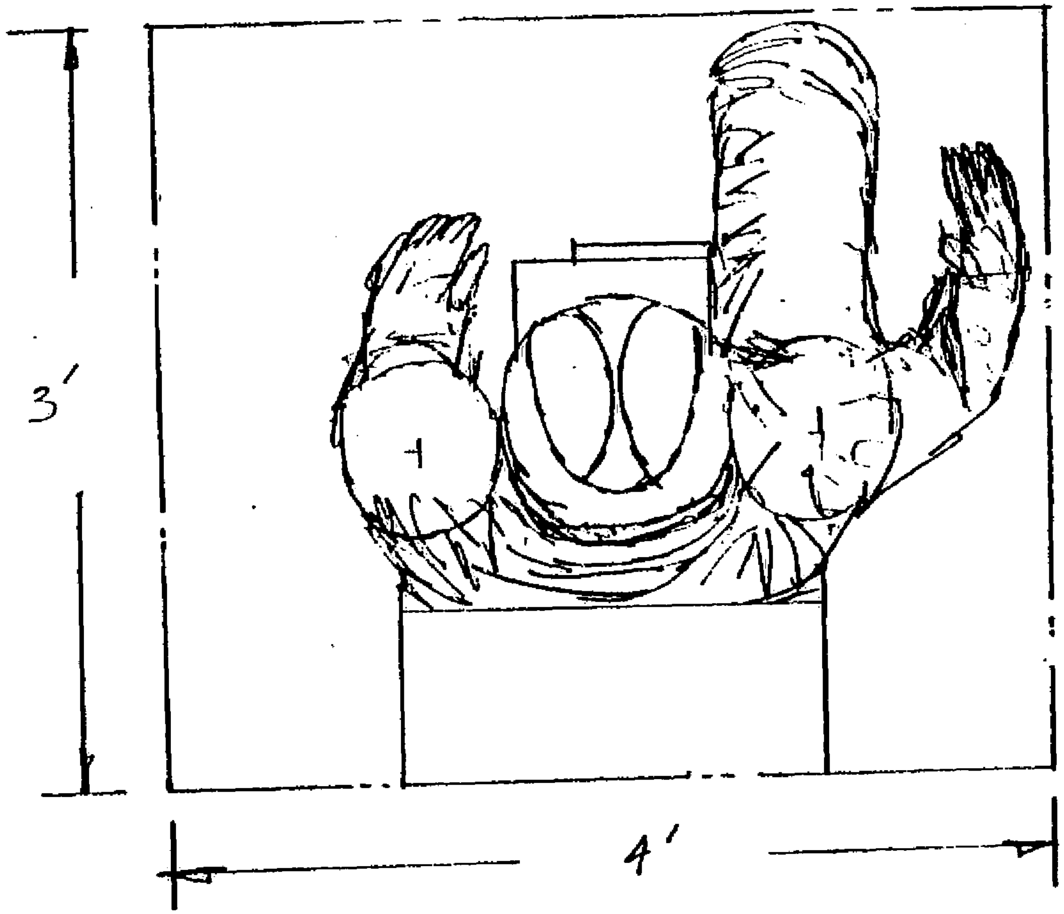


RECHARGE STATION EQUIPMENT
FIGURE 9

EQUIPMENT	NO. REQ'D	WEIGHT EA. (lbs)	WEIGHT TOTAL (lbs)	VOLUME EA. (FT^3)	VOLUME TOTAL (FT^3)		
RMTS / BATTERY / O_2 RECHARGE	2	26	52	1.8	3.6		
CO_2 REGENERATION	2	78	156	5.8	11.6		
REGENERATIVE EMU w/ SCU, AAP	3	469	1407	.22	66		Revised
WORK STATION, TOOLS, FIXTURES, MANUALS	—	100	100	—	—		
BODY STOCKING, CLEANING SUPPLIES	15	5 oz EA	4.7	20 IN^3	.17	*	
LCVG	2	6.5	13	.8	1.6		
TOTALS			1732		82.9		Revised

* 90 DAY RESUPPLY, ~150 EVA'S

REGENERATIVE EMU DONNING VOLUME
95TH PERCENTILE



DONNING VOLUME: $3' \times 4' \times 7.3' = 88\ ft^3$

FIGURE 10

RECHARGE STATION AI[illegible] E ACCESS REQUIREMENTS

FIGURE 11

SYSTEM	REQUIRED FRONT ACCESS AREA FT^2	ACCESS/AISLE VOLUME FT^3 *
DONNING STATION	29	87
STORAGE 2 EMUS	21	63
REGENERATIVE CO_2 EQUIPMENT	9.4	28.2
RECHARGE CONTROLLER	3.1	9.3
REPAIR STATION	14.3	42.9
SCU	6.3	18.9
TOTAL	83.1 FT^2	249.3 FT^3

* ASSUMES 3' DEPTH AND NO OVERLAPPING FUNCTIONS

FIGURE 12

EMU STOWAGE VOLUMES

	VOLUME - FT^3	DIMENSIONS
EMU STOWED IN AAP	22.1	56.7" X 27" X 25"
PLSS	5.1	8.9" X 42.7" X 23.0"
HELMET - IN CASE	3.0	18" X 17" X 17"
LCVG	.8	17" X 17" X 5"
GLOVES	.2 PR.	6" X 6" X 10" PR.
GLOVES - IN CONTAINER	.5 PR.	11" DIA X 8.5" PR.
ARMS	1.9 PR.	15" X 24" X 9.2" PR.
LEGS - W/ FEET	3.2 PR.	17" X 27" X 12" PR.

FIGURE 13

VEHICLE CONFIGURATION QUESTIONS

— LOCATION OF AIRLOCK W/ RESPECT TO RECHARGE FACILITY

— AISLE SIZE & REQUIREMENTS

— MODULE DIAMETER

— CEILING HEIGHTS

— TYPICAL CREW ORIENTATION W/ RESPECT TO MODULE

— MAINTENANCE PHILOSOPHY

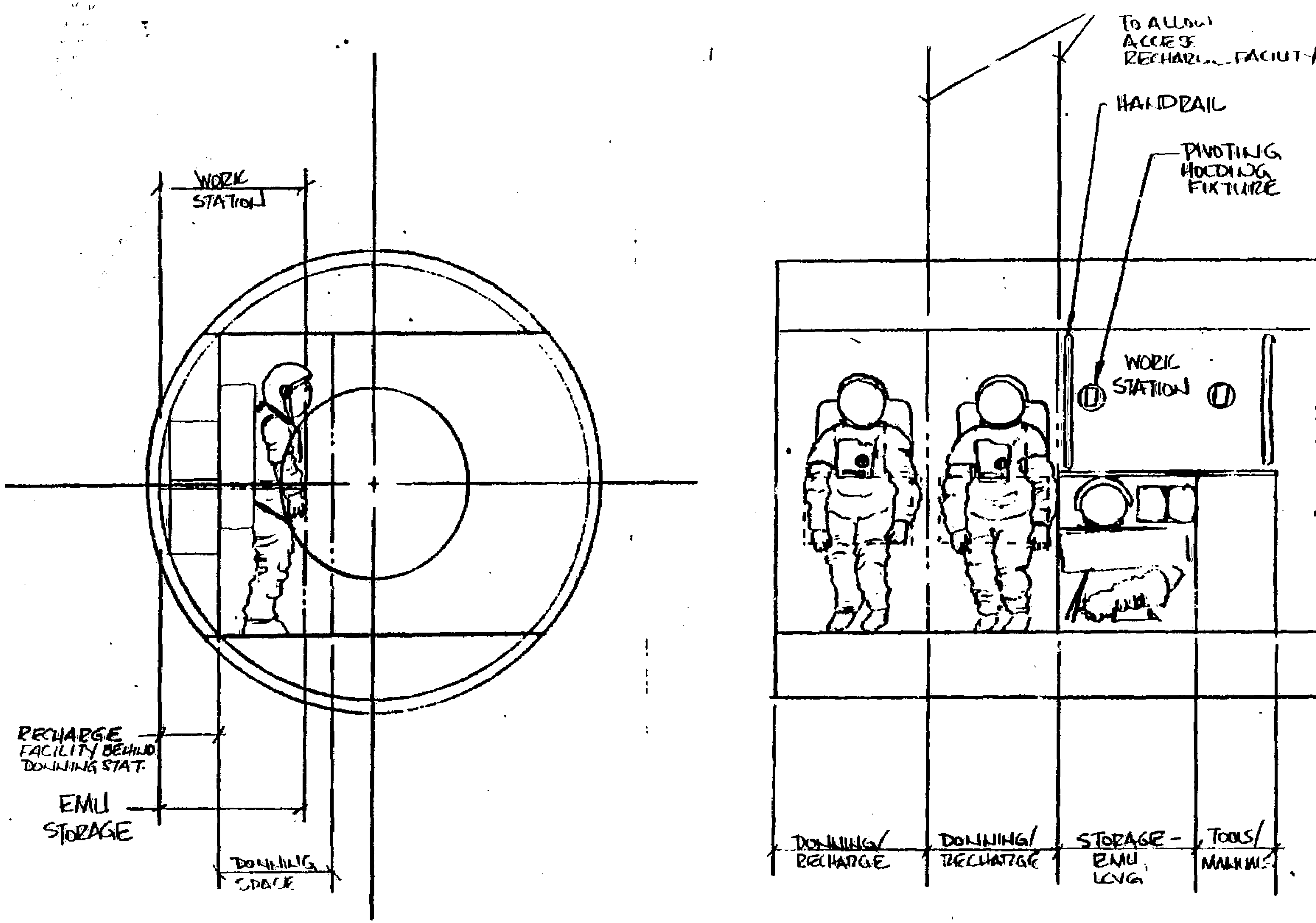

WORK STATION
RECHARGE FACILITY BEHIND DONNING STAT.
EMU STORAGE
DONNING SPACE
HANDRAIL
PIVOTING HOLDING FIXTURE
WORK STATION
DONNING/ RECHARGE
DONNING/ RECHARGE
STORAGE - EMU, LCVG
TOOLS/

FIGURE 14

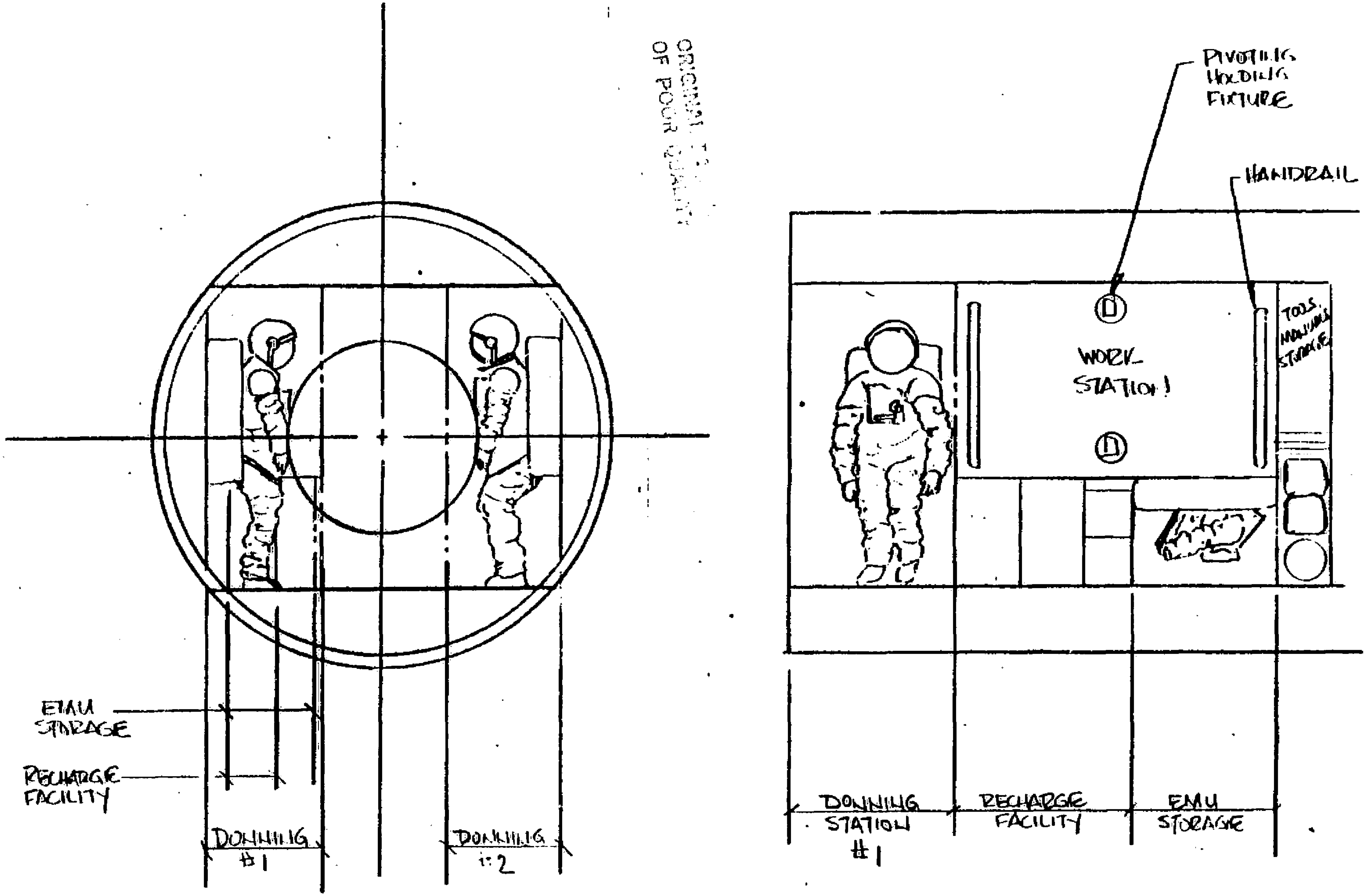
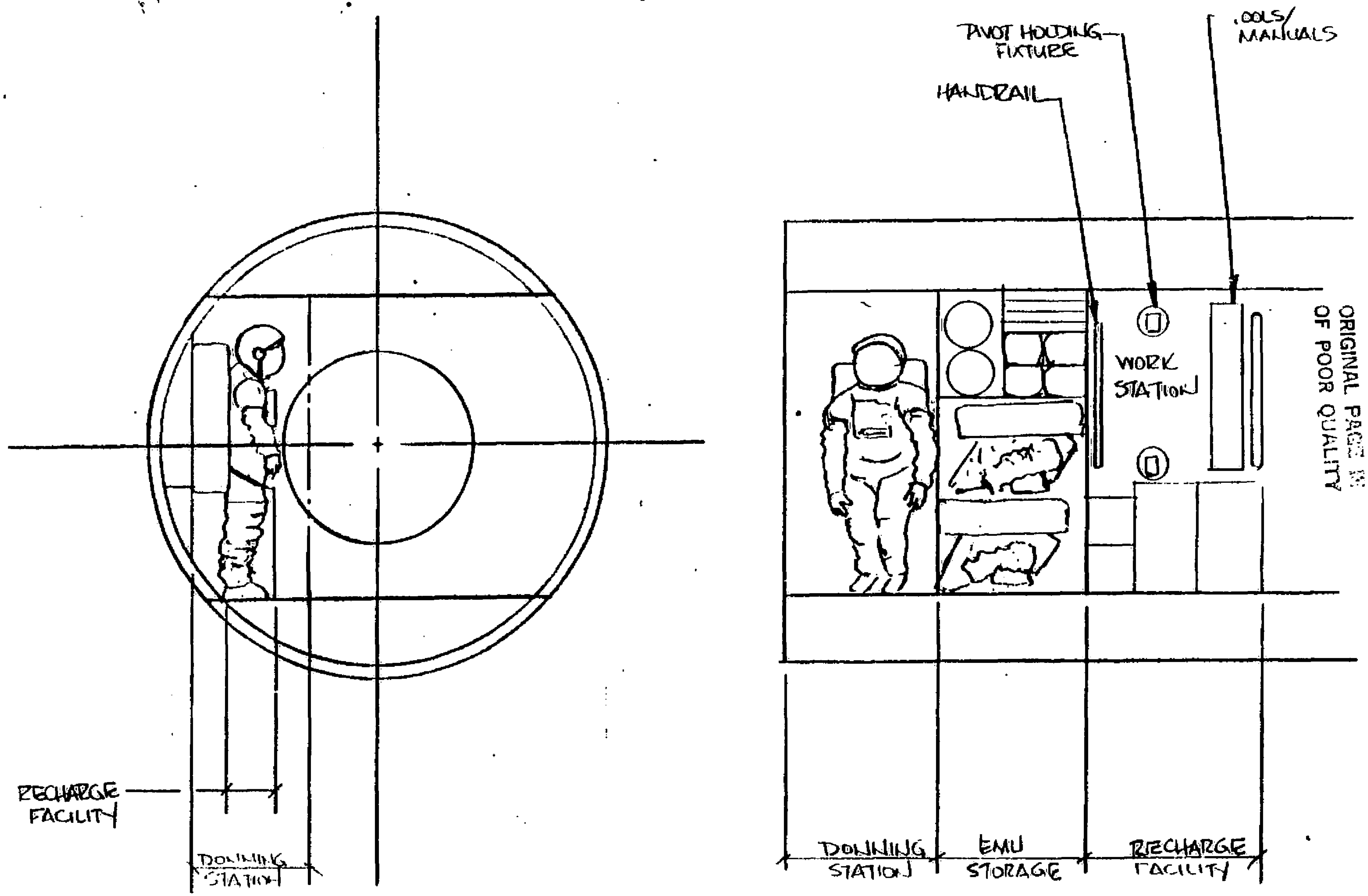
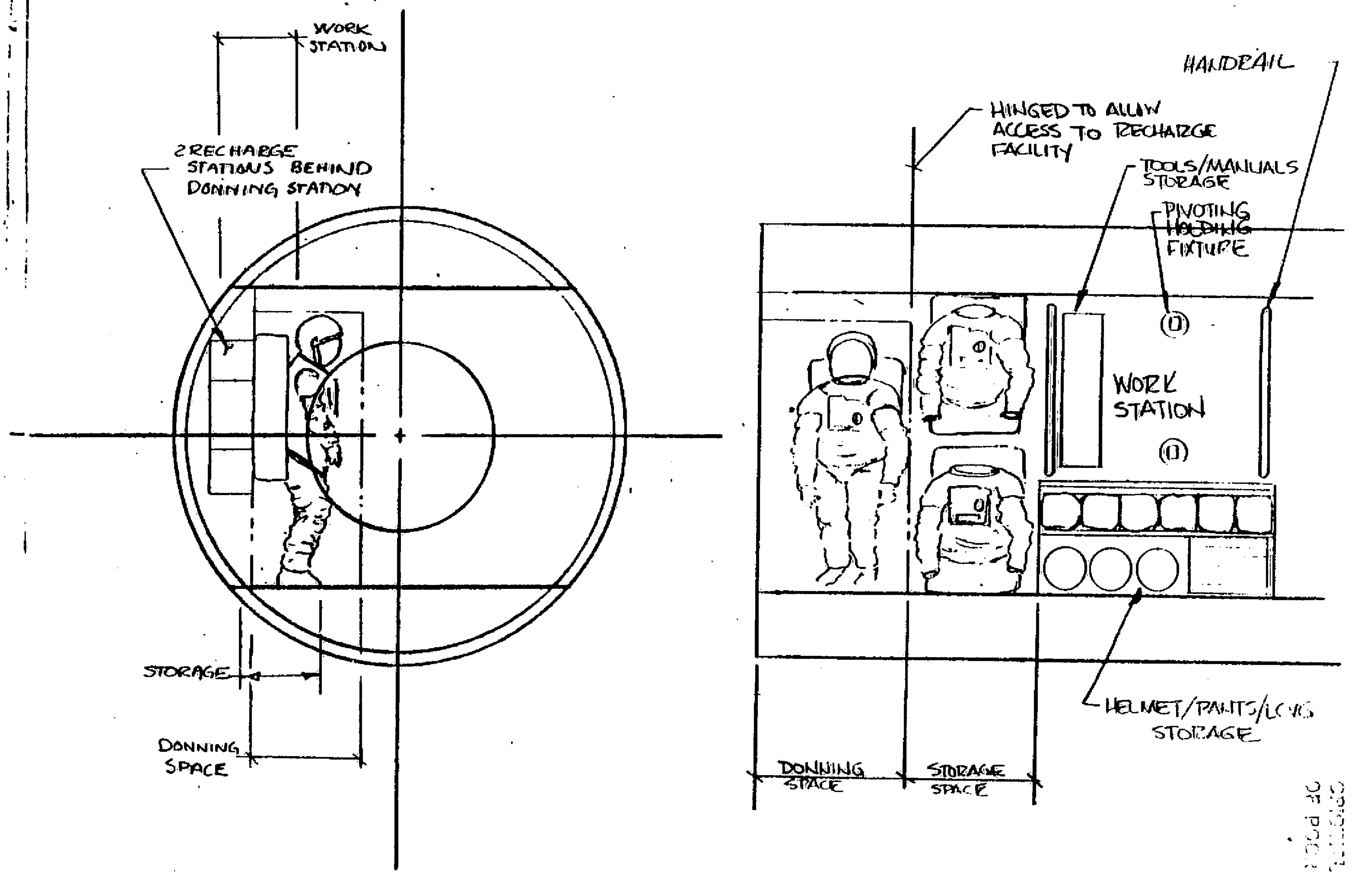

EMU STORAGE
RECHARGE FACILITY
DONNING #1
DONNING #2
PIVOTING HOLDING FIXTURE
HANDRAIL
WORK STATION 1
TOOLS, MANUALS STORAGE
DONNING STATION #1
RECHARGE FACILITY
EMU STORAGE

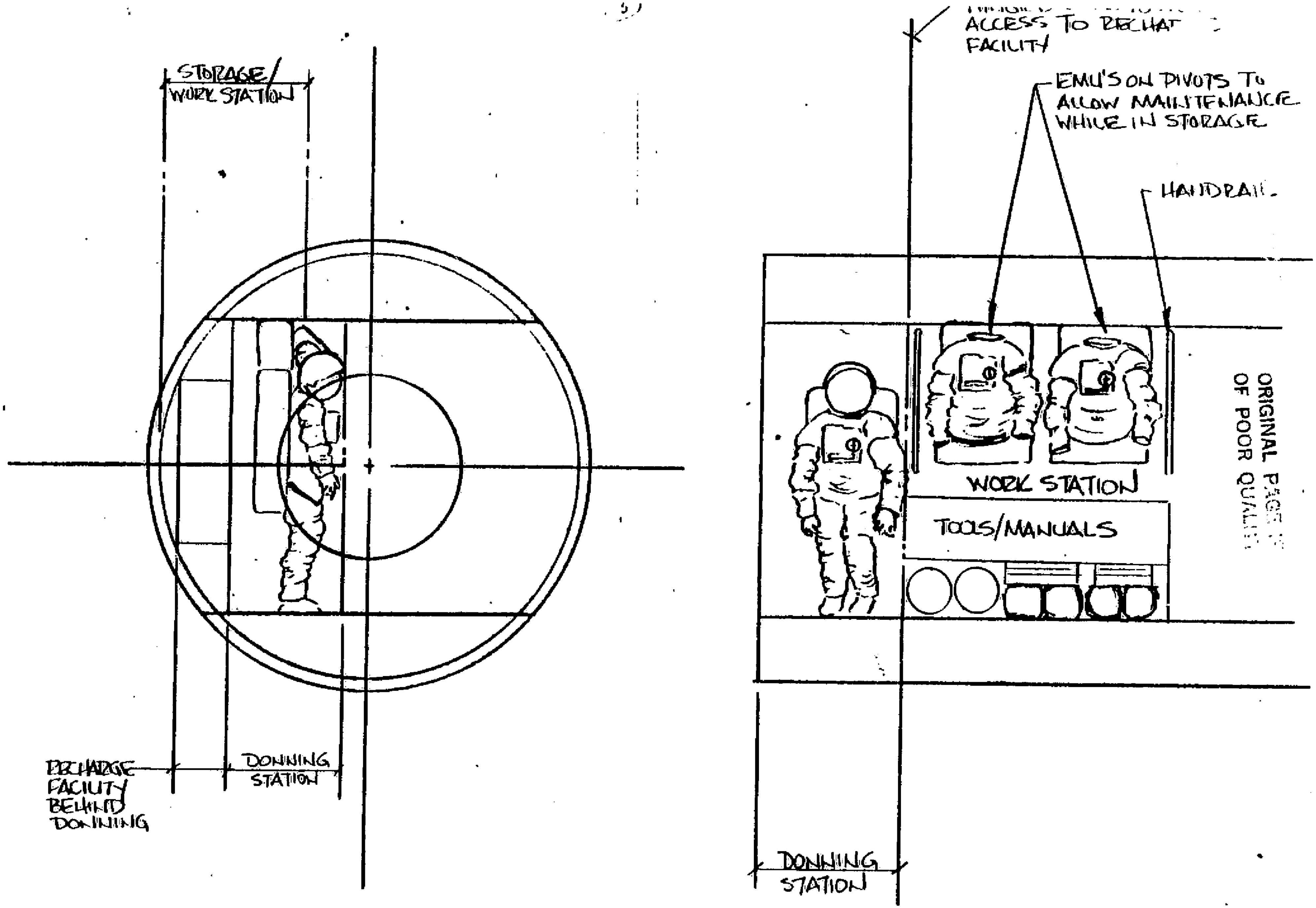
FIGURE 15


RECHARGE FACILITY
DONNING STATION
PIVOT HOLDING FIXTURE
HANDRAIL
.OOLS/ MANUALS
WORK STATION
DONNING STATION
EMU STORAGE
RECHARGE FACILITY



WORK STATION
2 RECHARGE STATIONS BEHIND DONNING STATION
STORAGE
DONNING SPACE
HANDRAIL
HINGED TO ALLOW ACCESS TO RECHARGE FACILITY
TOOLS/MANUALS STORAGE
PIVOTING FIXTURE
WORK STATION
HELMET/PANTS/LCVG STORAGE
DONNING SPACE
STORAGE SPACE

FIGURE 17



STORAGE/ WORK STATION
RECHARGE FACILITY BEHIND DONNING
DONNING STATION
ACCESS TO RECHAT FACILITY
EMU'S ON PIVOTS TO ALLOW MAINTENANCE WHILE IN STORAGE
HANDRAIL
WORK STATION
TOOLS/MANUALS
DONNING STATION

FIGURE 19

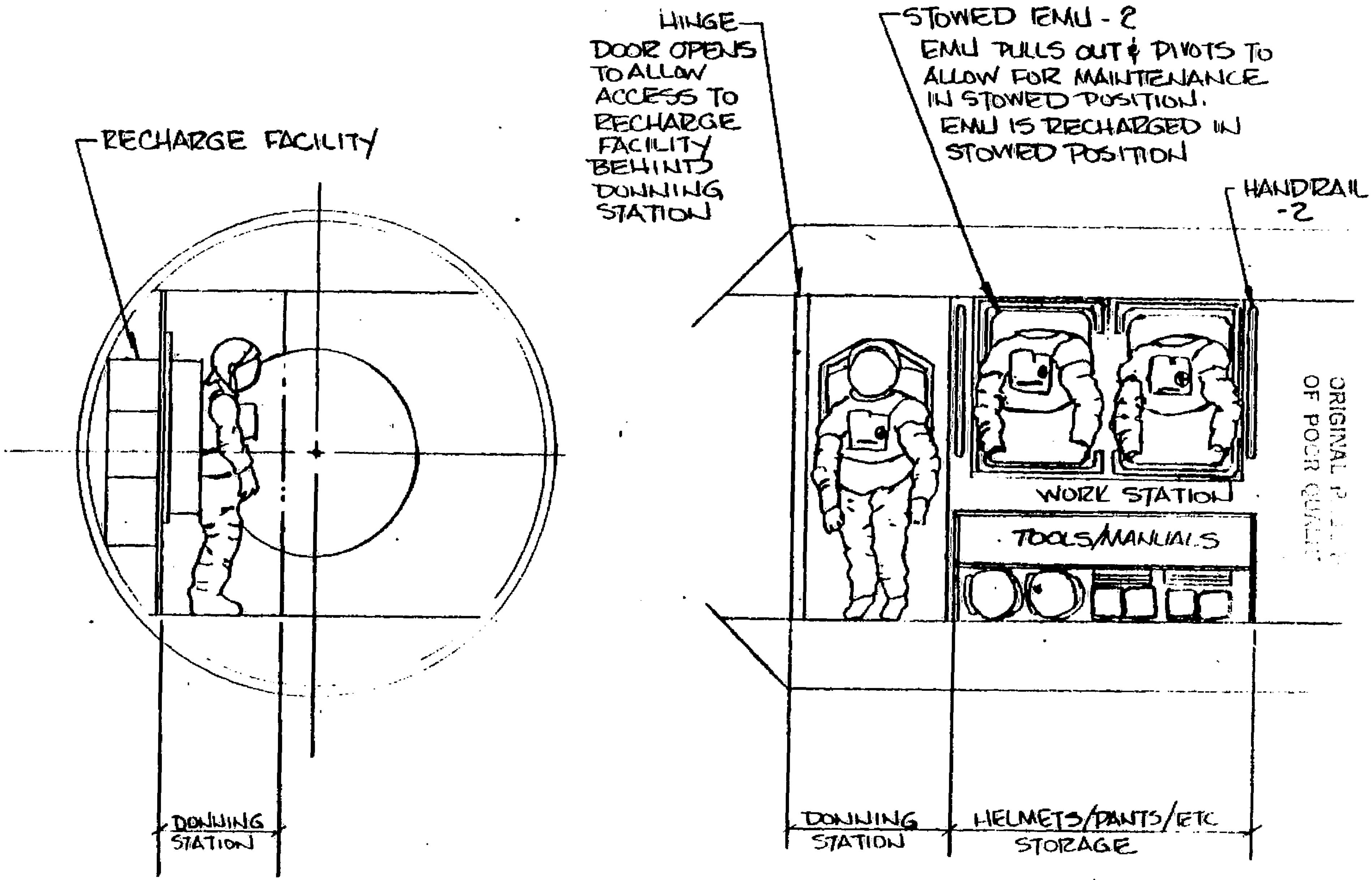
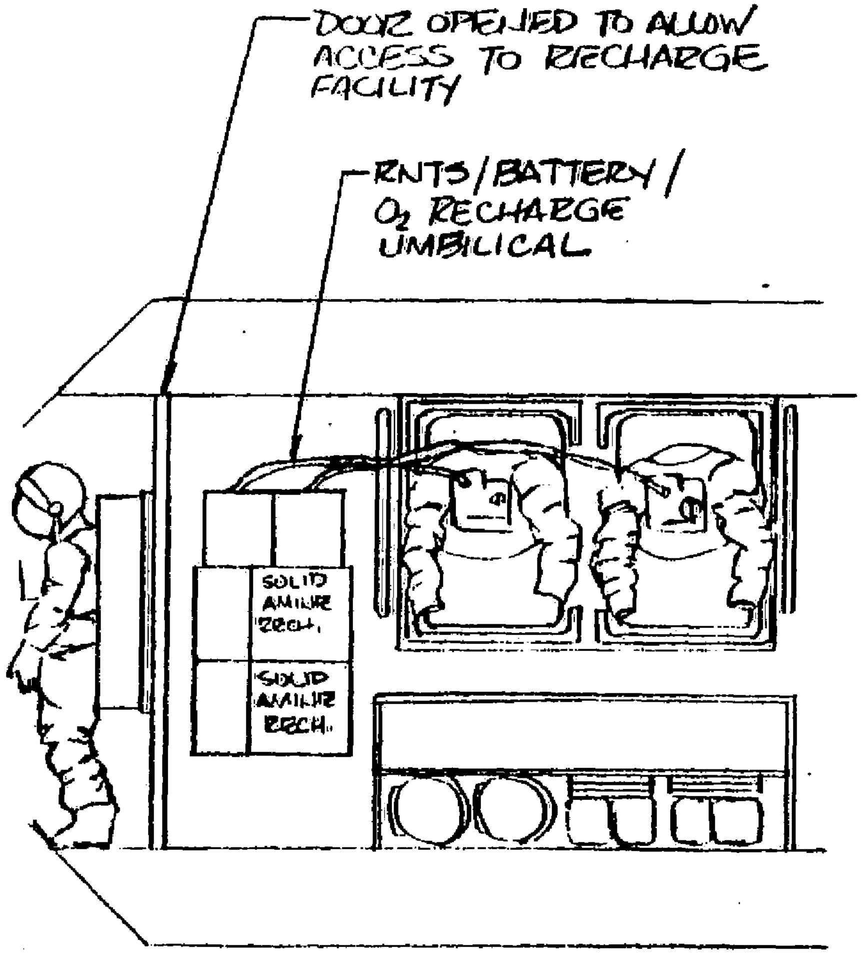


FIGURE 19
CONCEPT 5A
SH.1 OF 2

SCALE: 1/40



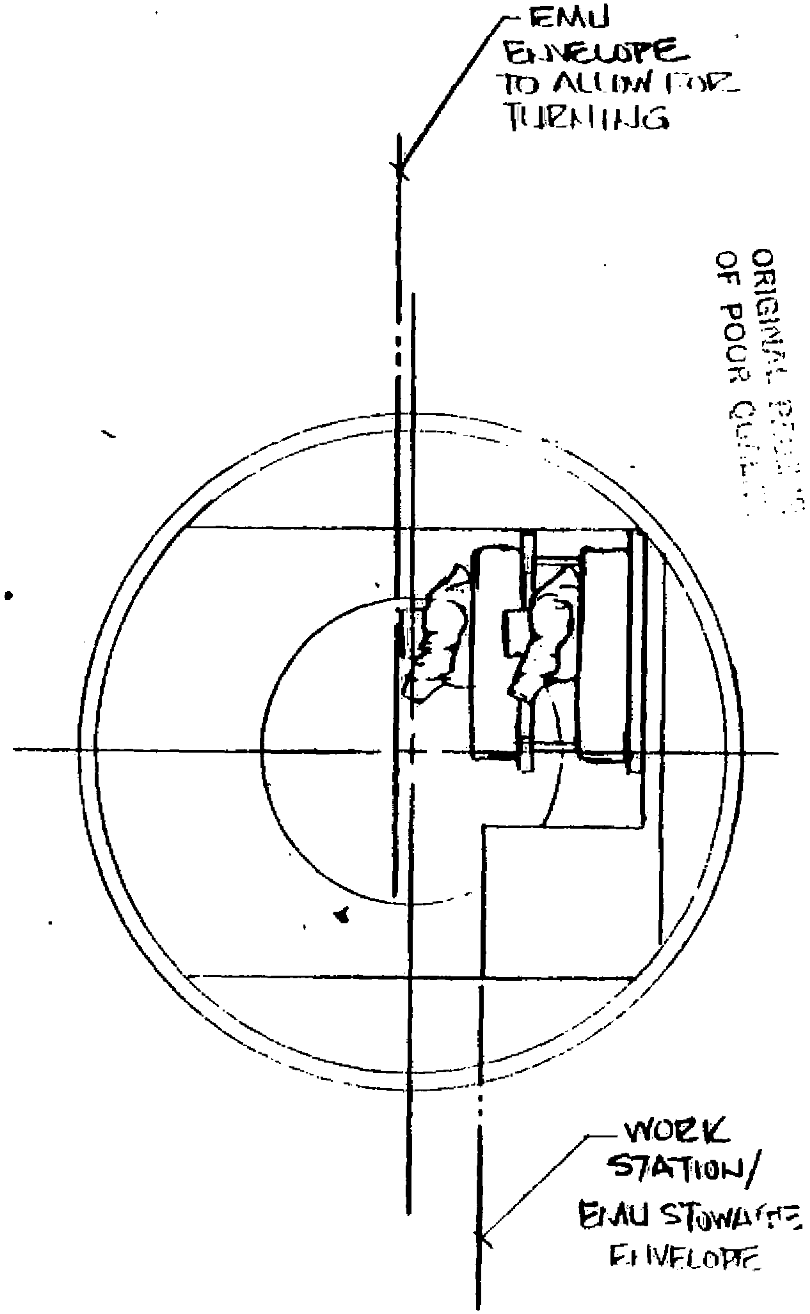
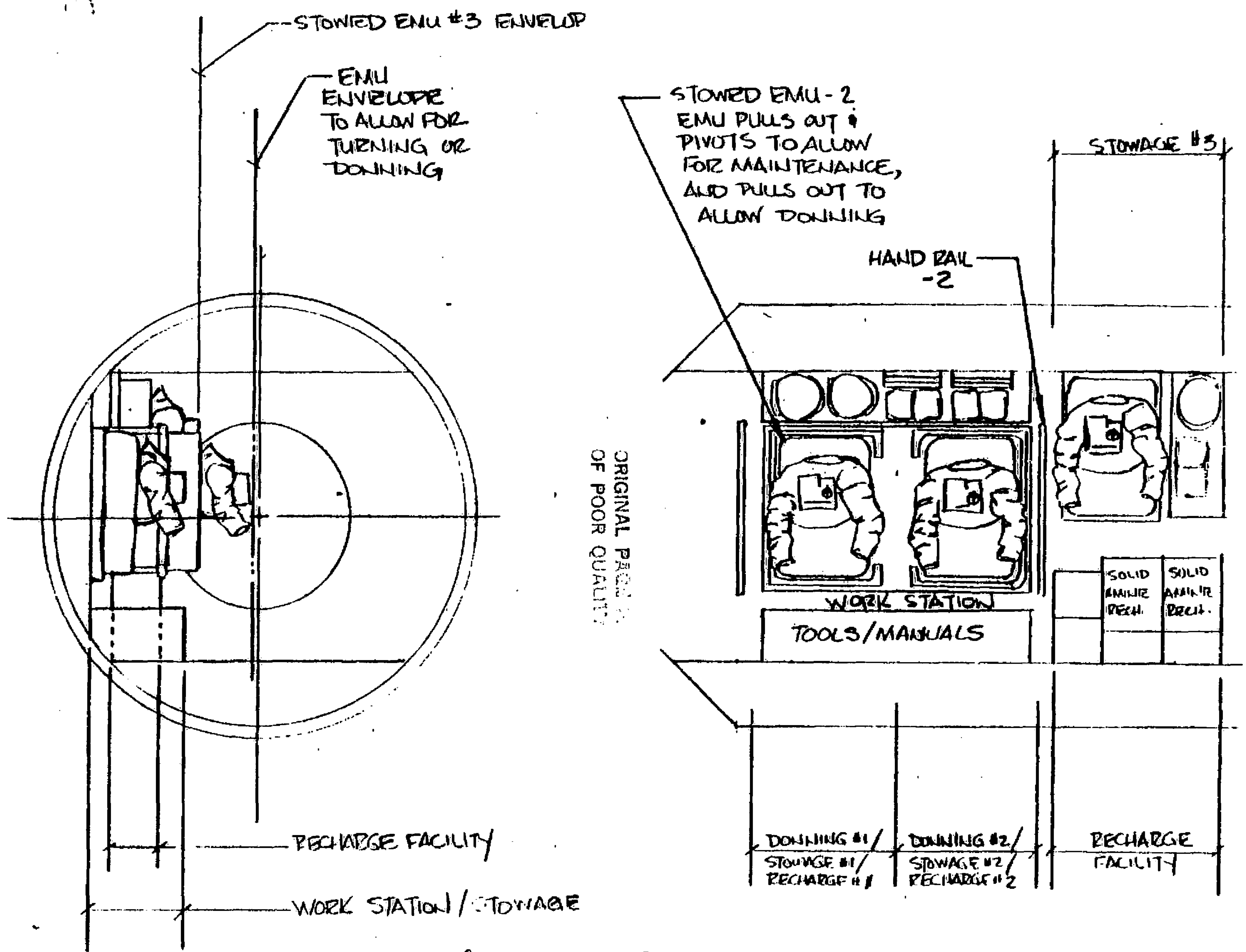


FIGURE 2[illegible]
CONCEPT 5A

SHEET 2 OF 2

SCALE: 1/40



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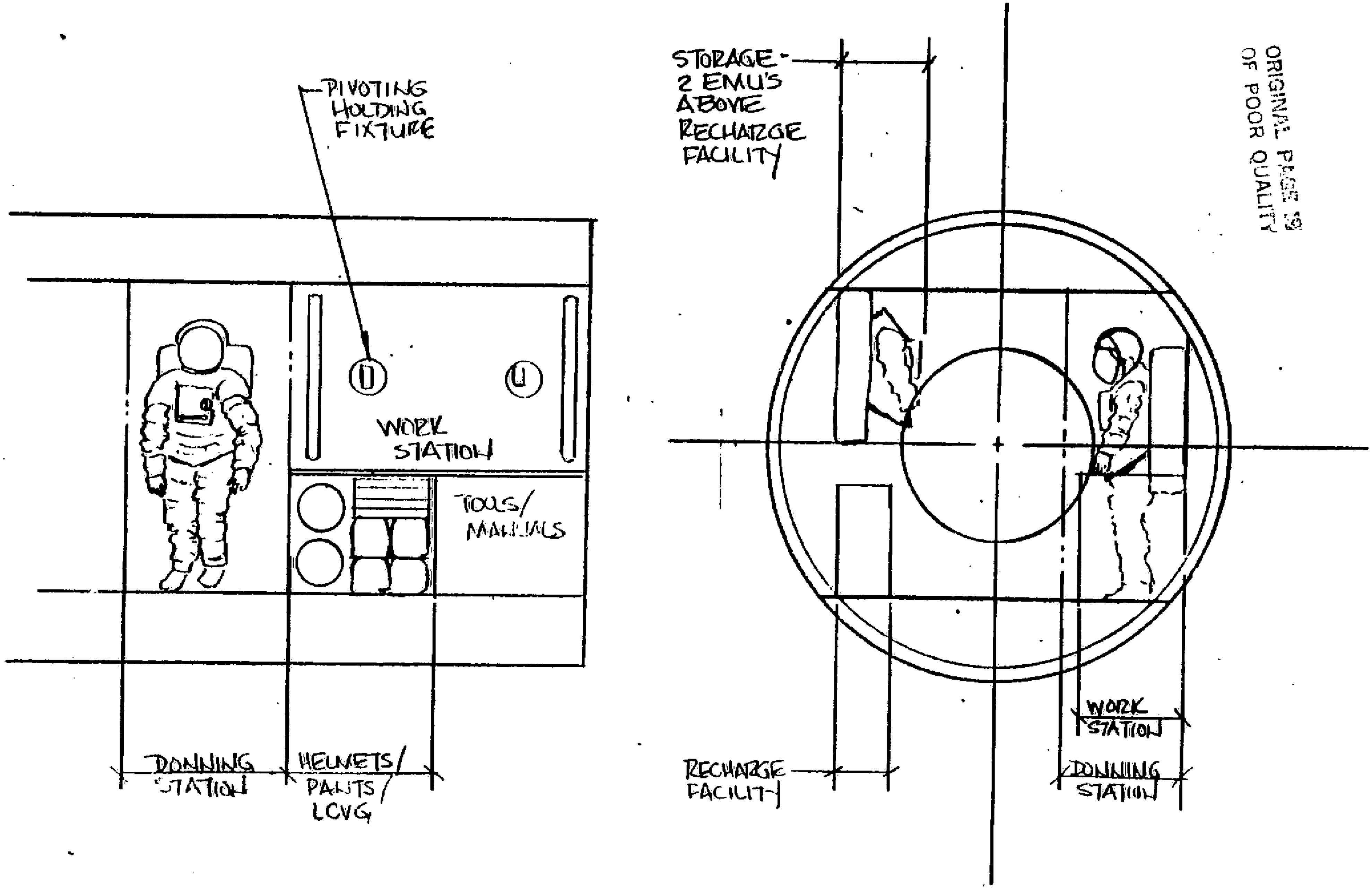
CONCEPT 5B

SCALE: 1/40

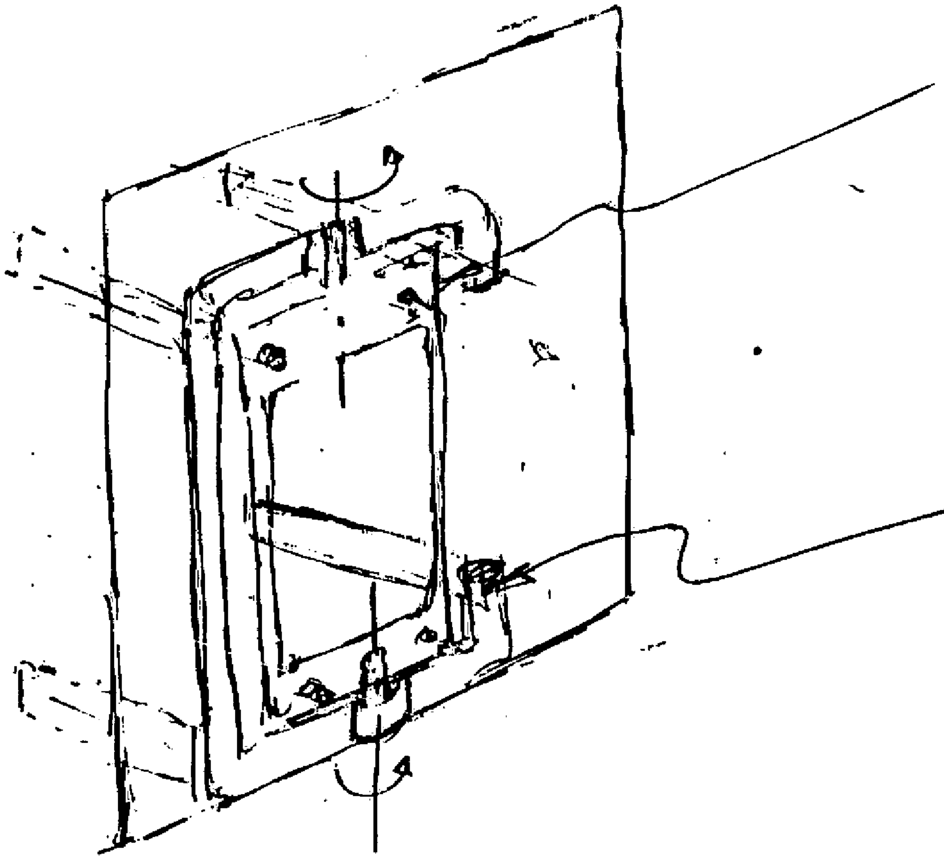


PIVOTING HOLDING FIXTURE
WORK STATION
TOOLS/ MANUALS
DONNING STATION
HELMETS/ PANTS/ LCVG
STORAGE - 2 EMU'S ABOVE RECHARGE FACILITY
WORK STATION
RECHARGE FACILITY
DONNING STATION

FIGURE 22.

