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TRADE STUDIES

JOHNSON SPACE CENTER
HOUSTON, TEXAS
77058

SPACE BIOLOGY

INITIATIVE

VOLUME I

EXECUTIVE SUMMARY

TRADE STUDIES

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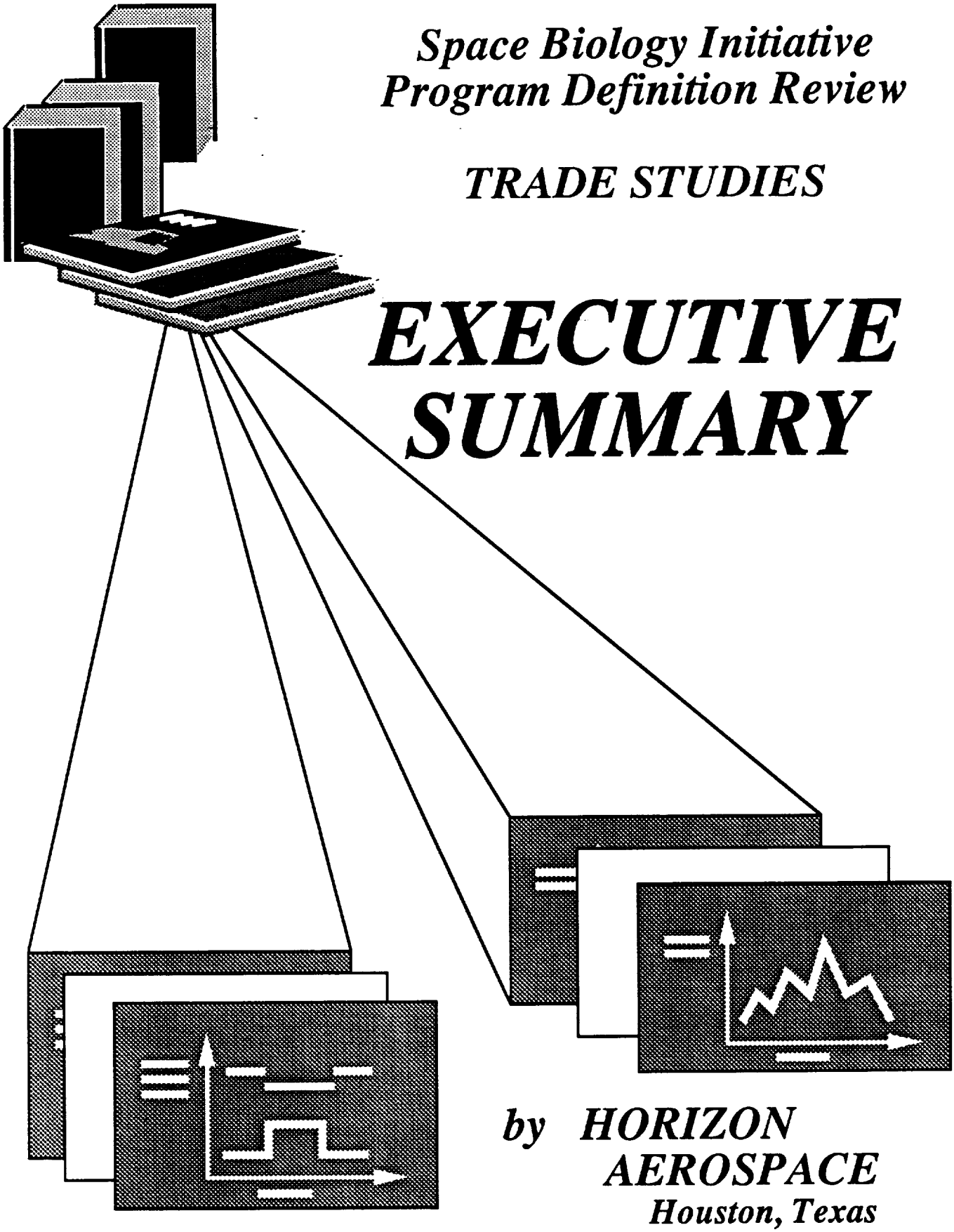
SPACE BIOLOGY

INITIATIVE

Space Biology Initiative
Program Definition Review

TRADE STUDIES

EXECUTIVE SUMMARY



by HORIZON AEROSPACE
Houston, Texas

EXECUTIVE
SUMMARY

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EXECUTIVE SUMMARY

1.0 INTRODUCTION

1.1 GENERAL

The expanding capabilities of the Space Transportation System and the Space Station Freedom will provide new opportunities for the exploration of biological and biomedical questions and problems that heretofore have been beyond the scope of man's capabilities. By building on past programs, the Space Biology Initiative (SBI) program will open new doors leading to a better understanding of problems that have plagued mankind since the beginning of time, and bring the solutions to these problems within reach.

1.2 STUDY IDENTITY

The six studies which are the subjects of this report are entitled:

- Design Modularity and Commonality
- Modification of Existing Hardware (COTS) vs. New Hardware Build Cost Analysis
- Automation Cost vs. Crew Utilization
- Hardware Miniaturization versus Cost
- Space Station Freedom / Spacelab Modules Compatibility vs.Cost
- Prototype Utilization In The Development of Space Hardware

1.3 STUDY PRODUCT

The product of these six studies was intended to provide a knowledge base and methodology that enables equipment produced for the Space Biology Initiative program to meet specific design and functional requirements in the most efficient and cost effective form consistent with overall mission integration parameters. Each study promulgates rules of thumb, formulas, and matrices that serves as a handbook for the use and guidance of designers and engineers in design, development, and procurement of SBI hardware and software.

TABLE 1.5-1 SBI HARDWARE CATAGORIES AND FUNCTION

CATAGORIES	FUNCTIONS
Cardiovascular	Analysis
Cytology	Calibration
Environmental Monitoring	Closed Ecological Life Support System (CELSS)
Exobiology	Collection
Hematology	Health Maintenance
Histology	Measurement
Logistics	Preparation
Miscellaneous	Storage
Neurophysiology	
Plant Sciences	
Pulmonary	
Surgical Science	
Urology	

Each of the six studies produced unique data and information according to the study subject, however there are objectives that are common to all six, i.e:

- Provide a historical cost and knowledge data base
- Develop statistical cost analysis methods
- Develop relative cost impacts

1.4 TECHNOLOGY ASSESSMENT

The study reports are technically related to the extent that technology assessment parameters can be established so that "apples to apples" comparisons between report subjects can be derived. However, it should be noted that the depth to which these comparisons could be carried was limited by the time and resources available for the subject studies. Further work to define and exploit the interaction between these studies is necessary. See

section 6.0, RECOMMENDATIONS, of this executive summary. To assist in developing this relationship, all SBI hardware items were classified as to system catagory, (cardiovascular, hematology, pulmonary, etc.), then further catagorized as to function, (analysis, collection, measurement, etc.). See Table 1.4-1.

1.5 REPORT CONTENT

The Final Report consists of this Executive Summary and six volumes, one for each study. This Executive Summary highlights the conclusions and recommendations for each of the six studies as contained in the Final Report, with emphasis on the items of commonality in the areas covered.

2.0 STUDY OBJECTIVES

2.1 DESIGN MODULARITY AND COMMONALITY

The objective of this study was to define the relative costs impacts (up or down) of developing Space Biology hardware using design modularity and commonality. Recommendations for how the hardware development should be accomplished to meet optimum design modularity requirements for Life Sciences investigation hardware was provided. In addition, this study defined the relative cost impacts of implementing commonality of hardware for all Space Biology hardware. Cost analysis and supporting recommendations for levels of modularity and commonality was presented. The study provided a statistical cost analysis method with the capability to support development of production design modularity and commonality impacts to parametric cost analysis.

2.2 MODIFICATION OF EXISTING HARDWARE VERSUS NEW HARDWARE

This study compared the relative costs of modifying existing commercial off-the-shelf (COTS) hardware to that of fabricating new hardware. The study surveyed and identified a historical basis for new build versus modifying COTS to meet current NMI specifications for Manned Space Flight hardware. This study also identified selected SBI hardware as potential candidates for off-the-shelf modification and provided statistical estimates on the relative cost of modifying COTS versus new build. See table 2.2-1. This table identifies the SBI items with the highest potential for "buy and modify" cost savings It estimates the percentage of redesign required and the potential savings realized therefrom.

Hardware Item #	Hardware Item Name	Mass (kg)	% Buy	% Mod to Buy	% OTS	Potential % Cost Savings
168	CELSS	1000	20	20	14	15
169	Gas Grain Simulator Facility	800	33	30	23	25
126	Scintillation Counter	90	95	30	67	71
74	Force Resistance System	70	95	25	71	72
145	Automated Microbic System	70	95	40	57	67
155	Total Hydrocarbon Analyzer	70	100	30	70	74
161	Inventory Control System	70	95	15	81	76
163	Test/Ckout/Calibration Instrumentation	70	50	20	40	39
106	Neck Baro-Cuff	45	95	30	66	71
61	Mass Spectrometer	41	70	35	45	51
147	Head Torso Phantom	32	3	35	2	2
63	Pulmonary Gas Cylinder Assem.	30	95	10	85	77
110	Plant Gas Chromatograph/Mass Spec	25	70	35	46	53
115	Chemistry System	23	50	30	35	38
138	Hematology	23	50	30	35	38
165	Experiment Control Computer System	20	80	30	56	60
82	Motion Analysis System	20	90	20	72	70
99	Animal Biotelemetry System	20	95	20	76	74
100	Blood Pressure & Flow Instrumentation	20	85	20	68	67
109	Venous Pressure Transducer/Display	20	85	20	68	67
57	Bag-in-Box	19	80	20	64	62
111	Plant Gas Cylinder Assem.	19	95	10	86	77
119	Gas Cylinder Assembly	19	95	10	86	77