FIGURE

EMU RECHARGE ..ATION HANGER



PEVA VS. P_{CABIN} FOR NO PREBREATHE

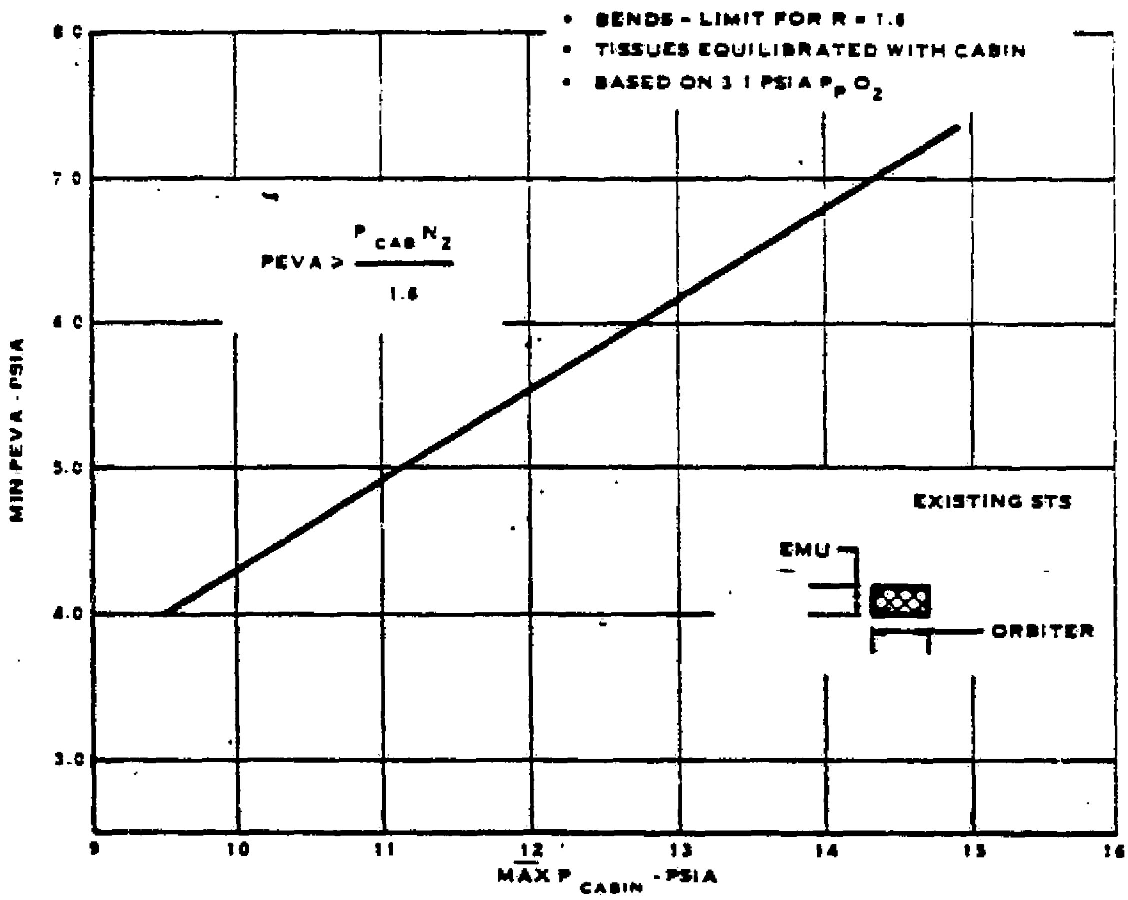
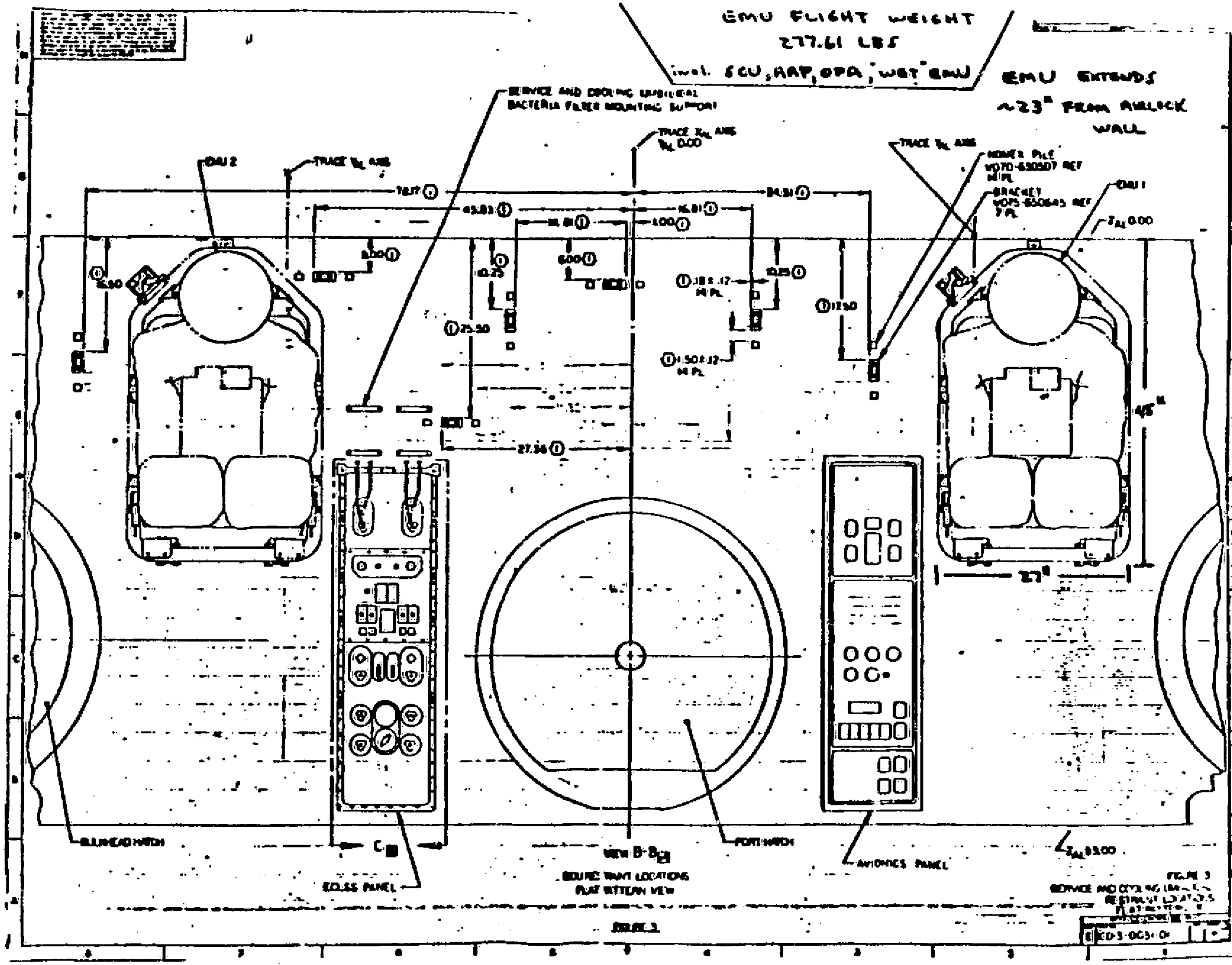


FIGURE 24

FIGURE 25



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OF POOR QUALITY

FIGURE 26

SSA IMPACTED JOINTS

PEVA psia	5.25	6.00	6.75	7.50
Shoulder	-15%	-30%	-50%	-65%
Waist	-20%	-35%	-40%	-60%
Brief/Hip	-10%	-30%	-55%	-70%
Elbow	-10%	-20%	-30%	-65%
Knee	-10%	-20%	-25%	-35%
Ankle	-5%	-10%	-15%	-20%
Glove				

Extend Existing Concepts ← | → Require New Concepts

FIGURE 27

DEMONSTRATOR SUIT

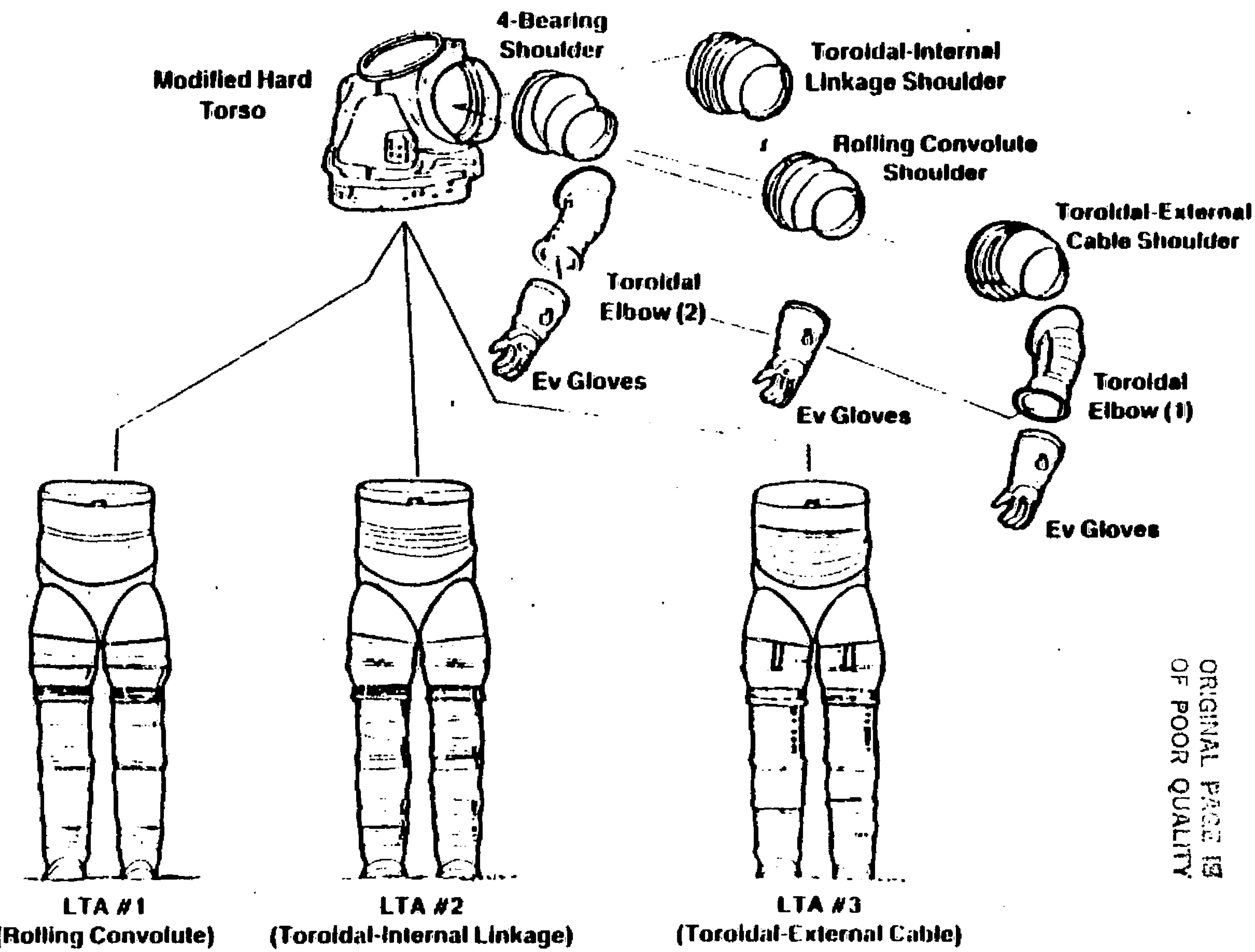
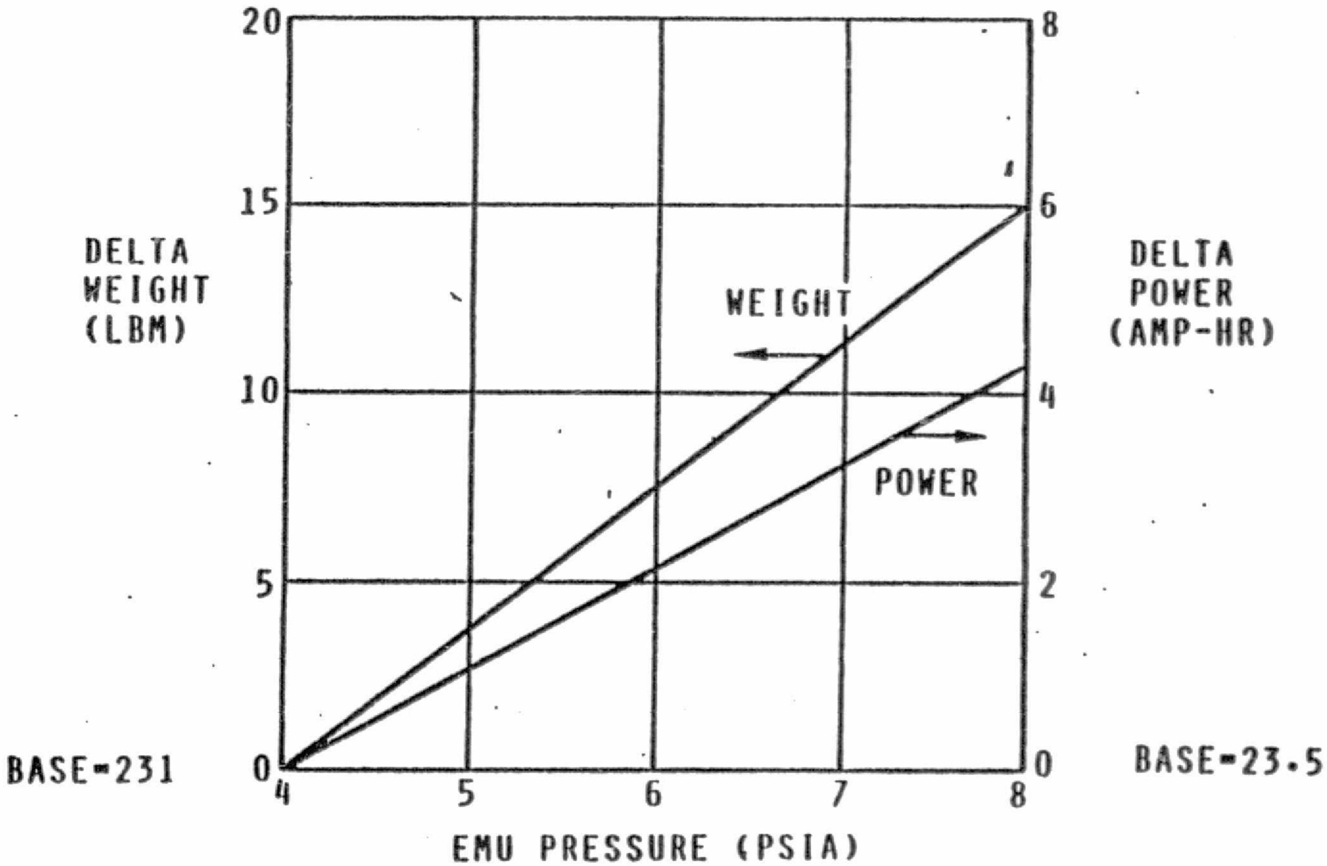
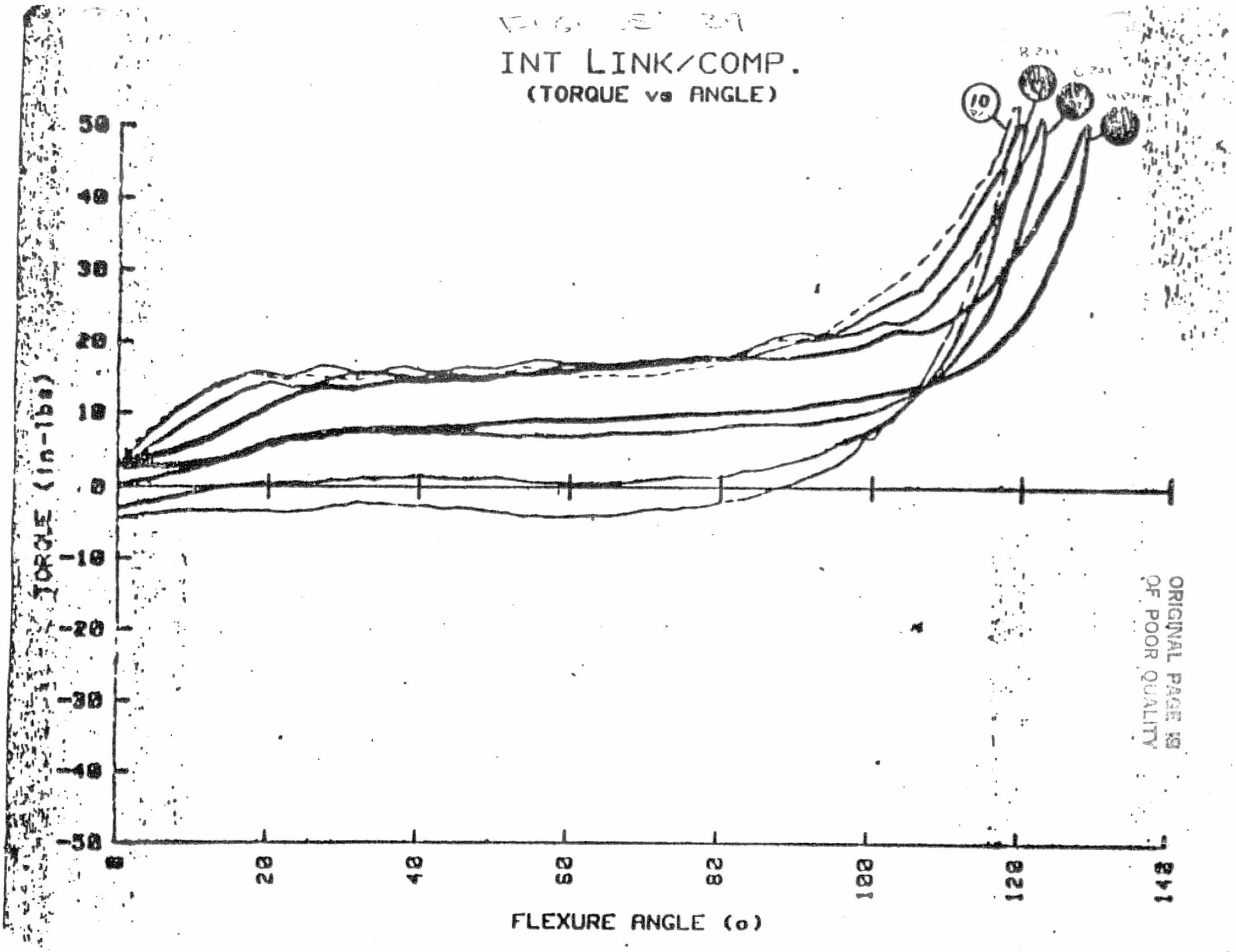


FIGURE 28

WEIGHT & POWER IMPACT OF EMU PRESSURE




INT LINK/COMP.
(TORQUE vs ANGLE)
TORQUE (in-lbs)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
20
40
60
80
100
120
140
10
FLEXURE ANGLE (o)

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TR-524-3

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Recommendations Report

Prepared Under

Program 1277

for

Purchase Contract CC0061

Contact: Franz H. Schubert
Telephone: 216 - 464-3291

January 15, 1983

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The LSI overview and recommendations sections removed from this package for inclusion in Volume 4, Section 5.2

APPENDIX 1

ESTABLISHMENT OF AN ADVANCED LIFE SUPPORT SYSTEMS
PROGRAM MASTER MANAGEMENT PLAN

Executive Summary

7.4.6 ECLSS - Life Systems, Inc.

APPENDIX 2

VARIATION IN R&D EXPENDITURES FOR THE OFFICE OF SPACE SCIENCE, LIFE SCIENCES DIRECTORATE, AND THE COMBINED ADVANCED LIFE SUPPORT SYSTEMS AND ADVANCED PROTECTIVE SYSTEMS CATEGORIES

1. Figure A2-1 compares the three budgets: OSS, Life Sciences and Life Support and Protective Systems.
2. Figure A2-2 compares the Life Sciences with the combined Life Support System and Advanced Protective Systems. The split that occurs in 1976 in the latter's budget reflects the transfer of half the R&D funding to the Office of Manned Spaceflight, which was subsequently phased down to a negligible level.
3. Figure A2-3 shows the Advanced Life Support System and Advanced Protective Systems funding, including the comparison in constant 1976 dollars.

Note, all three curves reflect the impact of the recent, FY 81 budget cut, indicating that the Advanced Life Support System and Advanced Protective System took an exhorbitant share of the budget reduction of the Office of Space Science and the Life Sciences Directorate. This is management's decision acceptable as long as, however, management is aware of the decision and its impact.

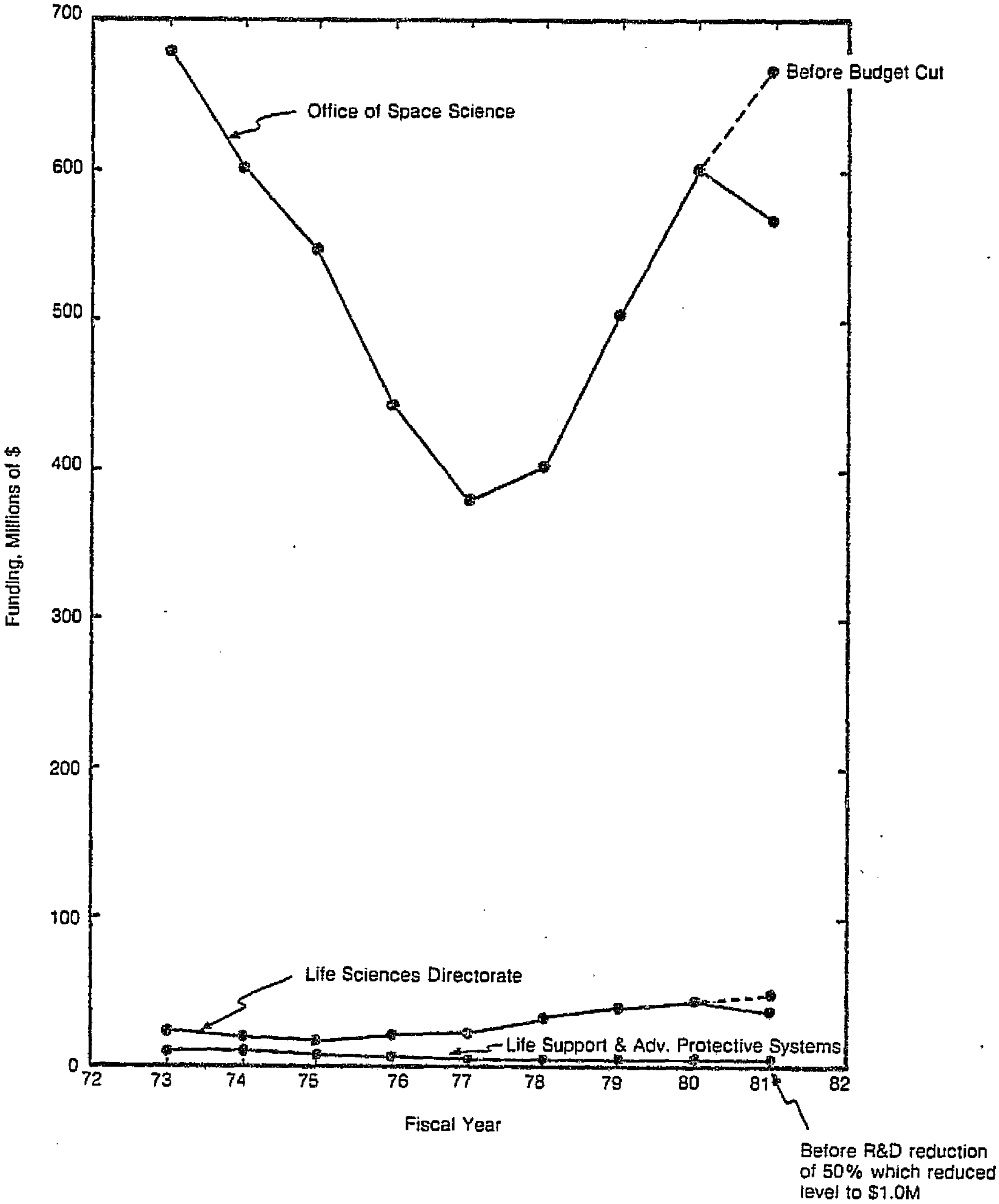

FIGURE A2-1 EXPENDITURE FOR R&D: OSS, LIFE SCIENCES AND ALSS AND APS

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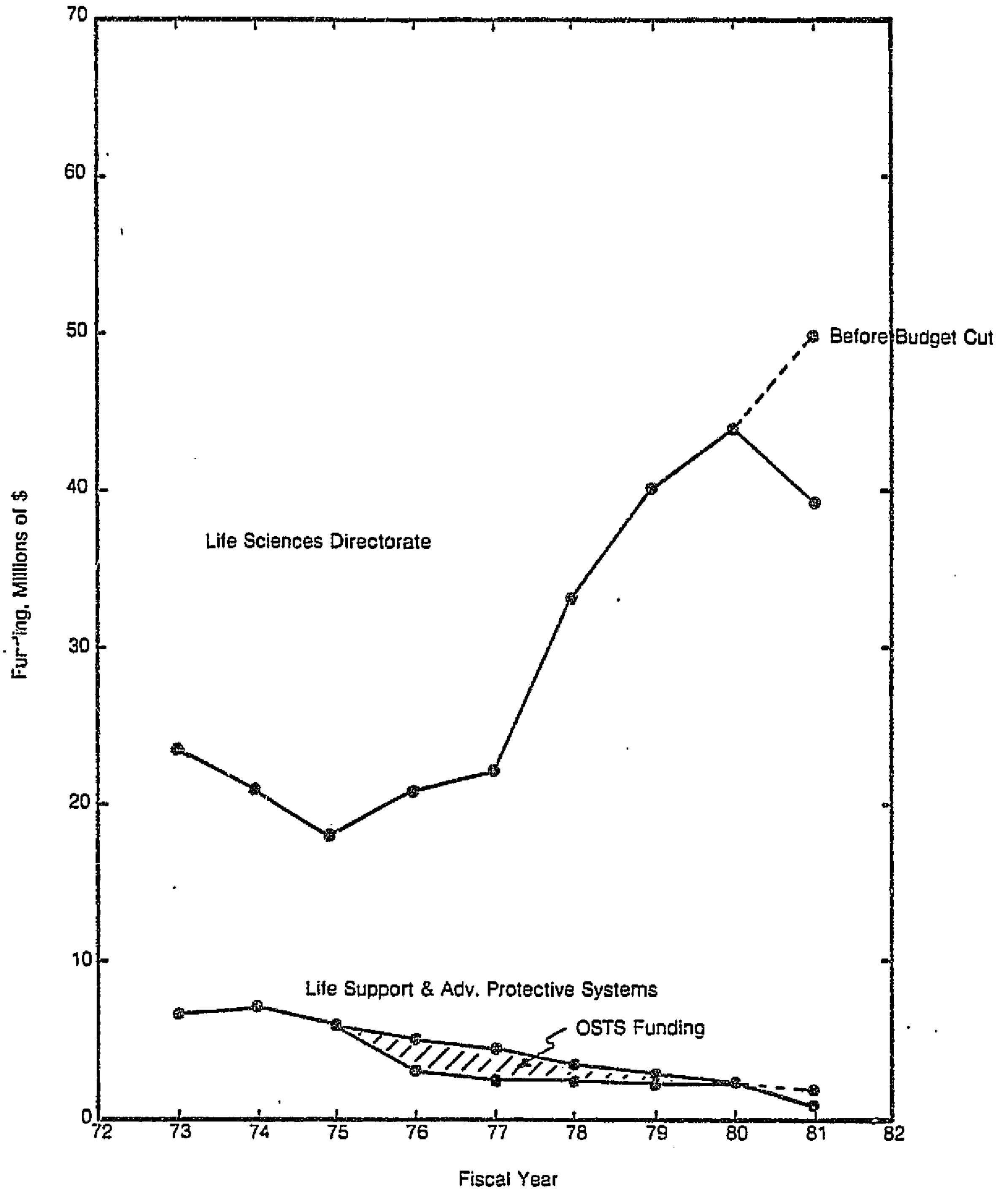

FIGURE A2-2 EXPENDITURES FOR R&D: LIFE SCIENCES AND ALSS AND APS

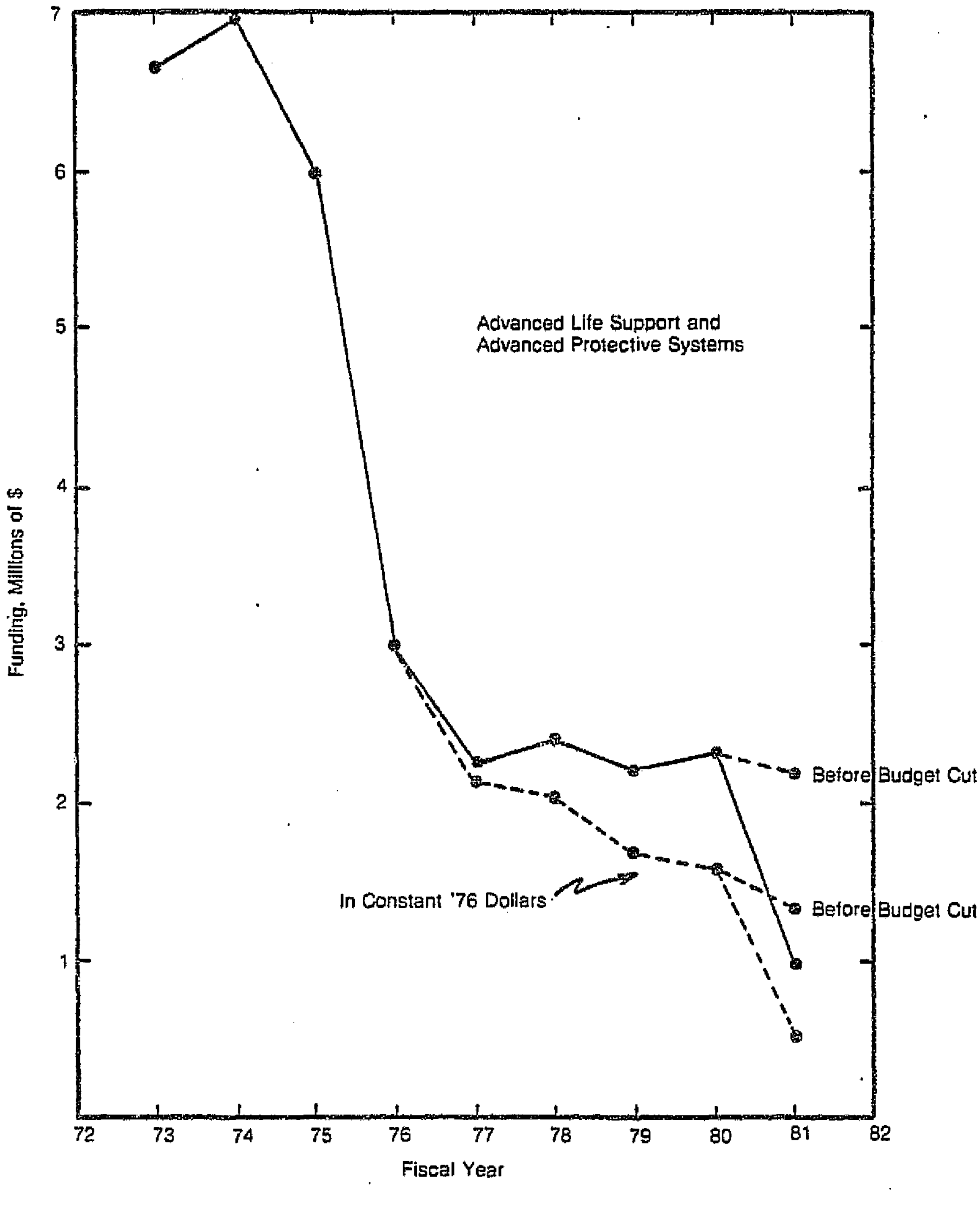

FIGURE A2-3 EXPENDITURE FOR R&D: ADVANCED LIFE SUPPORT SYSTEMS AND ADVANCED PROTECTIVE SYSTEMS

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TR-524-5-2

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Performance and Load Specifications

Prepared Under

Program No. 1277

for

Purchase Contract CC0061

Contact: Franz H. Schubert

Telephone: 216 - 464-3291

March 14, 1983

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LIST OF TABLES

1.0 INTRODUCTION

Purchase Contract CC0061 provides a mechanism for Life Systems to transmit to the Boeing Aerospace Company information related to a Space Station ECLSS. Although this information does not directly influence Space Station needs, attributes and architectural options, except in a minor way for the latter, it does provide a technology foundation from which eventual Space Station ECLSS functions will be performed and equipment provided to carry them out.

The present document summarizes in one location various ECLSS related specifications for the functional needs in the areas of the Air Revitalization System (ARS) and the Water Recovery System (WRS).

2.0 ECLSS PERFORMANCE REQUIREMENTS

Table 1 summarizes the ECLSS performance requirements[1] being used on the Space Station studies. These are close to those used for previous studies.[2-5] The fail-operational criteria provides the ability to sustain a failure and retain full operational capability for safe mission continuation. The 14 day emergency requirements are those acceptable if a second, consecutive failure occurs in non-maintainable equipment. It may be that the cause for acceptance of these should be redefined because of the minimum ten year in-orbit life requirement of the Space Station. This is functionally very different than all other space vehicles.

3.0 ECLSS AVERAGE DESIGN LOADS

The ECLSS average design loads are given in Table 2 for the Space Station[6] with the Space Operations Center Values[5] shown for comparison. Again, these are close to those used for previous studies but often differ significantly in values in areas of significance to ECLSS system and subsystem designers. For example, the Space Operations Center used a drinking water load of 4.09 lb/man-day while the Space Station's load is 2.86. The food preparation water load was 1.58 lb/ man-day versus 3.9 for the Space Station. The combined difference is 5.67 to 6.76 lb/man-day or about 20% more for the Space Station. A NASA consistent set of average loads is needed and these should be referenced to a primary data source. This will simplify comparisons of designs generated by different teams.

4.0 SITUATIONS LEADING TO OFF NOMINAL OPERATION

Various situations can lead to off nominal ARS and WRS operations. They include:

1. Space Station initial build where less than a full complement of crew will exist.

2. The timeframe during which Space Station crews are exchanged and a greater than normal crew size will exist.

3. During the times when crews accumulate in a given location such as loss of a Habitat Module of an intermediate or growth station, a higher than normal crew activity in a given location because of mission requirements, maintenance, etc.

TABLE 1 ECLSS PERFORMANCE REQUIREMENTS

Parameter	Units	Operational	90-Day Degraded[1]	21-Day Emergency
CO_2 Partial Pressure	mm Hg	3.0 Max.	7.6 Max.	12 Max.
Temperature	F	65 - 75	60 - 85	60 - 90
Dew Point[2]	F	40 - 60	35 - 70	35 - 70
Ventilation	ft/min	15 - 40	10 - 100	5 - 200
Potable Water	lb/man-day	6.8 - 8.1	6.8 min	6.8 min
Hygiene Water	lb/man-day	12 min	6 min	3 min
Wash Water	lb/man-day	28 min	14 min	0
O_2 Partial Pressure[3]	psia	2.7 - 3.2	2.4 - 3.8	2.3 - 3.9
Total Pressure	psia	14.7	10 - 14.7	10 - 14.7
Trace Contaminants	-	24 hr Ind. Standard	8 hr Ind. Standard	8 hr Ind. Standard
Microbial Count	per ft^3	100	-	-
Maximum Crew Member	Per Space Station	8	8	12
Maximum Crew Member	Per Habitat Module	4	8	8

1. Degraded levels meet "Fail Operational" reliability criteria.
2. In no case shall relative humidities exceed the range of 25 - 75%
3. In no case shall the O_2 partial pressure be below 2.3 psia, or the O_2 concentration exceed 26.9%.

TABLE 2 ECLSS DESIGN AVERAGE LOADS

	Station Values[6]	SOC Value[5]
Metabolic O_2	1.84	1.84 lb/man day
Leakage Air	TBD	5.00 lb/day total station
EVA O_2	1.32	1.22 lb/8 hr EVA
EVA CO_2	1.67	1.48 lb/8 hr EVA
Metabolic CO_2	2.20	2.20 lb/man day
Drinking Water	2.86	4.09 lb/man day
Food Preparation Water	3.90	1.58 lb/man day
Metabolic Water Production	0.78	0.70 lb/man day
Clothing Wash Water	27.50	27.50 lb/man day
Hand Wash Water	7.00	4.00 lb/man day
Shower Water	5.00	8.00 lb/man day
EVA Water	9.68	9.68 lb/8 hr EVA*
Perspiration and Respiration Water	4.02	4.02 lb/man day
Urinal Flush Water	1.09	1.09 lb/man day*[a]
Urine Water	3.31	3.31 lb/man day*[a]
Food Solids	1.36	1.60 lb/man day
Food Water	1.10	1.00 lb/man day
Food Packaging	1.00	1.00 lb/man day*
Urine Solids	0.13	0.13 lb/man day
Fecal Solids	0.07	0.07 lb/man day
Sweat Solids	0.04	0.04 lb/man day
EVA Wastewater	2.00	2.00 lb/8 hr EVA
Charcoal Required	0.13	0.13 lb/man day*
Metabolic Sensible Heat	7,010	7,000 BTU/man day
Hygiene Latent Water	0.94	0.94 lb/man day
Food Preparation Latent Water	0.06	0.06 lb/man day*
Experiments Latent Water	1.00	1.00 lb/day
Laundry Latent Water	0.13	0.13 lb/man day
Waste Wash Water Solids[b]	0.44%	0.44
Expended Water Solids	0.13%	0.13
Air Lock Gas Loss	2.40 lb/EVA	2.40 lb/use
Trash	1.80	1.80 lb/man day*
Trash Volume	0.10	0.10 ft^3/man day*

*Not cited in reference but taken from the Space Operations Center Study.[5]
(a) Cited reference identified urine, at 4.4 lb/day, approximately combined total of urinal flush water and urine water
(b) Assumed shower and hand wash.

4. Failure of a primary functional subsystem, e.g., one of the cabin dehumidifiers.

5. Delay in resupply of expendables and spares, i.e., delivery of the logistics module.

6. Total or partial loss of the primary energy source (e.g., solar array).

7. A mission directed requirement to avoid all overboard venting for extended time periods.

5.0 SUMMARY

The ECLSS performance and average design loads are similar to, but differ significantly in some areas from, those NASA has used for prior Space Station studies. Care must be taken, therefore, since some changes will impact the design characteristics of functional hardware.

6.0 REFERENCES

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3. McDonnell Douglas Co., "Space Station Preliminary Design, Preliminary Systems Design Data," Volume 1, Book 3, NAS8-25140: Crew Systems; July, 1970.

4. General Dynamics, "Study for Basic Subsystem Module Preliminary Definition," Final Report, NAS9-6796; 1973.

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7. Carlisle, R. F. and Romero, J. M., "Space Station Technology Readiness," paper presented at the ASME, Phoenix, AZ; November 17, 1982.

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TR-524-4

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Source Document List

Prepared Under

Program 1277

for

Purchase Control CC0061

Contact: Franz H. Schubert
Telephone: 216 - 464-3291

February 27, 1983

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1.0 GOVERNMENT REPORTS

1.1 Government Specifications

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2. NASA JSC, "Regenerative Life Support Evaluation (RLSE) Performance and Interface Specification;" January, 1976.

3. NASA JSC, "Design and Performance Requirements, General Space Station Prototype;" December, 1969.

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2. Johnson Space Center, "Space Station Systems Definition," Book 5, Draft, October, 1982.

3. NASA Johnson Space Center, "Space Operations Center: A Concept Analysis," Volume I and II, JSC-16277, November 29, 1979.

4. NASA, "NASA Five-Year Planning: Fiscal Years 1980 thorugh 1984," January 30, 1979.

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TR-524-5-1

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

ECLSS: ARS and WRS Options

Prepared Under

Program 1220

for

Boeing Aerospace Company

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February 15, 1983

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1.0 INTRODUCTION

Task 1 of the Purchase Contract provides for the completion of ECLSS equipment analyses associated with:

a. Water recovery options
b. Air revitalization options

The present report summarizes the most realistic options for each of the two major ECLSS functions (Air Revitalization System and Water Recovery System). The selected approaches are then iterated. Finally, the recommended baseline approach and alternative technology for each of the five ECLSS functions and their associated functional subsystems are presented.

2.0 AIR REVITALIZATION OPTIONS[a]

The following are a list of ARS functions (e.g., CO_2 Removal) and technology approaches to meet the functional requirements.

CO_2 Removal
- LiOH
- Electrochemical CO_2 Concentration (EDC)[b]
- Steam Desorbed Amine (IR-45)
- Molecular Sieves
- Carbonation Cell

CO_2 Reduction
- Sabatier
- Bosch
- Solid Electrolyte

O_2 Resupply
- Compressed Gas
- Cryogenic Liquid
- Water Electrolysis
  - Alkaline Electrolyte
  - Acid/Solid Polymer Electrolyte
  - Water Vapor/Acid Electrolyte[b]
  - Solid Electrolyte

Trace Contaminant Control
- Nonregenerable Charcoal/Catalytic Oxidation
- Regenerable Charcoal/Catalytic Oxidation
- Catalytic Oxidation/Sorption

(a) Water Vapor removal from the air accomplished in the Cabin Heating Air Conditioning and Ventilation Functional Group (Cabin Temperature and Humidity Control System).
(b) The EDC and water vapor electrolysis have also been combined into a portable Independent Air Revitalization System (IARS).

Bacterial Contamination Control
- Filtration
- Electrostatic Precipitation
- Impingement
- Air Centrifuge
- Electrophoresis

Atmosphere Monitoring
- Gas Chromatograph/Mass Spectrometer

3.0 WATER RECOVERY OPTIONS

The following is a list of functional approaches to each of four major elements of a water recovery system.

Pretreatment
- Oxone/H_2SO_4
- Biopal/H_2SO_4/Antifoam
- Chronic Trioxide/H_2SO_4

Water/Solids Separation
- Vapor Distillation/Compression
- Vapor Distillation/Thermoelectric
- Vapor Distillation/Pyrolysis
- Thermoelectric/Membrane Evaporation
- Flash Evaporation/Pyrolysis
- Flash Evaporation/Compression/Pyrolysis
- Closed Cycle Air Evaporation
- Open Cycle Air Evaporation
- Vapor Diffusion
- Vapor Diffusion/Compression
- Wet Oxidation
- Super Critical Wet Oxidation
- Electrodialysis
- Reverse Osmosis
- Multifiltration
- Hyperfiltration

Post-Treatment
- Ultraviolet/Ozone Oxidation
- Activated Carbon
- Biocide (I_2) Addition
- Taste Enhancement

Water Quality Monitoring
- pH (H_2 ion concentration)
- Conductivity
- Electrochemical Organic Content
- Total Organic Content
- Ammonia (Dissolved)

4.0 ARS FUNCTIONAL EQUIPMENT

Table 1 presents the selected ARS baseline equipment/approach. Note the portable, independent air revitalization system has been included. Whether NASA continues to feel a need exists for a portable IARS remains to be determined.

5.0 SELECTED WRS FUNCTIONAL EQUIPMENT

Table 2 presents the WRS baseline equipment/approach selected.

6.0 SPACE STATION ECLSS BASELINE APPROACH AND ALTERNATIVES

For completeness, we have expanded the activity under Task 1 of the Purchase Contract. It includes the recommended baseline approach and alternative technology for each of the five ECLSS functions:

1. Air Revitalization System
2. Atmosphere Pressure and Composition Control
3. Cabin Temperature and Humidity Control
4. Water Reclamation System
5. Personal Hygiene and and Waste Management

The results are contained in Table 3.

7.0 SUMMARY

Based on trade studies and analyses, options were identified for ARS and WRS portions of an ECLSS. Baseline equipment/approaches were then selected for each of the ARS and WRS functions they are required to perform. Finally, the recommended baseline approach and any alternative technology was cited for each of the five ECLSS major functions and the functional subsystems of which they are composed.

TABLE 1 SELECTED ARS FUNCTIONAL EQUIPMENT

Function	Baseline Equipment/Approach
CO_2 Removal	EDC (Electrochemical CO_2 Concentration).
CO_2 Reduction	Bosch (carbon formation) to avoid overboard venting or Sabatier (CH_4 formation) if overboard venting allowed.
O_2 Generation	Static feed aqueous water electrolysis (possibly the same unit(s) used with the RFCS).
Trace Contaminant Control	Catalytic oxidation, regenerable sorters and microbial filters.
Atmosphere Monitoring	Gas chromatograph with mass spectrophometer.
Portable Independent Air Revitalization	EDC and Water Vapor Electrolysis as a topping unit for periodic overloads (like a portable air conditioner).

TABLE 2 WRS FUNCTIONAL EQUIPMENT

Function	Baseline Equipment/Approach
Pretreatment	Oxone with sulfuric acid.
Urine and Hygiene Wash Water Recovery[(a)]	Vapor Compression Distillation Subsystem with Thermoelectric membrane as the backup.
Cabin Condensate and Clothing and Dish Wash Water Recovery	Hyperfiltration with reverse osmosis as the backup.
Post-treatment	Activated charcoal with ultraviolet/ozone oxidation possibly being required if the recovered water is to be acceptable for potability by the medical people.
Water Quality Monitoring	Use pH, conductivity and organic solute (e.g., electrochemical organics content). Experience may show that organic are only present when inorganics are so that the conductivity reflecting inorganics will also reflect the organics.
Biocide Addition	Iodine (I_2) with the level automatically regulated with an I_2 monitor.
Water Storage	Shuttle type bellows tanks.
Use Point Biocide Monitor	I_2 monitor to verify biocide present indicating that no microorganisms are present.
Sterilization	Steam sterilization may be a capability used selectively but currently not planned.
Back Contamination Prevention	Microbial Check Valve at selected locations using an iodinated ion exchange resin.

(a) Also handles concentrates from the non-phase change water recovery process.

TABLE 3 SPACE STATION ECLSS EQUIPMENT

ECLSS Functions & Functional Subsystems	Recommended Baseline Approach[a]	Alternative Technology[a]
Air Revitalization System[b]		
CO_2 Concentration	*Electrochemical CO_2 Concentrator*	*Steam Desorbed IR-45 Amine*
CO_2 Reduction	*Sabatier (CH_4) Reactor*	*Bosch (Carbon) Reactor*
O_2 Generation	*Static Feed, Water Electrolysis*	*Acid Electrolyte, Water Electrolysis*
Trace Contaminant Control	*High Temp. Cat. Oxidizer, Regen. Carbon*	*High Temp. Cat. Oxidizer, Expendable Carbon*
Atmosphere Monitoring	*Mass Spectrometer*	None
Atmosphere Pressure & Composition Control[c]		
O_2 Storage	High Pressure Gas	Cryogenic
N_2 Storage	High Pressure Gas	Cryogenic
N_2 Generation	*Catalytic N_2H_4 Decomposition*	Cryogenic
Composition Control/Monitor	Shuttle Technology	None
Pressure Control	Shuttle Technology	None
Cabin Temperature & Humidity Control		
Temperature Control	Stainless Steel Plate Fin.	None
Humidity Control	Stainless Steel Plate Fin., Slurper	None
Ventilation Circulation	Ventilation Fans	None
Water Reclamation System		
Pretreatment	*Oxone with H_2SO_4*	*Biopal, Antifoam & H_2SO_4*
Water Recovery, Urine	*Vapor Compression Distillation*	*Thermoelectric, Membrane*
Water Recovery, Condensate & Hygiene	*Ultrafiltration*	*Reverse Osmosis*
Post-Treatment	Activated Charcoal	*UV Enhanced O_3 Oxidation*
Water Quality Monitoring	*Electrochemical Organic Content, pH, Cond.*	*Total Organic Carbon, pH, Conductivity*
Biocide Addition & Monitoring	*I_2 Injection*	*Steam Sterilization*
Microorganism Monitoring	*I_2 (Biocide) Spectrophometric Monitoring*	*Microorganism Monitor*
Water Storage	Stainless Steel, Metal Bellows Tanks	None Required
Personal Hygiene & Waste Management		
Hygiene		
- Cold	Stainless Steel Cooler	None Required
- Hot	Cartridge Type Electric Heater	None Required
- Handwash	Covered Spray & Air Transport	None Required
- Full Body Shower	*Enclosed Stall & Handheld Spray*	None Required
- Laundry (Washer/Dryer)	*Spin, Tumble Wash/Tumble Air Dry*	None Required
Waste Management		
- Toilet	Modified Shuttle Commode	None Required
- Urinal	Shuttle Technology	None Required
- Solids Collection	Stainless Steel Receptacles	None Required
- Trash Compaction	*Mechanical Shredding/Grinding*	None Required
- Compacted Solids Storage	Stainless Steel	*Super Critical Wet Oxidation*
- Concentrated Waste Liquid Storage	Stainless Steel, Metal Bellows	*Super Critical Wet Oxidation*
Habitability Provisions[d]	- Part of Another Space Station System -	

(a) All new technology is in italics.
(b) The Independent/Portable Air Revitalization System is not shown.
(c) The airlock pump, dump and relief, and pump down accumulators can optionally be included here.
(d) Part of the Habitability and Crew Support System is not included here.

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TR-524-5-3

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Overboard Venting

Prepared Under

Program No. 1277

for

Purchase Contract CC0061

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January 31, 1983

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1.0 INTRODUCTION

Task 1 of the Purchase Contract had as item c the requirement to study techniques for reducing overboard venting from ECLSS hardware. The present report reviews the results of the studies completed.

First a review was made of major and minor overboard venting sources, then techniques for reducing overboard venting were identified.

2.0 MAJOR OVERBOARD VENTING SOURCES

The major overboard venting sources identified include the following:

1. The Sabatier CO_2 Reduction Subsystem has a requirement to vent methane gas and with it the unreacted CO_2 and minor quantities of water vapor. If, however, a steam desorbed amine was used for CO_2 concentration, loss of nitrogen (N_2) gas would also occur. This results because the steam desorbed amine CO_2 removal system does not accumulate pure CO_2 but contains ullage quantities of N_2.

2. The Bosch CO_2 Reduction Subsystem forms carbon as a product. The stoichiometric balance for CO_2 reduction, however, leaves an excess of hydrogen (H_2) which must then be vented continuously or frequently. Again, the same steam desorbed amine CO_2 removal limitations associated with N_2 would exist.

3. If the water electrolysis (Oxygen Generator) Subsystem was maintained operational when the CO_2 removal or CO_2 reduction functions were shut off, all the H_2 generated would have to be vented.

4. When the Space Station required a cabin decompression, oxygen (O_2) CO_2, water, N_2 and trace gases would vent overboard.

5. Whenever the airlock is used quantities of O_2, CO_2, water, N_2 and trace gases are vented overboard.

6. Exhaust gases from the commode handling fecal matter.

3.0 MINOR OVERBOARD VENTING SOURCES

Those overboard venting sources considered minor include:

1. The noncondensable gases that occur during phase separation water recovery techniques. Such techniques include the Vapor Compression Distillation Subsystem and the Thermoelectric/Membrane Subsystem. The thermoelectric/membrane recovery system exhausts over six times the water vapor with the noncondensable gases as the VCDS. This results because the thermoelectric/membrane approach operates at 150 F versus 85 F for the VCDS (higher steam densities, hence more mass of water per given volume of noncondensables).

2. All subsystems that require N_2 purging of gas fluid lines on shutdown for maintenance. Systems expected to require such N_2 purging include the Water Electrolysis Subsystem, the Electrochemical CO_2 Subsystem, the CO_2 Reduction Subsystem and the Regenerative Fuel Cell System.

3. Any function that utilizes vacuum recharging to reactivate active carbon/charcoal absorbers.

4. The N_2 Supply System, utilizing hydrazine as the chemical stored form of N_2, vents small quantities of H_2. This occurs in the third of three N_2-from-H_2 separation steps. This, the third step, employs space vacuum to remove H_2 so as to prevent any H_2 exhausting with the product H_2.

5. Hydrogen from fuel cell produced water.

6. Exhausts from extravehicular activity life support equipment. Typically this has included water vapor used for cooling.

4.0 TECHNIQUES FOR REDUCING OVERBOARD VENTING

Several techniques were identified for reducing overboard venting. These included techniques which would limit venting to H_2 which is considered a more acceptable venting material. The techniques identified include:

1. Utilize the EDC (Electrochemical Depolarized CO_2 Concentrator) to perform the CO_2 removal function. It ensures that the CO_2 Reduction Subsystem is fed only CO_2 and H_2 with no N_2.

2. Utilization of a Bosch type CO_2 reduction process. It does not continuously generate methane gas and unreacted CO_2. The Bosch process, however, is fed approximately 10% excess H_2 which would still have to be vented overboard. This could be used in the station keeping thrusters.

3. Establish operating modes whereby the water electrolysis (O_2 generation) subsystem shuts down whenever the CO_2 Reduction Subsystem shuts down or, if an EDC is used for CO_2 removal, it shuts down.

4. Instead of passing the exhaust gases from the commode and phase separation type water recovery techniques (e.g., VCDS or thermoelectric/membrane) overboard, vent then to the catalytic oxidizer of the Trace Contaminant Removal Subsystem.

5. Exhaust the product of the N_2 purging of gas fluid lines to the catalytic oxidizer of the Trace Contaminant Removal Subsystem.

6. By specification eliminate vacuum recharge of activated carbon/charcoal as an acceptable recharge technique.

7. Continue to utilize a purge pump to transfer the gases in an airlock back to the cabin prior to opening the airlock to space vacuum.

8. Selection of the VCDS over the thermoelectric/membrane water recovery system reduces the overboard steam venting by a factor of six plus. In addition, select a filtration type system for treating 68% of the water to be processed (i.e., cabin condensate and clothing and dish waste wash water). This minimizes the water to be treated by the phase change process to 32% of the total water recovered. (Thermoelectric process operates at 150 F while the VCD operates at 85 F, so the former vents more water vapor with the noncondensable purging).

9. An evaluation was made concerning how long the regenerative ECLSS air revitalization functions could be turned off to postpone any overboard venting. The cabin dehumidification subsystem must operate almost continuously since dew points would typically exceed specifications in less than 20 minutes. The CO_2 removal process can be shutdown for approximately 8 to 12 hours depending upon a variety of conditions. It is not expected, however, that periods longer than 24 hours could be tolerated without the regenerative CO_2 removal subsystem being operational. A lithium hydroxide CO_2 removal system could be used to extend these timeframes at an expendable/logistics penalty. The Oxygen Generating Subsystem can be shutdown for several days before the oxygen partial pressure reaches the lower specification, provided the atmosphere had been "enriched" to the high specification level. The Space Station's N_2 supply utilizing hydrazine as the stored form of N_2 can be shutdown for periods exceeding a week before its partial pressure reaches its lower tolerance limit.

10. The small quantities of H_2 venting from the third stage of the N_2 Supply System can be eliminated by passing the N_2/H_2 mixture containing trace quantities of ammonia through the catalytic oxidizer rather than through a <u>third</u> stage N_2 from H_2 separator. The latter employs space vacuum to reduce the partial pressure of H_2 to such a level that, for all practical purposes, all ammonia is disassociated.

The above techniques leave unresolved how to avoid overboard venting from the cabin decompression requirement and the H_2 from fuel cell produced water. The later is transferred to space vacuum from the H_2 from water separator.

5.0 SUMMARY

Total elimination of all overboard venting does not appear practical. It is possible, however, to considerably minimize overboard venting and, further, to restrict the bulk of it to a more acceptable gas, H_2. Also, utilizing the Space Station volume as a "storage" reservoir, so no venting can be tolerated for short or increments of time (e.g., about 24 hours). Such operation, however, would require preconditioning the air for low concentrations of CO_2 to tolerate the buildup of CO_2 and that would occur when the CO_2 reduction functions are not operating.

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TR-524-5-4

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Integrated Versus Dispersed Subsystems

Prepared Under

Program 1277

for

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January 15, 1983

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1.0 INTRODUCTION

To date, little work has been done integrating life support subsystems as part of the Environment Control/Life Support System (ECLSS) for a Space Station. Under the Purchase Contract an analysis was made of the advantages and disadvantages of doing such integrations for the air revitalization and water recovery functions of an ECLSS. This report summarizes the results of the study.

2.0 INTEGRATION MERITS

Integrating subsystems into a system for the air revitalization and water recovery functions has almost only advantages and no disadvantages. For example they would:

1. Lower equivalent weight and volume penalties because many components (e.g., automated controllers, values) are not duplicated with the integrated approach.

2. Lower development risk since no chance for mismatching of subsystem interfaces (e.g., EDC operates with $H_2 + CO_2$ exhausting at 3.5 psig and the Sabatier - CRS requiring a 5 + psig).

3. Considerably reduce interfaces. As Table 1 shows for the Air Revitalization System (ARS), individual subsystems need a total of 48 interfaces, the integrated approach only 9. A similar situation, but less extensive, exists with the integrated Water Recovery System.

4. Lower plumbing, hence, lower plumbing connections.

5. Simplify nitrogen purging techniques.

6. Lower product documentation, training, testing, etc. costs.

7. Increase reliability because of fewer components, less connections, lower complicity, etc.

3.0 SUMMARY

Integrating ARS subsystems and WRS subsystems and components will reduce the cost, weight, power, volume, complexity, maintainability, training and endurance test costs, and will increase the reliability of an ECLSS.

TABLE 1 SUMMARY OF SABATIER BASED ARS INTERFACES

Individual Subsystem	No. of Inter.	H_2 In	H_2 O	H_2O In	H_2O O	H_2/CO_2 In	H_2/CO_2 O	Low P N_2 In	Low P N_2 O	Cabin Air In	Cabin Air O	Coolant In	Coolant O	Vaca In	Vaca O	ACS In	ACS O	O_2 In	O_2 O	Cabin + N_2 In	Cabin + N_2 O	Hi P N_2 In	Hi P N_2 O
EDC/CHCS	14	X		X	X		X	X		X	X X X	X X	X X		X								
Sabatier-CRS	13	X	X X		X	X		X		X	X X	X	X		X		X						
OGS	10		X X	X				X				X	X		X X				X			X	
NSS	6		X					X X	X	X					X								
TCCS	5										X	X	X					X		X			
Prior ARS Approach	48	2	5	2	2	1	1	5	1	3	6	5	5	0	5	0	1	1	1	1	0	1	0
Optimum ARS	9	0	0	0	1	0	0	1	0	1	1	1	1	0	1	0	1	0	0	0	0	1	0

O = Out
P = Pressure
ACS = Attitude Control System
EDC = Electrochemical Depolarized CO_2 Concentrator
CHCS = Cabin Humidity/Control Subsystem
OGS = O_2 Generation Subsystem
NSS = N_2 Supply Subsystem

Submitted to:

Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Attention: Keith Miller, MS 84-06
H. F. Carr, MIS 84-86 (Cover Letter)

TR-524-5-5

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Phase Change Recovery Process Comparison - VCDS vs TIMES

Prepared Under

Program 1220

for

Boeing Aerospace Company

Contact: Franz H. Schubert

Telephone: 216 - 464-3291

February 15, 1983

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1.0 INTRODUCTION

A comparison study was completed between two candidate phase change water recovery subsystems. The two subsystems are the Vapor Compression Distillation Subsystem (VCDS) and the Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES).