TABLE 2.2-1 SBI HARDWARE MAKE-OR-BUY CANDIDATES

2.3 AUTOMATION VERSUS CREW UTILIZATION

This study developed the methodology, scoring mechanism, and rules of thumb that will form the basis of a handbook to aid the designer or hardware engineer in identifying functional elements of Life Sciences hardware that are good candidates for automation. It should also aid in determining when and to what realistic level automation should be incorporated in a specific SBI hardware unit. The designer should be able to assess the impacts of each level of automation on:

- Crew time utilization
- Equipment performance
- Crew training time
- Hardware diagnostics and maintenance
- Hardware repair
- Costs impacts of different levels of automation

In addition, the study also identified the advantages of automated hardware versus non-automated hardware designs.

2.4 HARDWARE MINIATURIZATION VERSUS COST

The objective of this study was to determine the optimum hardware miniaturization level with the lowest cost impact for Space Biology Initiative hardware. Space biology hardware and/or components, subassemblies, and assemblies which were the most likely candidates for application of miniaturization were defined and relative cost impacts of such miniaturization were analyzed. The study provided a statistical analysis method with the capability to support development of parametric cost analysis impacts for levels of production design miniaturization.

2.5 SPACE STATION FREEDOM/SPACELAB MODULE COMPATIBILITY

This study identified the differences in rack requirements for Spacelab, the Shuttle Orbiter, and the United States (US) Laboratory Module, European Space Agency (ESA) Columbus module, and the Japanese Experiment Module (JEM) of Space Station Freedom. The study also assessed the feasibility of designing standardized mechanical, structural, electrical, data, video, thermal, and fluid interfaces to allow space flight hardware designed for use in the US Laboratory Module to be used in other locations.

2.6 PROTOTYPE UTILIZATION

The objective of this study was to define the factors which space flight hardware developers and planners should consider when determining:

- Number of hardware units required to support program
- Design level of units
- Most efficent means of utilizing the units

The analysis considered technology risk, maintainability, reliability, and safety design requirements for achieving the delivery of highest quality flight hardware. Relative cost impacts of the utilization of prototyping were identified.

3.0. STUDY APPROACH AND METHODOLOGY

3.1 DATA BASE

It was necessary to establish a historical data base for each of the six subjects to be studied. Statistical and anecdotal data from previous programs, industrial experience, and "corporate memory" of experienced personnel form the basis of this knowledge base. Many recognized authorities were interviewed, and their opinions appear throughout the studies Many of these opinions are controversial. The reader should consider them as expert opinions, subject to interpretation. The studies are annotated to identify the authority quoted.

3.2 HARDWARE IDENTITY

The list of 90+ hardware items, (see Table 3.2-1), identified for the SBI program was too extensive and unwieldy to fit the study resources, therefore the list was filtered to produce a representative number of items. Some of the filters applied were:

- Mass
- Volume
- Power Consumption
- Scientific Merit
- Experience
- Judgement

BLL 3.2-1 LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

Baselined: December 1988

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
16	Animal Tissue Biopsy Equipment	S	0.03	8	0				A
17	Blood Collection System	S	0.02	1	0				J
22	Electrofusion Device	S	0.06	TBD	TBD				J
23	Fixation Unit	S	0.02	4	0				A*J
28	Muscle Biopsy Equipment	S	0.01	1	0				A
29	Perfusion & Fixation Unit	S	0.01	2	0				A
30	Plant Care Unit	S	0.05	10	50				A
31	Plant Harvest/Dissection Unit	S	0.01	4	20				A
33	Saliva Collection Unit	S	0.01	1	0	0.001	0.2	0	J
34	Sample Preparation Device	S	0.17	22	150				J*A
38	Sweat Collection Device	S	0.01	TBD	0	0.005	5.05	15	J
39	CO2 Administration Device	S	0.01	3	0				A
40	Rodent Blood Collection System	S	0.03	10	50				A
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S	0.01	2	50				A
42	Rodent Guillotine	S	0.01	4	0				A
43	Rodent Restraint	S	0.01	3	0				A
44	Rodent Surgery Platform	S	0.01	3	0				A
45	Rodent Surgery/Dissection Unit	S	0.01	3	0				A
46	Rodent Urine Collection System	S	0.03	10	50				A
47	Rodent Veterinary Unit	S	0.03	10	0				A
48	Primate Blood Collection System	S	0.05	2	140				A
49	Primate Handling Equipment	S	0.01	1	0				A
50	Primate LBNP Device	S	0.05	3	140				A
51	Primate Surgery Platform	S	0.04	5	0				A
52	Primate Surgery/Dissection Unit	S	0.02	5	0				A
53	Primate Urine Collection System	S	0.01	10	14				A
54	Primate Veterinary Unit	S	0.03	10	0				A
55	Small Primate Restraint	S	0.05	2	0				A
56	Bag Assembly	S	0.01	1	0				J
57	Bag-In-Box	S	0.15	19	0		-		J
59	Electronics Control Assembly	S	0.08	13	100				J
60	Mask/Regulator System	S	0.01	3	30				J
61	Mass Spectrometer	S	0.02	10	100	0.087	40.7	200	J
62	Pulmonary Function Equipment Stowage Assembly	S	0.39	20	0	0.051	20	0	J
63	Pulmonary Gas Cylinder Assembly	S	0.09	30	0				J
64	Rebreathing Assembly	S	0.02	1	0				J
65	Spirometry Assembly	S	0.01	1	0				J
66	Syringe (3 Liter Calibration)	S	0.01	2	0				J
67	Accelerometer And Recorder	S	0.04	16	35		16.06		J

A=ARC, J=JSC, *=Prime

Updated: 3/22/89

TABLE 3.2-1 LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

Baselined: December 1988

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS			UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP			RESP
			VOLUME (cu. m)	MASS (kg)	POWER (watts)	VOLUME (cu. m)	MASS (kg)	POWER (watts)	
68	Anthropometric Measurement System	S	0.02	TBD	0		1		J
70	Compliance Volumometer	S	0.06	TBD	TBD	0.0152	16	130	J
71	Electroencephalomagnetogram (EEMG)	S	0.06	TBD	TBD		2		J
74	Force Resistance System	S	0.40	70	100			220	J
75	Fundus Camera	S	0.03	TBD	TBD	0.003	2	Battery Op	J
77	Hard Tissue Imaging System	S	0.29	136	300				J
78	Mass Calibration Unit	S	0.01	2	0				J
82	Motion Analysis System	S	0.05	20	100				J
83	Plethysmograph Measuring System	S	0.01	3	30				J
84	Soft Tissue Imaging System	S	0.96	300	800				J
85	Tonometer	S	0.01	TBD	0	0.000226	0.06	Battery Op	J
87	EEG Cap	S	0.01	2	0				J
88	EEG Signal Conditioner	S	0.01	2	20				J
98	Visual Tracking System	S	0.01	2	20				J
99	Animal Biotelemetry System	S	0.05	20	100				A
100	Blood Pressure And Flow Instrumentation	S	0.06	20	200				AJ*
101	Cardiodynamic Monitor	S	0.02	4	150				J
102	Electrocardiograph (ECG)	S	0.01	2	20				J
103	Holter Recorder	S	0.01	2	0				J
106	Neck Baro-Cuff	S	0.10	TBD	TBD	0.132	45.2	145	J
109	Venous Pressure Transducer/Display	S	0.05	20	100				J
110	Plant Gas Chromatograph/Mass Spectrometer	S	0.20	25	100				A
111	Plant Gas Cylinder Assembly	S	0.09	19	0				A
112	Plant HPLC Ion Chromatograph	S	0.12	40	200				A
113	Blood Gas Analyzer	S	0.13	45	250				J
115	Chemistry System	S	0.08	23	100				J
116	Continuous Flow Electrophoresis Device	S	0.06	TBD	TBD				J
119	Gas Cylinder Assembly	S	0.09	19	0				J
124	Qualitative Reagent Strip And Reader	S	0.03	10	100		-		J
126	Scintillation Counter	S	0.24	90	500				J
129	Cell Handling Accessories	S	0.05	20	50				A*J
130	Cell Harvestor	S	0.06	19	50				A*J
131	Cell Perfusion Apparatus	S	0.06	TBD	TBD				AJ*
134	Centrifuge Hematocrit	S	0.01	2	20				AJ*
135	Chromosomal Slide Preparation Device	S	0.01	2	20				J
136	Fluoromeasure Probe	S	0.05	TBD	TBD				J
138	Hematology System	S	0.07	23	200				J
139	Image Digitizing System	S	0.25	70	500	0.03	11.4		J
142	Skin Window Device	S	0.01	2	0				J