2.0 BACKGROUND

Both the VCDS and TIMES use a phase change process coupled with a technique to reduce the overall power levels by using the heat liberated during the condensation process to evaporate water from a recirculating waste fluid stream. The VCDS uses a rotary lobe compressor to achieve the temperature gradient to transport the heat while the TIMES uses a thermoelectric device.

3.0 SUMMARY OF RESULTS

The results of the study are summarized in Tables 3-1 through 3-5. Tables 3-1 through 3-4 give a qualitative appraisal of the two techniques by listing advantages of the VCDS, disadvantages of the VCDS, advantages of the TIMES and disadvantages of the TIMES, respectively. Quantitative results are summarized in Table 3-5. Appendix 1 gives supporting information used to define the VCDS numbers summarized in Table 3-5.

Appendix 2 contains a photograph of the VCDS hardware sized for a 72 lb/day recovery rate and currently under test at Life Systems.

TABLE 3-1 ADVANTAGES OF THE VAPOR COMPRESSION DISTILLATION SUBSYSTEM (VCDS)

- The VCDS is a low temperature (less than 90 F) water-from-urine recovery process which minimizes post-treat expendables compared to high temperature (greater than 110 F) processes (due to minimum carry over of volatiles and minimal breakdown of urea, resulting in a high quality product water).
- The low temperature VCDS process can tolerate high solids concentration within the recyle loop, with up to 50% solids possible without undue reduction in water recovery rate. As a result, high water extraction from the waste water is possible, with up to 96 to 97% demonstrated.
- The VCDS has inherently the highest coefficient of performance of a phase change water recovery process since condensation and evaporation occur in free films on opposite sides of a thin metallic separator.
- The VCDS is a self-regulating process, operating near ambient temperature levels and requiring no thermal control.
- The VCDS is insensitive to plugging or rupture since it does not use any membranes.
- Eighty-one percent of the basic process energy goes into the generation of temperature differential via the steam compressor. Only 19% are needed to generate the evaporator gravity field and water extraction velocity head.

TABLE 3-2 DISADVANTAGES OF THE VAPOR COMPRESSION DISTILLATION SUBSYSTEM (VCDS)

- The VCDS uses a rotating evaporating condensor to create a gravity field for liquid gas separation.
- The VCDS uses a rotary lobe compressor to generate the temperature differential necessary to transfer the heat of condensation to the evaporation site.
- The VCDS has a subatmospheric portion within the recycle loop increasing the requirements on the recirculation pump (higher pressure ratio).
- Upon power failure with resulting still stoppage, evaporator liquids can separate from the evaporator surface, requiring a liquid droplet containment device/concept to prevent waste fluid to migrate to the product water side.

TABLE 3-3 ADVANTAGES OF THE THERMOELECTRIC INTEGRATED MEMBRANE EVAPORATION SUBSYSTEM (TIMES)

- The TIMES uses static thermoelectric devices instead of a rotary lobe compressor to transfer the heat of condensation to be used to evaporate water from the recirculating waste water stream.
- The TIMES has a gravity insensitive liquid containment technique on the evaporator side (i.e., using hollow fiber membranes).
- The recycle fluid loop in the TIMES is at atmospheric pressure providing for easier pumping, i.e., more favorable pump pressure ratios.
- The TIMES has static evaporation and condensing surfaces.

TABLE 3-4 DISADVANTAGES OF THE THERMOELECTRIC INTEGRATED MEMBRANE EVAPORATION SUBSYSTEMS(TIMES)

- The TIMES requires elevated temperatures (150 versus 85 F) to achieve practical water production rates. The TIMES produces a poor water quality, hence, requires larger quantities of post-treat expendables. The poor water quality results from volatiles diffusing through the hollow fiber walls and from urea breakdown at the elevated temperatures.
- The hollow fiber membrane evaporator can only operate up to 40% (versus 50%) solids at practical recovery rates and/or practical number of fibers. The result is a lower overall water recovery from wastes (94 versus 96%).
- The TIMES experiences a purge loss six times that of the VCD due to operation at higher temperature, i.e., higher steam densities.
- The TIMES is susceptible to rendering the hollow fiber membrane useless when power is lost due to cool down and resulting precipitation of solids in the recycle loop.
- The TIMES requires twice the energy per pound of water produced due to the inherent inefficiency of the process (hollow fiber membrane resistance, low efficiency of thermoelectric devices).
- The hollow fiber membrane evaporator is inherently unsafe since bad water or loss of the total system may result due to leakage in case a single fiber of the more than 2,000 fibers breaks.
- Plugging of hollow fiber membrane pores as a function of time with solids requires caustic chemicals as an expendable to rejuvenate membranes to maintain practical production rates.
- The TIMES will operate with variable efficiency even at constant recycle fluid concentrations due to changes expected in the thermoelectric element efficiencies as voltages vary from 26.5 to 31.5 V (as expected with low power penalty sources). Variations from the the low to the high voltage will increase heat loads by 40%.
- The TIMES must use a zero gravity compatible liquid gas separation concept in the condensing section.
- The porous condensor/separator plates are life limiting.
- The recycle filter tank is difficult to maintain since it must be kept hot to maintain system efficiencies. At change out, a cool down may result in system loss due to percipitation of solids in the hollow fiber membranes unless separate zone heating and controls are used.
- The TIMES has two pieces of rotating equipment, i.e., two pumps, one for condensate recovery/thermal control and one for the recycle loop fluid.

TABLE 3-5 PHASE CHANGE WATER RECOVERY CONCEPT COMPARISON[a]

Parameter	Current Hardware VCDS (NAS9-16374)	Current Hardware TIMES 70 lb/d[b]	Current Hardware TIMES 44 lb/d	Projected Space Station Modular Unit VCDS	Projected Space Station Modular Unit TIMES
Weight (dry), lb	205	215	150	91	111
Volume, ft^3	15.7	11.4	8.0	4.9	5.0
Power, W	134	269	169	72	142
Production Rate (Des. Pt.), lb/hr	70	70	44	40	40
Specific Energy, W-h/lb	46	92	92	43	85
Process Temperature, F	85	150	150	85	150
Condenser Pressure, psia	0.6	2.6	2.6	0.6	2.6
Water Recovery, %	95.5	91.4	91.4	95.5	91.4
Recyle Tank[c]					
Weight, lb	16	20[d]	20[d]	15[g]	19[d,g]
Volume, ft^3	0.64	0.80[d]	0.80[d]	1.2	1.5[d]
Purge Losses, %	0.5	3.0	3.0	0.5	3.0
Total Equivalent wt (TEW)[e], lb	343	492	324	165	257
Specific TEW, lb-h/lb	118	169	177	99	154
Water Quality[f]					
Conductivity, mmho	21	198	198	21	198
NH_3, ppm	0.3	0.8	0.8	0.3	0.8
Overall Coefficient Performance	6.7	3.2	3.2	7.1	3.5

(a) Excluding Control/Monitor Instrumentation.
(b) Calculated based on 44 lb/day unit.
(c) 90-day resupply.
(d) Based on 40% final solids concentration versus 50% baseline with VCDS.
(e) Based on 590 lb/kW and 438 lb/kW power and heat rejection penalty, respectively.
(f) As needed to define post-treatment expendables, i.e., prior to post-treat.
(g) Sized for 90 days of operation.

APPENDIX 2

SUPPORTING DATA FOR THE DEFINITON OF A VCDS FOR THE SPACE STATION

February 14, 1983
FHS-2-8

Boeing Aerospace Company
Advanced Space Systems
P.O. Box 3999
Seattle, WA 98124

Attention: Mr. Keith Miller, Lead Engineer

Subject: Technology Information Transmittal

Reference: Purchase Contract CC0061

Dear Mr. Miller:

Enclosed are five tables and three figures defining our Phase Change Water Recovery System using Vapor Compression Distillation. The hardware shown and projected has been based on our most current Vapor Compression Distillation Subsystem (VCDS) contractual and internal research and development activities. As you know, we are currently testing a 72 lb/day capacity unit for NASA JSC under Contract NAS9-16374.

The guidelines that we have used in sizing the hardware have been based on the Space Station Program Description Document, System Requirements and Characteristics, Book 3, November, 1982. Specifically, the hygiene and washwater requirements have been based on Table 2.7-1 of that document. Also, Paragraphs 2.7.4.2d and 2.7.4.2e have been used as guides to define the requirements (i.e., urine and expended hygiene water shall be processed by a concept incorporating a phase change to produce potable quality water that is also acceptable for waster electrolysis and other EC/LSS uses).

To remain consistent with our previously projected EC/LSS equipment redundancy and locations, I have located two phase change recovery units in each of the two habitats for a total of four units to process the 142.4 lb/day. While two units per habitat are not the lowest weight, it does result in a higher reliability compared to one phase change recovery unit per habitat. Potentially a final analysis from the top down may settle that particular question.

It should be noted that the phase change recovery unit does not include a waste storage tank since that is considered to be part of the liquid waste collection system aboard the Space Station. However, each of the four modular units has its own recycle filter tank sized for a 90-day resupply time period.

As you may note a fair amount of time has been spent in defining the wastewater sources both from liquid quantities as well as solids content. If you should

continued-

note any discrepancies compared to the numbers that you are familiar with, please inform us so we can settle and agree on a common requirement/data base.

Please call me should you have any questions on the submitted material. We shall also keep you posted on our test results with the current phase change VDCS.

Very truly yours,

LIFE SYSTEMS, INC.

Franz H. Schubert
Program Manager

FHS/mcg

Encls.

SPACE STATION EC/LSS LIQUID-SOLID WASTES DESIGN AVERAGE LOADS

Waste Type	Loading Rate, lb/man-day	Solids Content Weight, %	Solids Load, lb/man-day	Water Load, lb/man-day
Condensate/washwater[(a)]				
Clothing Wash	28.0	0.44	0.12	27.88
Shower	8.0	0.12	0.01	7.99
Condensate[(b)]	7.0	nil	-	7.00
Hand/Face Wash	4.0	0.12	0.01	3.99
Condensate/Washwater Totals	47.0	0.30	0.14	46.86
Urine/Flush				
Urine	3.3	3.8	0.13	3.17
Urine Flush	1.1	nil	-	1.10
Urine/Flush Totals	4.4	3.0	0.13	4.27
Solid Wastes[(c)]				
Food Waste[(d)]	0.4	37.0	0.16	0.24
Feces	0.3	25.0	0.075	0.225
Food Packaging	1.0	95.0	0.95	0.05
Spares Packaging	0.1	95.0	0.095	0.005
Experiments Waste[(e)]	0.4	95.0	0.38	0.02
EC/LSS Processing[(f)]	0.3	95.0	0.285	0.015
Utility/Hygiene Wipes	0.3	95.0	0.285	0.015
Teletype/Notepaper	0.1	95.0	0.095	0.005
Solid Wastes Totals	2.9	80.0	2.33	0.58
Liquid-Solid Wastes Totals[(g)]	26.1	10.0	2.6	23.5
Eight-Man Totals, lb/day (truncated)	209	10	21	188

(a) Data from Boeing SOC Study (NASA CR-160944, Rev. A).
(b) Includes perspiration/respiration (4.0 lb/man-day), hygiene/laundry/experiments latent water (2.0 lb/man-day), and CO_2 concentrator water production (1.0 lb/man-day).
(c) Adapted from Rockwell Space Station Waste Management Study (ASME Paper 70-Av/SpT-24).
(d) 10% of total reconstituted food (4/3 lb/man-day: 1.6 food solids, 1.1 food water, and 1.6 food preparation water) assumed to become waste.
(e) Packaging, film, bioscience waste, etc.
(f) Includes charcoal, filter media, etc., and medicinal wastes.
(g) Includes condensate/washwater concentrate, urine/flush, and solid wastes.

CONDENSATE/WASHWATER DESIGN AVERAGE LOADS[a]

Condensate	
Perspiration/respiration, lb/man-day	4.0
Latent water (hygience/laundry/experiments), lb/man-day	2.0
CO_2 concentrator water production, lb/man-day	1.0
Total condensate, lb/man-day	7.0
Condensate solids content, wt %	nil
Washwater	
Shower/hand washwater, lb/man-day	12.0
Shower/hand washwater solids content, wt %	0.12
Laundry washwater, lb/man-day	28.0
Laundry washwater solids content, wt %	0.44
Total washwater, lb/man-day	40.0
Total condensate/washwater, lb/man-day	47.0
Condensate/washwater concentrate,[b] lb/man-day	18.8

(a) Data from Beoing SOC Study (NAS CR-160944, Rev. A).
(b) Assumed 60% recovery (40% concentrate) from membrane separation process (reverse osmosis, electrodialysis, or hyperfiltration).

URINE/FLUSH DESIGN AVERAGE LOADS[a]

Urine, lb/man-day	3.3
Urine solids content, wt %	3.8
Urine flush, lb/man-day	1.1
Total urine/flush, lb/man-day	4.4

(a) Adapted from Beoing SOC Study (ibid).

PHASE CHANGE WATER RECOVERY DESIGN SPECIFICATIONS/REQUIREMENTS

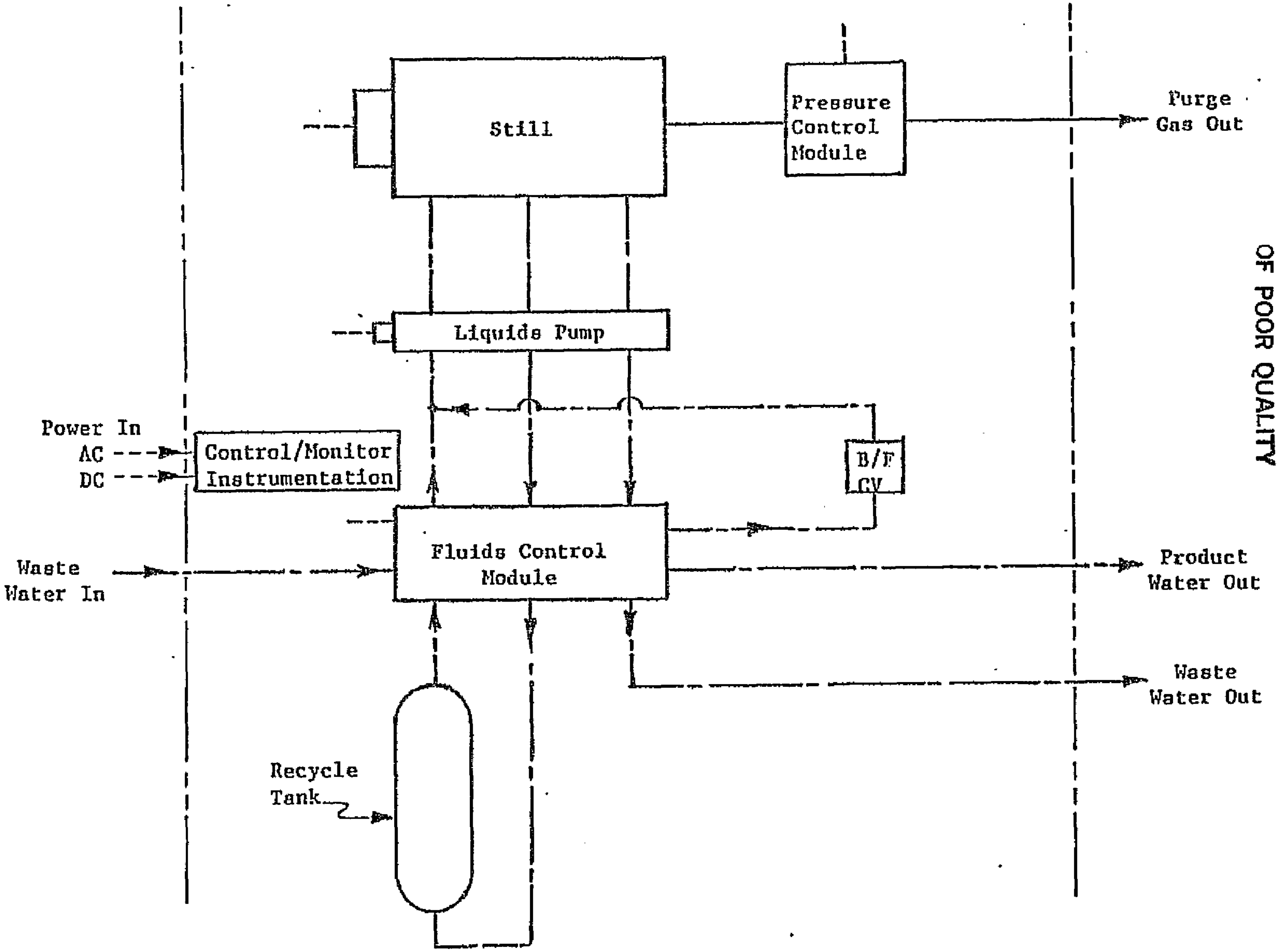
Crew Size	8
Processing Rate, kg/d (lb/d)	
Urine & Flush Water[(a)]	16.0 (35.2)
Wash Water (Hygiene)	43.6 (96.0)
Concentrate[(b)]	5.1 (11.2)
Total	64.7 (142.4)
Water Recovery Rate, kg/d (lb/d)	
Urine & Flush Water[(a)]	14.8 (32.5)
Wash Water (Hygiene)	43.5 (95.8)
Concentrate	4.5 (9.8)
Total	62.8 (138.1)
Solids Concentration, %	
Urine (without Flush Water)	3.80
Wash Water	0.12
Concentrate	1.50
Total	8.80
Product Water Pressure, kPa (psia)	170.4 (24.7)
Duty Cycle, %	$\leq$90[(c)]
Final Solids Concentration of Waste, %	50
Cabin Temperature, K (F)	291 to 297 (65 to 75)
Cabin Pressure, kPa (psia)	101 (14.7)
Electrical Power,	
VDC	27.5 to 32.5
VAC (400 Hz)	115/200
Gravity	0 to 1
Hardware Location	Two Units per Habitat

(a) With Pretreatment.
(b) From Non-phase Change Water Recovery Processes equivalent to 5% of feed to processes and 0.44% solids in feed (28 lb/man-day x 0.05 x 8 men = 11.2 lb/day).
(c) Results in an equivalent of 40 lb/day processing rate for each of four Phase Change Water Recovery Units.

PROJECTED COMPONENT WEIGHT, POWER AND
HEAT GENERATION SUMMARY FOR MODULAR VCDS UNIT[a]

Component	Weight, lb	Size, Inches	Volume, Ft^3	Power, W AC	Power, W DC	Heat Gen., W
Still	44	12 Dia. x 18	1.18	--	43	43
Recycle Tank (Dry)[b]	15	12 Dia. x 26	1.70	--	--	--
Fluids Pump	14	5 Dia. x 9	0.10	20	--	20
Fluids Control Module	5	8 x 8 x 7	0.26	--	9	9
Pressure Control Module	2	4 x 6 x 7	0.10	--	--	--
Bacteria/Flow Check Valve	1	2 Dia. x 5	0.01	--	--	--
Packaging (12%)	10	--		--	--	--
Total	91	12 x 28 x 25 (Envelope)	N/A (Envelope)	20	52	72

(a) Sized to process 35.6 lb/day of liquid waste at a 90% duty cycle or an equivalent rate of 1.65 lb/h (40 lb/day).
(b) Sized for 90 day operation at 0.26 lb/man-day of solids



PHASE CHANGE WATER RECLAMATION SYSTEM (VCDS), SCHEMATIC SHOWING COMPONENTS

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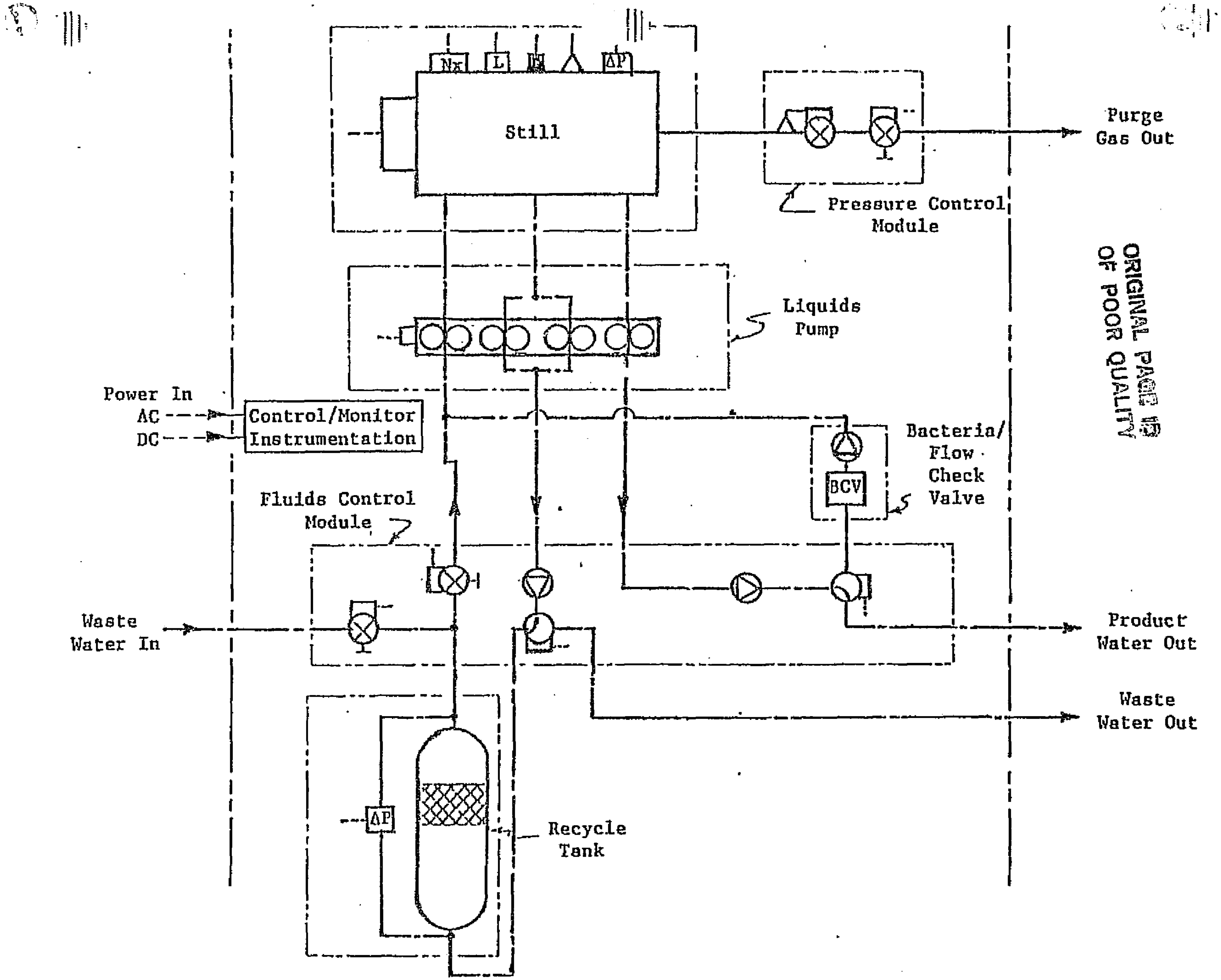
Life Systems, Inc.



PHASE CHANGE WATER RECLAMATION SYSTEM (VCDS), DETAILED FUNCTIONAL SCHEMATIC

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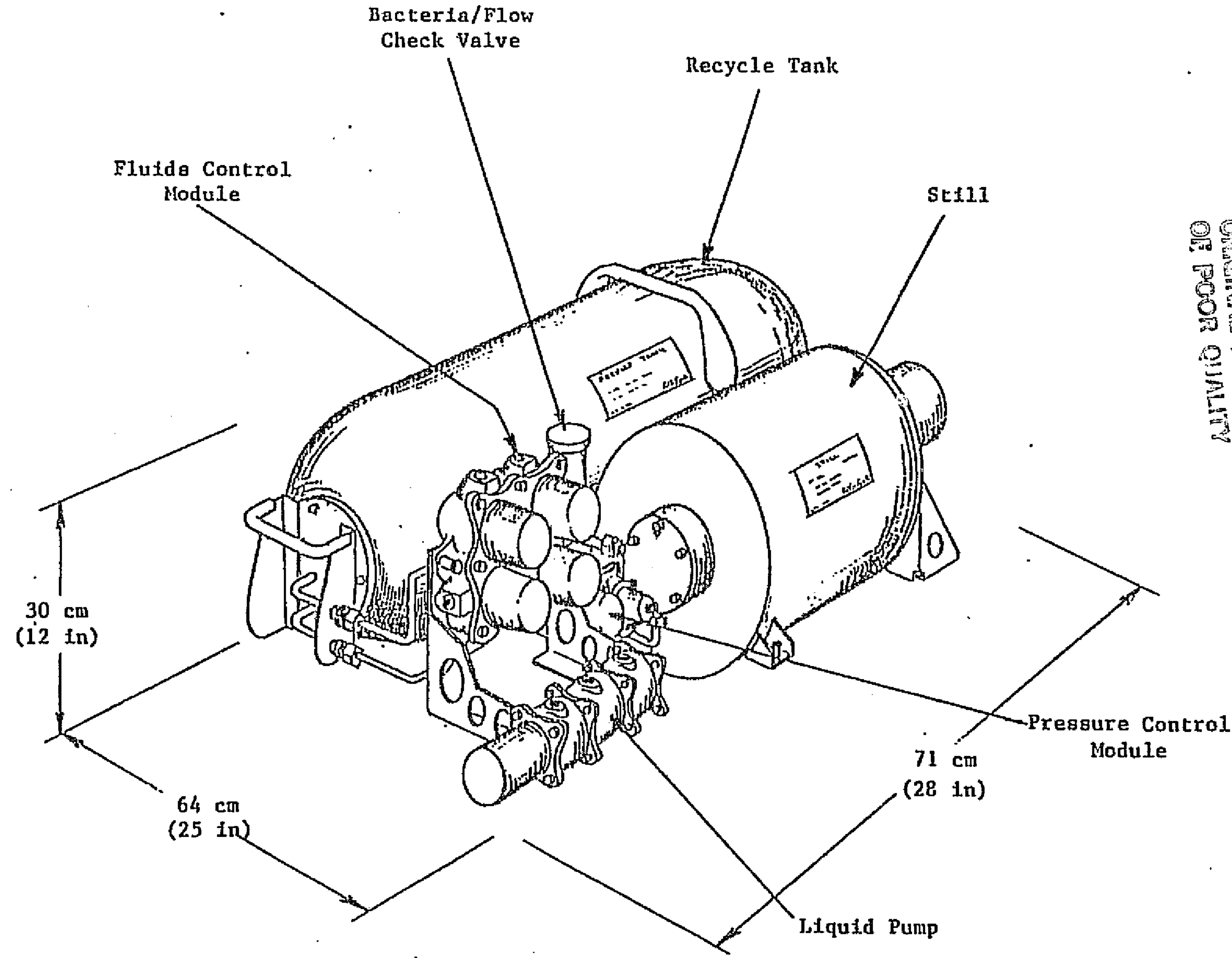
Life Systems, Inc.



PHASE CHANGE WATER RECLAMATION SYSTEM (VCDS), 40 lb/day CAPACITY

APPENDIX 2

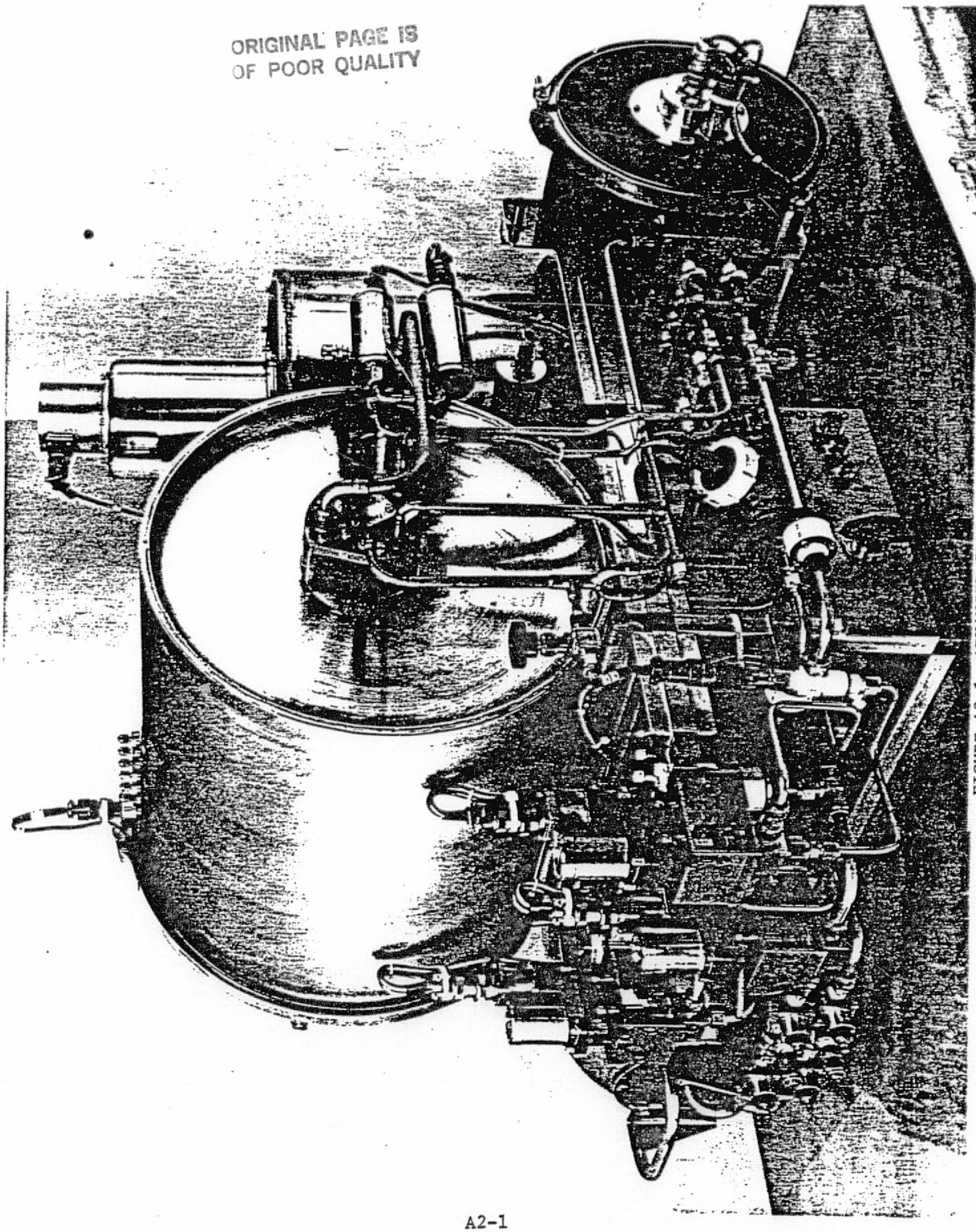


FIGURE A2-1 ADVANCED PREPROTOTYPE VCDS

Life Systems, Inc.

Submitted to:

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P. O. Box 3999
Seattle, WA 98124

Attention: Keith Miller, MS 84-06
H. F. Carr, MIS 84-86 (Cover Letter)

TR-524-6

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Quantitative Comparisons of CO_2 Concentrator Subsystems

Prepared Under

PA No. 1220

for

Boeing Aerospace Company

Contact: Franz H. Schubert

Telephone: 216 - 464-3291

March 1, 1983

TABLE OF CONTENTS

1.0 INTRODUCTION

Recently[1,2], Ham. Standard has presented claims that the Steam Desorbed Amine CO_2 Concentrator Subsystem has weight, power, etc. advantages over NASA's developed Electrochemical CO_2 Concentrating Subsystem. While most people familiar with the CO_2 Concentrator Subsystem technology are aware the Electrochemical CO_2 Concentrator historically has been found to be simpler and smaller in size (weight, power, volume, maintainability, etc.), the historical trade studies supporting this have not been accumulated in one spot.

The purpose of this Technical Report is to assemble many of the prior trade studies that quantitatively compare the Electrochemical and Steam Desorbed Amine CO_2 Concentrator Subsystems.

2.0 APPROACH

A review was made of prior Space Station studies such as those by Rockwell, McDonnell Douglas, Ham. Standard and Life Systems. The CO_2 comparison results from these studies were duplicated and incorporated into this document.

3.0 RESULTS

The information assembled include the following eight attachments:

1 A reproduction of Ham. Standards' Space Station Prototype CO_2 Concentrator Comparisons for the electrochemical, amine, and molecular sieves at CO_2 partial pressure levels (pCO_2) of 1, 3 and 5 mm Hg. It also contains their concept assumptions, sited IR-45 amine problems, process conceptual schematics and graphic plots of the data.

2 The McDonnell Douglas comparison of CO_2 Concentrator Subsystems, carried out by M. Yakut during a cost analysis of the electrochemical, amine and molecular sieves CO_2 concentrators.

---

1. Shuey, M.A., "Advanced Life Support - Orbital Work Base", XXXII Congress, International Astronautical Federation, Rome, Italy, September 6, 1981.
2. Boeing Aerospace Company, Space Operations Center System Analysis", Systems Analysis Report D180-26495-4, July, 1981.

3 Rockwell's results of its study evaluating CO_2 removal and concentration concepts at the 3 mm Hg partial pressure of CO_2 including molecular sieves, steam desorbed resin, HS-B and electrochemical at the 0.23 mm Hg of pCO_2.

4 A Life Systems comparison of electrochemical, molecular sieves and steam desorption systems as contained in ASME publication 70-Av/SpT-8.

5 The results of a Life Systems trade study of nine designs for CO_2 removal. The discussion focused on Electrochemical CO_2 Concentrator vs. Steam Desorbed Amine. Table 10 illustrates one approach to one aspect of comparing subsystems that proved helpful. Figure 1, original color-coded was very helpful in convincing NASA the electrochemical CO_2 concentrator should be developed because it is so simple.

6 The calculations contained in SSP documentation leading to the trade study results presented in Attachment 1 for the electrochemical and IR-45 amine systems.

7 A duplicate of the trade study results for electrochemical, independent air revitalization, HS-C (two approaches) and lithium hydroxide for three 7-person Shuttle mission options.

8 A Ham. Standard amine subsystem weight breakdown corrected for items omitted from their weight summary but on their subsystem schematic and corrected for the "first time ever" transference of steam desorption hardware requirements to the Sabatier CO_2 Reduction Subsystem. (If they would really believe this, it would be a divergence from 15 years of reporting subsystem results.)

From the results presented in the Attachments, it shows NASA's past decision for funding and selecting the Electrochemical approach as a primary CO_2 Removal Subsystem for Space Station, with the amine as a backup, is well-founded. Mr. Shuey's reporting[1] the "clear advantages" to the steam desorbed amine in his IAF '81 paper appear to be a misrepresentation of facts. The use of trade-off tricks by certain personnel at Ham. Standard appears an injustice to NASA, the American people and ourselves.

4.0 SUMMARY

An effort has been completed which assembles in one location prior trade-off comparisons between the Electrochemical CO_2 Concentrator and the Steam Desorbed Amine Subsystems. From it, the biased Ham. Standard claims are found to be unsupported and to contain significant misrepresentation of facts.

COMPARISON CO_2 CONCENTRATORS:[a,b] 1.0 mm Hg

Comparison Factor	Electro-chemical	Amine[c]	Molecular Sieves[d]
Weight, lb	794	1,302	3,940
Volume, ft^3	54	89	268
Power			
Electrical	4,778	19,390	54,743
Thermal	—	290	1,600
Peak Heating Load, Btu/hr	0	65,200	191,615
Peak Cooling Load, Btu/hr	14,140	65,200	191,615
Total Equivalent Weight			
Electric	3,082	7,948	26,624
Thermal	3,082	5,419	16,500
Development	Moderate	Moderate	Low

(a) Ham. Standard, "Space Station Prototype ETC/LSS, System Level Trade Studies," Document No. 11, July 7, 1970.
(b) All designed for a crew of 12 persons, 2.2 lb CO_2/person day, cabin volume of 4,500 ft^3 inlet pressure 10 psia, 591 lb/kW 28 VDC, 710 lb/kW 115 VAC, 154 lb/kW sun side unregulated DC, 270 lb/kW sun side regulated DC and 351 lb/kW sun side regulated AC, 0.005 lb/Btu/hr at 200 F heat source penalty, 0.05 lb/Btu/hr heat rejection to coolant and 0.09 lb/Btu/hr heat rejection to cabin air.
(c) Based on one data point available at the time.
(d) High temperature (375 F) versus low (180 F).

COMPARISON CO_2 CONCENTRATORS:[a,b] 3.0 mm Hg

Comparison Factor	Electro-chemical	Amine[c]	Molecular Sieves[d]
Weight, lb	621	841	1,239
Volume, ft^3	42	57	84
Power			
Electrical	2,938	10,348	13,668
Thermal	---	148	975
Peak Heating Load, Btu/hr	0	34,900	43,321
Peak Cooling Load, Btu/hr	9,604	34,900	43,321
Total Equivalent Weight			
Electric	1,998	4,389	5,983
Thermal	1,998	3,079	4,438
Development	Moderate	Moderate	Low

(a) Ham. Standard, "Space Station Prototypé ETC/LSS, System Level Trade Studies," Document No. 11, July 7, 1970.
(b) All designed for a crew of 12 persons, 2.2 lb CO_2/person day, cabin volume of 4,500 ft^3 inlet pressure 10 psia, 591 lb/kW 28 VDC, 710 lb/kW 115 VAC, 154 lb/kW sun side unregulated DC, 270 lb/kW sun side regulated DC and 351 lb/kW sun side regulated AC, 0.005 lb/Btu/hr at 200 F heat source penalty, 0.05 lb/Btu/hr heat rejection to coolant and 0.09 lb/Btu/hr heat rejection to cabin air.
(c) Based on one data point available at the time.
(d) High temperature (375 F) versus low (180 F).

COMPARISON CO_2 CONCENTRATORS:[a,b] 5.0 mm Hg

Comparison Factor	Electro-chemical	Amine[c]	Molecular Sieves[d]
Weight, lb	441	708	893
Volume, ft^3	30	48	61
Power			
Electrical	2,014	7,773	8,270
Thermal	---	123	751
Peak Heating Load, Btu/hr	0	26,100	25,663
Peak Cooling Load, Btu/hr	6,624	26,100	25,663
Total Equivalent Weight			
Electric	1,383	3,377	3,787
Thermal	1,383	2,413	2,906
Development	Moderate	Moderate	Low

(a) Ham. Standard, "Space Station Prototype ETC/LSS, System Level Trade Studies," Document No. 11, July 7, 1970.

(b) All designed for a crew of 12 persons, 2.2 lb CO_2/person day, cabin volume of 4,500 ft^3 inlet pressure 10 psia, 591 lb/kW 28 VDC, 710 lb/kW 115 VAC, 154 lb/kW sun side unregulated DC, 270 lb/kW sun side regulated DC and 351 lb/kW sun side regulated AC, 0.005 lb/Btu/hr at 200 F heat source penalty, 0.05 lb/Btu/hr heat rejection to coolant and 0.09 lb/Btu/hr heat rejection to cabin air.

(c) Based on one data point available at the time.

(d) High temperature (375 F) versus low (180 F).

Concept Assumptions

Molecular Sieve

1. Removed efficiency of 35% for all pCO_2s
2. Desorption pressure of 1 psia
3. Desorption temperature of 375 F
4. Performance based on Ham. Standard data

Steam Desorbed IR-45

1. Test removal efficiency of 85% constant for all pCO_2s
2. Loading varies directly as $(pCO_2)^n$ based on 1 and 4 mm Hg, n = 0.57
3. Performance based on Ham. Standard data
4. Use of compressor not required

Electrochemical Concentrator

1. Removal efficiency constant for all pCO_2s
2. No credit given for power produced
3. Hydrogen and O_2 produced by central electrolysis unit
4. System penalized for O_2 required from electrolysis cell based on O_2 consumption varying linearly with pCO_2
5. Based on vendor input for pCO_2 of 3 mm Hg
6. Heat rejected to cabin versus to liquid coolant

Ham. Standard cited IR-45 amine problems

1. Bed expansion and contraction as water content varies through the cycle. This may lead to channeling in zero gravity.

2. Other zero gravity problems are:

   a. Steam - CO_2 separation - may influence the sharpness of separation between steam and CO_2.
   b. Water separation - effects of water formed during cycle.
   c. Steam generation - development of device that can generate steam rapidly is required.

3. Will long term degradation occur.

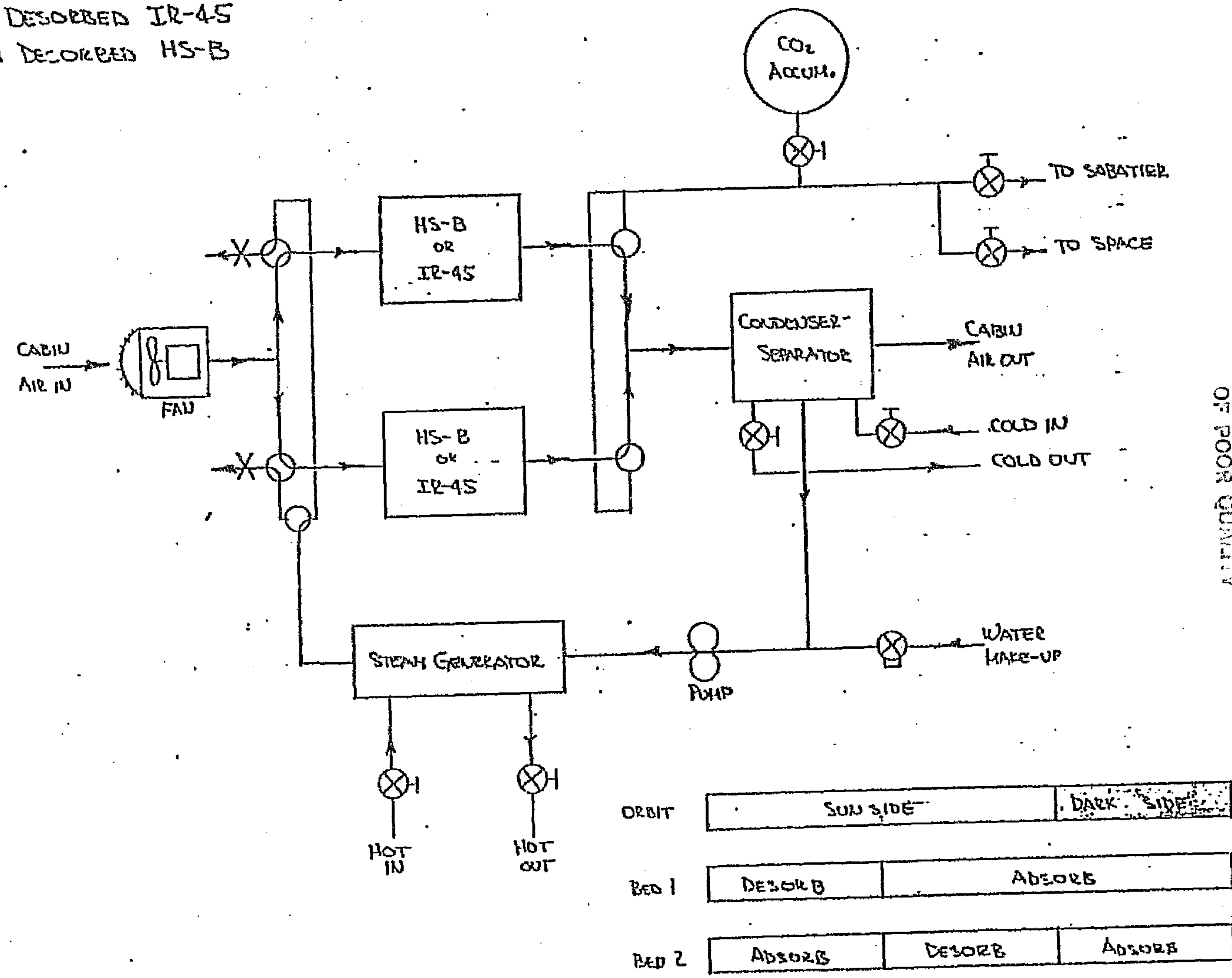
HS-B

1. Performance data meager.

2. Material is flammable and unavailable in mesh sizes below about 30 mesh.

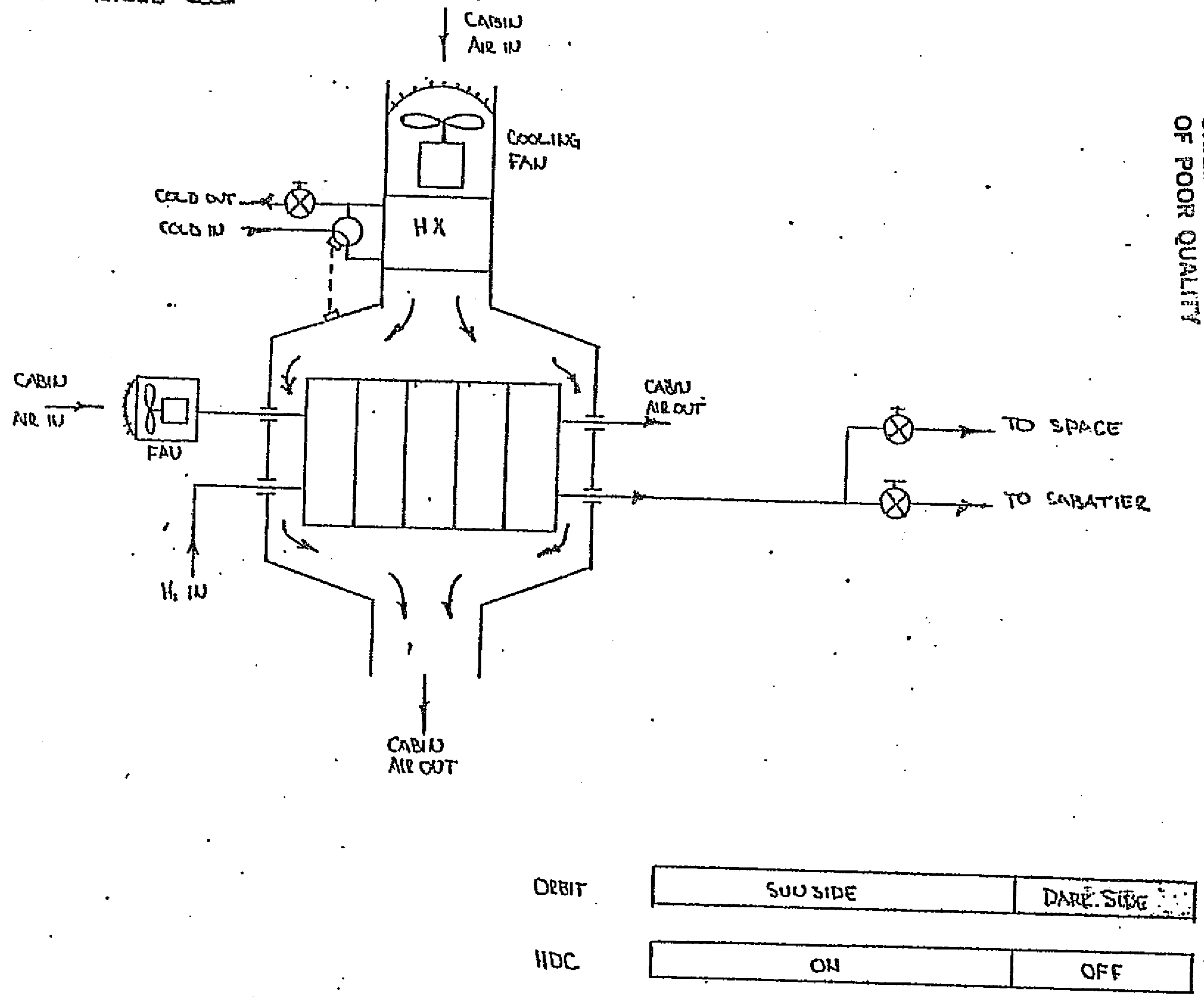
FIGURE 1

STEAM DESORBED IR-45
STEAM DESORBED HS-B



HYDROGEN DEPOLARIZED CELL

FIGURE 3



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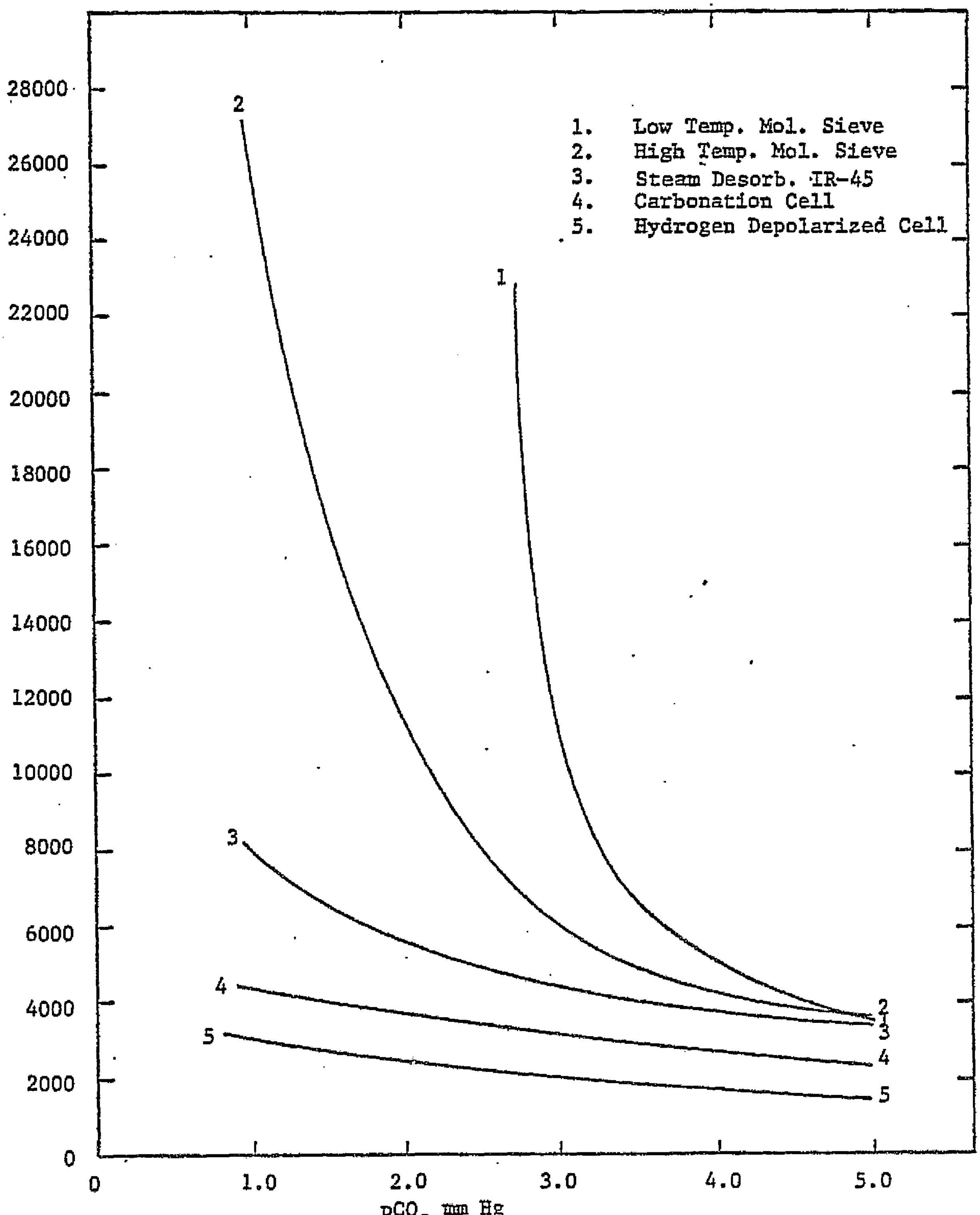

FIGURE SSPC CO_2 CONCENTRATOR STUDY
TOTAL EQUIVALENT WEIGHT vs. pCO_2 ELECTRICAL THERMAL SOURCE
(154 lb/kw UNREGULATED SUN-SIDE D.C.)