Updated: 3/22/89

A-ARC, J-JSC, *-Prime

BLL 3.2-1 LIFE SCIENCES HARDWARE LIST R THE SPACE STATION FREEDOM ERA

Baselined: December 1988

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
145	Automated Microbic System	S	0.20	70	500	0.2	70	110	J
147	Head/Torso Phantom	S	0.12	TBD	0		32		J
149	Microbial Preparation System	S	0.01	2	20	0.01	2	110	J
151	Reuter Microbiology Air Sampler	S	0.01	1	0	0.005	1.45		AJ*
152	Solid Sorbent Air Sampler	S	0.01	5	0				J
153	Spectrometer (Proton/Heavy Ion)	S	0.03	10	20				J
154	Tissue Equivalent Proportional Counter	S	0.01	TBD	0	0.001	2	0	J
155	Total Hydrocarbon Analyzer	S	0.20	70	250				J
161	Inventory Control System	S	0.20	70	500				AJ*
162	Lab Materials Packaging & Handling Equipment	S	0.20	70	500				A*J
163	Test/Checkout/Calibration Instrumentation	S	0.20	70	200				AJ*
165	Experiment Control Computer System	S	0.05	20	400				J*A
167	Voice Recorder	S	0.01	1	0	0.003	0.26	Battery Op	J
168	CELSS Test Facility	S	1.92	1000	1300				A
169	Gas Grain Simulator	S	1.92	800	1500				A

A-ARC, J-JSC, *-Prime

3.3 HARDWARE CANDIDATE LIST

The "short list", (see Table 3.3-1), produced by the filter process was then subjected to the evaluation and analytical processes unique to Design Modularity and Commonality, Modification of Existing Hardware, Hardware Miniaturization, and Space Station Freedom / Spacelab Module Compatibility studies. The methodology used for the Prototype Utilization Study, and the Automation vs. Crew Utilization Study was more generic in nature, and did not require analysis of specific, identified SBI hardware.

3.4 COST ASSESSMENT TECHNIQUES

The cost assessment techniques used in these studies should be noted. The cost related task in these trade studies was to develop and provide data on factors which assist the cost estimators in using tools to develop the effect of the trade study speciality area on SBI estimates. The life cycle costs would be most important in judging the long term benefits of a new project. However, consideration of life cycle costs requires knowledge of the probable project life, operational use time lines, maintenance concepts, and logistics relationships. These data were not available at the time of these initial trade studies. Therefore, the trade studies addressed primarily the relative cost impact analysis of the design and development phase of the SBI. Life cycle costs were dealt with on a comparative, subjective basis in order to illustrate the influence of life cycle cost factors on the various trade study subjects.

See Table 3.4-1..This table makes an assessment of the life cycle cost drivers on each of the six studies, and evaluates the overall life cycle cost impact.

3.5 COST ESTIMATING RELATIONSHIPS (CER)

No attempt was made to estimate hard dollar cost, or to arrive at a rough order of magnitude figure for any specific hardware item. Instead, cost estimating relationships (CERs) and cost impact analysis methods were used. CERs are empirical formulas that express expected costs on the basis of past program experience, based primarily on system weight, and modified by subjective application of factors of system complexity, design factor, and constants derived from previous program experience. CERs have proven their usefulness in many previous programs, but caution must be exercised when they are applied to relatively lightweight hardware. When a CER-derived number appears to be outrageous, it probably is. Cost impact analysis methods were based on parametric studies to establish and/or quantify cost drivers and cost trend effects.