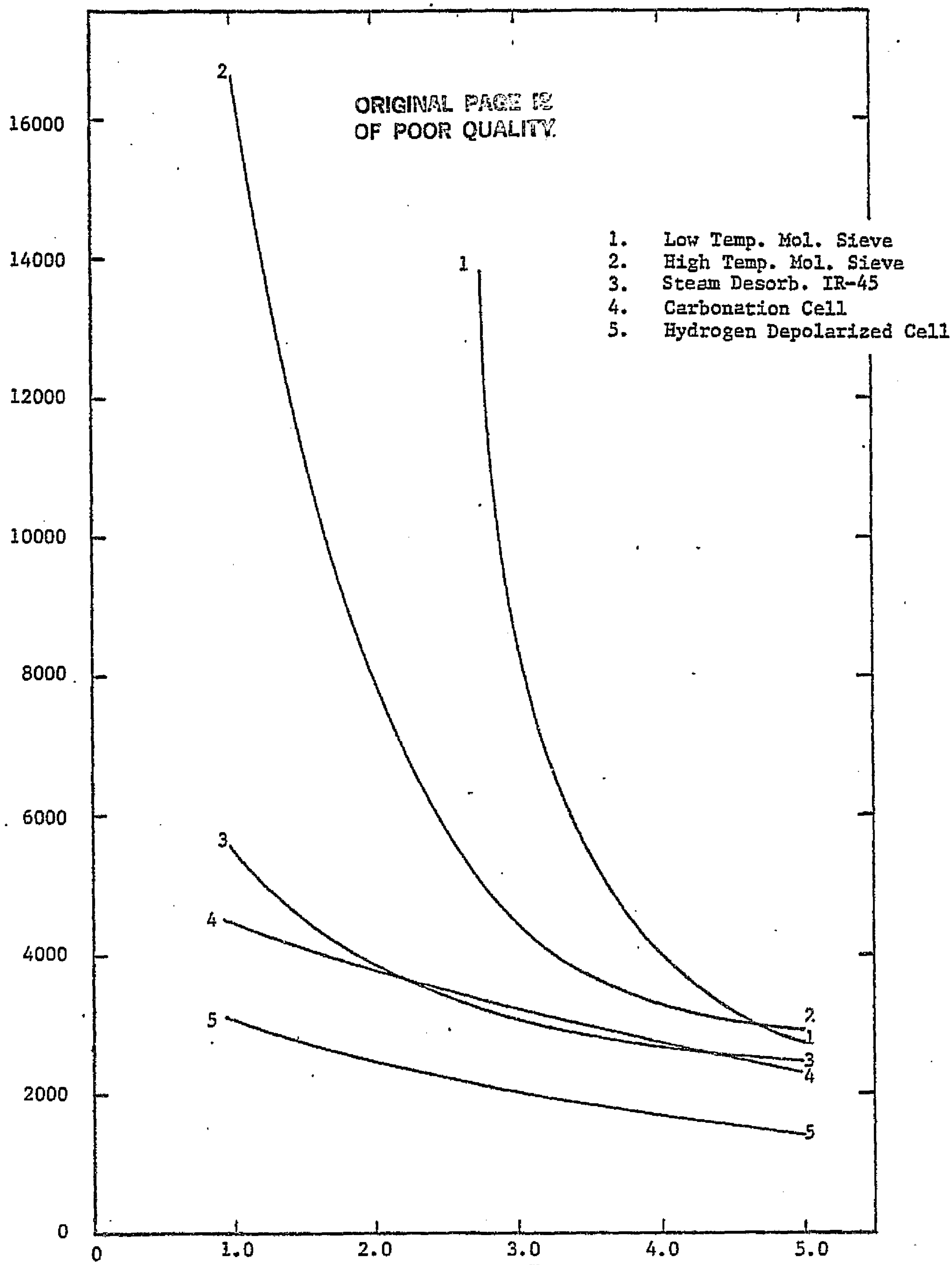

FIGURE SSP CO_2 CONCENTRATOR STUDY
TOTAL EQUIVALENT WEIGHT vs. pCO_2 SOLAR COLLECTOR THERMAL SOURCE

QUANTITATIVE COMPARISON OF CO_2 CONCENTRATOR SUBSYSTEMS[a,b]

Comparison Factor	CO_2 Concentration Subsystems		
	Electro-chemical	Amine	Molecular Sieves
Subsystem Weight	197.9	474.4	852.8
Spares Weight	166.4	346.2	507.9
Total Weight	364.3	820.6	1,360.7
Electrical Power, W			
DC	20	25	25
AC	300	620	754
Total Volume, ft^3	22	24	63
CO_2 Delivery Purity, %	100	98	98
Coolant Flow Rate, lb/hr	Not Req'd.	100	1,100
Coolant Inlet Temp., F	Not Req'd.	60-80	65
Heating Fluid Flow Rate, lb/hr	Not Req'd.	100	925
Heating Fluid Inlet Temp., F	Not Req'd.	180-200	275
Coolant Air Flow Rate (Intermittent), CFM	200	Not Req'd.	Not Req'd.
Atmospheric Flow Rate, CFM	60	45	75
Number Component Types	21	21	23
Number of Components			
Basic System	40	40	61
Spares	34	31	35
Design CO_2 Removal Rate, lb/hr	0.6[c]	0.6	1.07
CO_2 Inlet Partial Pressure mm/Hg	3.0	1.5-3.8	2.86
Pressure Rise (at 10 psia), in. H_2O	NC[d]	NC	9.2

(a) Yakut, H.M., "Cost Analysis of Carbon Dioxide Concentrators," MDAC Report MDC 6-4631, Contract NAS8-28377, June, 1973.
(b) All designed for a crew size of six persons, average CO_2 produced of 2.2 lb/person day, maximum CO_2 produced (max.) 3.11 lb/person day and CO_2 delivery pressure to CO_2 reduction subsystem of 30-40 psia.
(c) Not cited but calculated as (2.2 lb/person-day) (6-person) (1 day/24 hr.)
(d) NC = Not cited.

Note: System has, since reporting date of 1973, undergone three developments (CX-6, CS-6 and CS-3) with flight qualifiable version under construction (CS-1). Also changed from air to liquid cooled for further power and weight reductions.

ATTACHMENT 3

RADIOISOTOPE SPACE STATION
from DRL 43, SD 70-502-3, January 1971

PART III. 3-MM Hg CO_2 ATMOSPHERIC CONTROL STUDY

1.0 SUMMARY

A study was performed to evaluate concepts for CO_2 removal and concentration at 3-mm Hg partial pressure of CO_2. This study task was identified in the Phase B Space Station options period statement of work and is presented in this RIB Station report, although the data are applicable to the entire Station program.

The normal CO_2 design concentration of 5 mm Hg was used for the Space Station preliminary design. A reduction in the CO_2 concentration to 3 mm Hg is desirable to more closely duplicate the 0.23-mm Hg earth environment, thus minimizing long-duration effects on the crew and providing a better common basis for earth-to-space experiment comparisons. This report evaluates concepts for CO_2 removal at 3 mm PCO_2 and identifies the effect of implementing a 3-mm PCO_2 design requirement for the Space Station. The design impact on the Solar Array Station (SAB), the Nuclear Reactor (NRB) Station, and the Radioisotope (RIB) Station was assessed and a brief analysis of PCO_2 control to 0.23 mm Hg was performed.

Candidate concepts evaluated for 3-mm Hg PCO_2 control were:

- High temperature molecular sieve (375 F)
- Steam-desorbed resin (solid amine)
- HS-B (proprietary Hamilton Standard concept)
- Carbonation cell
- Hydrogen depolarized cell

Low temperature molecular sieve (180 F) as selected for Space Station preliminary design was not considered because preliminary evaluations have shown that its weight and power requirements are excessive at 3 mm Hg PCO_2.

1.1 DESIGN REQUIREMENTS

Design requirements for the CO_2 removal trade study are summarized as follows:

20 lb O2/35 ... man) 12 x = 2.2 lb CO2/lb O2 = TI

Table III-14. Power and Expendables for Minimum Power Operation of CO_2 Removal Candidates

Item	Molecular Sieve	Steam Desorbed Resin	HS-B	H_2 Depolarized Unit
O_2 lost via CO_2 (lb)	673	673	673	673
O_2 ullage (lb)	58	0	50	0
N_2 ullage (lb)	682	0	160	0
O_2 consumed (lb)	—	—	—	420
H_2 consumed (lb)	—	—	—	53
H_2O ullage (lb)	0	0	1566	0
Power savings* (watts)	1830	0	1000	0
Total power required (watts)	3380	4220	1530	140

NOTES:
1. Based on an all-electric system
2. Tankage penalties not included
3. Molecular sieve and HS-B vacuum desorbed; no change in steam desorbed resin and H_2 depolarized unit except that CO_2 is dumped to space.
4. 35-day operation, 12-man crew

*Decrease from normal operating power level

Table III-15. CO_2 Removal Characteristics at 0.23 mm Hg PCO_2

Characteristic \ Concept	Steam Desorbed Resin	HS-B	H_2 Depolarized Cell	
Operating hardware wt. (lb)	4,700	3,200	1,800	1300 H_2 depolar. 500 electrolysis
AC power (watts)	7,200	6,400	5,700	1000 H_2 depolar. 4700 electrolysis
Thermal power (Btu/hr)	15,000	21,000	0	
Heat rejection (Btu/hr)	39,600	42,700	10,000	

COMPARISON OF NINE-MAN CARBON DIOXIDE CONCENTRATING SYSTEMS: 500 DAYS

	Concentrator	Molecular Sieve (4-Bed)			Steam Desorption		
Reliability	>0.999600	0.999578			0.999433		
Mean Time Between Failures (hr)	>20,000	10,500			17,100		
Equivalent Weight (lb)		(1)	(2)	(3)	(1)	(2)	(3)
Basic Unit	48	385	393	385	269	231	200
Spares/Redundancy	92	331	331	331	231	231	231
Electrical Power	-52	376	237	237	453	81	81
Thermal Power	--	--	15	--	--	62	--
Radiator Load	49	114	114	114	195	195	195
Other Credits/Penalties	377	--	--	--	--	--	--
Total	514	1206	1090	1067	1148	800	700
Volume (ft^3)							
Installed	6		28			18	
Spares	4		9			6	
Total	10		37			24	
Basic Unit & Spares Density (lb/ft^3)	14	19	20	19	15	13	11
Crew Time (hr/mission)							
Scheduled	0.5		0			16	
Unscheduled	1.5		2.3			1.8	
Peak Power	585	1008	180	180	837	528	528

(1) A solar cell/battery power system. Electrical process heat.
(2) A solar cell/battery power system. Radioisotope process heat.
(3) A Brayton cycle power system. Waste heat for process heat.
4) Quattrone, P.D.; Babinsky, A.D. and Wynveen, R.A., "Carbon Dioxide Control and Oxygen Generation," ASME Publication 70-Av/SpT-8, ASME Conference, Los Angeles, CA; June 21, 1970.

ATTACHMENT 5

ER-110

TRADE-OFF STUDY AND CONCEPTUAL DESIGNS OF CO_2 REMOVAL SYSTEMS

August 13, 1969

Internal Research and Development

Project Number 523-000101

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1.0 INTRODUCTION

Crew members of a spacecraft consume approximately 2 lb of oxygen per day. Of this, between 80 and 90 percent is exhaled as carbon dioxide. To lower launch weight costs(1) and avoid the need to carry large quantities of make-up oxygen, it must be extracted from the exhaled carbon dioxide. To date this requires that the carbon dioxide must be concentrated from the cabin atmosphere and, in the process, maintain the maximum CO_2 partial pressure of less than 3.8 mm Hg. This level corresponds to the 0.5 percent by volume at 1 atmosphere total pressure.

1.1 Background

At least nine different carbon dioxide concentrating systems have been partially developed. They are the:

- Hydrogen Depolarized Concentrator
- Two-bed Amine Sorption with Steam Desorption
- Carbonation Cell
- Four-bed, Molecular Sieve, Sorption
- Two-bed Amine Sorption
- Electrodialysis
- Membrane Diffusion
- Liquid Absorption
- Mechanical Freezeout

1.2 Problem

The problem is to select the most optimum system for concentrating carbon dioxide. This requires that the system concept be demonstrated on actual self-contained hardware. It is desirable, if not essential, that the subsystem hardware be tested in a closed-cycle, life support system during a 120-day manned test. A further problem is to accomplish this in a cost-effective manner.

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(1) Dr. George Mueller, in a statement for Aviation Week and Space Technology, August 11, 1969, noted with today's techniques, the cost to transport material to the moon's surface is $100,000 per pound.

2.0 TECHNICAL DISCUSSION

2.1 Concentrator versus Carbonation Cell

As part of its internal research and development activities, Life Systems has completed a comparison of the two best electrochemical carbon dioxide concentrating systems--the Concentrator[1] and the Carbonation Cell. The Concentrator System was found to be more attractive because it used fewer and simpler controls, had a 60 percent lower equivalent weight, and provided uncontaminated carbon dioxide, premixed with hydrogen for feeding to the carbon dioxide reduction reactor.

Table 1 summarizes the comparison of nine-man versions of the Concentrator and the Carbonation Cell Systems. The Concentrator system includes a penalty associated with obtaining the oxygen and hydrogen required in the concentrating process from a Water Electrolysis System.[2]

If hydrogen and oxygen were available aboard the spacecraft at no penalty, the nine manned Concentrator System would have an equivalent weight (including heat load and power load penalties) of 90 pounds and a power output of 115 watts.

Table 2 presents the comparison summary at the component level. Table 3 summarizes the advantages of the Concentrator over the Carbonation Cell System.

2.2 Concentrator versus Steam Desorption

A comparison was then made of the Concentrator with the two-bed, amine sorption, steam desorption method for carbon dioxide concentration. The Concentrator was preferred in all fourteen categories of criteria used.

2.2.1 Performance - The concentrator has no zero gravity with gas separation process nor any liquid line connections. The steam desorption system has a minimum of three gas-liquid separation processes in more than forty liquid line connections.

2.2.2 Safety - The concentrator system operates at the low 100 F temperature. No cabin atmosphere contamination results. The steam desorption system operates at steam temperatures. A mean carry-over may be a problem during operation or servicing. Neither system has bacteriological problems.

---

(1) Also referred to as the Hydrogen Depolarized Concentrator.

(2) Life Systems Engineering Report Number ER-108, "Trade-off Study and Conceptual Designs of Water Electrolysis Subsystems," August 1, 1969.

TABLE: 1 COMPARISON OF NINE MAN DEPOLARIZED AND CARBONATION CELL SYSTEMS: SYSTEM INTEGRATION LEVEL

EQUIVALENT WEIGHT: lb.	Depolarized	Carbonation
Basic Unit	48	116
Spares/Redundancy	46	107
Electrical Power (1)	-52	865
Thermal Power	--	--
Radiator Load (2)	49	186
Electrolysis Penalty		
Basic Unit/Spares	57	--
Electrical Power	315	--
Radiator Load	5	--
TOTAL: lb	468	1274
Peak Power: Watts	585	1925
Volume: Ft^3		
Installed (60% dense)	5.9	7.2
Spares	3.5	3.0
TOTAL	9.4	10.2
System Weight: lb	141	223
Packaging Density: lb/Ft^3	15	22

1. Power penalty of 450 lb/Kw.

2. Heat rejection penalties of 0.11 lb/W (100°F), 0.082 lb/W (180°F) and 0.072 lb/W (200°F)

TABLE 2 COMPARISON OF NINE-MAN DEPOLARIZED AND CARBONATION CELL SYSTEM: COMPONENT LEVEL

Component	Depolarized System				Spares			Carbonation System				Spares		
	No.	Wt.	Vol.	Pow.	No.	Wt.	Vol.	No.	Wt.	Vol.	Pow.	No.	Wt.	Vol.
Fan	1	2.0	0.1	25	2	4.0	0.2	1	2.0	0.1	25	2	4.0	0.2
Accumulator	-	-	-	-	-	-	-	1	5.0	1.0	-	-	-	-
Check Valve	1	0.2	-	-	-	-	-	3	0.6	0.1	-	1	0.2	-
Isolation Valve	1	0.4	-	-	-	-	-	4	1.6	0.1	-	1	0.4	-
Water Vapor Exchanger	1	2.3	0.1	-	1	2.3	0.1	1	2.3	0.1	-	1	2.3	0.1
Water Pressure Regulator	-	-	-	-	-	-	-	2	2.0	0.1	-	4	4.0	0.2
Air "Compressor"	1	2.0	0.1	10	2	4.0	0.2	-	-	-	-	-	-	-
CO_2 "Compressor"	-	-	-	-	-	-	-	1	1.0	0.1	10	2	4.0	0.2
Carbonate Module	1	23.0	0.3	(170)	1	23.0	0.3	1	52.0	0.7	1284	1	52.0	0.7
Acid Module	-	-	-	-	-	-	-	1	13.7	0.2	562	1	13.7	0.2
Temperature Controllers	1	8.0	0.4	20	1	8.0	0.4	1	8.0	0.4	20	1	8.0	0.4
Power Converter	-	-	-	-	-	-	-	1	8.0	0.4	20	1	8.0	0.4
Miscellaneous	1	10.0	0.5	-	1	5.0	0.3	1	20.0	1.0	-	1	10.0	0.5
Subtotal	8	47.9	1.5	(115)	8	46.3	1.5	18	116.2	4.3	1911	16	106.6	2.9
Water Electrolysis Requirements	-	24.0	2.0	700	-	23.0	2.0	-	-	-	-	-	-	-
Volume at 60% Dense	-	-	5.9	-	-	-	-	-	-	7.2	-	-	-	-
TOTAL														
Weight		71.9				69.3			116				107	
Volume (60% Dense)			5.9				3.5			7.2				2.7
Power				585							1911			

TABLE 3 ADVANTAGES OF THE CONCENTRATOR (DEPOLARIZED) SYSTEM OVER THE CARBONATION CELL SYSTEM

1. More reliable because of fewer and simpler controls.

2. Less maintenance because the system is made up of fewer components.

3. Lower power, equivalent weight, and volume.

4. Provides carbon dioxide free of oxygen contamination.

5. Integrates better with all carbon dioxide reduction systems since H_2 and CO_2 are premixed.

6. Lower development cost.

2.2.3 Availability/Confidence - To date concentrator cells have run for more than 8,000 hours with servicing. Even longer times will be possible without servicing with continued development. No new items need to be developed with the Concentrator. Only limited operating time has been accumulated with the steam desorption system. Several significant components need development including the steam generator, liquid condenser-separators, and steam detector to signal need for cycling.

2.2.4 Reliability - The concentrator contains only 21 components of five different types and only one component with a failure rate of 100 times per million hours. The steam desorption system contains 121 components of 25 different types and five components have failure rates equal or greater than 100 times per million hours.

2.2.5 Crew Time - Maintainability will be less with the Concentrator system since fewer components are involved. In addition, less crew training and fewer fault-isolation equipment will be necessary. There is no scheduled maintenance required. The steam desorption system, being a more complex system, requires more training and more fault-isolation equipment. It requires multiple scheduled maintenance.

2.2.6 Equivalent Weight - The equivalent weight of a nine-man system is 470 lbs using a water electrolysis system for the hydrogen and oxygen or 90 lbs if hydrogen is available without penalty. The steam desorption system has an equivalent weight of 1150 lbs or 710 lbs if ~~"weight"~~ waste heat is available.

2.2.7 Development Cost - The Concentrator has a lower development cost. One basic system will be applicable to all space missions including space mission, lunar orbital, lunar base, or planetary explorations. Extensive component development remains with the steam desorption system. It appears to be less adaptable to changes in crew size.

2.2.8 Contamination - Neither the carbon dioxide nor the cabin atmosphere would be contaminated through the use of the Concentrator system. The steam desorption system results in carbon dioxide contaminated with oxygen, hydrogen, and any "catalyst poisons" which could be contained in the cabin air, such as sulfur-bearing compounds.

2.2.9 Interfaces - The Concentrator system interfaces only with the humidity control subsystem. The steam desorption system interfaces with the humidity control, thermal control, power conditioning, and water storage subsystems.

2.2.10 Flexibility - The Concentrator system is more flexible. The carbon dioxide removal rate can be throttled. The process can be cyclic or continuous. Overcapacities of 100 to 200 percent can be handled. It is basically a nonpower-consuming process and has one design regardless of whether or not waste heat would be available. The technology is widely applicable to such processes as oxygen generation, atmosphere resupply, attitude control, etc. The steam desorption system removes the carbon dioxide only through a cyclic process with a capacity limited by the cannister size. It is nonoperative in the absence of power. The design concept is dependent upon the availability of waste heat. The technology is limited in applicability to the carbon dioxide process.

2.2.11 Growth - Extensive improvements are possible on the Concentrator system. Currently 0.4 of a volt and 40 amps/sq ft has been selected as the design point for the unit being compared. In addition one mole of carbon dioxide has been assumed to be transferred for every 2 Faradays of electricity. Experimental results to date show that 0.6 volts is possible at 100 amps/sq ft and one mole of carbon dioxide can be transferred for every Faraday of electricity.

Optimization is possible with the steam desorption system but the drawbacks of its cyclic nature, its power consumption, and its need for gas-liquid separation still will remain.

2.2.12 Noise - The Concentrator system is completely static and therefore has a quiet operation except for the low speed air circulation fan required. The steam desorption process is noisy due to the need for one carbon dioxide compressor, three liquid fluid pumps, four cycling solenoids, and two valve-actuator motors.

2.2.13 Volume - The Concentrator occupies from 6 to 10 cu ft depending upon the assumption of a water electrolysis penalty. This is only 25 to 40% the volume required by the 24 cu ft steam desorption system.

2.2.14 Power Needs - Both the Concentrator and the steam desorption systems require air supply fans. The only power required by the Concentrator is that indirectly needed for the water electrolysis system. The steam desorption process, however, requires power for the steam generator, two four-way solenoids and their motors, two three-way solenoids, a water supply solenoid and a coolant solenoid, a carbon dioxide compressor, two water pumps, and a coolant pump.

2.2.15 System Level Comparison - Table 4 is a summary of the comparison of the two systems. Table 5 is a comparison summary of the system component reliabilities. Tables 6, 7, and 8 summarize the Essential, Primary, and Secondary Criteria comparisons for the two systems.

Table 9 is a matrix of Tables 6, 7 and 8.

2.2.16 Schematic Comparison - Figure 1 is a comparison of the schematics of the two systems.

TABLE 5 COMPARISON OF COMPONENTS, FAILURE RATES, AND SPARES FOR DEPOLARIZED AND STEAM DESORBED CONCENTRATORS[(a)]

	Component	Est.Failure Rate/10^6 Hrs	Operating Hrs.Without Failure	No. Components		Est.Fail/10^6 Hrs		No. Spares	
				Steam Dsrp.	Depolar. Concent.	Steam Dsrp.	Depolar. Concent.	Steam Dsrp.	Depolarized Concentrator
1.	Timer	100	10,000	1	-	100	0	1	-
2.	Steam Generator[(b)]	503	1,990	1	-	503	0	7	-
3.	Condenser/Separator	500	2,000	2	-	1000	0	10	-
4.	Motor-actuated Solenoid	50	20,000	2	-	100	0	4	-
5.	Three-way Solenoid	25	40,000	2	-	30	0	2	-
6.	Liquid Solenoid	1.0	1×10^6	1	-	1	0	1	-
7.	CO_2 Compressor	100	10,000	1	-	100	0	1	-
8.	H_2O Metering Pump	10	100,000	1	-	10	0	1	-
9.	H_2O Return Pump	10	100,000	1	-	10	0	1	-
10.	Coolant Pump	20	50,000	1	-	20	0	1	-
11.	Cabin Air Fan and Filter	11	91,000	1	1	11	11	1	1
12.	H_2O Regulator	10	100,000	3	-	30	0	2	-
13.	H_2O Purifier	0.1	1×10^7	1	-	(c)	0	1	-
14.	Canisters	0.1	1×10^7	2	-	(c)	0	1	-
15.	Module	50	20,000	-	1	0	50	1	-
16.	CO_2 Accumulator	0.1	1×10^7	1	-	(c)	0	-	-
17.	H_2O Accumulator	0.1	1×10^7	1	-	(c)	0	-	-
18.	Condensed H_2O Accumulator	0.1	1×10^7	2	-	(c)	0	-	-
19.	Water Vapor Exchanger	100	10,000	-	1	0	100	-	1
20.	Quick-Disconnect	1.0	1×10^6	35	16	35	16	4	2
21.	Check Valve	10	100,000	7	-	70	0	1	-
22.	Isolation Valve	0.1	1×10^7	12	5	1	(c)	1	1
23.	Diverter Valve (Manual)	0.1	1×10^7	1	-	(c)	0	1	-
24.	Coolant Feed Line Disconnects	1.0	1×10^6	11	-	11	0	1	-
25.	Water Line Disconnects	1.0	1×10^6	28	-	28	0	1	-
26.	Water Filter	1.0	1×10^6	2	-	2	0	-	-
27.	Coolant Filter	1.0	1×10^6	1	-	1	0	-	-
	Subtotals			121	24	2009	177	24	5
28.	Hoses	1.0	1×10^6	148	28	148	28	(d)	(d)
	TOTALS			269	52	2157[(e)]	205[(e)]	24	5

(a) But omitting controls, instrumentation, fault isolation equipment, etc.
(b) Composed of heater, heater controller, gas-liquid separator (≥ 212°F), heat exchanger, and heated gas lines and in-line components to present condensation.
(c) Less than 1 failure per million hours.
(d) Hoses are different sizes and lengths, it is necessary that supply of hoses be taken with provisions (e.g., tools, adapters) to insert into appropriate location.

TABLE 4 COMPARISON OF NINE MAN CARBON DIOXIDE CONCENTRATION SYSTEMS

	Depolarized		Carbonation	Steam Desorption		
Reliability	>> 0.999433		> 0.999433	0.999433		
Mean Time Between Failures	>20,000		>15,000	17,100		
Equivalent Weight (lb)						
Basic Unit	48	48	116	269	231	200
Spares/Redundancy	46	46	107	231	231	231
Electrical Power	-52	-52	865	453	81	81
Thermal Power	-	-	-	-	62	-
Radiator Load	49	49	186	195	195	195
Other Credits/Penalties	377	-	-	-	-	-
Total	468	91	1274	1148	800	700
Total Volume (ft^3)	10	6	10	24	24	24
Installed	6	4	7	18	18	10
Spares	4	2	3	6	6	6
Basic Unit & Spares Density (lb/ft^3)	15	16	22	15	13	11
Crew Time (hr/Mission)						
Scheduled	2.0	1.0	3.0	16.0	16.0	16.0
Unscheduled	0.0	0.0	0.0	1.8	1.8	1.8
Peak Power.	585	-115	1925	1008	180	180

TABLE 6 ESSENTIAL CRITERIA COMPARISON OF THE CONCENTRATOR AND STEAM DESORPTION CO_2 REMOVAL

Essential Criteria	Concentrator	Steam Desorption
A. Performance	Excellent. No zero gravity, liquid-gas separation. All components have MTBF $\geq$ 12,000 hours. Will meet CO_2 removal requirements	Poorer. Several gas-liquid separation processes included. Multiple liquid fluid lines requiring zero gravity servicing. Will meet requirements.
B. Safety	Very good. Low operating temperature (100°F operation), no cabin contamination, no hot spots, off-design operation is safe, system down time is safe, H_2 does not represent a potential fire and explosion hazard in a proper design. No bacteriological problems. No crew hazards.	Poorer. But a safe system. Operation at $\geq$ 212°F, products from resin burning are toxic, hot spots exist, minimum bacteriological problems. Potential crew hazards during servicing because of amine carryover.
C. Availability/ Confidence	Excellent due to subsystem status, concept unique for space with significant maintenance and reliability features. Should have high astronaut acceptance.	Poorer due to limited growth potential. Several significant components remain to be developed, e.g., steam generator, zero gravity liquid condenser-separators.

TABLE 7. PRIMARY CRITERIA COMPARISON OF THE CONCENTRATOR AND STEAM DESORPTION CO_2 REMOVAL

Primary Criteria	Concentrator	Steam Desorption
A. Reliability	Excellent. No timers, steam generators, gas-liquid separators or feed water supply requirements; 21 components of 5 different types. Complete redundancy with spares at the weight, volume, and power level of other systems using only a "single thread concept" with spares.	Poorer. There are 121 components of 25 different types; 10 components with failure rates greater than 10 failures per million hours.
B. Crew Time	Fewer components for less maintenance, less crew training, and less fault isolation equipment. Only one filter to change at a frequency depending upon spacecraft air purification. Multiple servicing expected on the water vapor exchanger.	Multiple scheduled maintenance on the timer, steam generator, condenser-separators, solenoids, and water regulators. At least one-time maintenance on the compressor, pumps, and water purifier cartridge.
C. Equivalent Weight	91 lb (if H_2 available without penalty); 468 lb using water electrolysis as the source.	1148 lb based on solar cell battery, 809 lb based on solar battery and isotope heat source, and 707 lb based on Brayton cycle and no penalty for "waste" heat--these figures ignore water and coolant pumps, their power requirements and miscellaneous accumulators, regulators, and water purification cartridge.
D. Development Costs	Minimum. One system for all space applications. Design virtually independent of crew size.	Must include development of steam generator, gas-liquid separator (212°F operating temperature), associated operating/maintenance procedures, etc. Design directly related to crew size.

TABLE 8. SECONDARY CRITERIA COMPARISON OF THE CONCENTRATOR AND STEAM DESORPTION CO_2 REMOVAL

Secondary Criteria	Concentrator	Steam Desorption
A. Contamination		
1. Of the CO_2	None (in addition it is delivered premixed with H_2)	O_2, N_2, amine carry over, and all "catalyst poisons" in the spacecraft "air", e.g., sulphur bearing compounds.
2. Of the cabin air	None	None
B. Interfaces with		
1. Humidity Control	Yes	Possibly, to enable elimination of of a condenser-separator.
2. Thermal Control	No	Yes, two condenser-separators and at least one compressor requires liquid coolant.
3. Power Conditioning	No (1)	Yes, mainly for the steam generator and extensive number of controls.
4. Water Storage	No	Yes and at a variable, cyclic use rate.
C. Flexibility		
1. In Co_2 Management	CO_2 removal rate can be throttled. CO_2 removal can be cyclic or continuous. Over capacities of 100 to 200 % can be handled.	CO_2 removal is cyclic. Capacity limited by cannister size.
2. To Interfaces	A nonpower consuming process. Same design regardless of waste heat or power source.	Non-operative in absence of power. Design concept and equivalent weight depends upon existence of waste heat.
3. Technology	Widely applicable. O_2 generation, atmosphere resupply, altitude control and emergency generation are typical alternate spacecraft use of the technology.	Appears to be limited to the CO_2 removal process.

TABLE 9 SELECTION MATRIX FOR CO_2 REMOVAL

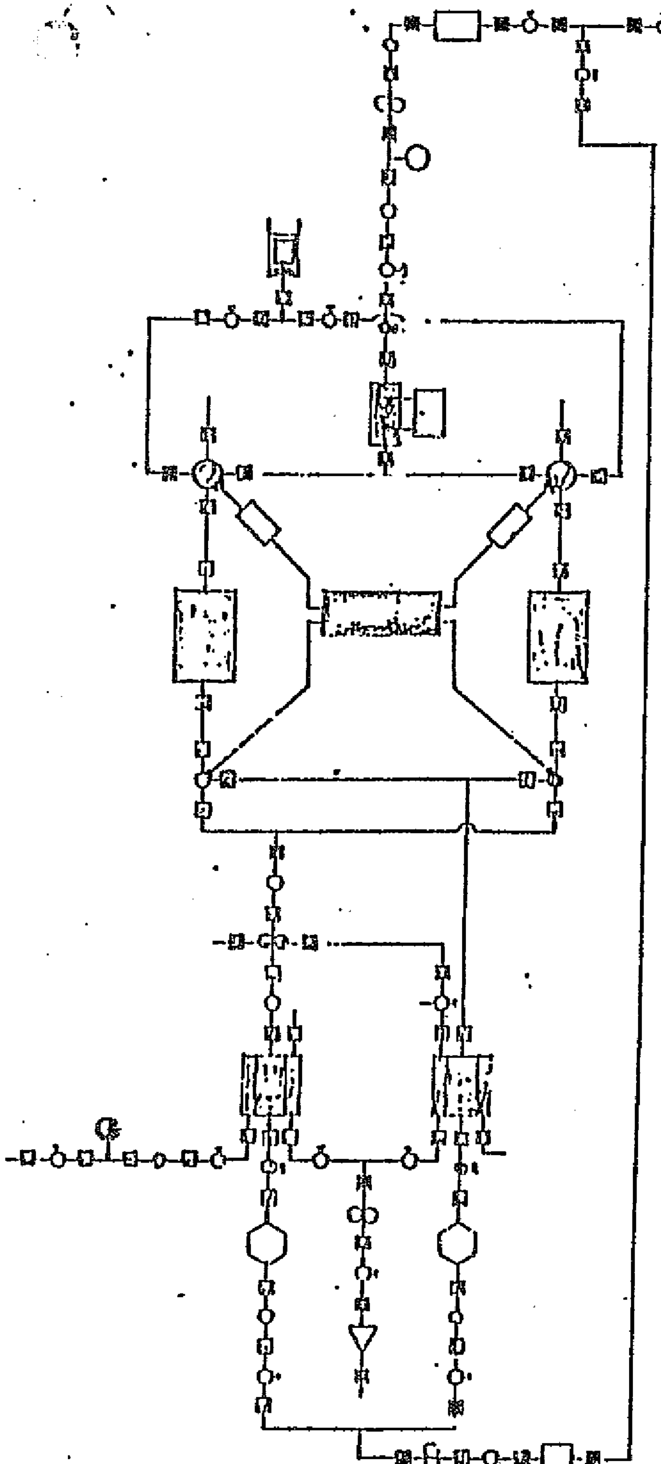
Criteria	Depolarized	Carbonation	Steam Desorption
Absolute			
Performance	Excellent	Very Good	Good
Safety	Good	Excellent	Good
Avail./Conf.	Very Good	Good.	Good
Primary			
Reliability	Excellent	Very Good	Very Good
Crew Time	Excellent	Very Good	Good
Equivalent Weight	Excellent	Very Good	Very Good
Secondary			
Contamination	Very Good	Very Good	Good
Interfaces	Excellent	Very Good	Good
Flexibility	Excellent	Excellent	Good
Growth	Excellent	Excellent	Good
Noise	Excellent	Excellent	Fair
Volume	Excellent	Very Good	Good
Power	Excellent to Very Good	Very Good	Good to Excellent
CO_2 Impurities	Excellent (None)	Good (1% O_2)	Fair (1-2% O_2 & N_2, sulfur, amine carryover)
Continuous Operation	Excellent (yes)	Excellent (yes)	Fair (no, cyclic)
Component Similarity	Excellent	Excellent	Fair
Water Electrolysis	Yes	Yes	No
Atmosphere Storage	Yes	Yes	No
Power Generation (emergency)	Yes	Yes	No

Table [illegible] continued

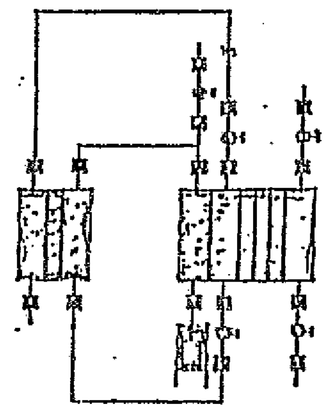
Secondary Criteria	Concentrator	Steam Desorption
D. Growth	Extensive improvements possible (currently 0.4 volt/40 ASF/2 moles CO_2 per mole O_2 vs 0.6 volt/100 ASF and 4 moles CO_2 per mole O_2 possible). Applicable to all missions with and without artificial gravity.	Optimization possible but basic drawbacks remain - cyclic process, power consuming, gas/liquid separation, etc.
E. Noise	Completely static (quiet) operation except for low speed air circulation fan.	Very noisy due to one-CO_2 compressor, Three liquid fluid pumps, four cycling solenoids, and two valve actuation motor
F. Volume	6 to 10 ft^3.	24 ft^3.
G. Power Required By	Air supply fan. (Indirectly power needed for the water electrolysis subsystem.)	1 steam generator (heater, controller, and fluid line heaters) 2 four-way solenoids and motors 2 three-way solenoids 1 water supply solenoid 1 CO_2 compressor 1 H_2O metering pump 1 H_2O return pump 1 coolant solenoid 1 coolant pump 1 air supply fan

1. An indirect interface exists when the H_2 comes from a Water Electrolysis Subsystem

FIGURE 1 SCHEMATIC COMPARISON AT SINGLE-THREAD, MAINTAINABILITY CONCEPT LEVEL

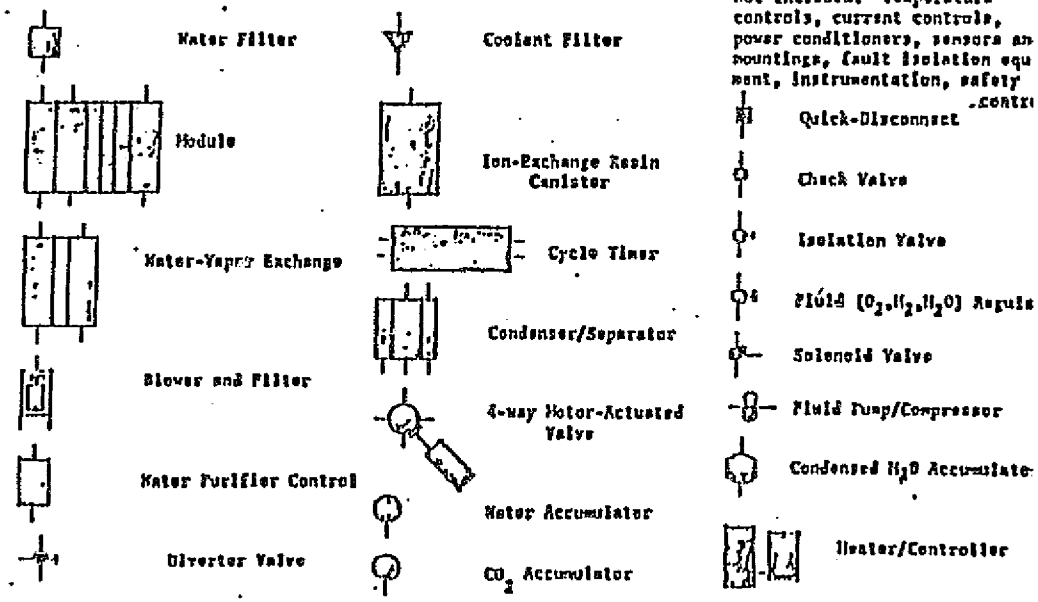


STEAM DESORPTION
SINGLE THREAD WITH QUICK-DISCONNECT



DEPOLARIZED CO_2 CONCENTRATOR

SYMBOL CODE



3.0 COMPARISON OF ALL SYSTEMS

Table 10 presents a component and spare summary for the eleven different systems contained in the footnote to the Table.

4.0 CONCLUSIONS

The Concentrator system is the most all-around optimum carbon dioxide concentrating system. Table 11 summarizes the reasons why.

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TABLE 10 COMPARISON OF CARBON DIOXIDE CONCENTRATING SYSTEM COMPONENTS/SPARES AS A FUNCTION OF CONCEPT

System Components	No. of Spares	The Number Required According to Concept[(a)]										
		1	2	3	4	5	6	7	8	9	10	11
Fan	2t[c]	1	1	1	1	1	1	1	1	1	1	1
Accumulator	-	1	1	1	1	1	1	1	-	1	1	1
Coolant Feed Lines	-	4	3	3	3	5	4	4	-	5	3	3
Timer Functions	3	8	6	6	-	-	-	-	-	-	-	10
Valves												
Motor-actuated Solenoid	1-1/2t	4	2	2	-	-	-	-	-	-	-	8
High Flow Gas	2	-	-	2	-	-	-	-	-	-	-	-
Low Flow Gas	2t	1	1	-	-	-	-	-	-	-	-	2
Liquid Flow	2t	2	2	1	-	-	-	-	-	-	-	-
Check	1/3t	3	3	3	3	3	3	3	1	6	3	2
Pressure Relief	0	2	2	1	1	-	-	1	-	1	-	-
Startup/Regulator	k	2	1	5	9	5	4	4	1	4	7	1
Manual Diverter	1t	1	1	1	1	-	-	-	-	1	-	1
Heater	1t	1	1	1	1	-	-	-	-	-	1	-
Heat Exchangers												
Gas-Gas	1	-	-	-	-	1	1	1	1	1	1	3
Gas-Liquid	1	2	1	1	-	-	-	-	-	1	-	2
Liquid-Liquid	1	-	-	-	-	-	-	-	-	-	2	-
Regulators												
Gas		-	-	-	-	-	-	-	-	-	-	-
Liquid	2t	-	1	4[d]	3[e]	2	2	1	-	1	-	-
ps and Motors												
Liquid with Gas Separation	3 (cont)	-	-	-	-	-	-	-	-	-	2	-
Turbine-Compressor	3 (cont)	-	-	-	-	-	-	-	-	-	-	1
Vacuum-Compressor	2t (cyc)	1	1	-	-	-	-	-	-	-	-	-
Compressor	2t(cont)	-	-	1	1	1	1	1	1	2	1	-
Liquid	3 (cont)	-	-	-	1	-	-	-	-	1	-	-
Condenser-Separators	6t	-	1	2[g]	2[g]	-	-	1	-	2[g]	1	-
Canisters												
With Heat Exchanger	1t	4	2	-	-	-	-	-	-	-	-	-
Without Heat Exchanger	1t	-	-	2[f]	-	-	-	-	-	-	-	2
Modules	1t	-	-	-	1	3	2	1	1	2	-	-
Module Power Converter	1t	-	-	-	1	3[h]	2	-	-	-	-	-
Heater Power Converter[b]	1t	1	1	1	1	-	-	-	-	-	1[j]	-
Steam Generator	1t	-	-	1	-	-	-	-	-	-	-	-
Module Current Controller	1t	-	-	-	1	1	1	1[i]	1	-	1	-
Heater Current Controller	2t	1	1	1	1	-	-	-	-	-	1	-
Total Components		39	32	40	32	26	22	20	7	29	26	37
Spares Specified		29	32	30	30	22	16	18	8	27	24	24

(a) The letters refer to the footnotes contained on the attached sheet.

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FOOTNOTES

COMPARISON OF CARBON DIOXIDE CONCENTRATING SYSTEM COMPONENTS/SPARES AS A FUNCTION OF CONCEPT

[a] Concept Code:
1. Four-bed Sorption
2. Two-bed Sorption
3. Two-bed Sorption, Steam Desorption
4. Electrodialysis
5. Three-stage Carbonation Cell
6. Two-stage Carbonation Cell
7. Hydrogen Depolarized Cell
8. Optimized Concentration Cell
9. Membrane Diffusion
10. Liquid Absorption
11. Mechanical Freezeout

[b] Alternately can be replaced by a liquid-liquid heat exchanger and solenoid valve.

[c] t = number of components in systems.

[d] Only 1/2t spares instead of normal 2t.

[e] Only 1-1/2t spares instead of normal 2t.

[f] Only 1/2t spares instead of normal 1t.

[g] Only 5t spares instead of normal 6t, if two condenser-separators are needed by the system.

[h] Only 2/3t spares instead of normal 1t.

[i] Twice the normal 1t spares.

[j] Twice the normal 1t spares.

[k] 2-spares included with concept 4 only or ~1/4t.

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TABLE 11 ADVANTAGES OF THE CONCENTRATOR FOR CO_2 REMOVAL

1. Ultimate in system simplicity--fewer parts, controls, and subsystem interfaces.

2. Ultimate in minimizing maintenance--6 types of components versus 20 to 40 with other approaches.

3. Non-power consuming during emergency operation.

4. Continuous versus cyclic operation--avoids all timers, motor-actuated valves, CO_2 accumulator.

5. Drying of process gas not required.

6. Highest purity CO_2--no N_2 or O_2 lost, or sulfur-bearing compounds to contaminate CO_2 reduction bed catalyst.

7. Integrates with all approaches to CO_2 reduction with the CO_2 provided premixed with H_2.

8. Components are common to those of other subsystems--valves, fittings, modules, regulators, etc.

9. Avoids unreliable condenser/separators to eliminate crew maintenance time.

10. Ability to throttle performance--desirable to conserve power or enable meeting emergencies.

11. Simple process--able to grow with the number of crewmen and mission length both through the technological improvements possible and the minor changes required in system size with changes in crew number.

12. Cyclic use of waste heat not required--independent of power source.

13. Low-temperature operation for safety and convenience.

14. Ambient pressure operation without dependence on cyclic pressure variations--space vacuum or vacuum pumps are not required.

15. Can use oxygen, nitrogen, CO_2, and methane as a purge gas.

H_2 Depolarized System

Continuous vs. sunside Operation

Continuous Δ's

power = (560 watt)(.710 lb/watt) = 398 lb

accumulated H_2 = $\frac{36}{60} \times 0.063 \frac{lb\ H_2}{hr}$ = 0.0378 lb H_2

$V_{H_2} = \frac{wRT}{PM} = \frac{0.0378 \times 10.73 \times 530}{45 \times 2.016} = 2.37\ ft^3$

2.5 ft^3 accumulator weighs ≃ 12 lb

Additional hardware weight = 150 lb

Total = 560

Sunside

power = (560)($\frac{94}{58}$)(.351) = 318 lb

hardware = 150 lb

Total = 468 lb

Conclusion: might as well use sunside only operation

note: P_c variation penalty could swing this decision the other way — power = $[210 + 350 \times \frac{94}{58} \times \frac{3}{8}][.351]$ = 372 lb

150

Sunside H_2-depolarized, $P_c = 3$ mm

Max P_c:

volume = 4500 ft^3

incremental $CO_2 = \frac{36}{60} \times 1.1 \frac{lb\ CO_2}{hr} = 0.66$ lb CO_2

$\Delta P_c = \frac{WRT}{VM} = \frac{(0.66)(10.73)(530)}{(4500)(44)} = 0.01897$ psi

$= 0.01897 \times \frac{760}{14.7} = 0.98$ mm

$\therefore$ Max $P_c = 4$ mm

~~Continuous H_2-depolarized, $P_c = 3$ mm~~

~~H_2 balance~~

~~O_2 use rate = 0.51 lb/hr~~

~~stoichiometric $H_2 = 0.51 \times 2 \times \frac{2.016}{32} = 0.0643$ lb/hr~~

~~Effect of P_c on Power (electrochemical)~~

~~$y = mx + b$, $V = mP + b$; $b = 0.606$ volt; $m = \frac{\Delta y}{\Delta x} = \frac{.666 - .606}{2} = .03$~~

~~$V = 0.03P + 0.606$ [$P = \%\ CO_2$]~~

~~$\frac{power_1}{power_2} = \frac{V_1}{V_2} = \frac{.03P_1 + .606}{.03P_2 + .606}$~~

Variation of P_c - Effect on H_2-depolarized

Going from $P_c = 3$ mm to $P_c = 1$ mm results in "25-30 percent increase in O_2 consumption rate"

assume $y = mx + b$

$$m = \frac{\Delta y}{\Delta x} = \frac{0.30}{2 \text{ mm}} = -0.15$$

$$b = 1 + 0.15(3) = 1.45$$

$$y = -0.15x + 1.45$$

Module weight factor = $1.45 - 0.15 P_c$

~~Process air blower weight factor =~~

~~$\left[\frac{W_1}{W_2} = \left(\frac{P_{c2}}{P_{c1}}\right)^n, \quad \frac{9.5}{15} = \left(\frac{1}{3}\right)^n, \quad n = 2.4 \right.$~~

~~$\left. \therefore W_1 = W_2 \left(\frac{P_2}{P_1}\right)^{2.4} = W_2 \left(\frac{3}{P_1}\right)^{2.4} = \frac{14 W_2}{P_1^{2.4}} \right]$~~

Blower power factor = $\frac{3}{P_c}$

Electrolysis penalty factor = $1.45 - 0.15 P_c$

Process blower weight factor =

$$\frac{W_1}{W_2} = \left(\frac{F_1}{F_2}\right)^n, \quad 1.58 = 3^n, \quad n = .417$$

$$\frac{W_1}{W_2} = \left(\frac{P_2}{P_1}\right)^{.417}, \quad W_p = W_3 \frac{1.58}{P^{.417}} = \frac{39.5}{P_c^{.417}}$$

H_2 - Depolarized

3 mm min* Sunside characteristics

module weight = 112 × 94/58 = 182 lb
air blower = 2 × 94/58 = 3
air duct = 4 × 94/58 = 6
heat exchanger = 4 × 94/58 = 6
controller = 5
Process air blower = ~~[illegible]~~
~~[illegible]~~
= $20\,[94/58]^{0.417}$ ≅ ~~[illegible]~~ 25

Air blower power = $200 \times (94/58)^{**}$ = 324 watt
controller power = 10
process air blower = $350\,(94/58)^{**}$ = 567

Heat exchanger cooling load = 5000(94/58) = 8100 Btu/h
Process air blower sensible load = 785(94/58) = 1270
Latent heat to cabin = 600(94/58) = 974

H_2 - Depolarized - 3 man

Electrolysis Penalty

O_2 consumption rate = 0.51 × 94/58 = 0.826 lb/hr

The 28.8 lb O_2/day electrolysis unit:

weight = 450 lb
volume = 22.5 ft^3
power = 4750 watt
coolant load = 5547 Btu/hr

} per T. Moore

Penalty: $\frac{0.51 \times 24}{28.8} = 0.425$

weight = 450 × .425 =	191 lb
power = 4750 × .425 =	2020 watt
coolant load = 5547 × .425 =	2360 Btu/

2-Bed Modified IR-45, 2nd Iteration

Cycle

| 58 | 36 |

#1 | Desorb: 29 | Absorb = 65 |

vapor transfer ↓ vapor transfer

#2 | ABSORB = 29 + | DESORB = 29 | ABSORB = 36 + ...