Item Priorities by Mass	Hardware Item #	Hardware Item Name	Mass		Power		Volume	
			Kg	Accumul.	(Watts)	Accumul.	M³	Accumul.
1	168	CELSS	1000	1000	1300	1300	1.92	1.92
2	169	Gas Grain Simulator	800	1800	1500	2800	1.92	3.84
3	84	Soft Tissue Imaging System	300	2100	800	3600	.96	4.80
4	77	Hard Tissue Imaging System	136	2236	300	3900	.29	5.09
5	126	Scintillation Counter	90	2326	500	4400	.24	5.33
6	74	Force Resistance System	70	2396	100	4500	.40	5.73
7	145	Automated Microbic System	70	2466	110	4610	.20	5.93
8	155	Total Hydrocarbon Analyzer	70	2536	250	4860	.20	6.13
9	161	Inventory Control System	70	2606	500	5360	.20	6.33
10	162	Lab Materials Pack & Hand. Equip.	70	2676	500	5860	.20	6.53
11	163	Test/Ckout/Calibration Instrumentation	70	2746	200	5860	.20	6.73
12	106	Neck Baro-Cuff	45	2791	145	6205	.13	6.86
13	113	Blood Gas Analyzer	45	2836	250	6455	.13	6.99
14	61	Mass Spectrometer	41	2897	200	6655	.09	7.08
15	112	Plant HPLC Ion Chromatograph	40	2917	200	6855	.12	7.2
16	147	Head Torso Phantom	32	2949	0	6855	.12	7.32
17	63	Pulmonary Gas Cylinder Assem.	30	2979	0	6855	.09	7.41
18	110	Plant Gas Chromatograph/Mass Spectrometer	25	3004	100	6955	.20	7.61
19	115	Chemistry System	23	3027	100	7055	.08	7.69
20	138	Hematology	23	3050	200	7255	.07	7.76
21	34	Sample Preparation Device	22	3072	150	7405	.17	7.93
22	165	Experiment Control Computer System	20	3092	400	7805	.05	7.98
23	62	Pulmonary Function Equip Stor. Assem.	20	3112	0	7805	.05	8.03
24	82	Motion Analysis System	20	3132	100	7905	.05	8.08
25	99	Animal Biotelemetry System	20	3152	100	8005	.05	8.13
26	100	Blood Pressure & Flow Instrumentation	20	3172	200	8205	.06	8.19
27	109	Venous Pressure Transducer/Display	20	3192	100	8305	.05	8.24
28	129	Cell Handling Accessories	20	3212	50	8355	.05	8.29
29	57	Bag-in-Box	19	3231	0	8355	.15	8.44
30	111	Plant Gas Cylinder Assem.	19	3250	0	8355	.09	8.53
31	119	Gas Cylinder Assembly	19	3269	50	8405	.09	8.62
32	130	Cell Harvester	19	3288	50	8455	.06	8.68

93 SBI H/W Items 89 Items have 3535 kg mass 10.0M³ of volume 10,359 watts of power 4 Items are TBD (all are small)

TABLE 3.3-1 SPACE BIOLOGY INITIATIVE SHORT LIST

PHASE \ STUDY	STUDY 1 Automation vs. Crew Utilization	STUDY 2 Prototype Utilization	STUDY 3 Hardware Miniaturization	STUDY 4 Modularity & Commonality	STUDY 5 COTS vs. New Hardware	STUDY 6 SL/SSF Compatibility
DESIGN	Most effective if incorporated in the initial effort. Cost increases with automation level, complexity factor.	Facilitates design effort, iterates design at low cost level, reduces cost of complex designs.	Design change always required. cost of redesign may be partially offset by size & weight reduction.	Requires programmatic support and some allowance for increased weight and cost in design phase.	Dependent upon availability and suitability of commercial modules and/or elements for SBI system application.	Requires inter-program coordination/communication and direction which is very difficult to achieve.
DEVELOPMENT	Modularity/commonality will help contain cost, expedite fabrication.	Speeds development process, verifies interface requirements, provides low cost development, verification and engineering units.	Fabrication may be complicated due to size reduction.	Development, manufacture or procurement is facilitated by modularity. Commonality cost impacts all positive.	Modified COTS appears to have significant potential advantage. Requires sound make or buy analysis and evaluation.	Common source would be highly desirable but will be hard to achieve due to specification differences and organizational barriers.
TEST & EVALUATION	Test costs are high due to reliability requirements, electronics complexity.	Provides low cost unit for test, allows testing beyond operating requirements and design limits.	Test costs may increase due to difficulty in set-up and trouble shooting.	Module testing, integrated testing and test trouble shooting are simplified and cost savings result.	Testing impact appears to be negative due to need for extra qualification tests and periodic retest (screening).	Should have only minor impact which stems from differences in test requirements.
SUSTAINING ENGINEERING	Vendor support required, otherwise minimal impact.	No impact.	No significant impact pro or con is apparent.	Individual engineering groups can operate with less systems integration effort.	Should be automatically supported by vendor's program. Generally positive. Modifications could pose problems.	Responsibility may be difficult to establish and to identify. Problem potential is small due to type of hardware.
TECHNOLOGY UPGRADE	Facilitates routine module replacement.	Simplifies proofing and configuration control processes.	May be less likely due to absence of alternate hardware availability	Facilitated and made easier by modular design.	Not predictable. Experience indicates that it can vary from easy to painful and awkward.	Should be possible within a rack or module. Compatibility will reduce the overall cost of inserting new technology upgrades.
MAINTENANCE & OPERATIONS	Complexity may add to maintenance costs, operations burden reduced or eliminated.	High reliability, inherent in iterated design, should reduce maintenance requirements and improve operations reliability.	Possible adverse impact on maintenance due to small size. Operation should not be affected.	Common module impacts on maintenance, logistics and operations are all positive and highly significant	Maintenance of unmodified portion could pose problem. Operation not affected if reliability is adequate.	Design for long life should mean small scale preventative maintenance is all that is required.
REPLACEMENT	No impact.	No impact.	May be less costly due to size and favorable impact on logistics.	Can be accomplished in planned phases and/or steps with minimum disruption to system operation.	COTS use suggests that low cost replacements are available. Advantage can erode with age.	Standard interfaces can only work to reduce the cost of replacement. Fewer spares, standard procedures, etc..
OVERALL LIFE CYCLE COST IMPACT	Will increase design and development costs, reduce crew involvement, operations and training costs, increase equipment efficiency and data fidelity.	Most cost savings realized in design/development phases. Can shorten procurement process, enhance confidence level. No negative impact downstream.	Tends to look negative. The need to miniaturize must be based upon reasons other than cost savings in development.	Life cycle cost impacts are all highly favorable except for design phase coordination and possible weight penalties.	Very significant life cycle cost advantage inherent in COTS. However, initial selection and mod program must be prudent.	Whatever the cost of inter-program coordination, ICD's etc., the impact on overall NASA cost is very beneficial.