Bed Size

Bed loading at 4 mm

$$= \frac{\left(9.5 \frac{\text{lb } CO_2}{\text{day}}\right)\left(\frac{45 \text{ min/cycle}}{1440 \text{ min/day}}\right)}{(3 \text{ beds})\left(6.5 \frac{\text{lb IR-45}}{\text{bed}}\right)} = 0.0152 \frac{\text{lb } C}{\text{lb be}}$$

then

$$W = \frac{\left(26.4 \frac{\text{lb } CO_2}{\text{day}}\right)\left(\frac{94 \text{ min/cycle}}{1440 \text{ min/day}}\right)}{(2 \text{ beds})\left(0.0152 \frac{\text{lb } CO_2}{\text{lb bed}}\right)} = \boxed{56.5 \frac{\text{lb IR-45}}{\text{bed}}}$$

~~This is rather high — see~~

up

Optimum water content data:

$$\frac{\text{loading at 4 mm}}{\text{loading at 1 mm}} = \frac{11}{5} = 2.2$$

~~assume $\frac{W_1}{W_2}$ = [illegible] $\left(\frac{P_{c1}}{P_{c2}}\right)^n$~~

~~$2.2 =$ [illegible]^n~~

if W = bed weight at P_c,

assume $$\frac{W_1}{W_2} = \left(\frac{P_{c2}}{P_{c1}}\right)^n$$

$$\frac{1}{2.2} = \left(\frac{1}{4}\right)^n$$

$$.454 = .25^n$$

$$n = 0.57$$

$$\therefore \frac{W_1}{W_2} = \left(\frac{P_{c2}}{P_{c1}}\right)^{0.57}$$

$$\frac{56.5}{W} = \frac{P_c^{0.57}}{4^{.57}} = \frac{P_c^{.57}}{2.2}$$

and $$\boxed{W = \frac{124}{P_c^{.57}}}$$ lb IR-45 per bed

Efficiency (continued)

Check:

If test flow had been 6.5 cfm/bed, same amount of CO_2 would have been removed. ε

$$6.5 \text{ cfm} = 477 \frac{\text{lb air}}{\text{day}}$$

$$\frac{30}{45} \times 477 = 318 \frac{\text{lb air}}{\text{bed-day}}$$

$$\frac{\text{lb } CO_2}{\text{lb air}} = 0.01177 \text{ at } 4 \text{ mm}$$

$$\text{throughput} = 318 \times 0.01177 = 3.74 \text{ lb } CO_2/\text{bed-day}$$

$$CO_2 \text{ removed} = \frac{9.5}{3} = 3.18 \text{ lb } CO_2/\text{bed-day}$$

$$\therefore \text{Potential } \varepsilon = \frac{3.18}{3.74} = 0.85$$

from before, $\varepsilon = 1$ air flow $= \frac{6.30}{P_c} \frac{\text{lb air}}{\text{min}} = \frac{123}{P_c}$ cfm

Then, actual air flow =

$$\boxed{\text{air flow} = \frac{7.42}{P_c} \frac{\text{lb air}}{\text{min}} = \frac{145}{P_c} \text{ cfm}}$$

(total air flow over 1 or both beds)

Fan Power

bed $\Delta P \simeq 0.9$ psi $= 24.9''$ for 13 cfm through 6.5 lb IR-45 at 10 psia. From 4-7-70, p. 5, for an 8" deep bed

$$\Delta P = 7.05 \frac{cfm}{w}$$

$$cfm = \frac{145}{P_c}$$

$$w = \frac{124}{P_c^{.57}}$$

$$\therefore \Delta P = 7.05 \times \frac{145}{P_c} \times \frac{P_c^{.57}}{124} = \frac{1.17}{P_c^{.43}}$$

$$\text{Power} = \frac{cfm\ \Delta P}{3} = \frac{145}{P_c} \times \frac{1.17}{P_c^{.43}} \times \frac{1}{3} = \frac{56.5}{P_c^{1.43}}$$

Power for ducts, valves etc $= \dfrac{145 \times 3}{3\ P_c} = \dfrac{145}{P_c}$

Total

$$\boxed{\text{Fan power} = \frac{56.5}{P_c^{1.43}} + \frac{145}{P_c}}$$

Desorption

$$Steam = \frac{56.3}{P_c^{.57}} \quad \frac{lb\ steam}{hr}$$

Based on recirculation of hot condensate, total heat = latent heat + losses:

$$Q_L = 1050 \times \frac{56.3}{P_c^{.57}} = \frac{5.92 \times 10^4}{P_c^{.57}} \frac{Btu}{hr}$$

Taking heat loss as 10% (to air):

$$Q = 1.1\, Q_L = \frac{6.52 \times 10^4}{P_c^{.57}} \frac{Btu}{hr}$$

$$\text{Heat power} = \frac{1.91 \times 10^4}{P_c^{.57}} \text{ watt}$$

$$\text{Heat rejection to condenser} = \frac{5.92 \times 10^4}{P_c^{.57}} \text{ Btu/hr}$$

$$\text{Heat rejection to air} = \frac{5.92 \times 10^3}{P_c^{.57}} \text{ Btu/hr}$$

$$\text{Condenser load} = \frac{5.92 \times 10^4}{P_c^{.57}} \frac{Btu}{hr} = \frac{1.735 \times 10^4}{P_c^{.57}} \text{ watt}$$

Revised 7/17/70

Summary for 2-bed System

$W = \frac{124}{P_c^{.57}}$ lb IR-45 per bed

air flow $= \frac{7.42}{P_c} \frac{\text{lb air}}{\text{min.}} = \frac{145}{P_c}$ cfm

fan power $= \frac{56.5}{P_c^{1.43}} + \frac{145}{P_c}$

$\Delta P = \frac{1.17}{P_c^{.43}} + 3$ inches H_2O

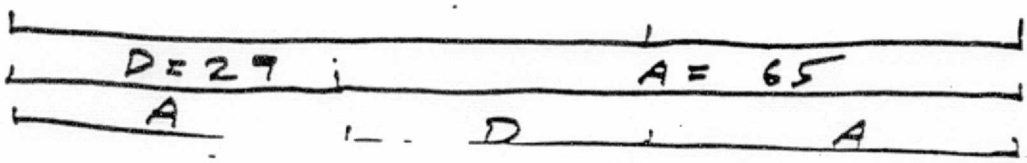
steam $= \frac{56.3}{P_c^{.57}} \frac{\text{lb}}{\text{hr}}$

heat $= \frac{6.52 \text{ (~~7.10~~)} \times 10^4}{P_c^{.57}} \frac{\text{Btu}}{\text{hr}}$

Power $= \frac{1.91 \text{ (~~2.08~~)} \times 10^4}{P_c^{.57}}$ watts for steam

Total power = fan power + steam power

cycle:



Boiler and Condenser Weight

Boiler

AILSS boiler = 7.5 lb for 1240 watts ~~= 4230 Btu/hr~~

$P_c = 1$: $W = 7.5 \times \frac{19{,}100 \; (\text{~~20,000~~})}{1240} =$ ~~126 lb~~ 116 lb

$P_c = 3$: $W = 7.5 \times \frac{11{,}120}{1240} =$ ~~67~~ 62 lb

$P_c = 5$: $W = 7.5 \times \frac{8330}{1240} =$ ~~50~~ 46 lb

Condenser

IR-45 test program condenser
= 11 pound core + 5 lb additional
Allowing 15% for additional load due to higher pressure steam:

$P_c = 1$: $\left(11 \times \frac{17{,}350 \; (\text{~~19,100~~, ~~20,300~~})}{1240} + 6 \times \left[\frac{17{,}350 \; (\text{~~19,100~~, ~~20,000~~})}{1240}\right]^{2/3}\right)$ ~~(1.15)~~ = ~~207~~ ~~260~~ 189 lb

$P_c = 3$: $\left(11 \times \frac{11{,}120}{1240} + 6 \times \left[\frac{11{,}120}{1240}\right]^{2/3}\right)(1.15) =$ ~~144 lb~~ 105 lb

$P_c = 5$: $\left(11 \times \frac{8330}{1240} + 6 \times \left[\frac{8330}{1240}\right]^{2/3}\right)(1.15) \simeq$ ~~109 lb~~ 8

Adding 10% for water separation:

$P_c = 1$: 285 lb
$P_c = 3$: 158
$P_c = 5$: 120

Canister Weight

IR-45 test can weighs 13 lb (empty) for 6.5 lb IR-45

$P_c = 1: \; 2 \times \left[124 + \left(\frac{124}{6.5}\right)^{2/3}(13)\right] = 434$ lb, loaded

$P_c = 2: \; 2\left[66 + \left(\frac{66}{6.5}\right)^{2/3}(13)\right] = 254$ lb

$P_c = 5: \; 2\left[50 + \left(\frac{50}{6.5}\right)^{2/3}(13)\right] = 202$ lb

Steam Flow

$P_c = 1$: 56.3 lb/hr =

$P_c = 3$: 30.1

$P_c = 5$: 22.5

Insulation

cans + 20%, 3" 6.5

$A = .785\,(6.5)^2(2) + (3.14)(6.5)(10) = 366$ in.^{2}

$W_i = \frac{1.2 \times 2 \times 366 \times 3}{1728} \times 3\frac{lb}{ft^3} = 4.6$ lb

$\frac{4.6}{27} = 0.17$ lb insulation/lb canister

TABLE 1 EXTENDED DURATION ORBITER DESIGN DATA

Crew Size	4 or 7 [a]
Mission Duration, d	7 to 120
Metabolic Consumption, kg/person-d (lb/person-d)	
Oxygen	0.80 (1.76)
Water, Food/Drink	2.59 (5.70)
Wash Water	1.16 (2.55)
Metabolic Production, kg/person-d (lb/person-d)	
Carbon Dioxide	0.96 (2.11)
Condensate	1.58 (3.49) [b]
Urine	1.56 (3.44) [b]
Feces	0.12 (0.27)
Orbiter Leakage, kg/d (lb/d)	
Cabin	2.72 (6.0)
Air Lock	0.45 (1.0)
Tunnel Adapter	0.45 (1.0)
Waste Management	0.82 (1.8)
EVA Requirements,[c] kg/d (lb/d)	
Oxygen	0.91 (2.0)
Water	9.08 (20.0)
Power Source, kW	
Fuel Cells	21
Power Module	25 to 35 [d]

(a) Short-term operation at a 10-person level required.
(b) Includes 1.50 kg/d (3.31 lb/d) water and 0.06 kg/d (0.13 lb/d) solids.
(c) Assumes 12 h EVA per day (2 persons for 6 h).
(d) Depending on Power Module configuration.

TABLE 3 CO_2 REMOVAL SUBSYSTEM DESIGN SPECIFICATIONS

Crew Size	4 or 7
CO_2 Removal Rate, kg/h (lb/h)	0.279 (0.615)
Cabin pCO_2, Pa (mm Hg)	
Daily Average	667 (5.0)
Maximum	1,013 (7.6)
Cabin pO_2, kPa (psia)	22.1 (3.2)
Cabin Temperature, K (F)	291 to 300 (65 to 80)
Cabin Dew Point, K (F)	277 to 289 (39 to 61)
Cabin Pressure, kPa (psia)	101 (14.7)
Process Air Humidity Range	See Figures 2 and 3
Liquid Coolant Temperature, K (F)	275 to 297 (35 to 71)
H_2 Supply Flow Rate, kg/h (lb/h)	0.018 (0.040)
H_2 Relative Humidity, %	0 to 5
Purge Gas	N_2
Purge Gas Pressure, kPa (psia)	173 or 1,484 (25 or 215)
Electrical Power, VAC[a]	115/200
, VDC	27.5 to 32.5
Gravity	0 to 1
Noise Criteria, db	55

(a) 400 Hz, 3Ø

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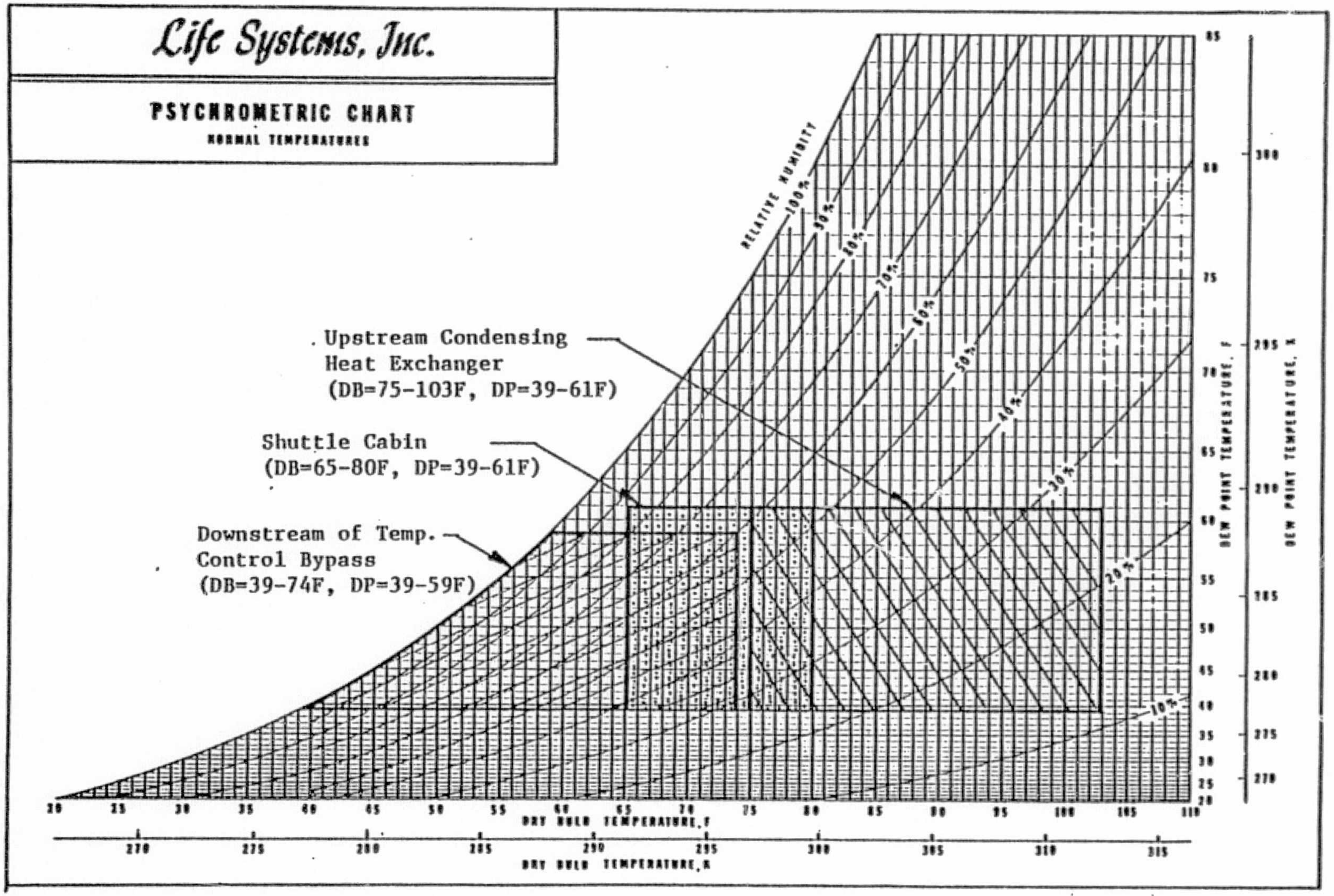

FIGURE 2 SHUTTLE AIR HUMIDITY SPECIFICATIONS

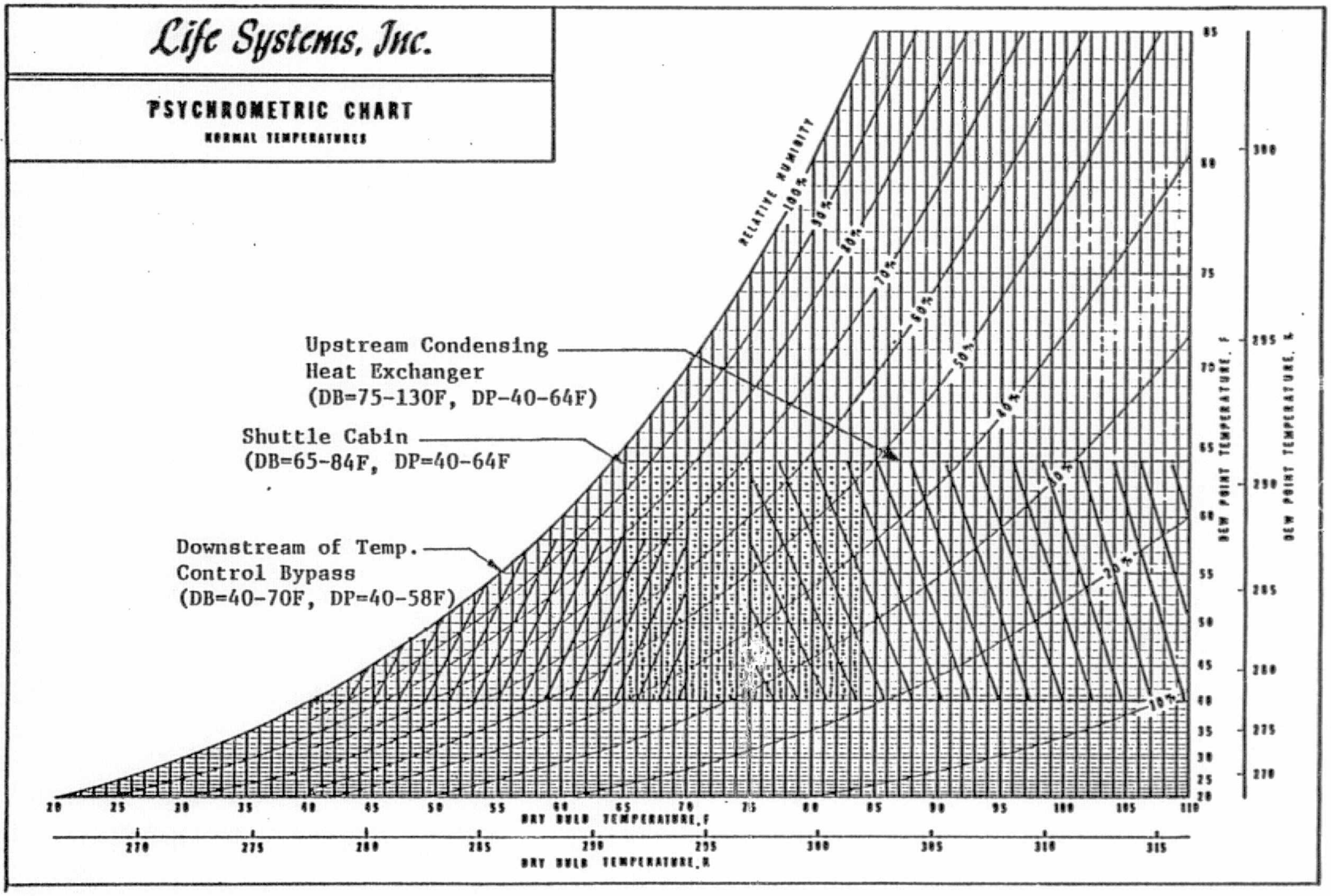

FIGURE 3 PROJECTED SHUTTLE AIR HUMIDITY RANGES

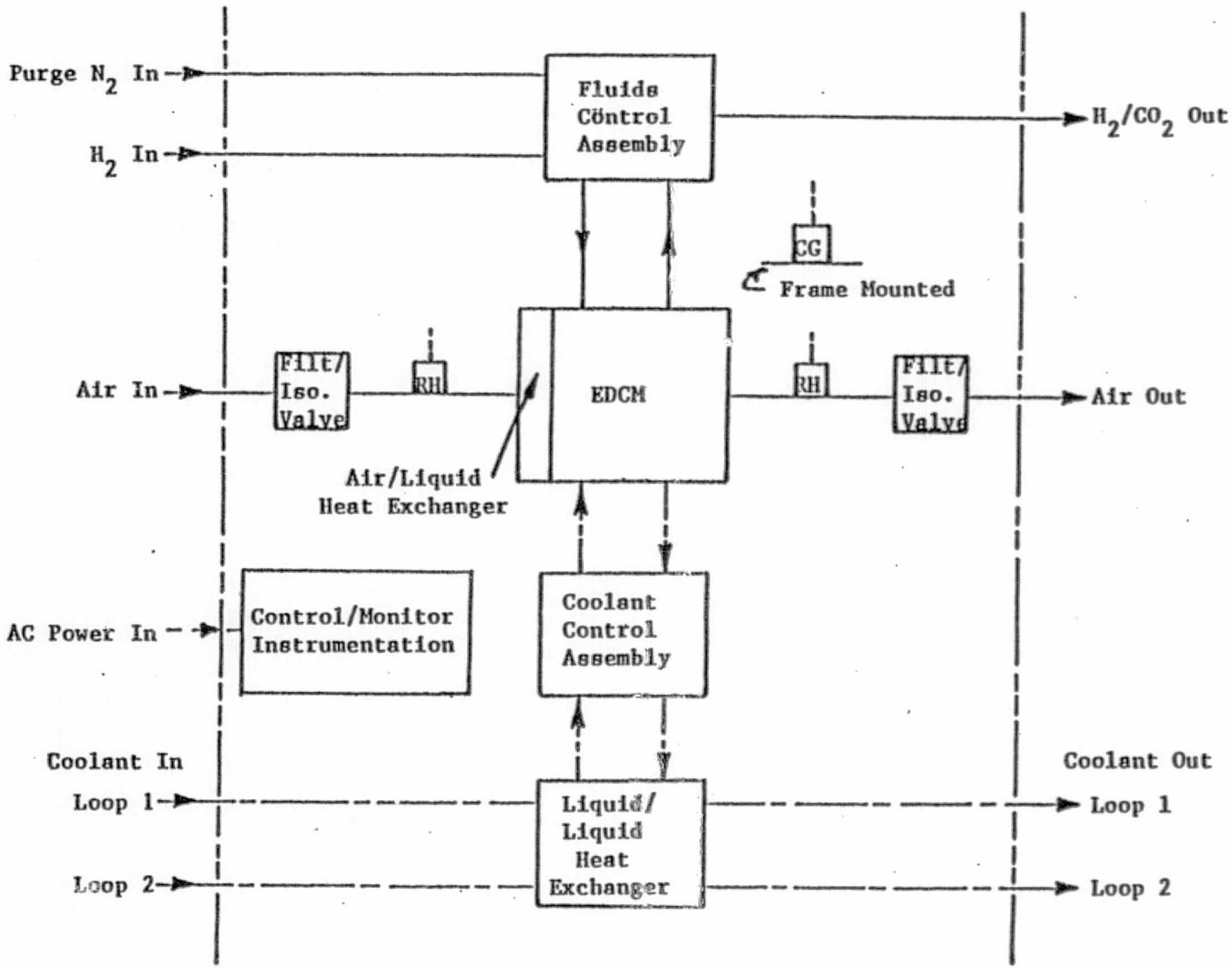

FIGURE 4 SHUTTLE EDC SCHEMATIC

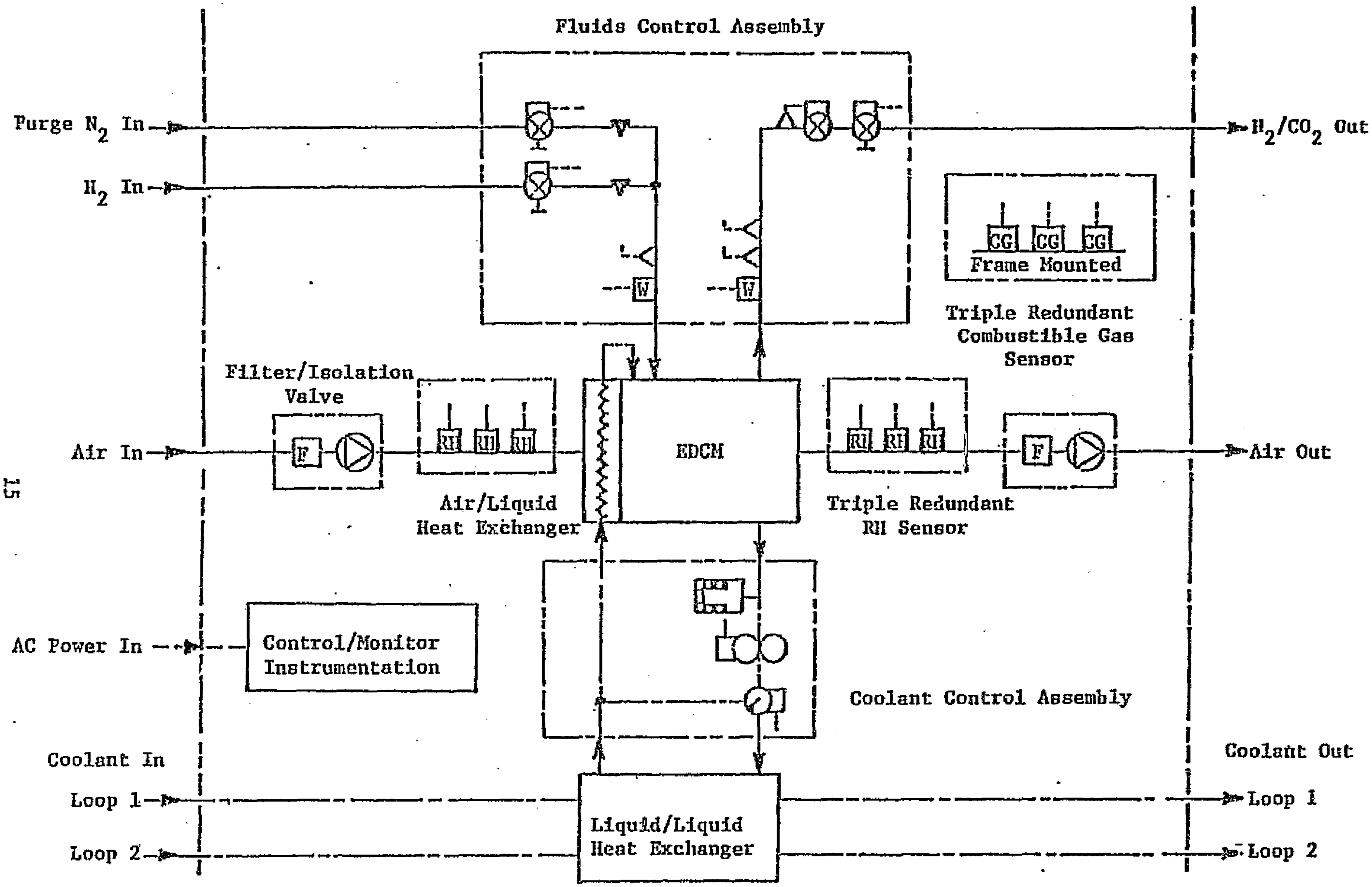

FIGURE 5 SHUTTLE EDC DETAILED SCHEMATIC

TABLE 5 EDC SUBSYSTEM COMPONENT WEIGHT, POWER AND HEAT GENERATION SUMMARY

		4-Person				7-Person			
Component	No. Req'd	Weight, kg (lb)	Power, W AC	Power, W DC	Heat Gen., W	Weight, kg (lb)	Power, W AC	Power, W DC	Heat Gen., W
EDCM	1	19.1 (42)	--	(-102)	163	24.1 (53)	--	(-163)	334
Fluids Control Assembly	1	2.3 (5)	--	10	10	2.3 (5)	--	10	10
Coolant Control Assembly	1	1.8 (4)	50	--	50	1.8 (4)	50	--	50
Heat Exchanger (Liq/Liq)	1	2.3 (5)	--	--	--	2.3 (5)	--	--	--
Heat Exchanger (Air/Liq)	1	2.3 (5)	--	--	--	2.3 (5)	--	--	--
Filter/Isolation Valve	2	0.9 (2)	--	--	--	0.9 (2)	--	--	--
RH Sensor	2	0.9 (2)	--	10	10	0.9 (2)	--	10	10
Combustible Gas Sensor	1	0 (0)	--	5	5	0 (0)	--	5	5
Instrumentation	1	3.2 (7)	--	15	15	3.2 (7)	--	15	15
Ducting/Frame (20%)	-	6.4 (14)	--	--	--	7.7 (17)	--	--	--
Total	11	39.0 (86)	50	(-62)	253	45.4 (100)	50	(-123)	424

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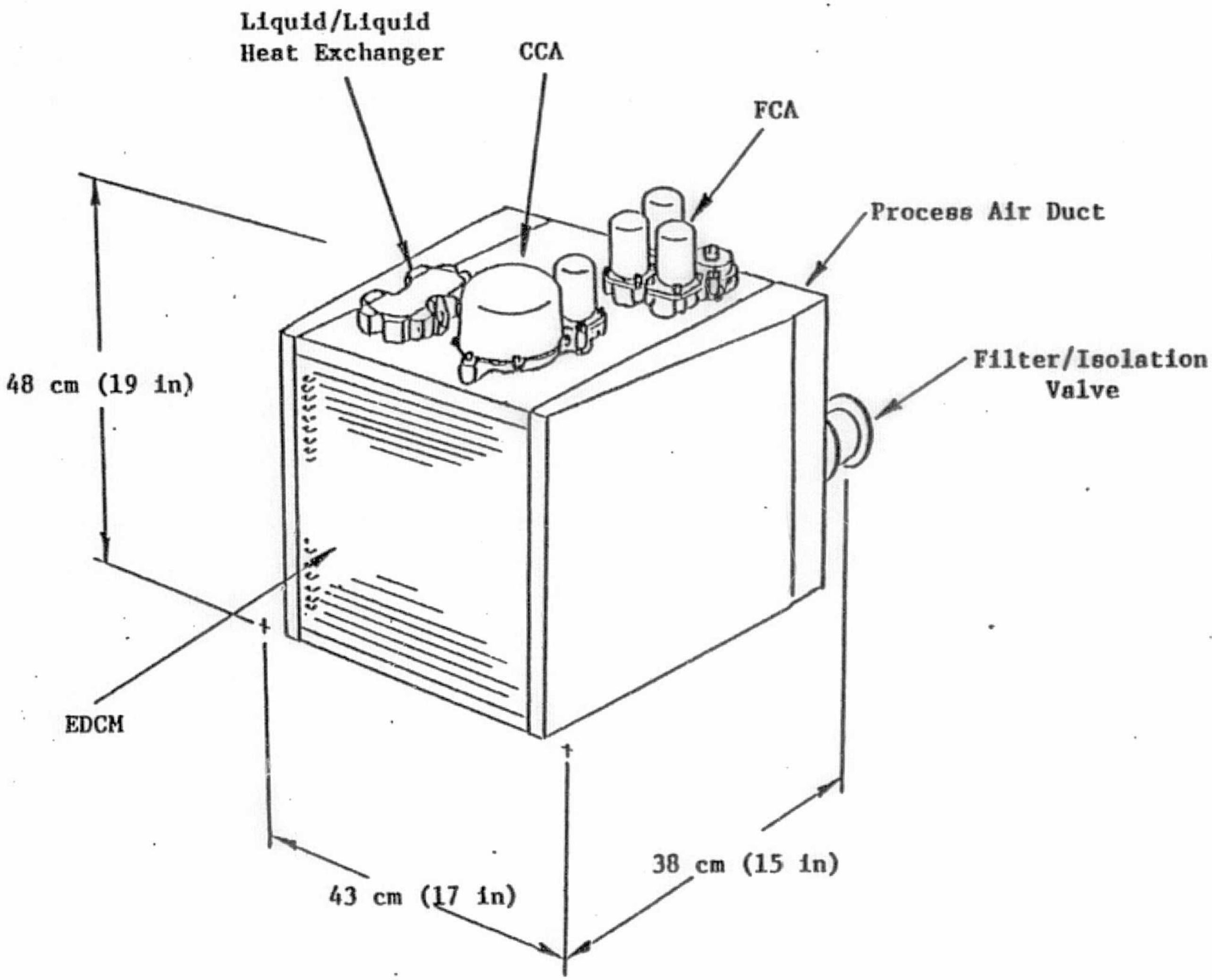

FIGURE 6 SHUTTLE EDC CONFIGURATION (SEVEN PERSON)

TABLE 6 SHUTTLE EDC SUBSYSTEM CHARACTERISTICS SUMMARY

Crew Size	4	7
Fixed Hardware Weight, kg (lb)	39.0 (86)	45.4 (100)
Overall Dimensions, cm (in)	41 x 43 x 38 (16 x 17 x 15)	48 x 43 x 38 (19 x 17 x 15)
Volume, m^3 (ft^3)	0.07 (2.4)	0.08 (2.8)
Power Required, WAC , WDC	50 -62[(a)]	50 -123[(a)]
Heat Load, W		
Sensible	253	424
Latent	46	86
CO_2 Removed, kg/d (lb/d)	3.83 (8.44)	6.72 (14.8)
O_2 Consumed, kg/d (lb/d)	1.52 (3.35)	2.85 (6.28)
H_2 Consumed, kg/d (lb/d)	0.229 (0.504)[(b)]	0.425 (0.936)[(b)]
H_2O Generated, kg/d (lb/d)	1.71 (3.77)	3.21 (7.06)

(a) Excess power generated by EDC available to Shuttle
(b) At 1.2 times the stoichiometric H_2 requirement

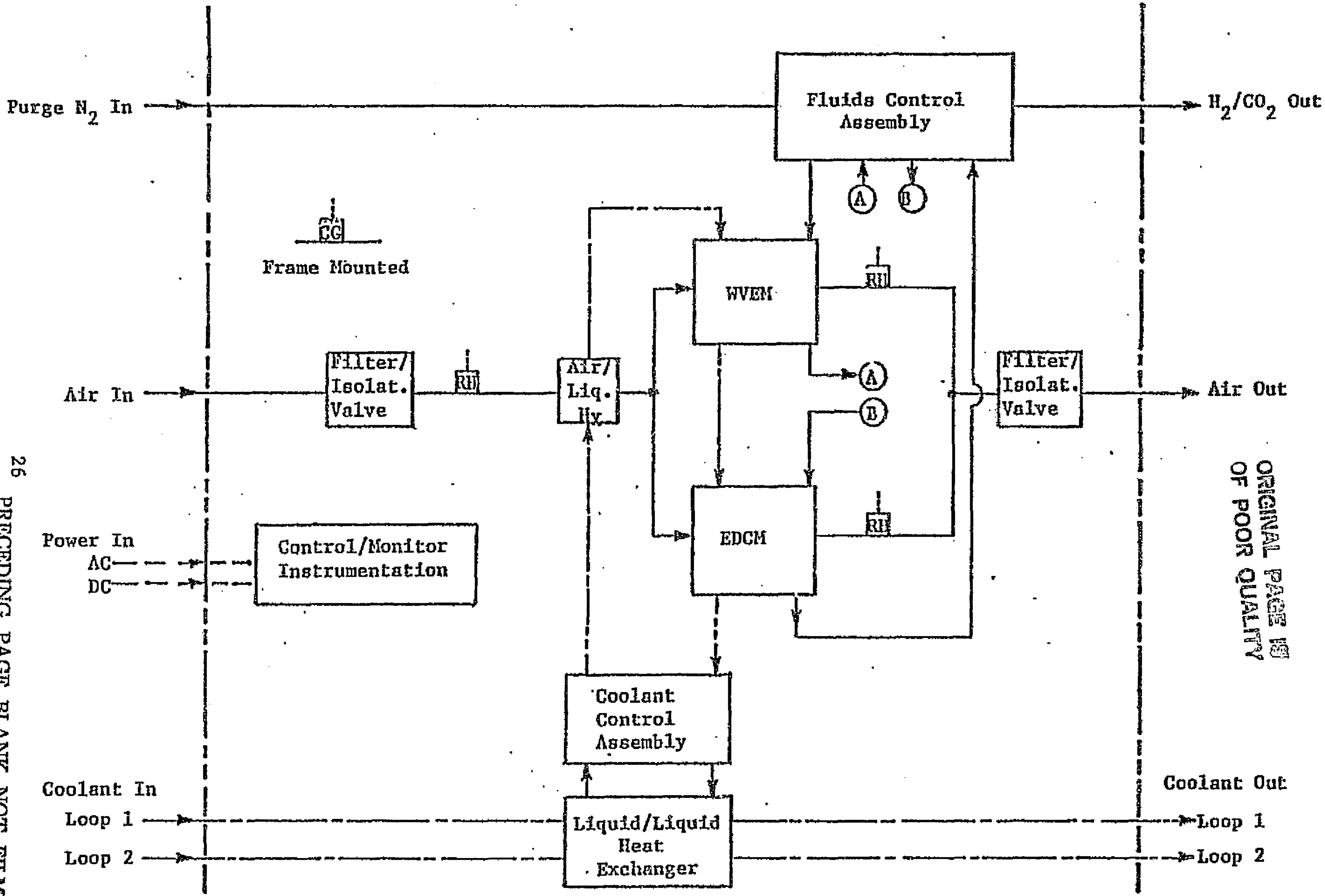

FIGURE 10 SHUTTLE EDC/WVE SCHEMATIC

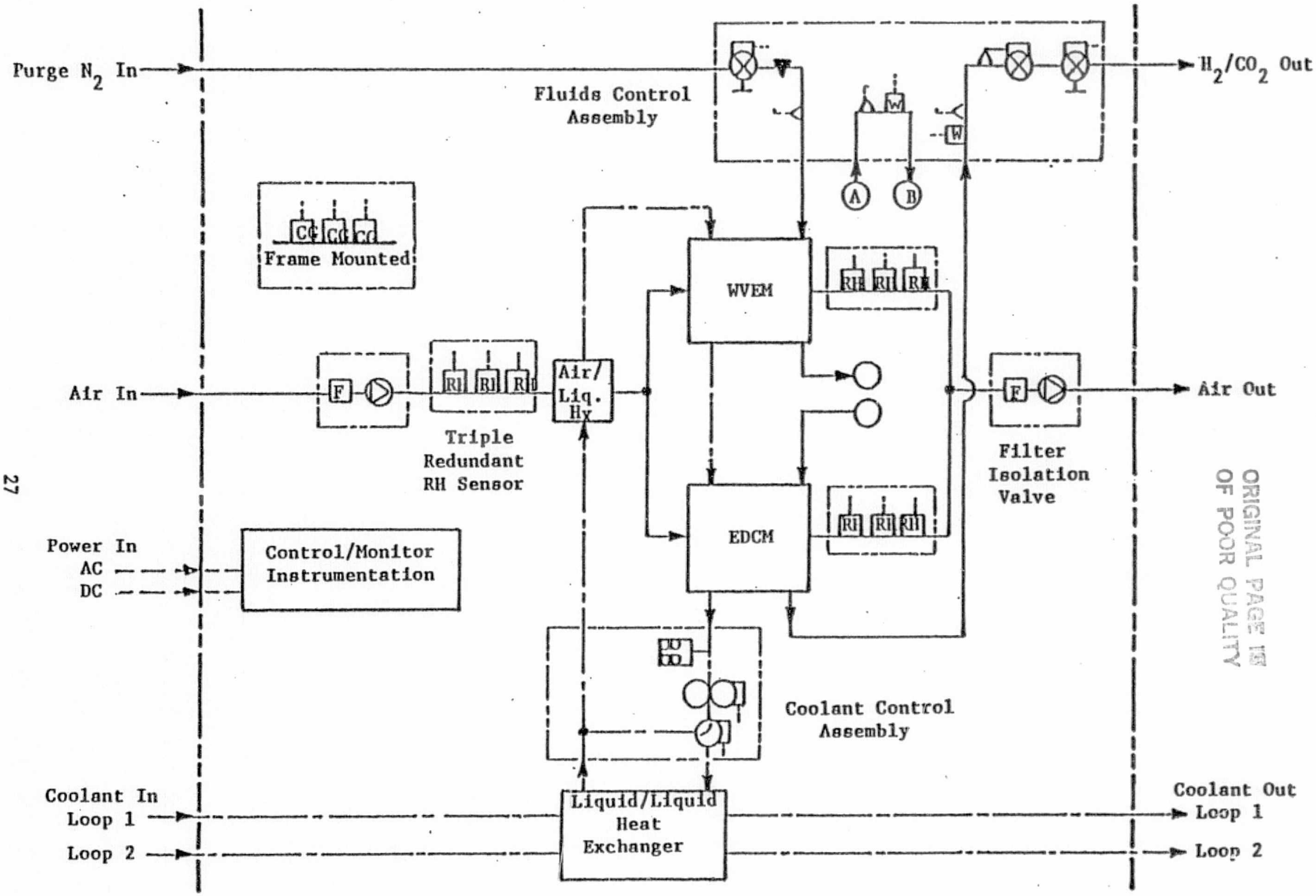

FIGURE 11 SHUTTLE EDC/WVE DETAILED SCHEMATIC

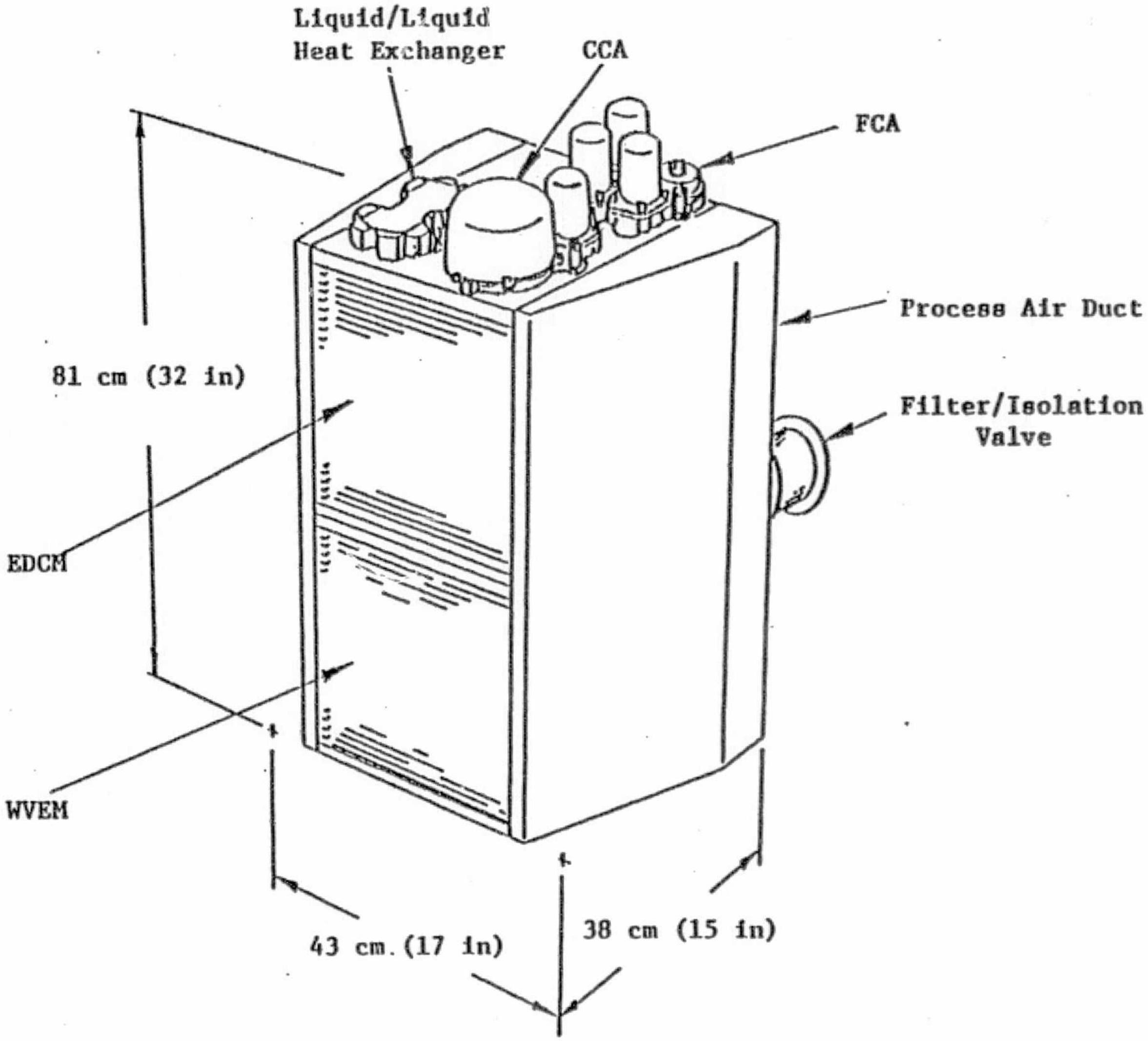

FIGURE 12 SHUTTLE EDC/WVE CONFIGURATION (SEVEN PERSON)

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TABLE 10 COMPARISON OF SHUTTLE CO_2 SUBSYSTEM CHARACTERISTICS: SEVEN-PERSON

Subsystem	Weight,[a] kg (lb)	Power, W AC	Power, W DC	Volume,[a] m^3 (ft^3)	Heat Rejection, W Sensible	Heat Rejection, W Latent	Expendables,[b] kg/d (lb/d) Water	O_2	H_2	N_2	LiOH
LiOH	35[c] (76)	11	--	0.07[d] (2.6)	157	74	-2.74 (-6.04)	--	--	--	18.9[e] (41.6)
HS-C/RH	151 (332)	115	23	0.59 (21)	153	-298	11.09 (24.43)	0.06 (0.14)	--	0.20 (0.44)	--
HS-C/Water Save	180 (397)	76	19	0.54 (19)	100	-120	4.46 (9.83)	0.14 (0.30)	--	0.43 (0.95)	--
EDC	71 (157)	50	-123	0.17 (6)	424	86	-3.21 (-7.06)	2.85 (6.28)	0.425 (0.936)	--	--
EDC/WVE	101 (223)	50	685	0.23 (8)	648	-17	0.63 (1.38)	-0.55 (-1.22)	--	--	--

(a) Includes contingency LiOH and vehicle ducting.
(b) Does not include tankage for cryogen for power generation.
(c) Contingency LiOH canisters (8) at 3.06 kg (6.73 lb) plus 41.7% for packaging weight.
(d) Contingency LiOH canisters (8) at 6.36 dm^3 (388 in^3) plus 42.5% for packaging volume.
(e) Expendable volume for LiOH canisters is 0.040 m^3/d (1.40 ft^3/d).

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TABLE 11 EXPENDABLES FOR POWER CONSUMED: SEVEN-PERSONS

Subsystem	Power,[a] W AC	Power,[a] W DC	Baseline Orbiter Expendables,[b] kg/d (lb/d) O_2	Baseline Orbiter Expendables,[b] kg/d (lb/d) H_2	Orbiter with PEP Expendables,[c] kg/d (lb/d) O_2	Orbiter with PEP Expendables,[c] kg/d (lb/d) H_2
LiOH	11	--	0.11 (0.25)	0.014 (0.031)	0.04 (0.09)	0.005 (0.012)
HS-C/RH	115	23	1.37 (3.01)	0.172 (0.378)	0.52 (1.14)	0.065 (0.143)
HS-C/Water Save	76	19	0.93 (2.05)	0.117 (0.258)	0.35 (0.78)	0.044 (0.098)
EDC	50	-123	-0.45[d] (-0.99)	-0.056[d] (-0.124)	-0.17[d] (-0.37)	-0.021[d] (-0.047)
EDC/WVE	50	685	5.88 (12.96)	0.740 (1.629)	2.22 (4.90)	0.280 (0.616)

(a) Power conversion efficiency of 76% for AC power.
(b) Fuel cell O_2 and H_2 consumption at 7.84 kg/kW-d (17.26 lb/kW-d) and 0.99 kg/kW-d (2.17 lb/kW-d), respectively.
(c) Fuel cell O_2 and H_2 consumption at 2.96 kg/kW-d (6.52 lb/kW-d) and 0.37 kg/kW-d (0.82 lb/kW-d), respectively.
(d) Assumes EDC power generated is used on-board the Shuttle.

TABLE 12 CO_2 REMOVAL SUBSYSTEMS' TOTAL MISSION EXPENDABLES

Subsystem	Expendables, kg/d (lb/d) FC[(a)]	SA/FC[(b)]	SA/BA[(c)]
LiOH	19.1 (42.2)	19.0 (41.8)	15.5 (34.2)
HS-C/RH	3.6 (7.9)	1.7 (3.7)	14.1 (31.1)
HS-C/Low Dump	3.2 (7.1)	1.9 (4.3)	6.6 (14.5)
EDC	5.5 (12.2)	6.2 (13.6)	2.6 (5.8)
EDC/WVE	12.1 (26.7)	3.9 (8.6)	-0.3 (-0.8)

(a) Mission Option One
(b) Mission Option Two
(c) Mission Option Three

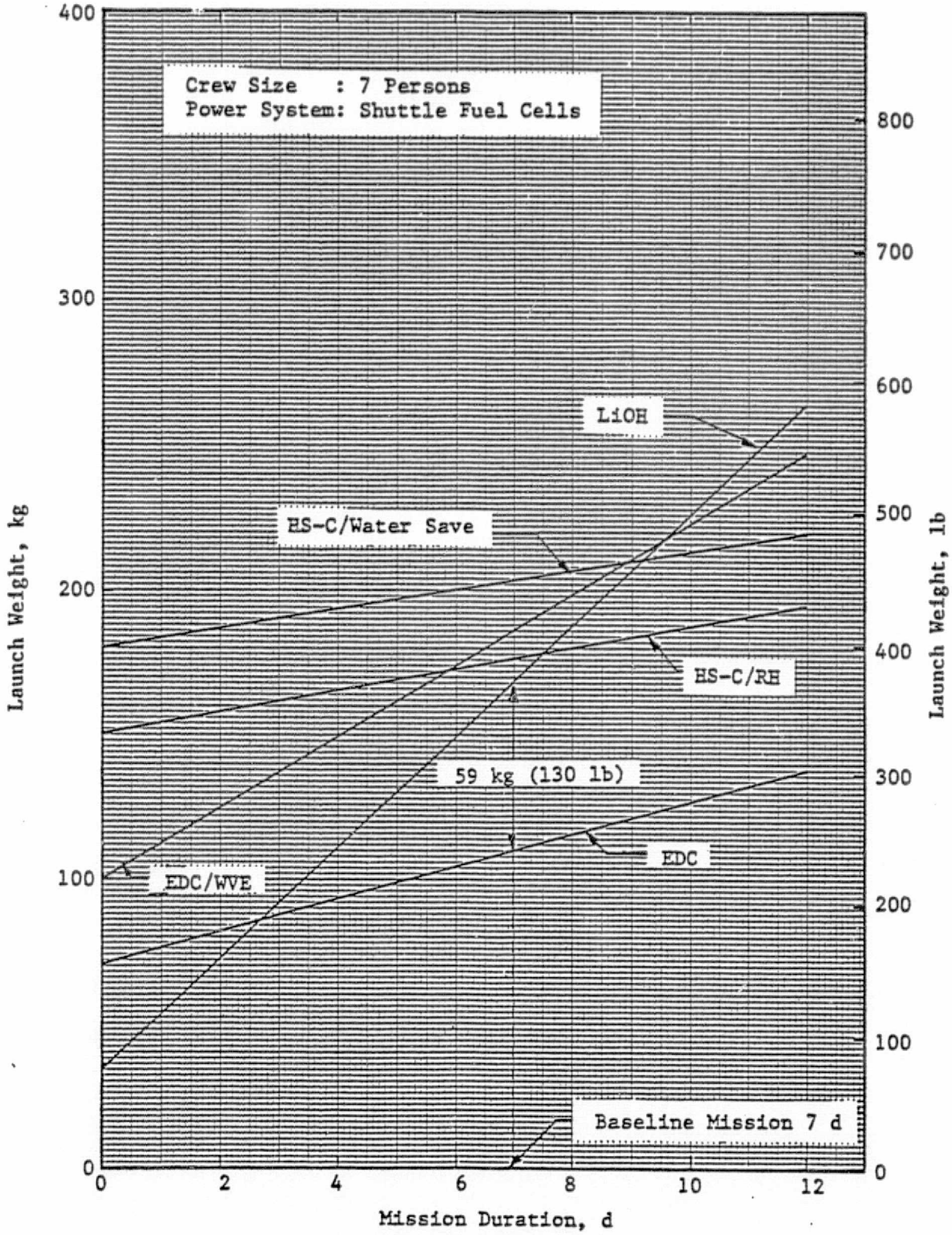

FIGURE 15 CO_2 REMOVAL SUBSYSTEMS LAUNCH WEIGHT COMPARISON: MISSION OPTION ONE

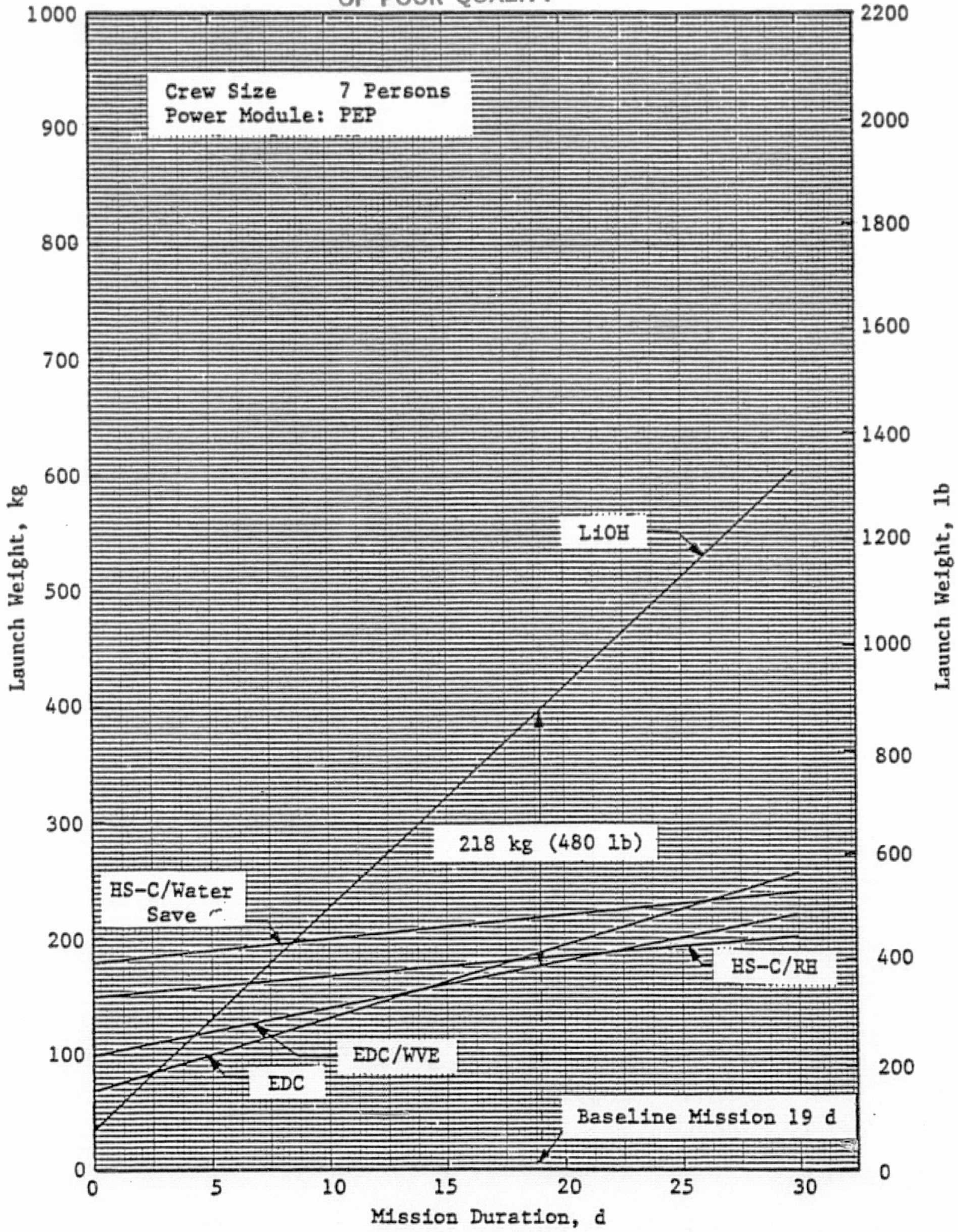

FIGURE 16 CO_2 REMOVAL SUBSYSTEMS LAUNCH WEIGHT COMPARISON: MISSION OPTION TWO

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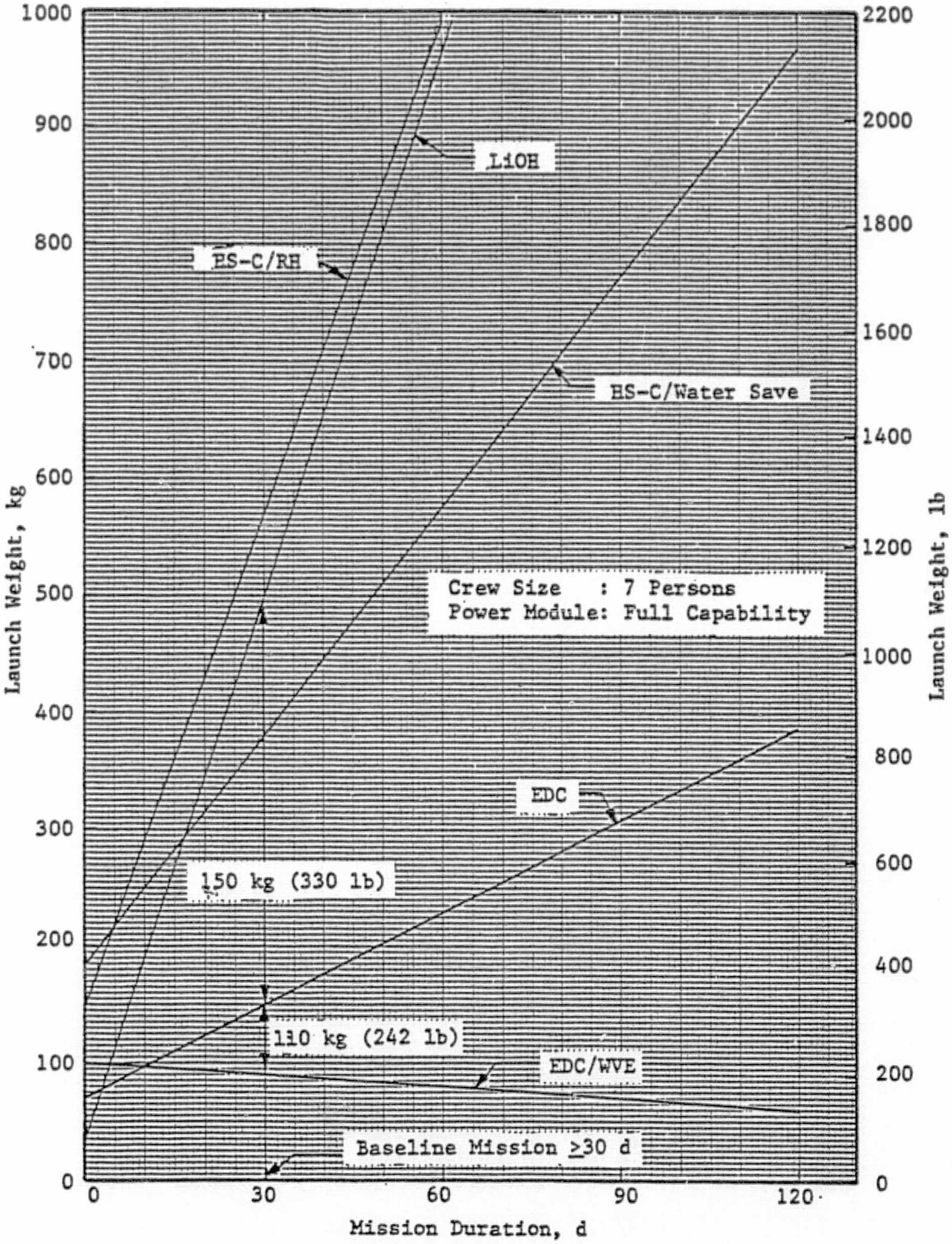

FIGURE 17 CO_2 REMOVAL SUBSYSTEMS LAUNCH WEIGHT COMPARISON: MISSION OPTION THREE

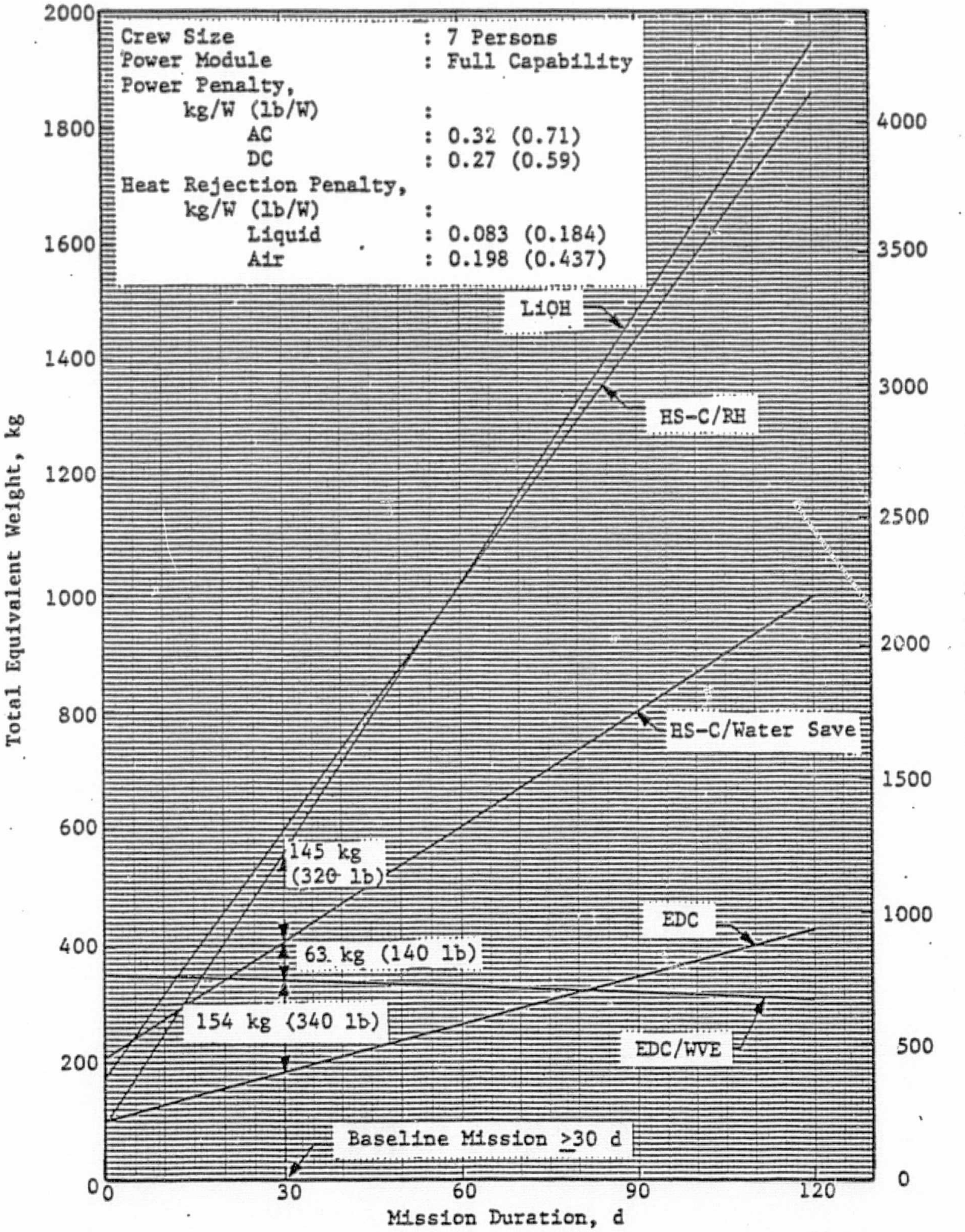

FIGURE 18 CO_2 REMOVAL SUBSYSTEM EQUIVALENT WEIGHT COMPARISON: MISSION OPTION THREE

STEAM DESORBED AMINE SUBSYSTEM WEIGHT[a]

Items	Weight, lb
Canister/Steam Generator Assembly (2)	50
Fan Assemblies (2)	18
Metering Pumps (2)	10
Water Accumulator	5
Controller	5
Pressure Regulating Valve	5
Solenoid Shutoff Valves (8)	14
Supporting Framing (~15%)	20
Ducting	1.8
Tubing	3
Subtotal	131.8
Items Omitted (see Attachment A)	18.4
Penalty for Items Added to S-CRS (see Attachment B)	45.2
	195.4

(a) Colling, A. K. et al., "Study Report Lightside Atmospheric Revitalization System," Contract NAS9-13624, October, 1980, pages 2, 137 and 138.

Items Omitted:

ΔP Sensor Across Fans	0.5
ΔP Sensors Across Canisters (2)	1.0
Temperature Sensors (Canisters) (4)	0.8
Temperature Sensors (Steam Gen.) (2)	0.4
Check Valves (H_2O) (2)	0.2
Relief Valves H_2O (Pumps) (2)	0.4
Liquid Level Sensor (Accumulator)	0.3
Flow Sensor	0.2
Temperature Sensors (2)	0.2
Canister (Air) Isolation Valves (4)	12
Subtotal	16.0
Added Packaging (15%)	2.4
Total for Item Omitted	18.4

Sabatier CO_2 Reduction Subsystem (S-CRS) Penalty

CO_2 Compressor	10
CO_2 Accumulator	17
Pressure Regulating Valve	5
Solenoid Valves (2)	3.6
Pressure Sensor	1
Charcoal Canister	1.4
Relief Valve (CO_2)	0.2
Check Valve (CO_2)	0.1
Added Portion of Controller	1
Subtotal	39.3
Added Packaging (15%)	5.9
Total S-CRS Penalty	45.2

HAMILTON STANDARD

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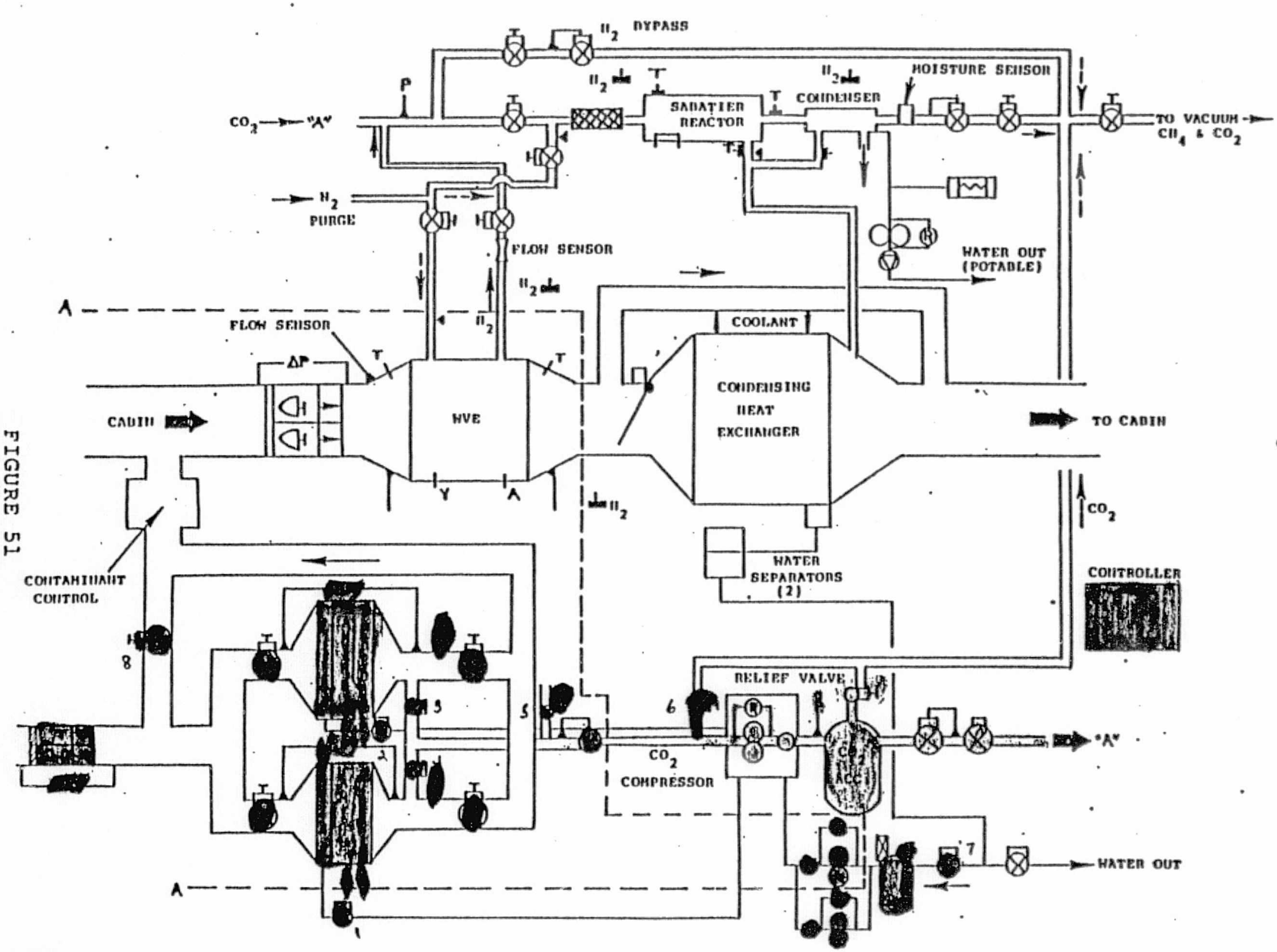

= was included
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FIGURE 51
LARS SCHEMATIC

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SVHSER 7224

Submitted to:

Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124

Attention: Keith Miller, MS 84-06
H. F. Carr, MIS 84-86 (Cover Letter)

TR-524-7

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Comparison Requirements

Prepared Under

PA No. 1220

for

Boeing Aerospace Company

Contact: Franz H. Schubert

Telephone: 216 - 464-3291

January 15, 1983

INTRODUCTION

As the Space Station program unfolds, NASA has an essential need for comparing various approaches to the Environmental Control/Life Support System (EC/LSS) alternatives. As part of its internal research and development activities, Life Systems has been completing various technical tasks to more accurately prepare these trade-off studies for more meaningful subsystem selections.

In TR-548, "Space Station Environmental Control/Life Support System Selection Criteria", a list of major selection criteria, their priority and grouping was assembled together with extensive listings of subcategories for each criteria. The present document summarizes the requirements to be met when preparing the information before making comparisons of EC/LSS options.

APPROACH

A survey was made of many prior NASA Space Station evaluation programs, including those of Rockwell, McDonnell Douglas, Boeing, General Dynamics, NASA, etc. From these a list of comparison requirements was assembled. A preliminary version is presented in Table 1. It is called preliminary because as our activities continue on Space Station trade study tasks, the comparison results are continually becoming more complete and quantitative.

SUMMARY

A list of nineteen comparison requirements was presented. They were coded as to which must be met and which should be met when making Space Station subsystem comparisons.

TABLE 1 LIST OF EC/LS SUBSYSTEM COMPARISON REQUIREMENTS

All subsystems compared must (or should indicated by adding at the end and in parenthesis the word "should"):

1. Perform same function at same capacity (and in some cases rate).

2. Be compared at same development level in spite of not being at the same development level.[a]

3. Include impact on (penalties to or benefit from) other EC/LS subsystems.[b]

4. Use the same weight penalty for power, heat rejection or cooling load, and thermal or heating load (see Table 2 for example).

5. Specify curve(s) upon which design is based and the conditions under which the curve applies and was obtained (e.g., after 100 hours or 10,000 hours of endurance testing).

6. Specify the reliability basis for each component used based on the estimated failure rate. This impacts redundancy (installed-operating or installed non-operating), spares and crew time (scheduled and unscheduled maintenance time). Spares relate to penalty for on-board supply of (e.g., 120 days) <u>and</u> resupply of (e.g., every 90 days). Since failure rate projections are very subjective numbers, a common basis for specifying failure rate is needed by NASA.

7. Be compared at the same maintainability approach, e.g., all with or without maintainable disconnects.

8. Meet the same and all Space Station environmental conditions of temperature, pressure, relative humidity, etc.

9. Itemize technology risk areas. (should)

10. Specify the assumptions made during the design effort.

(a) This favors the less developed subsystems since a full appreciation cannot exist of its problems and components needed to resolve them. The impact of this should be reflected in an increased cost in the development cost category.

(b) Avoid, for example, the technique used by Ham. Standard to make their version of the Steam Desorbed Amine CO_2 Concentrator low in weight, volume and power by transferring its CO_2 accumulator (17 lb), CO_2 compressor (10 lb), CO_2 regulating valves (10 lb), etc. and associated power (e.g., 250 watts for compressor) to the Sabatier CO_2 Reduction Subsystem.

12. Be based on a detailed mechanical schematic with sensors and any installed redundancy, i.e., a real world, workable schematic consistently treating all flight requirement issues and including all sensors needed. Do not use the block diagram or simplified schematic that is often used as a technical presentation aid.

13. Prepare a table listing subsystem size including components list and sizes. It identifies by component, spares and expendables needed and the total subsystem characteristics such as component weight, volume, power (by type), dimensions, reliability, failure rate, maintainability, etc. Note:

    a. All weights must be in lbs[a]
    b. All volumes must be in cu. in. unless otherwise stated.
    c. Spares are based on crew of 4, 120 days of on-board storage and 90 day resupply intervals.
    d. Expendibles are based on crew of 4, 120 days of on-board supply and 90 day resupply intervals.
    e. Basic system component unit weight refers to the installed, total operational weight of the component as a Line Replaceable Unit (LRU). It must include component-side mounting brackets and fittings but not vehicles mating mounting brackets or fittings. It must include expendable cartridge and replaceable subcomponent where applicable.
    f. Expendable unit weight refers to the replaceable section of life limited components. It can include chemicals, cartridge or replaceable section or subcomponent weight. The latter is referred to as "Line Replaceable Component" (e.g., of a LRU). Expendable quantity entry is to be based on a 120 days of on-board storage and a 90 days of resupply requirement.
    g. The total weight includes the weight of the units needed for the total basic system, spares for 120 days and expendibles for 120 days.
    h. Resupply weight includes the weight and expendibles to be resupplied every 90 days.
    i. Use an * to indicate the number is an estimate rather than backed up by technical computations or based on specific technical data or product literature.

14. Include a "component" category for Packaging in the table prepared under Item 13.

15. Include a "component" category for other supporting or interfacing EC/LSS penalties in the table prepared under Item 13.

(a) The underlines in this section refer to values that may change for the final Space Station.

16. Include an Instrumentation Identification List of sensors and controls needed (per example as Table 3). It should cite sensors needed, their function, if must be "on" continuously and frequency of monitoring, and calibration frequency and level of complexity.

17. Specify assumptions used.

18. Specify conformance of components to spacecraft acceptable metallic and non-metallic material specifications.

19. Be compared with a design to satisfy the worst case of the 3 operational levels:

    a. Operational
    b. Acceptable (e.g., 90 days)
    c. Emergency (e.g., 300 hours) (tolerant to worst single, non-maintainable failure)

TABLE 2 SPACE STATION WEIGHT PENALTIES

Penalties to be used are:

Power Penalties:

Continuous Use

115 VAC, 400 Hz	0.71 lb/W
28 VDC, Regulated	0.59 lb/W

Sunside Use

115 VAC, 400 Hz	0.35 lb/W
28 VDC, Regulated	0.27 lb/W
56 VDC, Unregulated	0.15 lb/W

Heat Rejection (Cooling Load or Radiator) Penalties:

Heat Rejection to Liquid Coolant	0.18 lb/W
Heat Rejection to Cabin Air	0.44 lb/W

Thermal (Heating Load) Penalty:

To be specified.

Date__/__/__

TABLE 3 INSTRUMENTATION LIST

SUBSYSTEM: ____________________

Sensors		Function		Requiring Continuous Monitoring		Calibration	
Item No.	Sensor Description	Control	Fault Detection	No.	Frequency	Complexity Level	Frequency
	Total						

Controls

No.	Type

Prepared By ____________________

Approved By ____________________

Submitted to:

Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Attention: Keith Miller, MS 84-06
H. F. Carr, MIS 84-86 (Cover Letter)

TR-524-8

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR SPACE STATION

Evaluation of Integrating the Regenerative Fuel Cell System with Other Space Station Systems

Prepared Under

Program No. 1277

for

Purchase Contract CC0061

Contact: Franz H. Schubert

Telephone: 216 - 464-3291

March 10, 1983

TABLE OF CONTENTS

LIST OF APPENDICES

1.0 INTRODUCTION

Life Systems is actively engaged in the development of Regenerative Fuel Cell System (RFCS) technology for NASA's Space Station. Under one contract Life Systems is developing a RFCS Breadboard for delivery to NASA JSC, while under another contract scale-up of light weight cell hardware (to 1.0 $ft.^2$ active area) is being accomplished for NASA LeRC.

2.0 BACKGROUND

The results of a recent study completed by the Boeing Aerospace Co. under contract NAS9-16151 have been reviewed as reflected in the program's Final Report (Analysis of Regenerative Fuel Cells, BAC Document No. D180-27160-1, Nov. 1982). Life Systems had contributed to that activity on an informal basis. This review and assistance served as a basis to evaluate the requirements and specifically potential integration options with other Space Station Systems, such as ECLSS and Reaction Control. The results of this evaluation are summarized herein.

3.0 SUMMARY OF RESULTS

Life Systems has used the work performed by BAC and referenced in Section 2.0 above as a basis to evaluate requirements and integration aspects. Also, new information that had been furnished by BAC with respect to orbit altitude (500 versus 370 km orbit altitude) has been incorporated since this affects reaction control requirements to a large degree.

The results have been presented in Appendix 1 and 2 to this document, using handwriting to actually convert Sections 2.0 and 8.0 of BAC's document D180-27160-1 to the new requirements. This was done so BAC personnel can very quickly spot the impact of the changes using a document that they are familiar with.

2.0 DEFINITION OF REQUIREMENTS AND PENALTIES

The following requirements and penalties are defined for the ~~SOC~~ SPACE STATION energy storage system.

<u>Orbital Conditions</u>	500 km (270 NM)
Altitude	~~370 km (200 NM) to 450 km (243 NM)~~
Inclination	28.5 degrees
Solar Cycle	Sunlight duration - 55 minutes
	Occult duration - 37 minutes

<u>Bus Voltage</u>	
Regen. Fuel Cells	200 +2%, -20% dc
Batteries	200 +10%, -30% dc
MIL 1539 (Ref.)	28 +21.4%, -21.4% dc

<u>Electric Power Requirements, Normal OperationAL RANGES</u>

See Figure 2.0-1. Load management results in less load during occultation than during sunlight.

~~Electric Power Requirements — Emergency Operation~~

~~See Figure 2.0-2~~

<u>Equipment Cooling</u>	
Cold Plate Mounting and Cooling (batteries & electronics)	11 percent of equipment weight
Radiator area for batteries (5°C)	14 W/ft^2 radiation surface
Radiator area for electronics (20°C)	19 W/ft^2 radiation surface
Radiator weight	1.27 lb/ft^2 of radiator (2 ft^2 radiation surface/ft^2 radiator in plan view)

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C-5 2, 3, 4, 5

		SUNLIGHT – W	OCCULTED – W
~~FULL~~ ~~SOC~~ INITIAL SPACE STATION	ELECTRIC LOADS	30,000 ~~50,000~~	25,000 ~~30,236~~
	ELECTROLYZER FOR RECHARGE	AS REQUIRED	———
	INTEGRATED SUBSYSTEMS ELECTROLYZER	~~FIGURE 2.0-3~~	SUNLIGHT ONLY
~~HALF~~ ~~SOC~~ INTERMEDIATE SPACE STATION	ELECTRIC LOADS	40,000 - 80,000 ~~27,860~~	25,000 - 50,000 ~~22,770~~
	ELECTROLYZER FOR RECHARGE	AS REQUIRED	———
	INTEGRATED SUBSYSTEMS ELECTROLYZER	FIGURE 2.0-3	SUNLIGHT ONLY
GROWTH SPACE ~~SOC~~ STATION	ELECTRIC LOADS	~~50,000~~ 40,000 - 100,000	~~30,230~~ 25,000 - 75,000
	~~EXPERIMENTS~~	~~40,000~~	~~30,000~~
	ELECTROLYZER FOR RECHARGE	AS REQUIRED	———
	INTEGRATED SUBSYSTEMS ELECTROLYZER	~~FIGURE 2.0-3~~	SUNLIGHT ONLY

Figure 2.0-1: Electrical Power Requirements — Normal OperationAL RANGES

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	WATER ELECTROLYSIS RATE — LB/DAY	NUMBER OF ELECTROLYZER SYSTEMS REQUIRED: CASE NO. 1 — NO INTEGRATION	NUMBER OF ELECTROLYZER SYSTEMS REQUIRED: CASE NO. 2 — INTEGRATION	GAS STORAGE CRITERIA
FUEL CELL ELECTROLYZER	PER ANALYSIS	~~3~~ 4	~~3~~ 4	EMERGENCIES ~~A, B AND C~~
LIFE SUPPORT ELECTROLYZER	27.3 ~~17.8~~ LB/DAY 1 ~~3~~	2		EMERGENCIES ~~A, B AND C~~
ORBIT MAINTENANCE ELECTROLYZER	3.8 ~~18.0~~ LB/DAY 2	2		EMERGENCIES ~~A, B AND C~~
		TOTAL: 7	TOTAL: 3	

1 ~~PEAK REQUIREMENT IS 20.2 LB/DAY, WITH 27% AT 800 PSI~~
BASED ON 2.07 lb/d METABOLIC, 1.19 lb/d FOR CO_2 REMOVAL AND 0.15 lb/d EQUIVALENT OVERBOARD LEAKAGE (PER PERSON)

~~2 FOR GROWTH SOC, REQUIRED 27.2 LB/DAY~~
~~FOR HALF SOC, REQUIRE 8.66 LB/DAY~~

~~3 FOR GROWTH SOC, REQUIRED 26.7 LB/DAY~~
~~FOR HALF SOC, REQUIRE 6.7 LB/DAY~~

2 BASED ON NOMINAL VALUES OF FIGURE 2.0-3A FOR SOLAR ARRAY DRAG AND A 1.4:1 RATIO OF SPACE STATION TO SOLAR ARRAY DRAG (AT 500 km ALTITUDE)

Figure 2.0-3: Electrolyzer/Storage Requirements for Integrated Subsystems — ~~Full SOC~~ INTERMEDIATE SPACE STATION

FIGURE 2.0-3A ANNUAL ORBIT MAKEUP PROPELLANT IN kg PER kW OF LOAD AT 500 km ALTITUDE

Atmosphere Density	I_{SP}, Sec. 230 (Hydrazine)	300 (BiProp)	380 (Water Electrolysis)	750 (H_2)
Minimum	1.46	1.12	0.88	.446
Nominal	7.3	5.6	4.4	2.23
Maximum	29.2	22.3	17.7	8.97

Radiator area for fuel cell

Temperature	Watts/ft^2 radiator surface
60°C	37.2
70°C	42.9
80°C	49.0
90°C	55.7

Power System Constraints on Regenerable Fuel Cell System

Number of fuel cell modules, ~~full SOC~~ INTERMEDIATE SPACE STATION — 4 ~~3~~ busses with minimum of 2 modules/buss, and minimum of 6 modules total

Design to carry full load with 2 modules out, though efficiency may suffer

Design to emergency load with 2 modules out.

Number of fuel cells modules, ~~half SOC~~ INITIAL SPACE STATION — 4 ~~3~~ busses with minimum of 1 module/bus.

Design to carry full load with 1 module out, though efficiency may suffer.

Design to emergency load with 2 modules out.

Number of fuel cell modules, growth ~~SOC~~ SPACE STATION — No redundant modules required for science equipment.

Design to carry full load with about 25% of the modules failed, though efficiency may suffer.

Number of Electrolyzer Modules — See Figure 2.0-3.

Power Supply/Controller Efficiency (including transmission loss)

Electrolyzer controller	99%
Battery Chargers	92%

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Solar Array Incremental Weight Penalty (weight per unit array - generated power)

~~Half SOC~~ INITIAL SPACE STATION	30.6 lb/kW
~~Full SOC~~ INTERMEDIATE SPACE STAT.	30.6 lb/kW
~~Growth SOC~~ GROWTH SPACE STATION	30.6 lb/kW

Note: Penalty for solar array drag LISTED IN FIGURE 2.0-3A ~~not included. This is a resupply penalty that is addressed separately.~~

8.0 EVALUATION OF INTEGRATION WITH OTHER SUBSYSTEMS

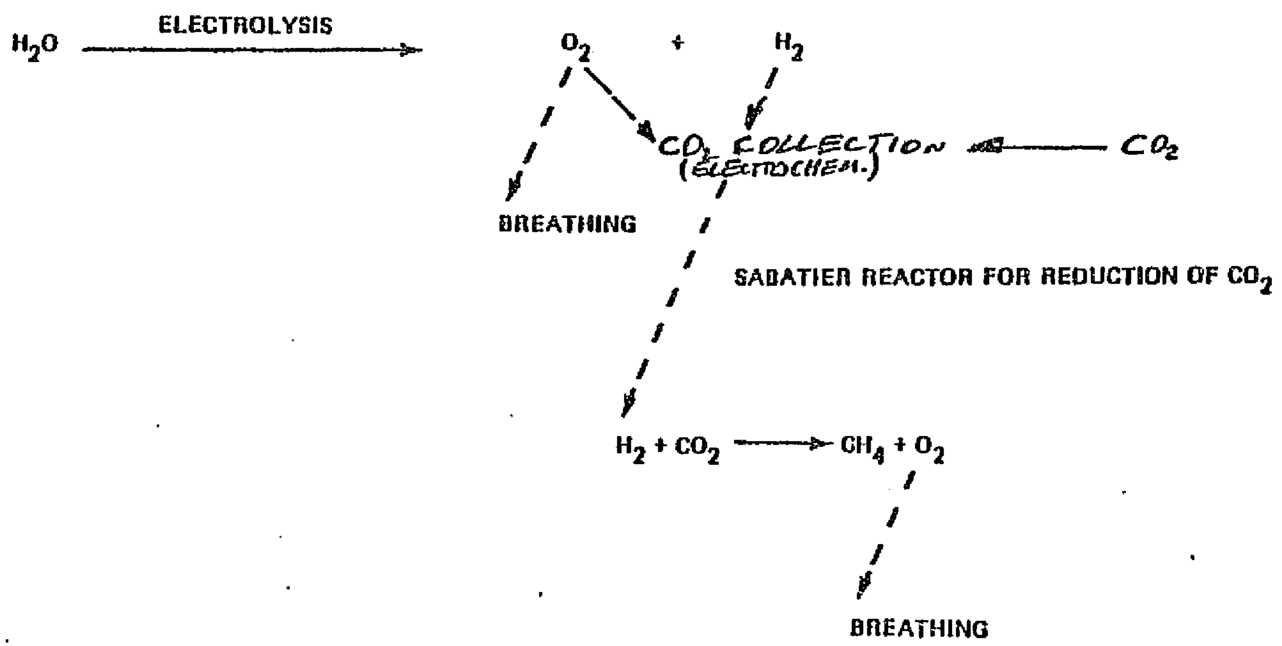
8.1 INTEGRATION OPTIONS AND REQUIREMENTS

The baseline DESIGN FOR THE SOC reaction control system for orbit makeup ~~uses~~ used hydrazine. ~~An~~ THE PROPOSED BASELINE FOR THE SPACE STATION PROPOSES THE USE OF ~~alternative to this is to use~~ hydrogen-oxygen propellant ~~either as separate gases or as~~ transported AS water which would be electrolyzed on board. The life support system also uses water, oxygen and hydrogen, and these gaseous systems can be integrated with the hydrogen-oxygen regenerable fuel cell system. ~~An additional possibility is the use of primary fuel cells for power, using hydrogen and oxygen from shuttle residuals; this fuel system can be integrated with the reaction control system.~~

The life support system can employ water electrolysis to provide oxygen needed for breathing OXYGEN AND HYDROGEN NEEDED FOR CO_2 COLLECTION and hydrogen needed for reduction of CO_2 in a Sabatier reactor. The requirements for this are summarized in Figure 8.1-1. Typically ~~17.8~~ 27.3 lb/day of water will be electrolyzed, but this can increase during extra-vehicular activity (EVA) to ~~20.2~~ 28.0 lb/day. High pressure oxygen is also needed intermittently for EVA use.

The ~~Full SOC~~ INTERMEDIATE SPACE STATION vehicle without a solar array is large and requires ~~19.35~~ 2.2 lb/day of electrolyzed water for orbit makeup~~, compared with 9.1 lb/day for the Half SOC~~. The solar array requires an additional ~~13.65~~ 1.6 lb/day, for a total of ~~33~~ 3.8 lb/day ~~for the Full SOC~~. This compares with approximately ~~324~~ 450 lb/day of water electrolysis for the energy storage system (AT 50 kW). Thus, the energy storage requirement dominates the orbit makeup requirement.

Power needs during emergencies are expected to be between 1500 W and 3000 W. The fuel cells would be very efficient at this low power level, but we have assumed that the fuel cell ancillaries, which are on the order of 600 W, should not be cut back in power. Assuming the worst case condition where the fuel cell must provide power continuously during light and dark, the hydrogen and oxygen consumption, given as the equivalent pounds of water, is 68.5 lb/day for a 3000 W electrical load (plus the 600 W load for fuel cell ancillaries); for a 1500 W electrical load (plus the 600 W load for fuel cell ancillaries) 40 lb/day are consumed. In addition, the life support consumption of oxygen will be ~~15.8~~ 24.2 lb/day, which is equivalent to the electrolysis of ~~17.8~~ 27.3 lb/day of water. Hydrogen and oxygen consumption during emergencies is summarized in Figure 8.1-2, based on I_{SP} = 380 sec. It should be noted that some emergencies will be of a



	H_2O REQUIREMENTS	
	NORMAL USE (6 MEN) [a)]	EVA ACTIVITY
LOW PRESSURE (< 20 PSI)	27.3 ~~17.0~~ LB/DAY	22.5 ~~14.7~~ LB/DAY
HIGH PRESSURE (000 PSI)	--------	5.5 LB/DAY

a) For Metabolic Oxygen, overboard leakage and CO_2 collection

Figure 8.1-1: Life Support Water Electrolysis Requirements

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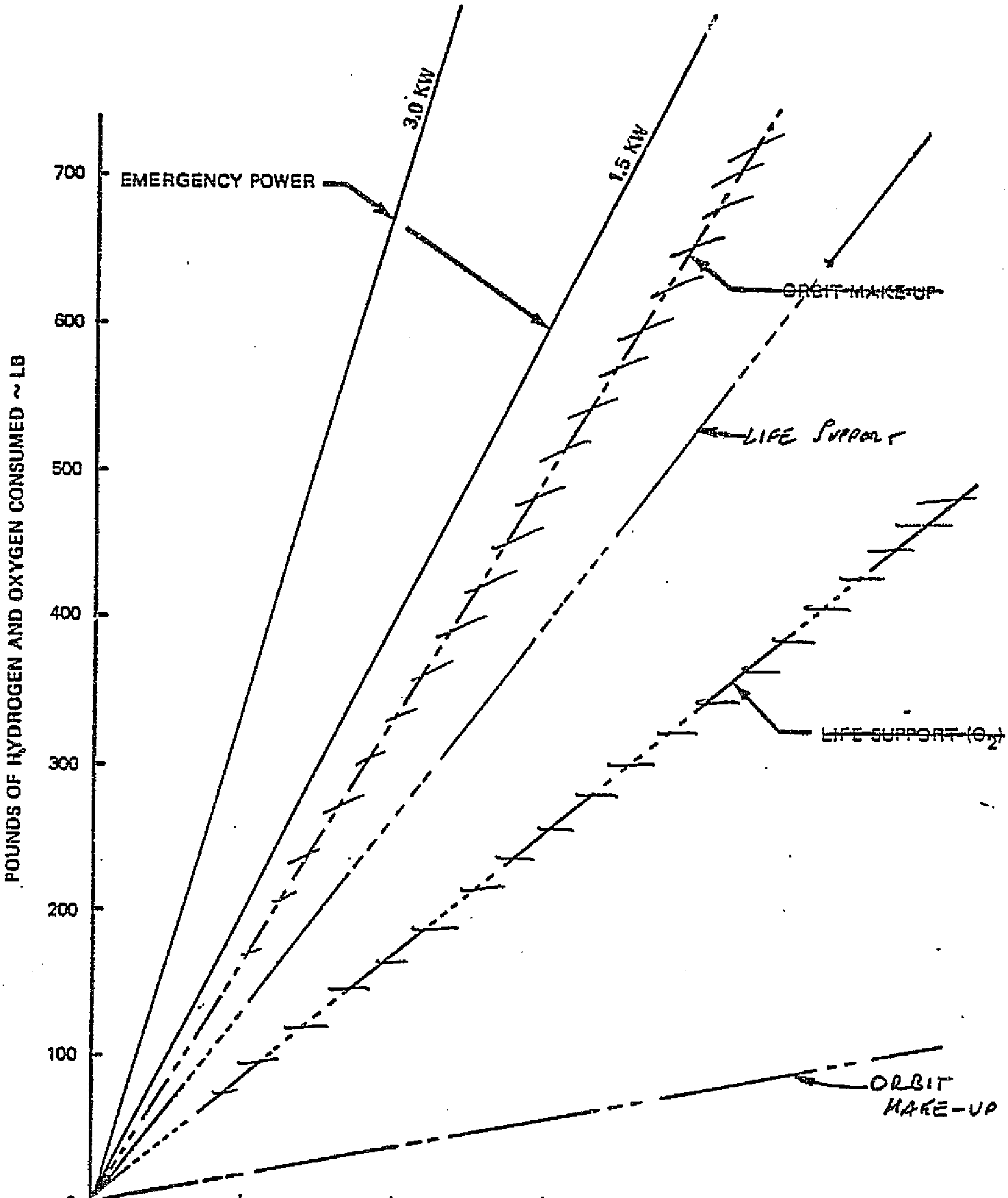

Figure 8.1-2: H_2 and O_2 Consumption for Emergencies

type where electrolysis of water during sunlit operation is possible, and others where it is not possible. That distinction has not been made in this analysis, and the worst case was assumed.

8.2 INTEGRATION WITH REACTION CONTROL SYSTEM

Reactants for orbit makeup are ~~33~~ 3.8 lb/day using hydrogen and oxygen in stoichiometric ratio, based on electrolysis of water. The Isp assumed was 380 sec and an orbit altitude of 500 km. This results in ~~12,045~~ 1392 lb/year of water transport to the ~~SOC~~ space station. Hydrazine, with an Isp of 230 sec. would total ~~19,900~~ 2,300 lb/year. Thus, the use of electrolyzed water would save ~~7855~~ 908 lb/year in resupply for orbit maintenance. For maximum atmospheric densities at 500 km orbits these numbers would be 5,600 lb/year of water, 9,200 lb/year of hydrazine or a 3,600 lb/year savings.
System pressure compatibility with the integrated approach should not be a problem. Hydrogen-oxygen thrusters have operated with rocket chambers at 100 psia and 50 psia and with a blow down to one third of these values. The minimum electrolysis gas pressure we have considered for integrated systems is 120 psia.

In addition to the ~~7855~~ 908 to 3,600 lb/year weight savings, it is worthwhile to avoid the shipping, handling and storage of hydrazine from the standpoint of safety. Hydrazine lines must be heated, and though that is normally not an important consideration, the long external line lengths required with the ~~SOC~~ space station exacerbates the problem, especially during power emergencies.

Another feature of the hydrogen-oxygen system is the ability to provide very small impulse bits, as compared with the hydrazine system; this obtains by gas release without combustion. Factors in favor of hydrazine are (1) the thruster technology is well developed; (2) hydrazine is a good source of nitrogen and hydrogen needed for life support; and (3) fuel processing is not required.

The required electrolysis for orbit maintenance may be attained either by dedicated units or by integrating with the electrolyzers of the energy storage system. Integration would increase the normal ~~324~~ regenerative fuel cell needs at 50 kw of 451 lb/day of water electrolysis by an additional ~~33~~ 2.8 lb/day, or only 0.8 ~~10.2~~ percent. ~~Maintaining the same~~ Increasing the current density only slightly will cause a negligible the increased weight ~~of the 55-percent efficient~~ decrease in the efficiency of the energy storage system ~~would be 56.5 lb., and for the 62-percent efficient system would be 116.2 lb~~. Integration in this way gives redundancy from the multiple electrolyzers.

With dedicated electrolyzers there is the need to provide suitable redundancy. A typical design would be one scaled ~~up~~ DOWN from the ~~18.0~~ 24.9 lb/day OF O2 unit described in Reference 1 a), p. 8. ~~16, p. 27~~. Three units would be provided so that two failures could be endured. Capacity would be ~~increased~~ CHANGED from ~~18.0~~ 24.9 lb/day to ~~33.0~~ 3.4 OF O2 OR 3.8 lb/d OF WATER lb/day, and current density would be ~~reduced~~ INCREASED FROM 191 to result in ~~300~~ 573 ASF after the second failure, that is, ~~166.7~~ ASF initially. The unit weight would scale ~~up~~ DOWN from ~~142~~ 299 lb to ~~221.3~~ 48 lb, and there would be three units, for a total of ~~663.8~~ 144 lb.

Since the current densities would be designed to be similar, electrolyzer module power consumption by the electrolyzer cells would be no different whether the system were integrated or not. However, ancillary power will be much increased for the dedicated units because of the relatively low power level. We expect ancillary power to increase from approximately 1.5 percent with the energy storage system to about ~~5.0~~ 6.0 percent with ~~the~~ SUCH A small, dedicated units. With dedicated electrolyzers, power consumption would be ~~6.33~~ 0.40 kW. Integrating with the energy storage system would save about ~~220~~ 18 watts.

8.3 INTEGRATION WITH LIFE SUPPORT

The life support system requires the electrolysis of ~~17.8~~ 27.3 lb/day OF WATER. The trades and rationale on integration of this with the RFC energy storage system are similar to that of electrolysis for orbit maintenance reactants. Thus, three dedicated electrolyzers would weight ~~383~~ 747 lb versus ~~30.8~~ 45 lb for integration with the 55 percent efficient energy storage system, or versus ~~63.4~~ 128 lb for integration with the 62 percent efficient system. Whether or not the life support system were integrated with the energy storage system, means must be provided for the 900 psia needed for EVA. This can best be done either by direct electrolysis to that pressure, or by means of an electrochemical oxygen compressor. The electrochemical oxygen compressor has an advantage in that it can be used also as a backup method for obtaining high pressure starting with either the energy storage oxygen or the reaction control oxygen. This compressor weighs 65 lb.

A more attractive integration system is exploitable if hydrogen and oxygen reactants are used for orbit makeup. The concept~~, as shown in Figure 8.3-1,~~ is to use non-stoichiometric combustion in the thrusters and thus obtain a higher specific impulse for propulsion. The oxygen that is saved can be used for life support. Thus, if water

a) F. H. SCHUBERT, ET. AL., "OXYGEN GENERATION SUBSYSTEM FOR SPACECRAFT," ASME PAPER NO 81-ENAS-40, SAN FRANCISCO, CA, JULY 1981.

were electrolyzed and the product hydrogen and oxygen used as is for reaction control, ~~33~~ 2.8 lb/day would be required. By operating at an oxygen/hydrogen mixture ratio of 5 to 1, the specific impulse is increased from 380 sec. to 405 sec. and the reactant requirement reduces from ~~33~~ 3.2 lb/day to ~~30.82~~ 3.5 lb/day.

The excess oxygen electrolyzed in the non-stoichiometric concept is ~~10.0~~ 1.72 lb/day and meets ~~much~~ some of the daily oxygen need of ~~15.8~~ 24.2 lb/day (based on ~~17.8~~ 27.3 lb/day of water). It should be noted that the weight saving is ~~33.0~~ 3.2 minus ~~30.82~~ 3.5, that is, ~~2.18~~ 0.3 lb/day or ~~795.7~~ 110 lb/year. Note must be made of the fact that in this concept there is litle excess hydrogen that would be available for reduction of CO_2 in a Sabatier reactor. However, there are other approaches to CO_2 reduction, such as a Bosch reactor.

An attractive approach for integration of the life support, energy storage, and reaction control systems is the opportunity to provide especially long duration emergency capability. Since large amounts of oxygen and hydrogen are needed for orbit makeup, a reserve of these gases can be maintained at high pressure and be available during emergencies for all three systems. Electrochemical pumping is a simple, lightweight way to obtain the desired high pressure, and oxygen compression is needed anyway for EVA. Tankage is the main penalty. For example, using the data in Figure 8.1-2, a 10-day emergency supply of all the gases needed for orbit makeup, 1.5 kW electric power, and life support would require approximately 1900 lb of tanks; also required would be 65 lb for a hydrogen compressor. Postponing orbit makeup until after the emergency would cut the tankage weight in half. Following an emergency or temporary use of these gases, the high pressure reserve can be replenished on board.

8.4 INTEGRATION SUMMARY

A summary of the benefits and penalties of the several integration options is given in Figure 8.4-1. Conclusions with regard to these options are as follows:

1. Electrolysis of orbit makeup water to hydrogen and oxygen is preferable to the use of hydrazine. The weight of equipment and the electric power required are modest compared to the weight saving obtainable.

2. Electrolysis integration of orbit makeup water with the energy storage system saves ~~550~~ 144 lb and appears to be worthwhile.

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A) H_2-O_2 VERSUS N_2H_4 FOR ORBIT MAKE-UP

	N_2H_4	H_2-O_2
WEIGHT	2,300 ~~40,000~~ LB/YR	1,392 ~~12,045~~ LB/YR (DELTA = 908 ~~7,855~~)
POWER	0	0.4 ~~6.9~~ KW

B) H_2-O_2 FOR ORBIT MAKE-UP — DEDICATED UNITS VERSUS INTEGRATE WITH ENERGY STORAGE

DEDICATED	INTEGRATED (DELTA)
164 ~~663.8~~ LB	~~55% SYSTEM: 53.5 LB, SAVE 220 W~~ ~~62% SYSTEM: 105.2 LB, SAVE 250 W~~ } NEGLIGIBLE

C) H_2-O_2 FOR ORBIT MAKE-UP — NON-STOIC BURN WITH INTEGRATION WITH LIFE SUPPORT AND ENERGY STORAGE VERSUS STOIC BURN

	STOIC BURN	NON-STOIC BURN AND INTEGRATION
ELECTROLYZER:	0.4 ~~6.3~~ KW	0.37 ~~5.9~~ KW (DELTA = 0.03 ~~0.4~~ KW)
WATER:	1392 ~~12,045~~ LB/YR	1282 ~~11,249~~ LB (DELTA = 110 ~~795.7~~ LB/YR)

D) H_2 AND O_2 FOR LIFE SUPPORT — DEDICATED UNITS VERSUS INTEGRATION WITH ENERGY STORAGE

	DEDICATED	INTEGRATED (DELTA)
POWER:	4.0 ~~3.4~~ KW	4.0 ~~3.4~~ KW
ELECTROLYZER WEIGHT: (FOR 3 UNITS)	747 ~~883~~ LB	55% SYSTEM: 65 ~~88.8~~ LB 62% SYSTEM: 108 ~~85.4~~ LB (SAVE 0.2 KW)
O_2 COMPRESSOR WEIGHT:	65 LB	65 LB

Figure 8.4-1: Summary of Integration Trades — Weight and Power

3. Non-stoichiometric combustion of hydrogen and oxygen saves nearly ~~300~~ 110 lb/yr and appears to be ~~worthwhile.~~ MARGINAL SINCE this saving may be contingent on development of an atmospheric CO_2 reduction process such as the Bosch reactor. IT IS NOT A RECOMMENDED OPTION.

4. Integration of life support water electrolysis with the electrolysis of the energy storage system offers a weight saving of approximately ~~350~~ 650 lb. It is judged that this is STILL not sufficient a weight saving (BUT VERY CLOSE!) to offset the advantages of a fully self-contained life support system. However, water electrolysis by the energy storage system should be a backup to the life support system.

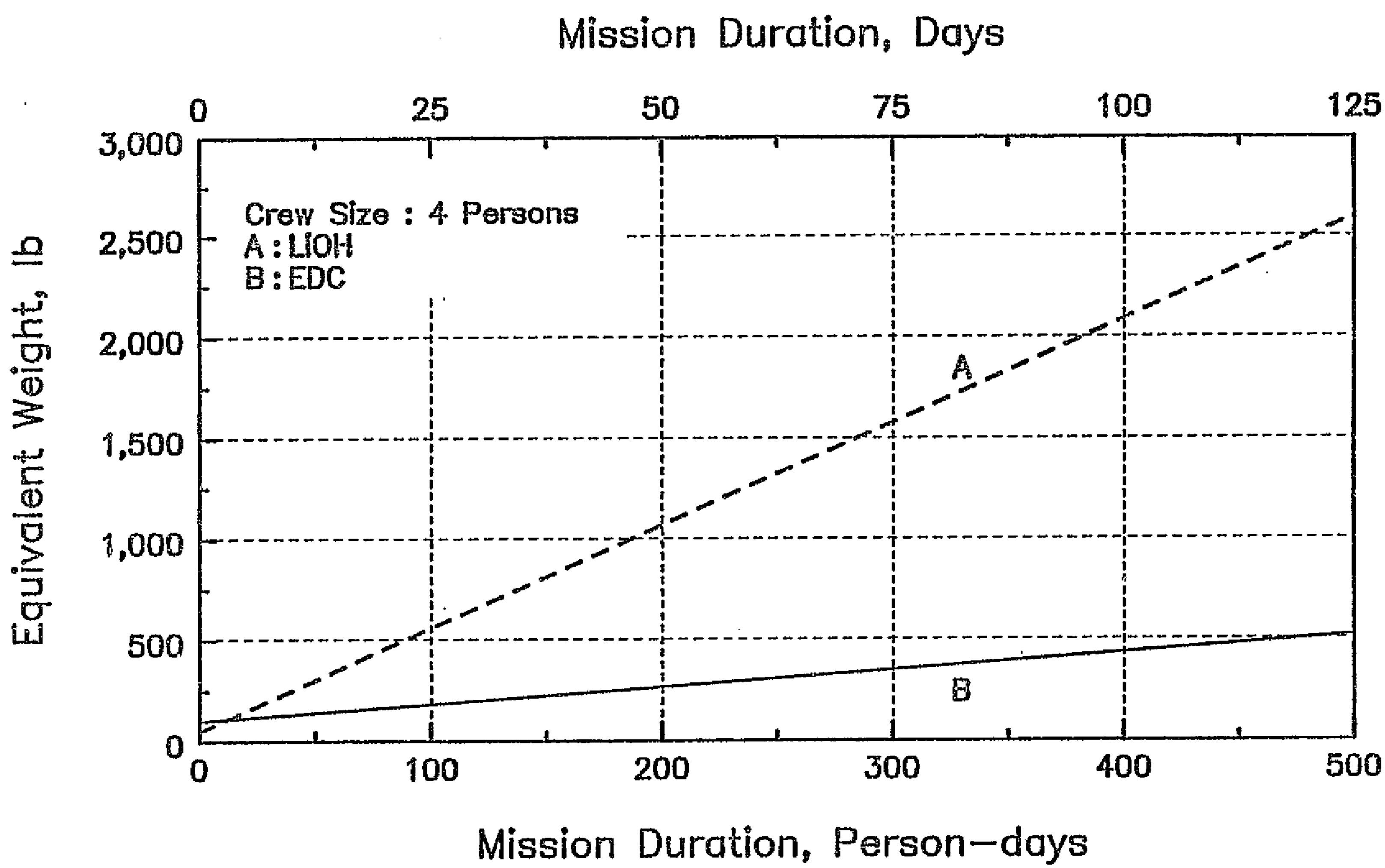
5. An on-board replenishable high pressure reserve of hydrogen and oxygen is a worthwhile opportunity for an integrated emergency gas system for life support, energy storage, and orbit makeup. Ten days emergency can be provided for with a weight penalty of 920 lb for tanks; if orbit makeup propulsion can be delayed until after the emergency, the penalty is halved.