Table 3.4-1 Life Cycle Costs

4.0 PARAMETERS AND GUIDELINES

4.1 HARDWARE DEFINITION

The filter process (see 3.2 above) produced a list of 32 representative items of SBI hardware to be considered in these studies, see Table 3.3-1. The complexity and importance of the subjects warrants an extensive analysis of each of the items in the total list in a follow-on study. Due to the practical needs of the real program schedule and budget, the depth of these studies was adjusted to satisfy the available resources and time. In particular, cost analyses emphasized the determination of influential factors and parametric relationships rather than developing detailed numerical cost figures. While program objectives and mission definitions may be stable in the early program phases, hardware item specifications often change many times before final design is complete. For this reason the trade study analyses focused on the catagory and function of each hardware item (Table 1.4-1) rather than the specific current definition of the item.

4.2 DATA ANALYSIS

In the process of acquiring trade study data, certain information was considered a snapshot of the data at the time it was recorded for this study. The data have been analyzed as defined at the time of recording; no attempt was made to maintain the currency of acquired trade study data. An analysis of the trade study data needs was performed to provide an understanding of the logical database requirements. Based on the knowldege gained in this analysis, the trade study data structures were developed and implemented on a computer system. The pertinent information collected from the data and documentation survey was input to the trade study data base.

4.3 COST IMPACTS

Costing techniques used in previous projects were surveyed and historical cost factors were collected for review of applicability to these trade studies. The applicable data were identified for use in cost analysis to demonstrate relative cost impacts of study results and recommendations as applied to space biology hardware. Previous program history indicates that biomedical and bioscience programs can be broken down into three major cost catagories: Non-Recurring Development, Recurring Production, and Recurring Operations, and that program costs are incurred as follows:

Non-Recurring Development	30 - 40%
Recurring Production	4 - 7%
Recurring Operations	54 - 64%

It is interesting to note that source data for the above cost allocations did not consider the costs associated with crew utilization.

4.4 DATA BASE

A literature review and database search was conducted immediately upon initiation of the studies. Information pertaining to each study subject was cataloged and considered for applicability to the related study task.

5.0 RESULTS

5.1 GENERAL

While each study produced unique results according to the subject and discrete direction of the study, there are underlying elements common to all six studies that establish common parameters and guidelines that will:

- Provide equipment designers reasonable and specific requirements
- Identify early decision nodes for equipment design and manufacture
- Establish manufacturing plans and Quality Control requirements that properly weight cost and schedule
- Accurately project and weight cost of ownership as well as cost of acquisition

The results of each individual study is summarized as follows:

5.2 DESIGN MODULARITY AND COMMONALITY

Consideration of modularity and commonality must be introduced early in the design process through a top down systems engineering effort that covers all related SBI hardware. Such an approach could result in a significant cost savings both in the cost of acquisition and the cost of ownership throughout the useful life of the equipment. The highest level of commonality (modules) will result in the greatest cost savings. Scientific merit of the hardware should be considered in making a decision to modularize. Addition of weight and complexity could nullify the advantages of modularization.