Attachment No.	Title
1	Comparison of Open Versus Closed Loop ECLSS Functions at 500 and 8,000 Person-Days
2	Size of Modular Space Station Electrochemical CO_2 Concentrators
3	Comparison of Water Electrolysis Subsystems for ECLSS and Energy Storage
4	Approaches to Maintainability
5	Qualitative Static Feed Water Electrolysis Comparison with Acid Electrolyte (SPE)
6	SOS and Space Station Functional Boundaries
7	ECLSS and ECLSS Related System Functional Boundaries
8	Space Station ECLSS Block Diagram
9	Impact of Modular Growth
10	EC/LSS Equipment Redundancy and Locations
11	EC/LSS Options for Evolutionary Space Station for Different Power Options
12	Productivity Analysis
13	EDC Prototype Photograph, 4-Person, 21 x 16 x 13 in, CS-4 (See also Attachment 2)

COMPARISON OF OPEN VERSUS CLOSED LOOP
ECLSS FUNCTIONS AT 500 and 8,000 PERSON-DAYS

FIGURE 1

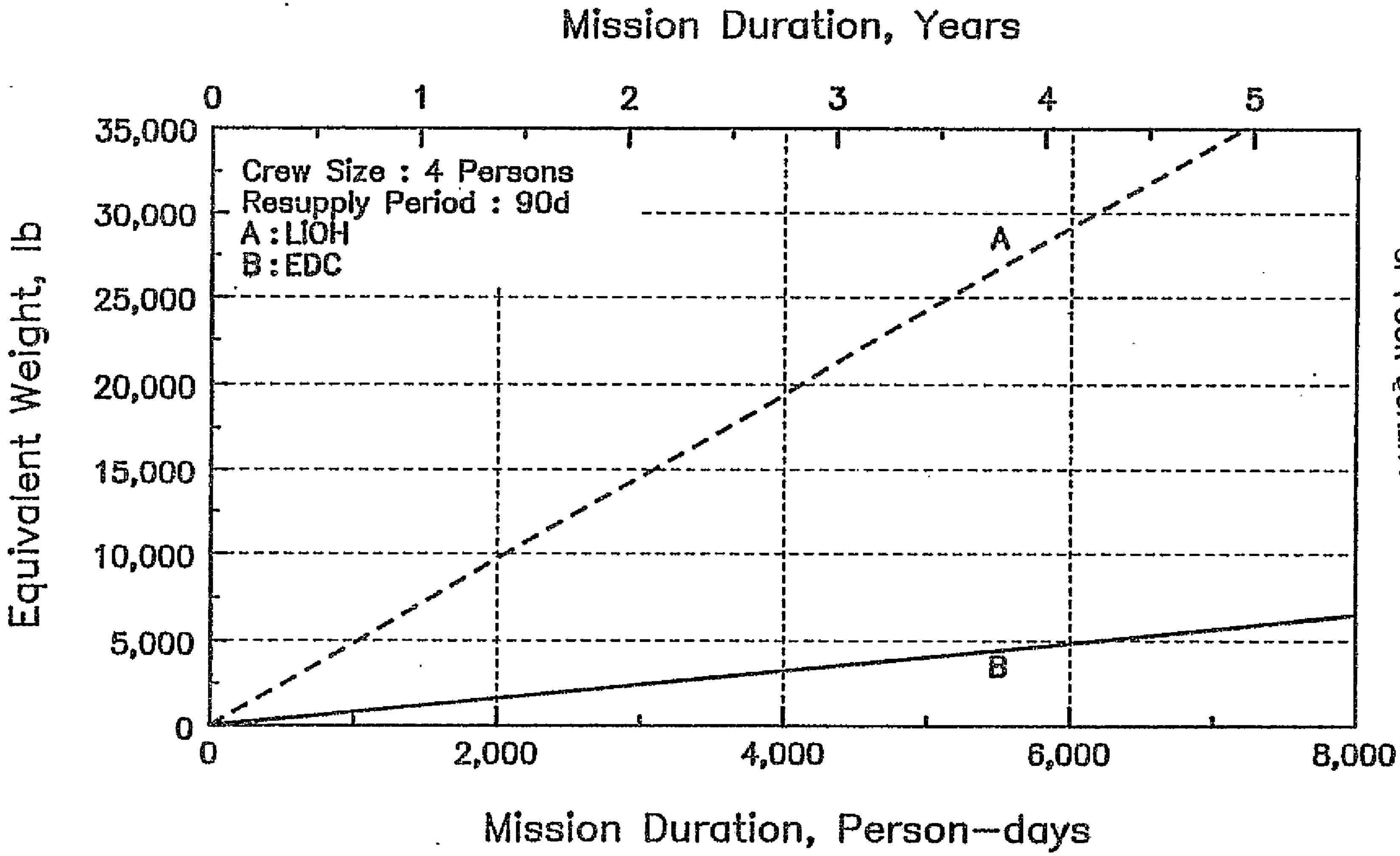
Regenerative vs Non-Regenerative CO_2 Removal



Life Systems

FIGURE 2

Regenerative vs Non-Regenerative CO_2 Removal



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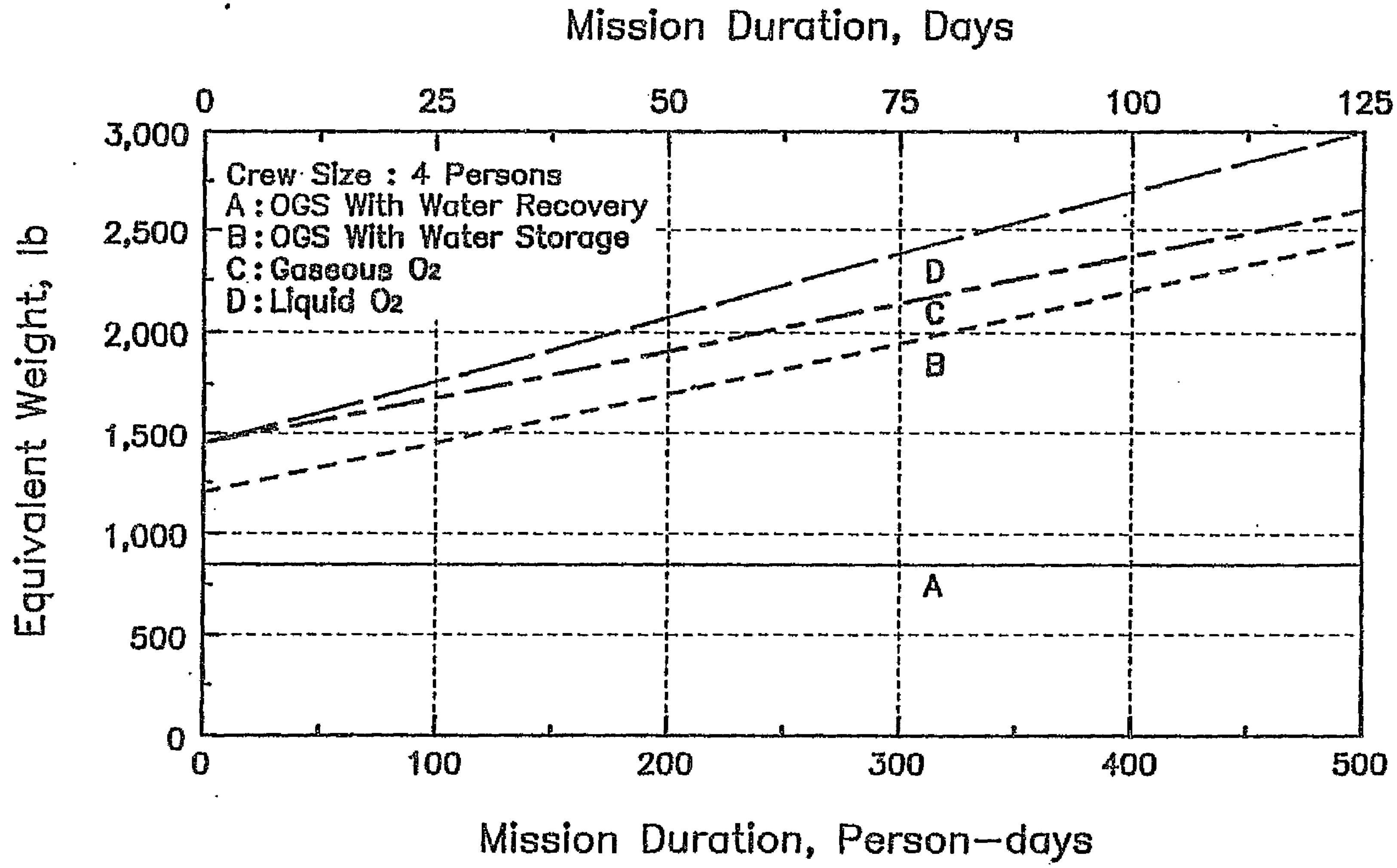
Life Systems

FIGURE 3

Stored O_2 vs O_2 Generation



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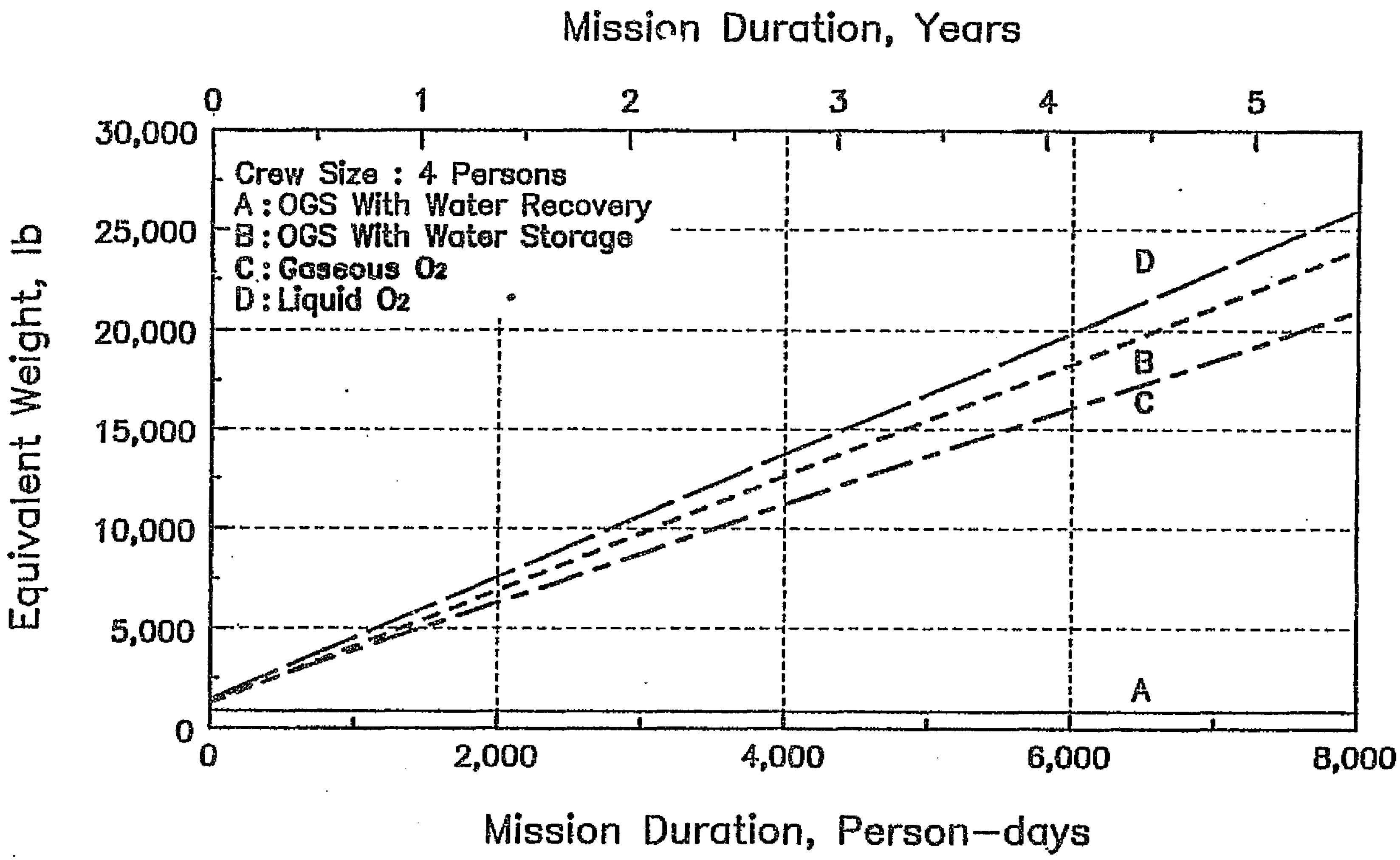
Life Systems

FIGURE 4

Stored O_2 vs O_2 Generation



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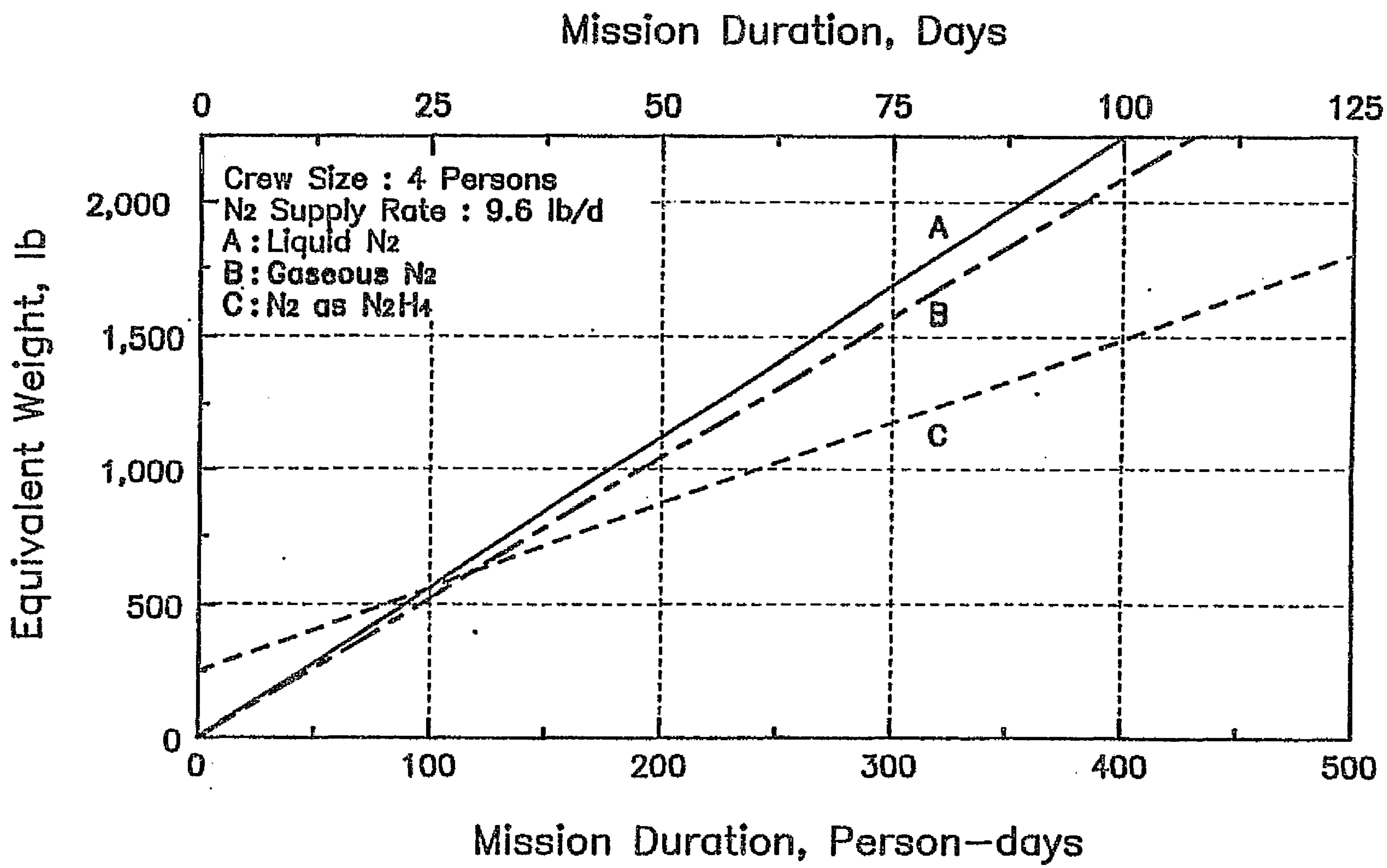
Life Systems

FIGURE 5

Stored N_2 vs N_2 Generation



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Life Systems

FIGURE 6

Stored N_2 vs N_2 Generation

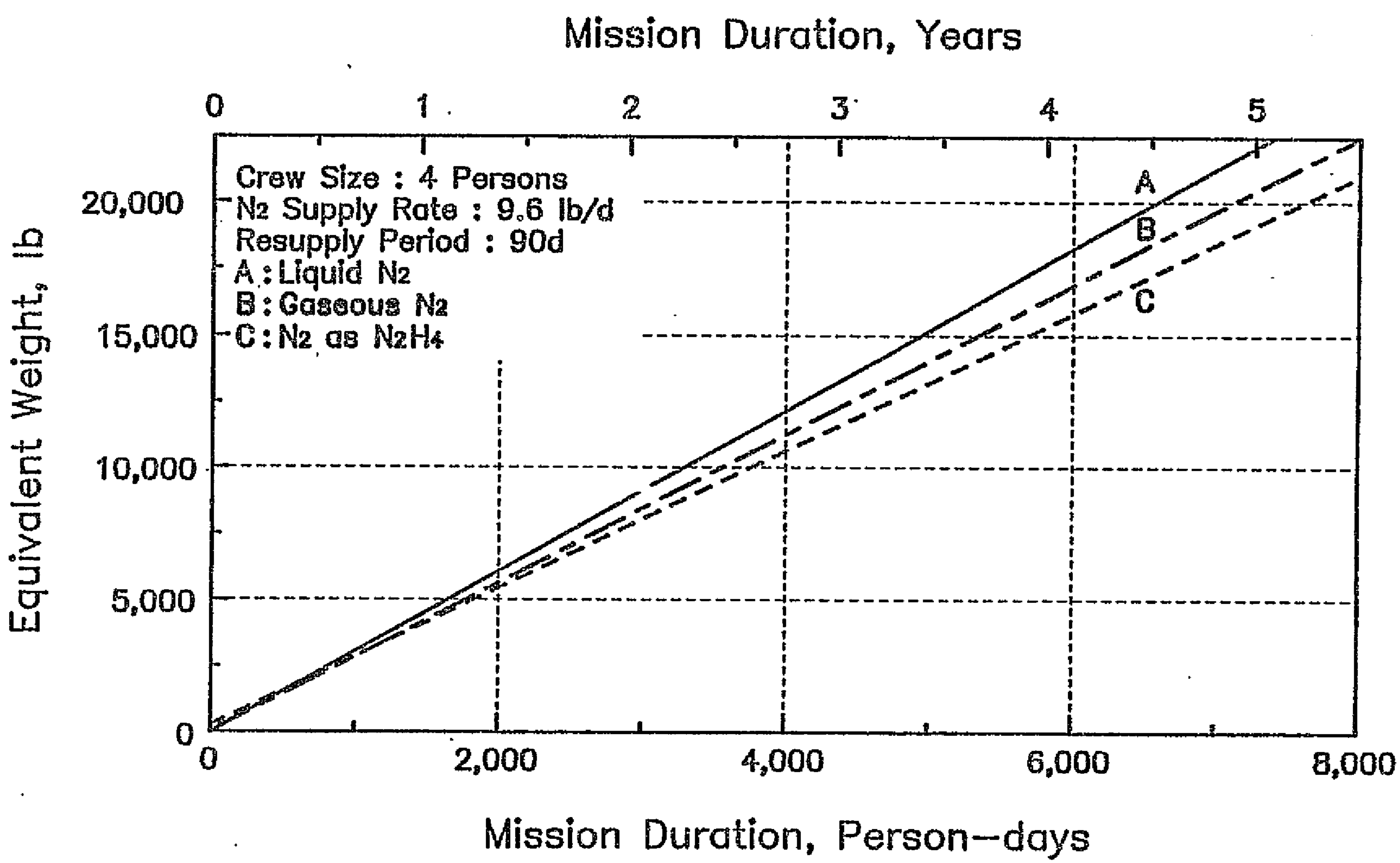

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FIGURE 7

Regenerative vs Non-Regenerative ARS

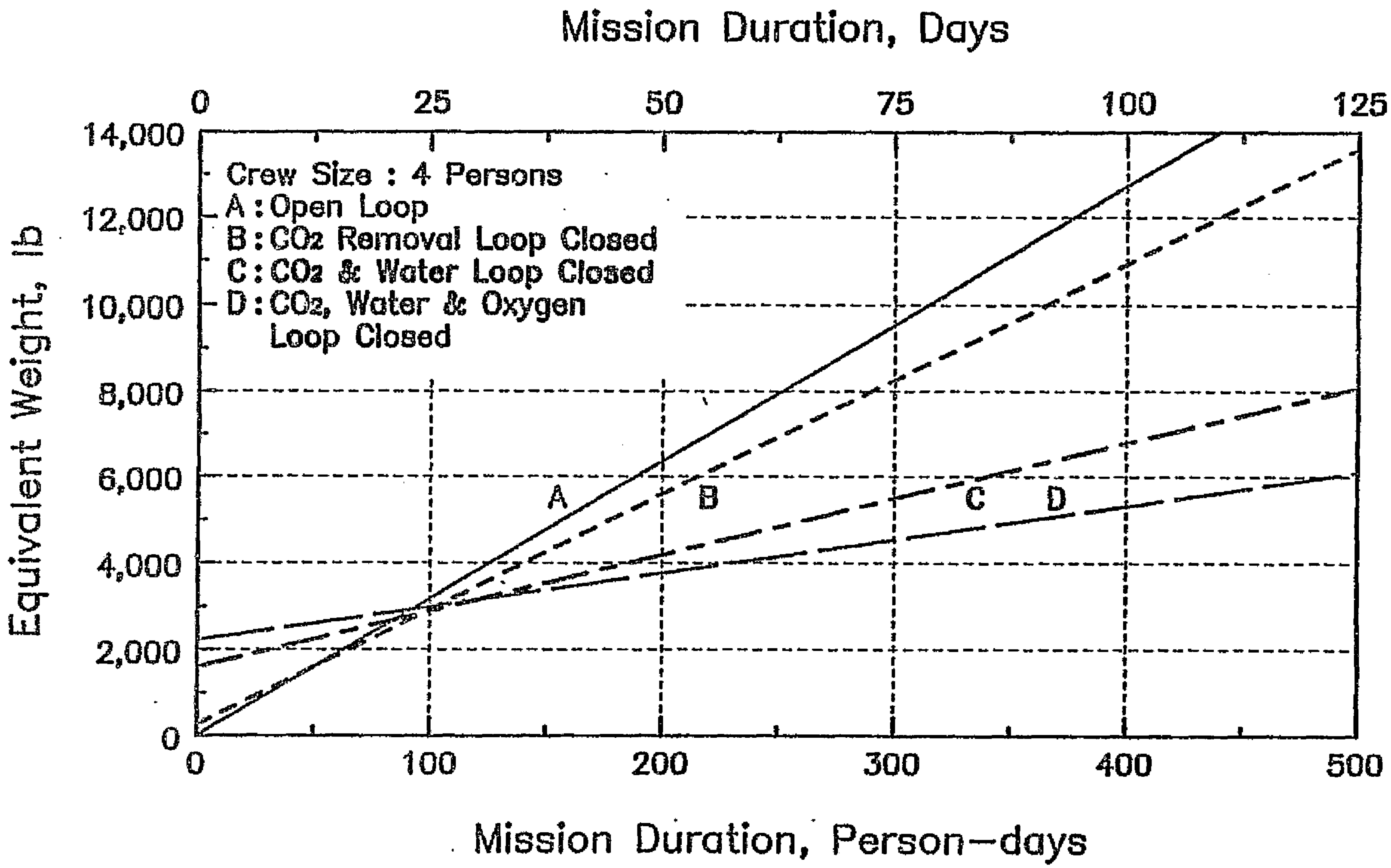

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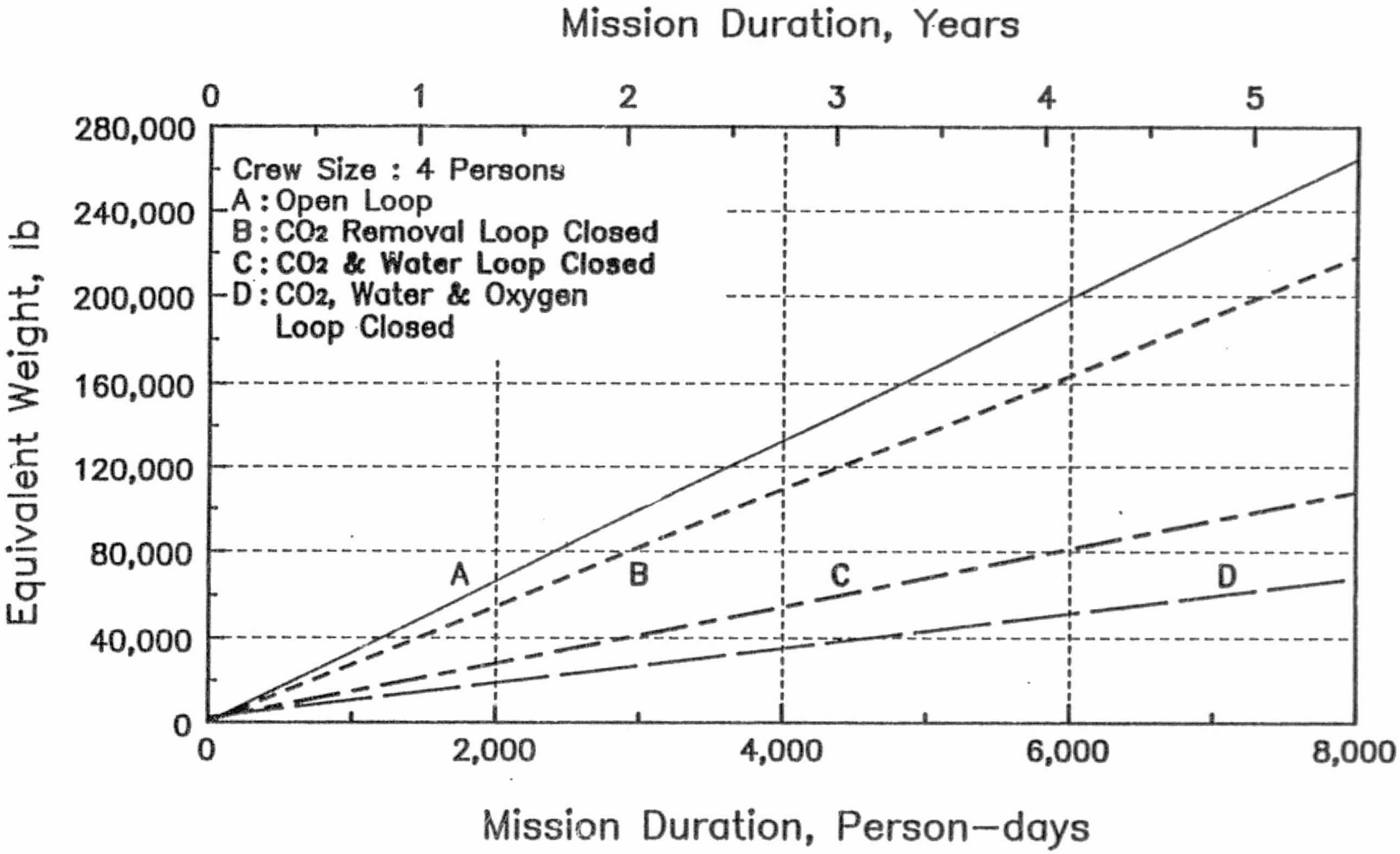
FIGURE 8

Regenerative vs Non-Regenerative ARS



Life Systems

SIZE OF MODULAR SPACE STATION

ELECTROCHEMICAL CO_2 CONCENTRATORS

Model No.	Capacity, People @ 3mm Hg	12mm Hg	Weight, Lb	Volume, Ft^3	Dimensions, In Ht	Wd	Ln	Power, W DC Out	AC In	Heat Load, W	No. of Cells	Expendibles, Lb/Day H_2	O_2
CS-1	1	2	50	1.6	13.4	15.5	13.5	10	50	114	6	0.12	0.95
CS-2	2	4	62	1.9	15.8	15.5	13.5	40	50	158	12	0.24	1.90
CS-3	3	6	74	2.2	18.2	15.5	13.5	70	50	201	18	0.36	2.84
CS-4	4	8	86	2.5	20.6	15.5	13.5	100	50	245	24	0.47	3.79
CS-6	6	12	110	3.1	25.4	15.5	13.5	160	80	364	36	0.72	5.69
CS-8	8	16	134	3.7	30.2	15.5	13.5	220	80	450	48	0.96	7.58
CS-12	12	24	182	4.8	39.8	15.5	13.5	340	80	626	72	1.44	11.58

a. Based on 2.20 lb CO_2/person-day and all sizes for the nominal partial CO_2 pressure of 3.0mm Hg.

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ATTACHMENT 2

SIZE OF MODULAR SPACE STATION

ELECTROCHEMICAL CO_2 CONCENTRATORS

Model No.	Capacity, People @ 3mm Hg	Capacity, People @ 12mm Hg	Weight, Lb	Volume, Ft³	Dimensions, In Ht	Dimensions, In Wd	Dimensions, In Ln	Power, W DC Out	Power, W AC In	Heat Load, W	No. of Cells	Expendibles, Lb/Day H_2	Expendibles, Lb/Day O_2
CS-1	1	2	50	1.6	13.4	15.5	13.5	10	50	114	6	0.12	0.95
CS-2	2	4	62	1.9	15.8	15.5	13.5	40	50	158	12	0.24	1.90
CS-3	3	6	74	2.2	18.2	15.5	13.5	70	50	201	18	0.36	2.84
CS-4	4	8	86	2.5	20.6	15.5	13.5	100	50	245	24	0.47	3.79
CS-6	6	12	110	3.1	25.4	15.5	13.5	160	80	364	36	0.72	5.69
CS-8	8	16	134	3.7	30.2	15.5	13.5	220	80	450	48	0.96	7.58
CS-12	12	24	182	4.8	39.8	15.5	13.5	340	80	626	72	1.44	11.58

a. Based on 2.20 lb CO_2/person-day and all sizes for the nominal partial CO_2 pressure of 3.0mm Hg.

ATTACHMENT 2

COMPARISON OF WATER ELECTROLYSIS SUBSYSTEMS FOR ECLSS AND ENERGY STORAGE

Characteristic	LSS	RFCS
Electrode Area, ft^2	0.1	1.0
Capacity, lb O_2/Hr	1.0	26.7
lb H_2O/Hr	1.1	30.0
Operating Conditions		
Temperature, F	180 (a)	180 (a)
Pressure, Psia	175	300
Current Density, ASF	150-200	150-300 (b)
Water Source	Reused, with Biocide	Fuel Cell, Potable/Distilled
Maintainability	Always was Planned	Not Inherent In Prior Approaches
Allowable Downtime	Days (c)	Short (Hours) (d)
Reliability	Thru Maintenance, Can be Down Longer	Thru Testing
Cyclic	Yes, but not essential	Yes, essential
Dew Point Product Gases, F	55	32
Dependence on Other Systems	CO_2 Reduction Cabin is O_2 Reservoir Power, Thermal	Fuel Cell Use Rate Power, Thermal
Significance to Propulsion	Small/None	Potentially Large
Open ECLSS	None Required	Still Required
Automation Aspects	Important, Multiple Subsystems Impacted	Less Important

(a) It may be difficult to reach the 180F because the Life Systems' water electrolysis electrodes have such low voltages (little inefficiencies) which are highly desirable.
(b) A specification requirement versus an equivalent weight tradeoff which indicates lower current densities are preferred.
(c) But with simultaneous loss of the concentrated, and with no H_2 available, unreacted CO_4 having to be vented overboard.
(d) Assumes no backup will exist to the primary energy storage function (RFCS).

APPROACHES TO MAINTAINABILITY

1. Overdesign hardware so less stress experienced during operation (derating).

2. Allow for performance degradation.

3. Incorporate redundancy, operating and/or nonoperating.

4. Provide for maintenance at:

   a. Line replaceable unit level (LRU)
   b. Line replaceable component level (i.e., part of a LRU)

5. Provide for accessibility, e.g., front only, front & back, etc.

6. Prepare clear definition of elemental activities of active repair time:

   a. Preparation for maintenance
   b. Verification of malfunction
   c. Fault location
   d. Replacement part acquisition
   e. Repair
   f. Final checkout malfunction repaired

7. Incorporate all the fault diagnostic levels into the computerized control/monitor instrumentation:

   a. Fault Avoidance
   b. Fault Prediction
   c. Fault Detection
   d. Fault Isolation
   e. Fault Correction
   f. Fault Tolerance

8. Complete FDIA (fault detection isolation analyses). Define.

9. Define fault detection methods.

10. Define fault isolation methods.

11. Establish for each component:

    a. Crew action required
    b. Tools required (code)
    c. Maintenance Time

       1. Scheduled/Servicing
       2. Unscheduled

d. Allowable downtime, hr

1. Available downtime

i Allowed delayed action
ii Probable isolation
iii Repair/replace

2. Recharge/Restart
3. Checkout
4. Return to specification

12. Establish spares needed

QUALITATIVE STATIC FEED WATER ELECTROLYSIS COMPARISON WITH ACID ELECTROLYTE (SPE)

LSI OXYGEN GENERATION SYSTEM DEVELOPMENTS

- From Water Electrolysis
- From CO_2 Electrolysis

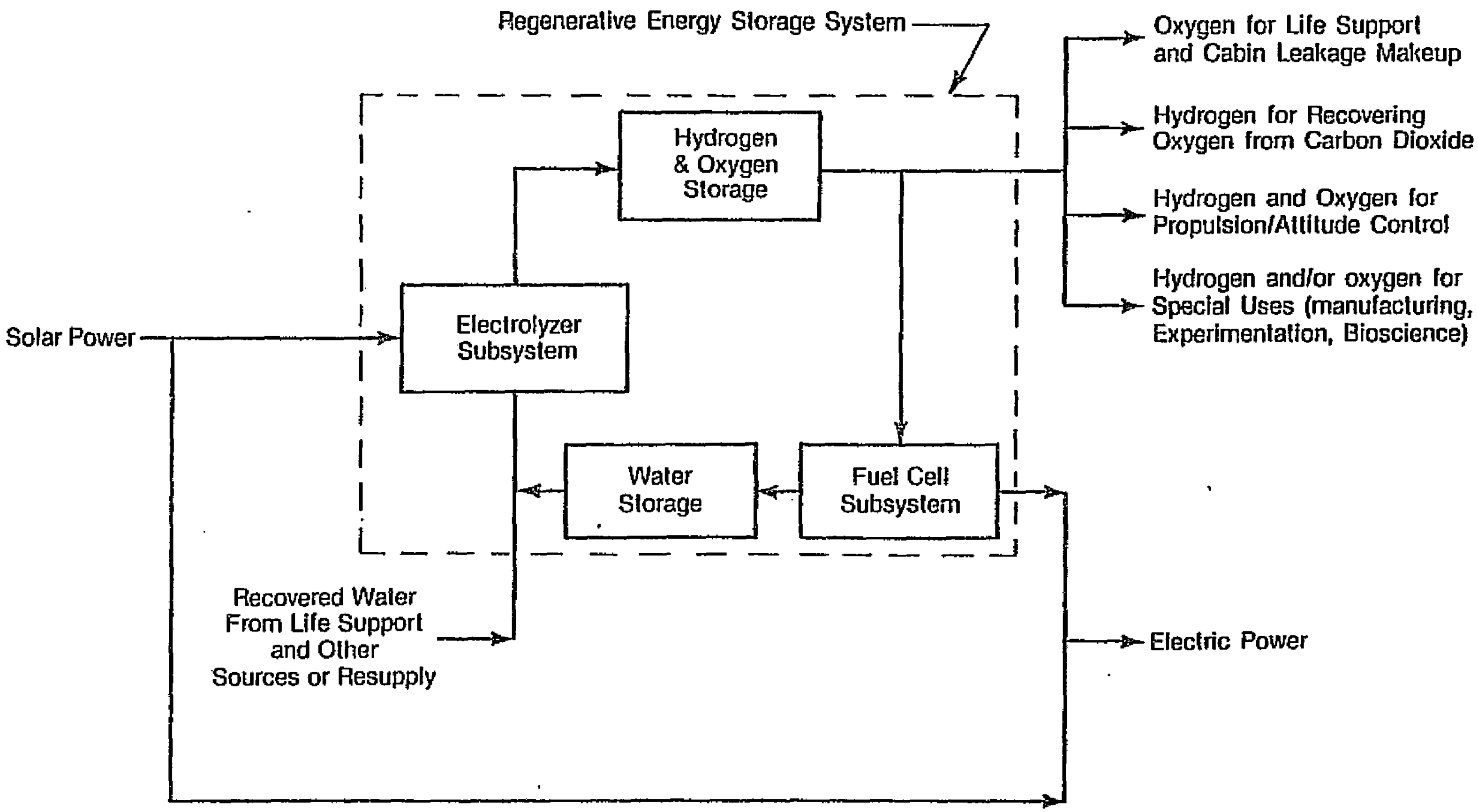
WATER ELECTROLYSIS APPROACHES

- Liquid Water Feed
- Water Vapor Feed

ELECTROLYSIS ELECTROLYTE APPROACHES

- Aqueous Alkaline
- Aqueous Acid
- Solid Oxide (High Temperature)

WATER ELECTROLYSIS—A SPACECRAFT UTILITY



SPACE WATER ELECTROLYSIS SYSTEM DESIGN GOALS

- Fail-Safe Operation
- Automated Computer Based Operation
- Unlimited Shelf Life
- System Life of > 20 Years
- Module Life of > 5 Years
- Zero Gravity Compatible
- Cyclic Operation (54 Min. On/36 Min. Off)
- Maintainable at —
  a. Line Replaceable Unit Level
  b. Line Replaceable Component Level

STARTING ASSUMPTIONS

- Safety, Reliability and Power are Critical Design Drivers
  - — Safety ∝ H_2 Volume, No. H_2 Connections, Operating Pressure, Pressure Differential Tolerance
  - — Power ∝ Cell Voltage, Current Efficiency, Parasitic Load
  - — Reliability ∝ No. Components, Type of Components (e.g., No. Rotating Ones), Materials of Construction, Quality of Engineering
  - — Useful Life ∝ Maintainability, Materials of Construction, Operating Temperature, Pressure, Current Density

- Water Electrolysis System Highest Power Consumer in Air Revitalization System

- Development and Flight Cost is proportional to Complexity

- Fewer Liquid Line Components Lowers:

  a. Weight
  b. Volume
  c. Cost
  d. Maintainability Needs

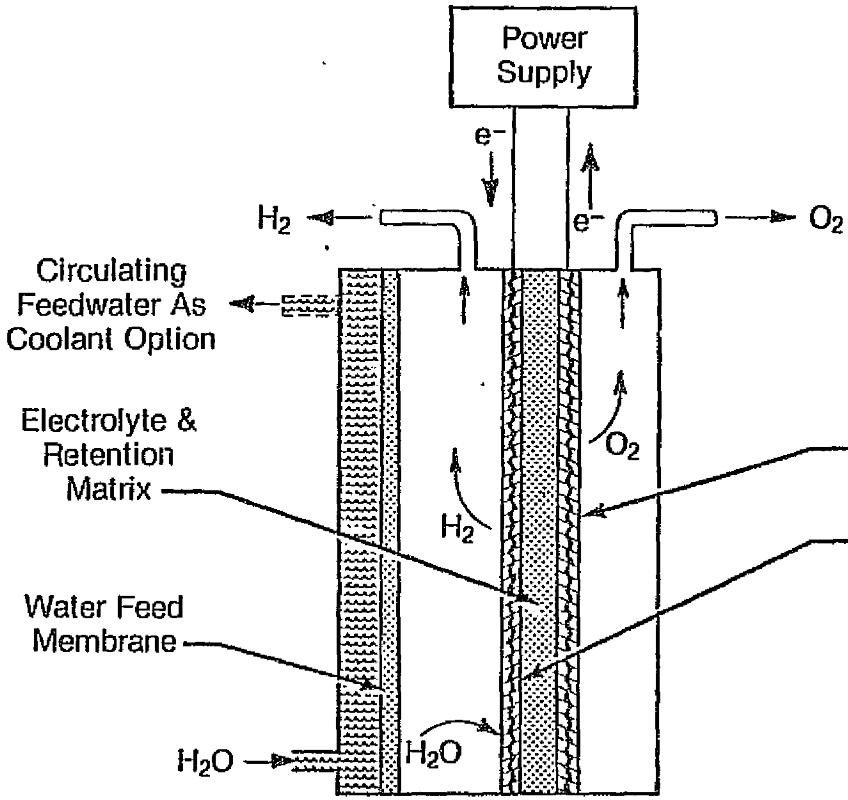
  and Increases:

  a. Reliability
  b. User Acceptance

STATIC FEED WATER ELECTROLYSIS CONCEPT

- Electrolyte Nature — Aqueous KOH
- Electrolyte Incorporation — Custom Made Porous Matrix
- Waste Heat Removal —
  a. Now: Circulating Coolant Water
  b. Future: Circulating Feed Water
  c. Future: None for ≤ 300 ASF
- Water Addition —
  a. To Module — Static Liquid
  b. To Cell — Vapor Distillation

ELECTROLYZER CELL SCHEMATIC AND REACTIONS



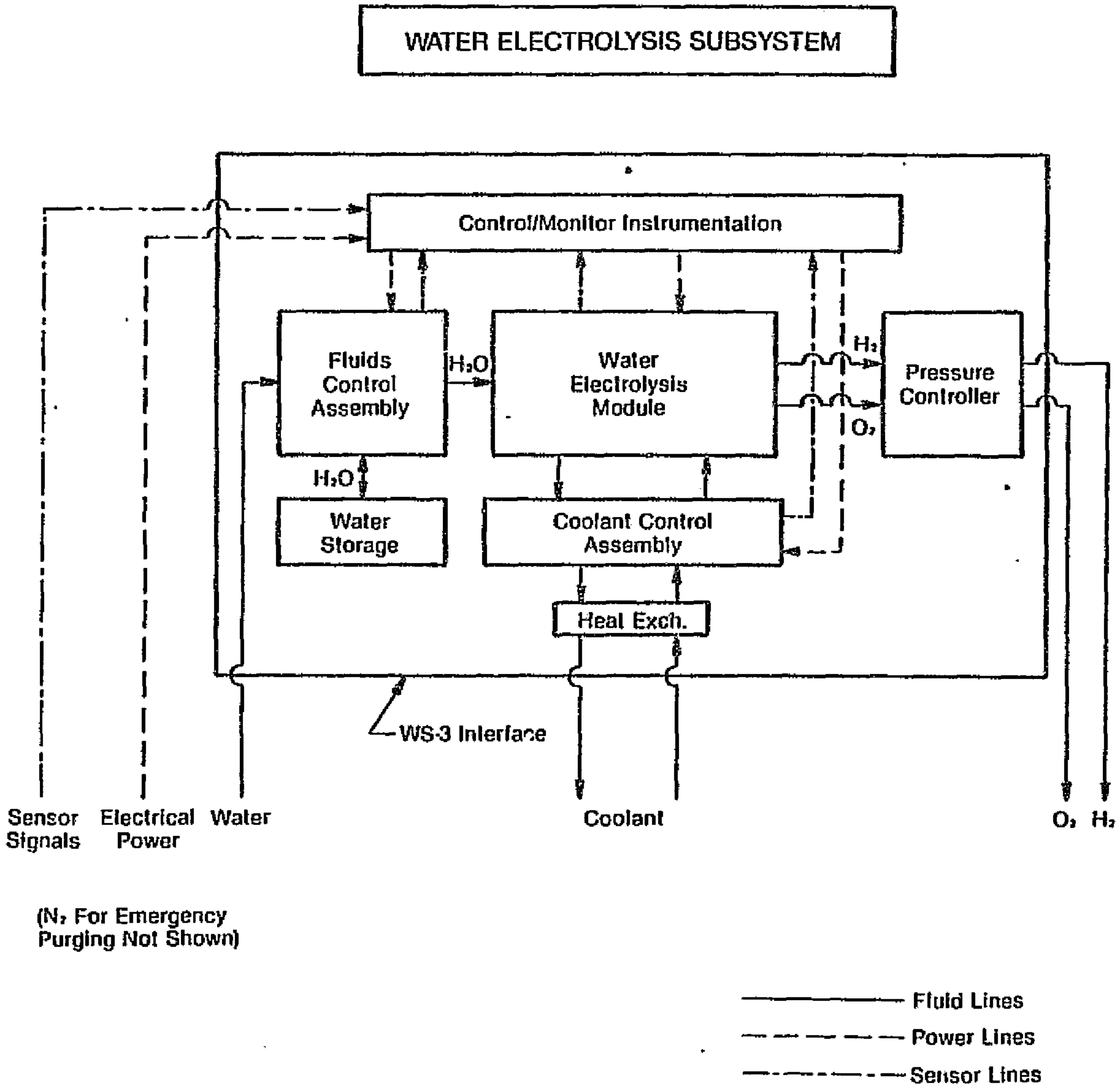
Reactions

Anode (+): $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

Cathode (-): $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

Overall: $2H_2O + \text{Power} \rightarrow 2H_2 + O_2$

WS-3 BLOCK DIAGRAM



(N_2 For Emergency Purging Not Shown)

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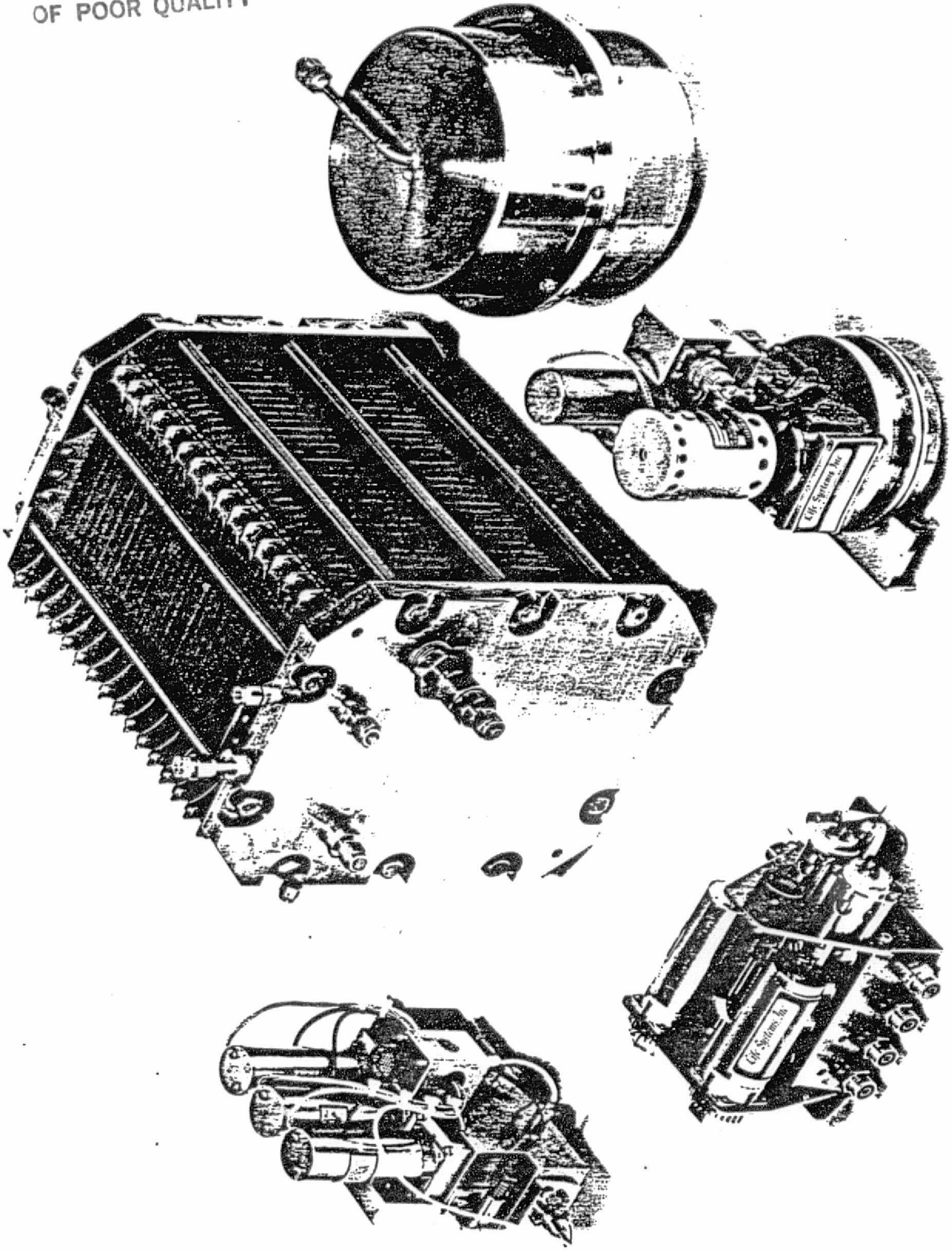
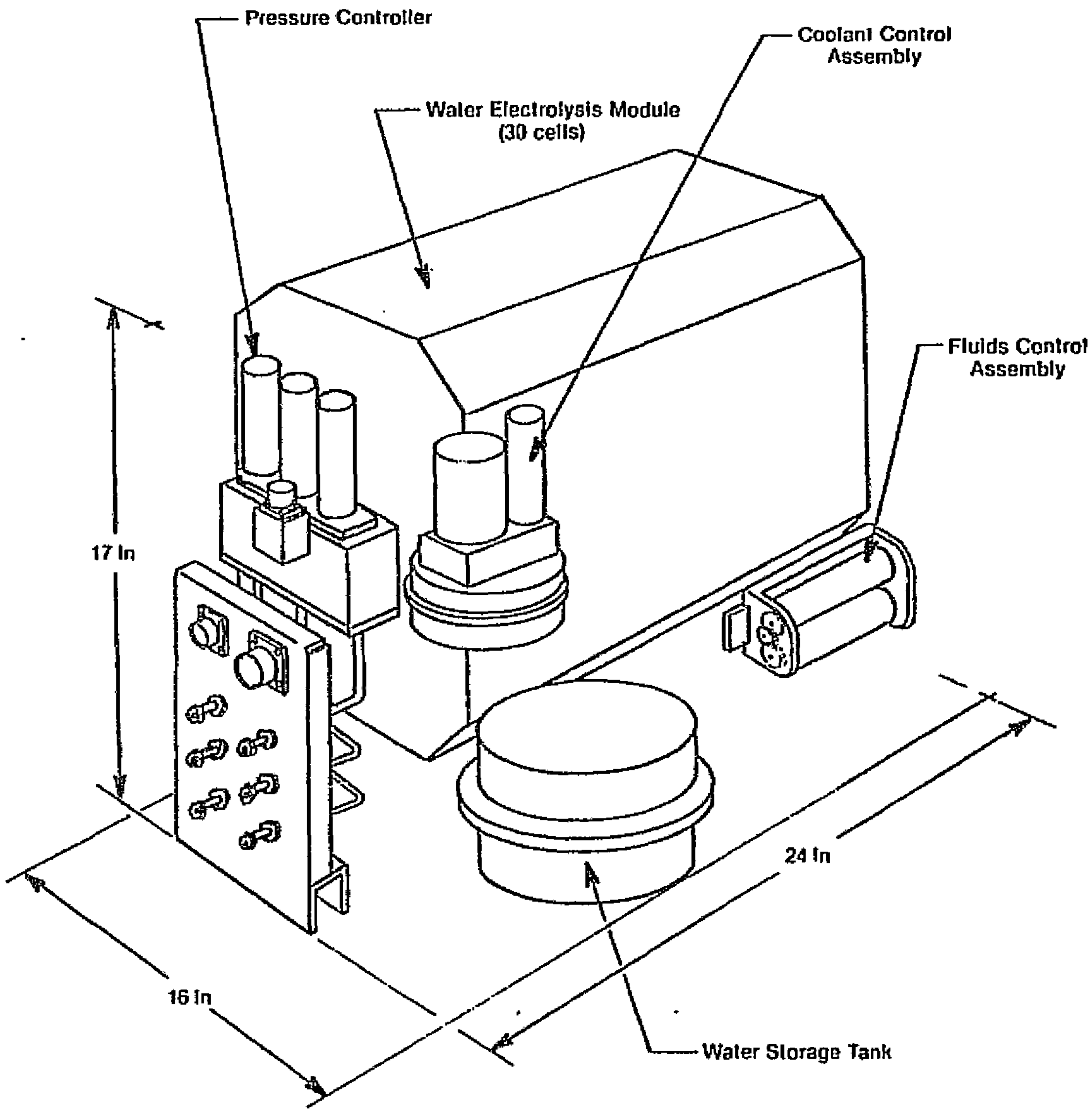
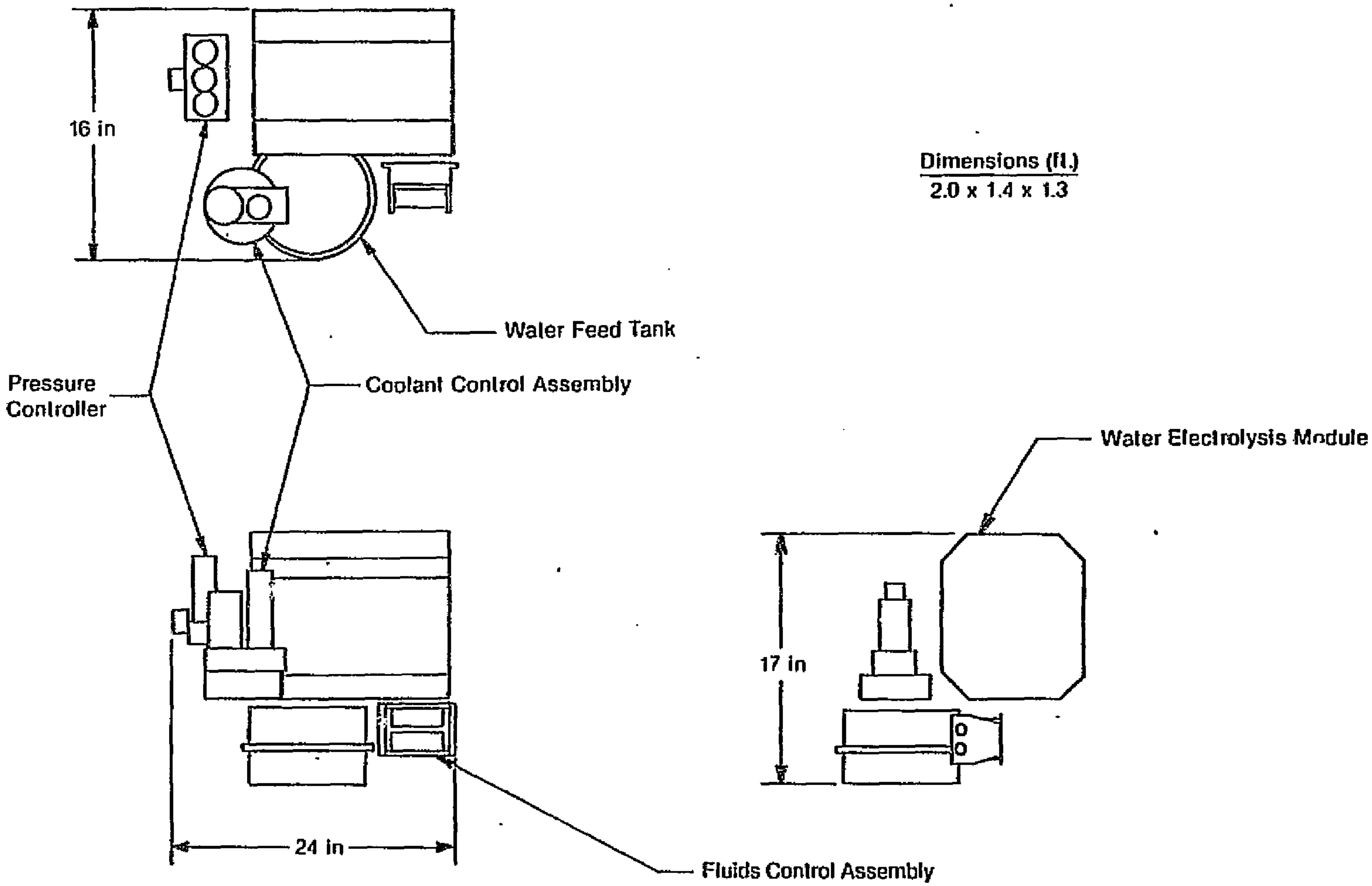


PREPROTOTYPE WATER ELECTROLYSIS SUBSYSTEM



ELECTROLYZER PACKAGING DIMENSIONS



Dimensions (ft.)
2.0 x 1.4 x 1.3

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ESTIMATED WS-3 MECHANICAL/ELECTROCHEMICAL PACKAGE CHARACTERISTICS (1982 Technology)

	Design
• H_2 Generation, lb/d	2.2
• O_2 Generation, lb/d	18.7
• Fixed Hardware Weight, lb	147
• Dimensions, ft	2.0 x 1.4 x 1.3
• Volume, cu ft	3.8
• Power, W[(a)]	
AC	70
DC[(b)]	1,720
• Heat Rejection, W[(b)]	238
• No. of 0.1 Sq. Ft. Cells	30

[(a)] Designed for 350ASF, 180 F, 185 to 300 psia and 1.64V (all poorest super electrodes) versus 1.57 (all best super electrodes, i.e., 1,640 watts).

[(b)] Includes 85% efficient Power Controller.

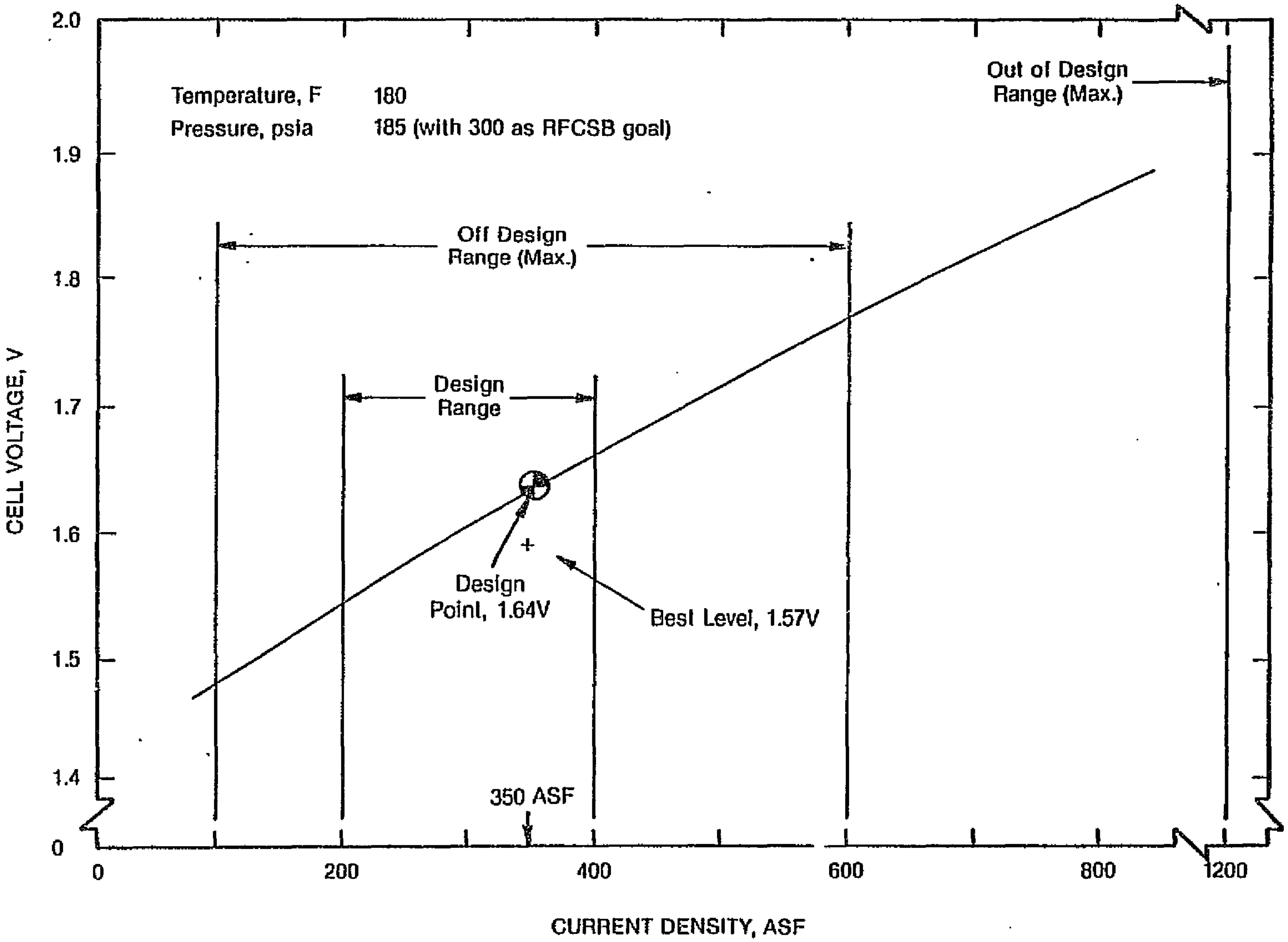
WS-3 MECHANICAL/ELECTROCHEMICAL COMPONENTS LIST (1982 TECHNOLOGY)

Part No.	Component	No. Req'd	Indiv. Wt., lb	Total Wt., lb	Indiv. Dimensions, in	Total Volume ft^3	Total Power, W[a]
1	SFWEM	1	93.7	93.7	10.5 x 13.0 x 15.0	1.185	1,722
2	Pressure Controller	1	10.7	10.7	2.8 x 7.0 x 7.0	0.079	(b)
3	Coolant Control Assembly	1	9.3	9.3	4.0 dia x 8.0	0.058	70
4	Fluid Control Assembly	1	8.8	8.8	4.8 x 3.0 x 3.5	0.029	(b)
5	Water Feed Tank	1	7.5	7.5	7.5 dia x 3.0	0.077	--
6	Heat Exchanger	1	1.5	1.5	0.6 dia x 8.0	0.001	--
7	Frame (Aluminum)	AR[c]	15.0	15.0	--	--	--

Total Weight, lb: 147
Total Power, kW: 1.79

(a) Sensor related power included in that for C/M I.
(b) Included in C/M I.
(c) As Required.

DESIGN PERFORMANCE CURVE: UPPER LEVEL SUPER ELECTRODES



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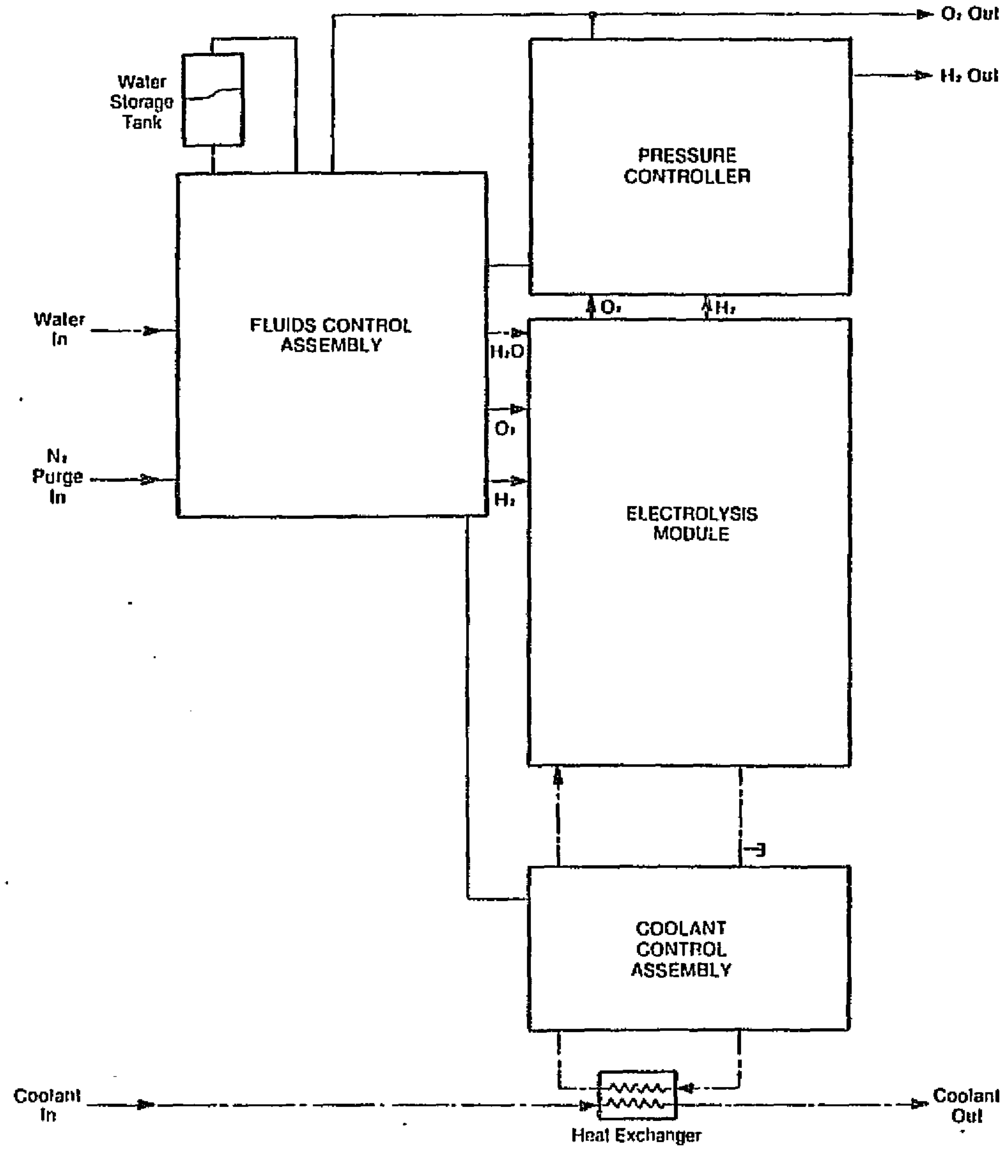
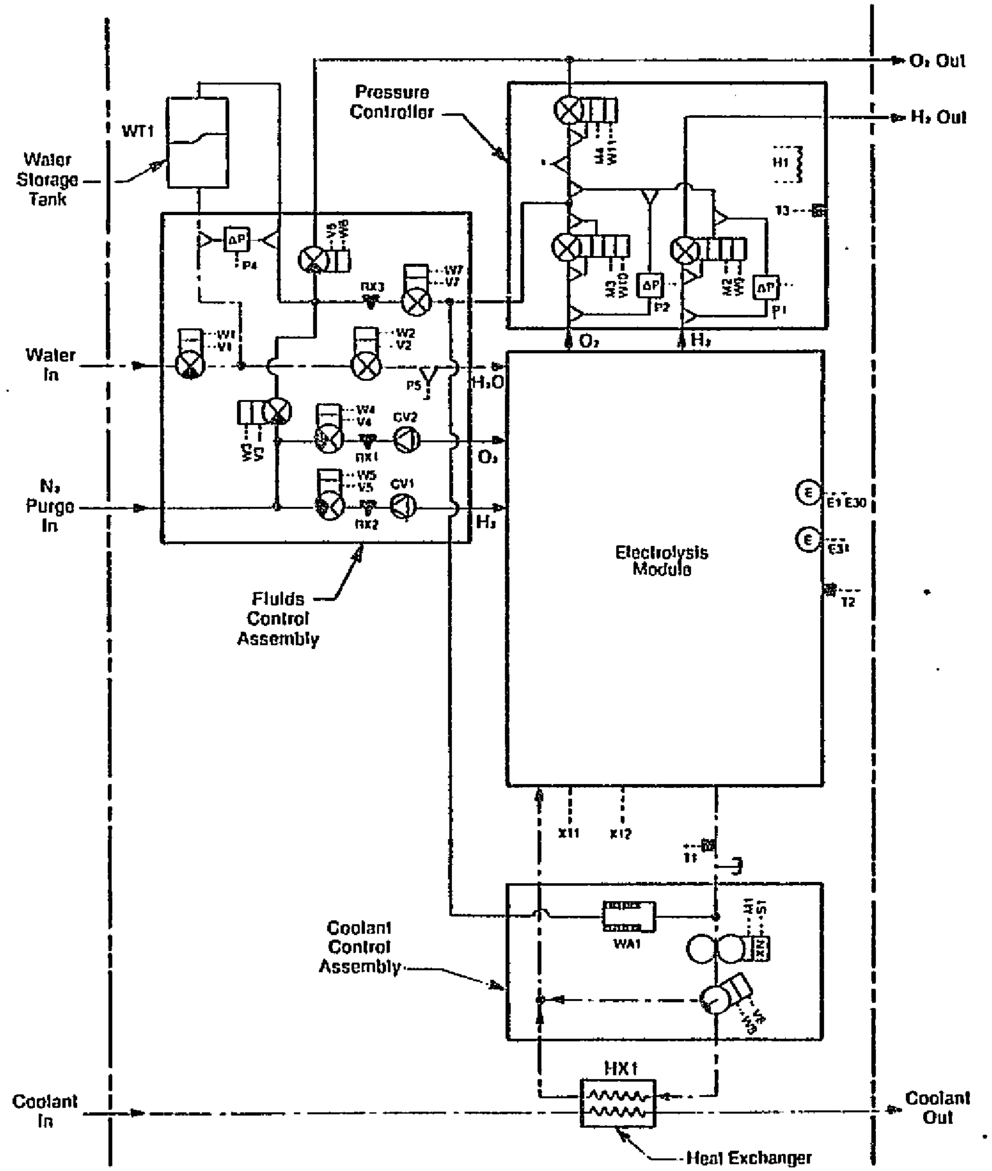
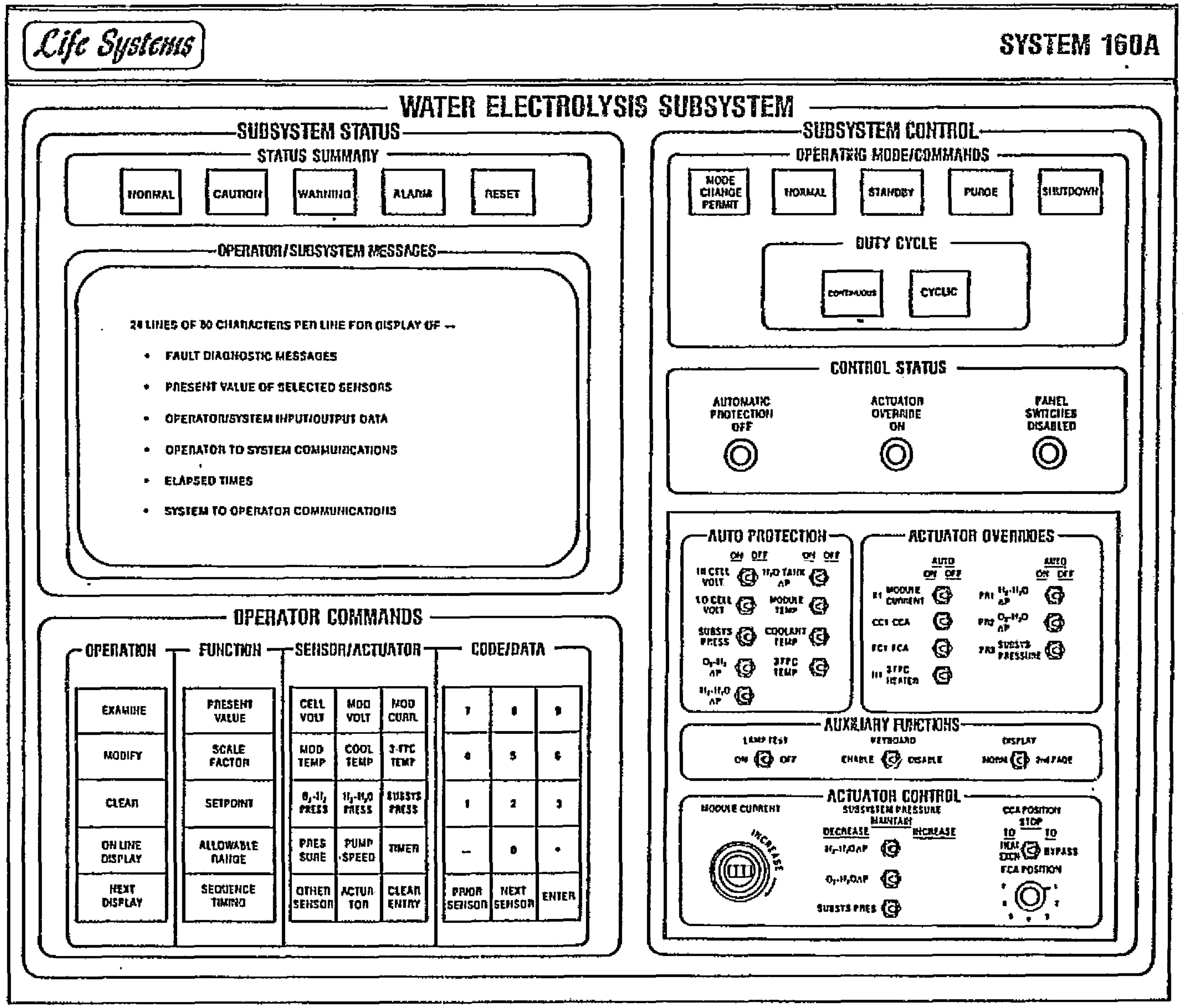
ELECTROLYZER MECHANICAL SCHEMATIC



DETAILED MECHANICAL SCHEMATIC WITH SENSORS



OPERATOR/SUBSYSTEM INTERFACE PANEL



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ADVANTAGES OF ACID ELECTROLYSIS SYSTEM

Operating Hardware

- Immobilized electrolyte — Water only bulk liquid
- 6 to 7 cells per inch possible — Only two compartments per cell

Operating Conditions

- Higher $H_2/0_2$ pressure differentials possible — But with loss of current efficiency as they increase
- Mass transport of water to electrolysis site not a function of pressure — But is of current density

Development Status

- Preprototype subsystem built (12 lb O_2/day)

LIMITATIONS OF THE ACID ELECTROLYSIS SYSTEM

Operating Hardware

- Complex Process Loops
  - — Recirculating H_2O passes thru 12 components requiring 20 liquid line disconnects (assuming 3 reliability = 1 heat exchanger) versus 3 items and 7 disconnects with SFWES
  - — H_2 product passes thru or to 7 components versus 1 with SFWES

- Dynamic Phase Separator Pump used for:
  a. H_2 from H_2O separation
  b. Recirculating feed water thru 7 components (3 heat exchangers)

- Recirculation requires continuous heating, cooling (to ambient temperature + 10 F) and reheating to maintain module at temperature

- Recirculating water loop continuously deionized to produce ultra-pure water to protect electrodes from electrode deactivating corrosive products — A scheduled maintenance/expendable requirement

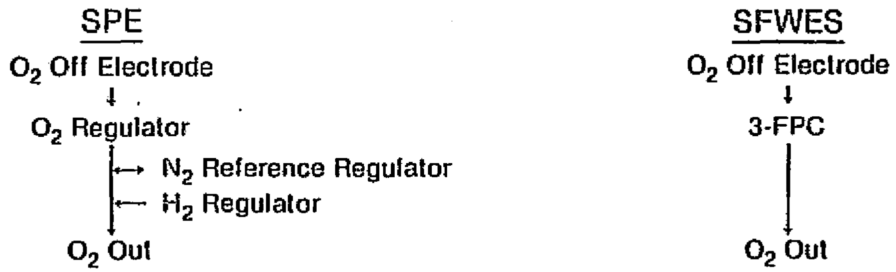
- Flammability of organic film separating H_2 and O_2 — A safety hazard

- H_2 Pressure Referenced Water Accumulator — A safety hazard and H_2 flow spikes occur when accumulator filled

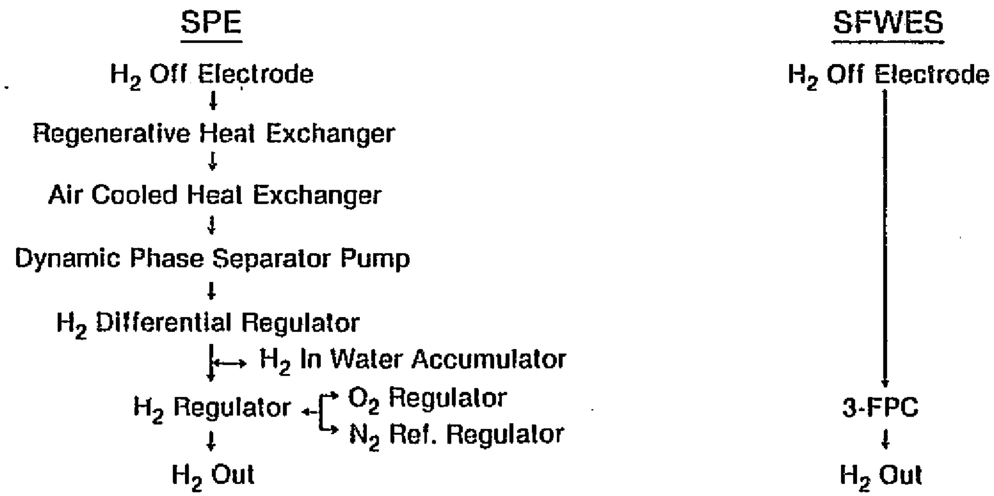
- H_2 and O_2 mix together in recirculating water so O_2/H_2 mixture sensors used in product gas lines to prevent hazardous mixture from forming

continued–

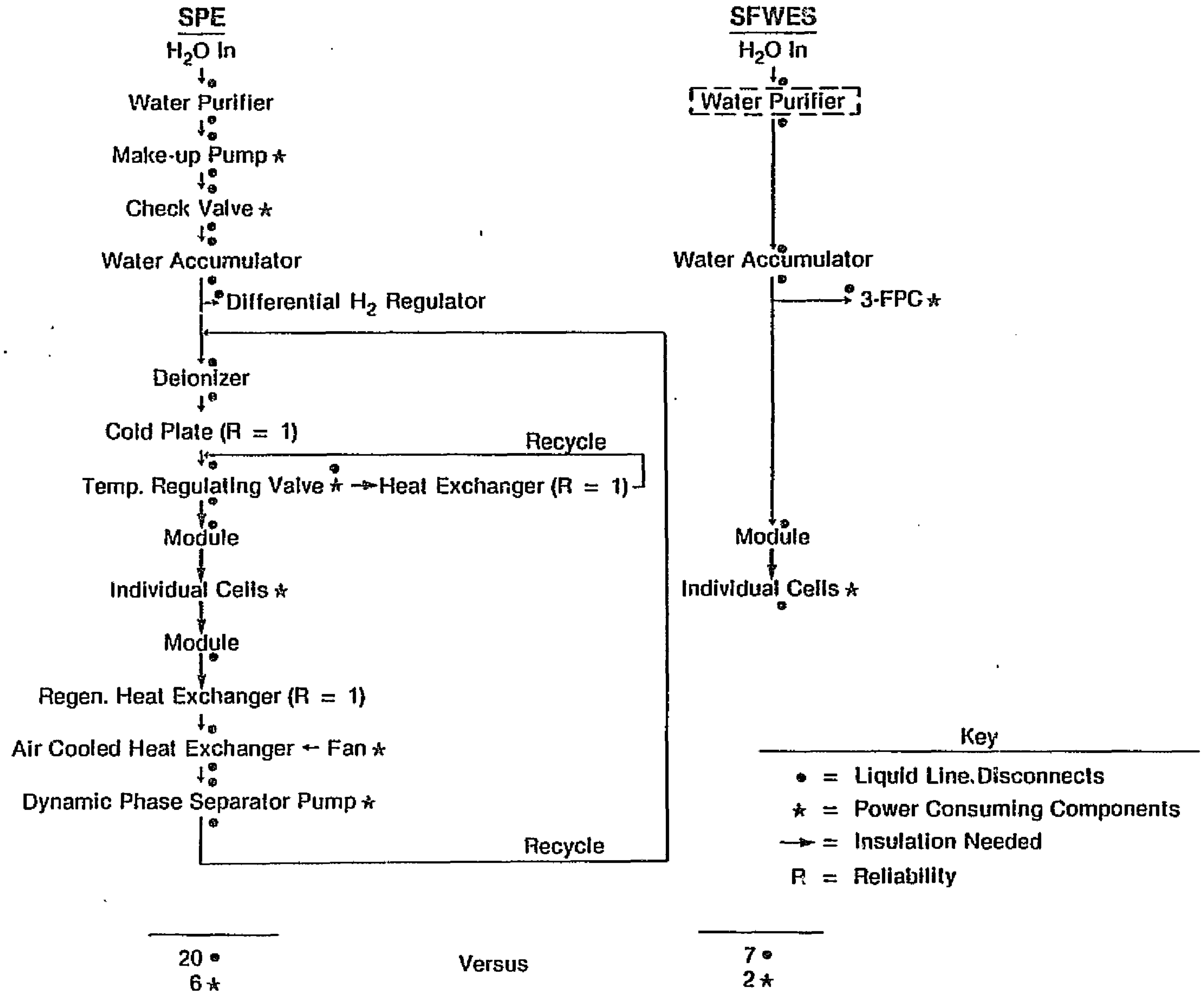
COMPARISON OF O_2 LINE COMPLEXITY



COMPARISON OF H_2 LINE COMPLEXITY



COMPARISON OF WATER LINE COMPLEXITY



LIMITATIONS OF THE ACID ELECTROLYSIS SYSTEM — *continued*

- Acidic electrolyte results in:
  - — O_2 evolving reaction limited kinetically (higher voltage needed)
  - — Expensive metallic components needed

Operating Conditions

- Raising operation temperature to increase voltage efficiency limited by inherent nature of organic polymer — Deformation and gas diffusion (problem increases at elevated pressures)[a]

- As pressure and pressure differentials increase current efficiency decreases[a]

- More water vapor must be condensed from product gases because acid electrolyte doesn't function as vapor pressure depressant

---

[a] 30% at 300 F, 1,000 psi and 5 mil Acid per developer.

ADVANTAGES OF STATIC FEED ELECTROLYSIS SYSTEM

Operating Hardware

- Feed water separated from cell electrodes so purity not critical and a failure mode eliminated

- Has lower system complexity — less components and less moving parts — Avoids:
  - Dynamic (gas from liquid) phase pump
  - Ultrapure (high capacity) deionizer
  - Feed water regenerative heat exchanger
  - Heating - cooling - reheating feed water
  - Has nonflammable, low cost asbestos matrices

Operating Conditions

- Lower system power than SPE
  - Lower cell voltage (1.5 vs. 1.6 V at 200 F, same temp. and pressure)
  - Lower auxiliary load (3 vs. 10% of total power)
  - Higher current efficiency (100 vs. 93% at 400 psia)
- Mass transport of product gases not obstructed by circulating water

Development Status

- Preprototype 1-person subsystem developed (2 lb O_2/day)
- Integrated into Air Revitalization System (4 lb O_2/day)

LIMITATIONS OF THE STATIC FEED ELECTROLYSIS SYSTEM

Operating Hardware.

- Bulk electrolyte in water feed compartments — Being eliminated
- Four compartment cell configuration limited to 3 cells per inch — But will be > 4 cells per inch when coolant/water feed combined

Operating Conditions

- Maximum current density a function of operating pressure — But 600 ASF, 600 psia, 180 F no problem and will be eliminated completely, with H_2O only in feed compartment

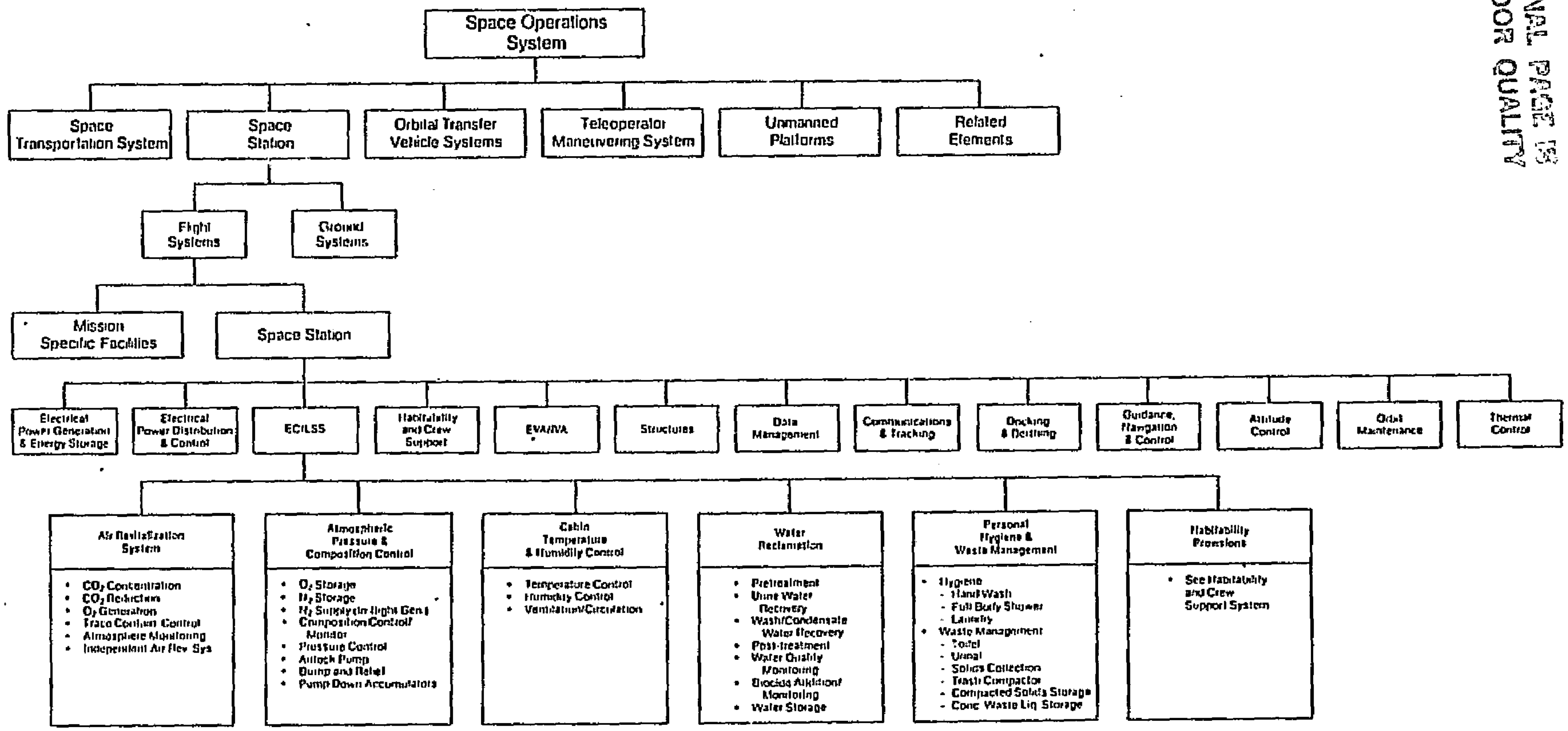
  Current long term asbestos matrix testing limited to < 200 F operating temperature — Project 400 F maximum

COMPARISON OF WES FEATURES[a]

	SFWES	SPWES
• Instant Startup	Yes	Yes[b]
• Avoids Intercell Electrolysis	Yes	Yes
• Avoids Electrolyte External to Module	Yes	Yes
• Able to Generate RFC Pressure (300 psia)	Yes	Yes
• Able to Operate Over Broad Range in Capacity		
a. 40 to 150%	Yes	Yes
b. 30 to 200%	Yes	Yes
• Avoids Biological Filter	Yes	Yes(?)
• Stability to Pressure Differentials		
a. > 10 psid	Yes	Yes
b. > 30 psid	Next	Yes
• Avoids Condenser/Separators	Yes	No
• Avoids Mechanical Pumps (Power, Noise, Reliability)	Yes	No
• Obtains 100% Current Efficiency	Yes	No
• Avoids Feed Water Contacting Electrodes	Yes	No
• Avoids Ultrapure Water Requirement	Yes	No
• Avoids Flammable Matrix	Yes	No
• Concentration of Electrolyte Fixed	No	Yes

[a]84th Intersociety Energy Conference Procedings, 8/73, p. 108.
[b]May require pump priming in zero gravity environment.

SOS AND SPACE STATION FUNCTIONAL BOUNDARIES



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ATTACHMENT 6

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ECLSS AND ECLSS RELATED SYSTEM FUNCTIONAL BOUNDARIES

Space Station

- Electrical Power Generation & Energy Storage
- Electrical Power Distribution & Control

EC/LSS

Air Revitalization System
- CO_2 Concentration
- CO_2 Reduction
- O_2 Generation
- Trace Contam. Control
- Atmosphere Monitoring
- Independent Air Rev. Sys.

Atmosphere Pressure & Composition Control
- O_2 Storage
- N_2 Storage
- N_2 Supply (In-flight Gener.)
- Composition Control/Monitor
- Pressure Control
- Airlock Pump
- Dump and Relief
- Pump Down Accumulators

Cabin Temperature & Humidity Control
- Temperature Control
- Humidity Control
- Ventilation/Circulation

Water Reclamation
- Pretreatment
- Water Recovery (Condensate, Hygiene, Urine)
- Post-treatment
- Biocide Addition/Monitoring
- Water Storage

Personal Hygiene & Waste Management
- Hygiene
  - Hand Wash
  - Full Body Shower
  - Laundry
- Waste Management
  - Toilet
  - Urinal
  - Solids Collection
  - Trash Compactor
  - Compacted Solids Storage
  - Conc. Waste Liq. Storage

Habitability and Crew Support

Habitability
- Emergency Equipment
- Bunks
- Housekeeping (e.g. Vacuum Cleaner)
- Lighting Fixtures
- Furnishings (e.g., Desk, Clothing)
- Exercise Equipment
- Recreational Equipment
- Acoustics

Crew Support
- Food/Beverages
- Food Provisions
- Galley
- Food Reconstitution Equipment
- Freezer
- Refrigerator/Chiller
- Oven
- Drinking Fountain
- Dish Washer/Dryer
- Scheduling
- Emergency Provisions and Planning
- Off-duty Activities
- Sleep
- Communications
- Man-Machine Interface

EVA/IVA

EVA
IVA/Portable Life Support System
Emergency Backup (O_2, H_2O, CO_2 Removal, Food)
Umbilical Life Support
LSS Recharger Regeneration

- Structures
- Data Management
- Communication & Tracking
- Docking & Berthing
- Guidance, Navigation & Control
- Attitude Control
- Orbit Maintenance
- Thermal Control

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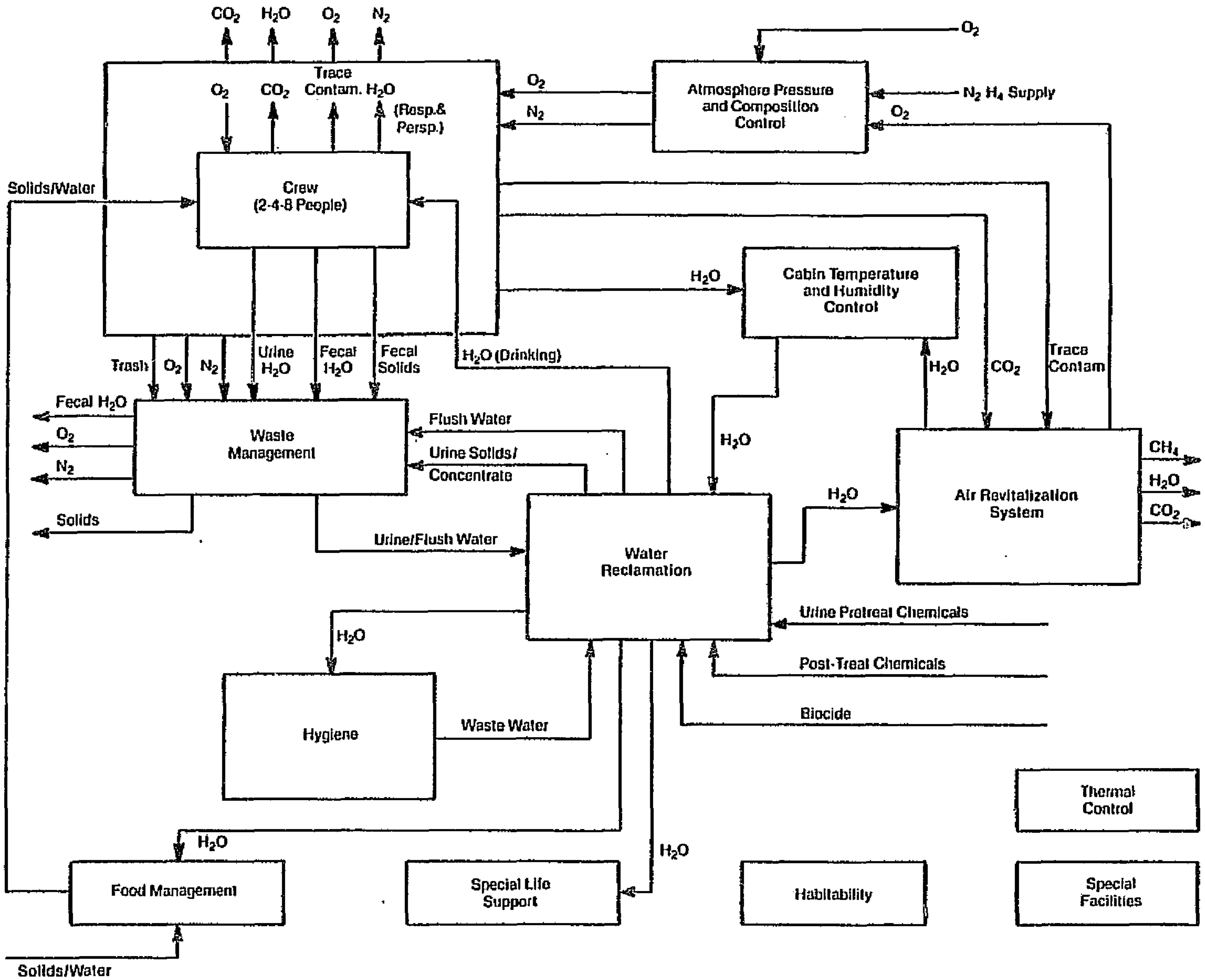
ATTACHMENT 7



SPACE STATION ECLSS BLOCK DIAGRAM

Life Systems, Inc.

ATTACHMENT 8

IMPACT OF MODULAR GROWTH

1. Location of equipment redundant (functions) and locations

2. Decreased vulnerability to single failure

3. Enhanced habitability provisions

    a. Increased available living volume/crew member
    b. Increase personal privacy
    c. Increase personal hygiene facilities
    d. Improved physical fitness/entertainment provisions
    e. Improved medical facilities
    f. Improved food selection and preparation methods

4. Decrease spare power capacity

5. Increased in flight experimental capabilities/facilities

6. Increased operational complexity

7. Greater station keeping penalties

8. Faster build-up of Space Station's contamination cloud

9. Allowance for incorporation of technology advancements

10. Initial penalty for growth provision scarring

11. Greater ratio of work hours to station operation hours increasing crew productivity

12. More EVA activity projected for larger crews and expanded mission capabilities

EC/LSS EQUIPMENT REDUNDANCY AND LOCATIONS

EC/LSS Function	Major Equipment	Number of Units Per Location Hab. 1	Hab. 2	SM 1	SM 2	LM	DM	Total Orig. & Modified Version[a]
Atmosphere Composition Control & Supply (Storage)	O_2 Storage	—	—	4	3	—	—	7
	N_2 Storage	—	—	1	6	—	—	7
	N_2 Supply (from N_2H_4)	—	—	1	1	(b)	—	2
	Pressure Control	1	1	1	1	—	—	4
	O_2/N_2 Composition Cont./Mont.	1	1	—	—	—	—	2
	Dump & Relief	1	1	1	1	—	—	4
	Airlock Pump	—	—	1	1	—	—	2
	Pump Down Accumulator	—	—	1	1	1	—	3
Cabin Heating, Air Conditioning and Ventilation	Temperature Heat Exchanger	4	4	2	2	—	—	10
	Dehumid. Heat Exchanger	2	2	1	—	—	—	5
	Ventilation Fan	4	4	2	2	—	2	12
Air Revitalization	CO_2 Removal	2	2	—	—	—	—	4
	CO_2 Reduction	2	2	—	—	—	—	4
	O_2 Supply	1	1	—	—	—	—	2
	Trace Contaminant Control[c]	2	2	—	—	—	—	4
	Atmosphere Monitoring	1	1	1	—	—	—	3
	Independent Air Revit. System[d]	—	—	1	1	—	—	2
Water Management	Waste Water Collection	1	1	1T[e]	—	—	—	3
	Waste Water Pretreatment[f]	1	1	—	—	—	—	2
	Urine/Final Water Recovery	2	2	—	—	—	—	4
	Water Post—Treatment	2	1	—	—	—	—	3
	Water Quality Monitoring	1	1	—	—	—	—	2
	Biocide Addition/Monitoring	1	1	1R	—	—	—	3
	Use-Point Biocide Monitor	2	2	1T	1	—	—	6
	Potable Water Storage	3	3	1R	—	—	—	7
	Reuse Water Storage	3	3	—	—	—	—	6
	Emergency Water Tanks	3T	—	1T	—	—	—	4
	Water Heater	1	1	—	—	—	—	2
	Water Chiller	1	1	1R	—	—	—	3
	Sterilized Water Supply	—	1	—	—	—	—	1

—*continued*

ATTACHMENT 10

TABLE 2 EC/LSS EQUIPMENT REDUNDANCY AND LOCATIONS — *continued*

EC/LSS Function	Major Equipment	Number of Units Per Location Hab. 1	Hab. 2	SM 1	SM 2	LM	DM	Total Orig. & Modified Version[a]
Waste Management	Toilet[g]	1	1	1B	—	—	—	3
	Urinal	1	1	1B	—	—	—	3
	Solids Collection Unit	1	1	—	—	—	—	2
	Trash Compactor	1T	1	—	—	—	—	2
	Concentrate Waste Water Storage	2	1	1T	—	1	—	5
Hygiene	Sponge Bath	1	1	1R	—	—	—	3
	Hand Wash	1	1	—	—	—	—	2
	Full Body Shower	1R(?)	1	—	—	—	—	2
	Laundry (Washer/Dryer)	1RT	1	—	—	—	—	1
Habitability	Emergency Equipment	1S	1S	1SM	—	—	—	3
	Bunk	1S	1S	1RS	—	—	—	3
	Housekeeping[h]	1S	1S	—	—	—	—	2
	Furnishings[i]	1S	1S	1S	1S	—	—	4
	Exercise Equipment	1R	1	—	—	—	—	2
	Recreational Equipment	—	1	—	—	—	—	1
Food Management	Food Galley	1R	1	—	—	—	—	2
	Food Reconstitution Equipment	1	1	—	—	—	—	2
	Freezer	—	1	—	—	1	—	
	Refrigerator/Chiller	1	1	—	—	—	—	2
	Oven	1	1	—	—	—	—	2
	Drinking Fountain	1	1	1R	—	—	—	3
	Dish Washer/Dryer	—	1	—	—	—	—	1
Dispensary	- Not included in discussion -							—
Thermal Control	Radiator[j]	2	2	—	—	—	—	4
	Water Coolant Recir. Pump[j]	2	2	—	—	—	—	4
	Freon Coolant Recir. Pump[j]	2	2	1	1	—	—	6
	Heat Exchanger	4	4	—	—	—	—	8
	Water Coolant Loop	(k)	(k)	(k)	(k)	—	(k)	—
	Cold Plate	10	10	26	26	—	—	72
	Interface Heat Exchanger	2	2	—	—	—	—	4

—*continued*

TABLE 2 EC/LSS EQUIPMENT REDUNDANCY AND LOCATIONS — *continued*

EC/LSS Function	Major Equipment	Number of Units Per Location						Total Orig. & Modified Version[a]
		Hab. 1	Hab. 2	SM 1	SM 2	LM	DM	
Instrumentation (Control & Monitoring)	Central Control	1	1M	—	—	—	—	2
	Central Fault Diagnostics	1	1M	—	—	—	—	2
	Distributed Controls	1S	1S	—	—	—	—	2
	Distributed Fault Diagnostics	1S	1S	1S	1S	1S	1S	6
	Operator/System Interfaces	1S	1S	—	—	—	—	2
	Fault Diagnostics Units	1S	1SM	—	—	—	—	2
Special Life Support	EVA Suits	3	3	—	—	—	—	6
	EVA Back Pack	3	3	—	—	—	—	3
	Portable Life Support	3	3	1T	1T	1	—	9
	EVA Water Storage Tank	—	—	—	22	—	22	
	EVA LSS Recharge	1	1R	—	—	1	—	3
	EVA LSS Regeneration	—	1	—	—	?	—	1
	Emergency Escape System	3	2	3T	—	—	—	8
	Backup Life Support (LiOH, O_2)	1R	—	—	—	15	—	16
Speciality Facility EC/LSS	- Not included in discussion -							—

(a) Including installed redundancy but not including space units or components.
(b) Liquid N_2H_4 storage in Logistics Module (LM).
(c) Including odor control and microbiological contaminations.
(d) Portable Independent Air Revitalization Unit; CO_2 removal, O_2 generation and partial water removal.
(e) Codes: B = Backup type; M = Modified version; R = Removal later; RT = Removal and transfer to Habitat No. 2; S = Set; T = Transferred to LM after operational; ? = Depends upon in-orbit timing of Habitat No. 1.
(f) Hygiene water, CO_2 reduction water, cabin condensate (not urine pretreatment unit).
(g) Including processing concentrated liquid waste from Urine/Final Water Recovery.
(h) For example, vacuum cleaner.
(i) Including clothing, desk, wall decor, etc., to make remote located home more enjoyable.
(j) Including associated control assembly.
(k) Both water coolant loops go through this location.

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EC/LSS OPTIONS FOR EVOLUTIONARY SPACE STATION FOR DIFFERENT POWER OPTIONS

Station Evolution/ Processes/Functions	Station Construction Phase: Fuel Cell (FC) or FC + Solar Array	Station Construction Phase: Batteries + Solar Array	Initial Capability: Fuel Cells + Solar Array	Initial Capability: Batteries + Solar Array	Full Capability[(a)]: Regenerative FC + Solar Array	Full Capability[(a)]: Batteries + Solar Array
Atmosphere Composition Control & Supply (Storage)	Cryogenic O_2, N_2 & H_2	Cryogenic O_2 & N_2	Cryogenic N_2, Electrolyzer O_2 & H_2	Cryogenic O_2 & N_2	Electrolyzer O_2 & H_2, N_2 from N_2H_4 Decomposi.	Same
Cabin Heating Air Conditioning & Ventilation	Shuttle technology Fans, Heat Exchanger & Condensing Heat Exchanger	Same	Same	Same	Same	Same
Air Revitalization	Regenerative CO_2 Removal and Reduction, O_2 Generation, Trace Contaminant Control, LiOH backup capability	Same	Same[(b)]	Same	Same or O_2 Generation Eliminated using Power System Electrolyzer, Independent ARS, LiOH eliminated	Same
Water Management	Potable & hygiene water from fuel cells[(c)]; Hot/cold water supply, drinking fountain	Potable & hygiene carried on-board at launch	Water (>50%) Recovery, Post-treatment, Water Quality Monitoring, Biocide Addition, No urine water[(c)]	Same plus capability to process urine[(c)]	Complete (98%) water recovery all sources[(c)]	Same but at larger capacity[(c)]
Waste Management	Shuttle technology Vacuum dried Fecal waste; Trash Compactor	Same	Same	Same	Same	Same

continued–

ATTACHMENT 11

Life Systems, Inc.

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Station Evolution/ Processes/Functions	Station Construction Phase		Initial Capability		Full Capability[(a)]	
	Fuel Cell (FC) or FC + Solar Array	Batteries + Solar Array	Fuel Cells + Solar Array	Batteries + Solar Array	Regenerative FC + Solar Array	Batteries + Solar Array
Hygiene	Sponge bath, hand wash, expendable clothing	Same	Same plus showers, laundry	Same but minimum water available for showers	Same plus dish washer	Same
Habitability	Emergency Equip., Exercise Equip., Furnishings, some house-keeping	Same	Same & balance of housekeeping items	Same	Same plus recreational equipment	Same
Food Management	Shuttle tech-nology	Same	Same + food galley oper-ational re-frigerator/ chiller, oven	Same	Same + freezer dish washer/ dryer	Same
Thermal Control	Radiators & freon loops external, cold plates, water loops internal	Same	Same	Same	Same	Same
Instrumentation (Control & Monitoring)	Distributed control & monitor	Same	Same plus central & local Fault Diagnostics	Same	Same	Same

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Station Evolution/ Processes/Functions	Station Construction Phase: Fuel Cell (FC) or FC + Solar Array	Station Construction Phase: Batteries + Solar Array	Initial Capability: Fuel Cells + Solar Array	Initial Capability: Batteries + Solar Array	Full Capability[a]: Regenerative FC + Solar Array	Full Capability[a]: Batteries + Solar Array
Special Life Support	Little EVA, mainly IVA, emergency O_2, CO_2 removal, food, water	Same	Same plus increased EVA, less IVA	Same	Same plus considerable EVA, regen. CO_2 removal	Same

(a) Increased redundancy and capacity and built-in over capacity.
(b) Capability for improved contamination control.
(c) Original storage capacity becomes emergency supply for other capabilities.

PRODUCTIVITY ANALYSIS EXAMPLE

Determine the Cost of the Nonregenerable CO_2 Removal Subsystem on the Orbiter.

Assumptions

1. Cost/Person-day in flight

$$\frac{40{,}000{,}000/\text{flight}}{(4 \text{ people})(7 \text{ days})} = \$1{,}430{,}000/\text{person-day}$$

2. Cost to change LiOH canisters

$$\frac{(0.5 \text{ hr})}{(\text{change})} \frac{(2 \text{ changes})}{(\text{day})} \frac{(7 \text{ days})}{(\text{mission})} \frac{(\$1{,}430{,}000)}{(\text{person-day})} \frac{(1 \text{ day})}{(24 \text{ hr})} = \$417{,}000/\text{Flight}$$

3. Cost of Canisters

$$\frac{(\$3{,}000 \text{ est.})}{(\text{canister})} \frac{(2 \text{ canisters})}{(\text{day})} \frac{(7 \text{ days})}{(\text{mission})} = \$42{,}000/\text{Flight}$$

4. Total Number of Orbiters

   Four

Results

Total Estimated Cost: \$460,000/Flight x 100 flights = \$46,000,000/Orbiter or
\$186,000,000/Fleet of Four