Commonality could result in saving development, production, operations, and training costs. Advantages of the application of commonality in the SBI program could have a potential for beneficial spillover effect into other programs, i.e., Crew Health Care Systems. Table 5.2-1, Commonality List of Functions/Assemblies, shows that of the 32 pieces of hardware on the "short

TABLE 5.2-1 COMMONALITY LIST OF FUNCTIONS / ASSEMBLIES

Function/Assembly H/W List from Table 5.4.2	Possible Number of SBI H/W Items with Common Functions/Assemblies	Percent Cost Decrease
1 Aerosol Generator	1	0
2 Amplifiers	6	51-59
3 Automation/Robotics	6	51-59
4 Cameras/Video	5	47-55
5 Centrifuge	4	43-51
6 Computers & Accessories	10	59-66
7 Converters	7	54-61
8 Detectors	5	47-55
9 Displays-Transducer	5	47-55
10 Environmental Control	8	55-63
11 Fluid Handling	6	51-59
12 Freezers	3	37-43
13 Gas Handling	9	57-65
14 Mass Spectrometer	4	43-51
15 Microbial Monitoring	2	25-31
16 Motors	4	43-51
17 Power Supply	7	54-61
18 Pumps	4	43-51
19 Radiation Handling	6	51-59
20 Recorders	10	59-66
21 Sample Prep Animal	4	43-51
22 Sample Prep Human	5	47-55
23 Sample Prep Plant	8	55-63
24 Scintillation Counter	4	43-51
25 Storage Locker	4	43-51
26 Temp.Press.Hum. Monitor	10	59-66
27 Thermal/Shock Isolation	6	51-59

Item # Prioritized by Mass	Hardware Item #	Hardware Item Name	Sufficient Data Available	Modularity Potential	Assessment Confidence Level	
					Low	High
1	168	CELSS		X-PL		X
2	169	Gas Grain Simulator Facility		X		X
3	84	Soft Tissue Imaging System	NO			
4	77	Hard Tissue Imaging System	NO			
5	126	Scintillation Counter		X		X
6	74	Force Resistance System		NO	X	
7	145	Automated Microbic System		X		X
8	155	Total Hydrocarbon Analyzer	NO			
9	161	Inventory Control System		X		X
10	162	Lab Materials Pack & Hand. Equip.		X	X	
11	163	Test/Ckout/Calibration Instrumentation		X		X
12	106	Neck Baro-Cuff		X		X
13	113	Blood Gas Analyzer		X	X	
14	61	Mass Spectrometer		X-P	X	
15	112	Plant HPLC Ion Chromatograph		X-PL		X
16	147	Head Torso Phantom		NO		X
17	63	Pulmonary Gas Cylinder Assem.		X-P	X	
18	110	Plant Gas Chromatograph/Mass Spec		X-PL	X	
19	115	Chemistry System		X	X	
20	138	Hematology		X	X	
21	34	Sample Preparation Device		X	X	
22	165	Experiment Control Computer System		X		X
23	62	Pulmonary Function Equip Stor. Assem.		X-P	X	
24	82	Motion Analysis System		NO		
25	99	Animal Biotelemetry System		NO		
26	100	Blood Pressure & Flow Instrumentation	NO			
27	109	Venous Pressure Transducer/Display	NO			
28	129	Cell Handling Accessories		X	X	
29	57	Bag-In-Box		X-P	X	
30	111	Plant Gas Cylinder Assem.		X-PL	X	
31	119	Gas Cylinder Assembly		X	X	
32	130	Cell Harvester		X	X	

P - Pulmonary Group
PL - Plant Monitoring Group

TABLE 5.2-2 SBI HARDWARE LIST FOR MODULARITY

list", reference Table 3.3-1, 27 of them are candidates for some degree of commonality. Of the remaining five items, there was insufficient data available to analyze them. This table also indicates that significant cost savings can accrue through common usage of assemblies and/or modules.

Modularity goes hand-in-hand with commonality. Table 5.2-2, SBI Hardware List for Modularity, shows that of the 32 short list items, 23 of them are candidates for some degree of modularity. Of the remaining nine, there was insufficient data to analyze five of them. However, costing methods used for this study indicate that while the cost to modify hardware of medium to heavy weight is reasonable, the cost per pound of modifying light weight hardware is much higher and may not be cost effective.

5.3 MODIFICATION OF EXISTING HARDWARE VERSUS NEW HARDWARE

The savings evident in the use of modified off-the-shelf hardware are of such significance that an analysis of new design versus modified COTS is justified for each SBI hardware item. See Figure 5.3-1. This figure shows that as ;the weight of the item to be modified increases, the cost per unit weight to modify decreases. This indicates that a decision to modify items at the smaller end of the scale should be approached with caution.

There is also a practical limit to the extent to which COTS equipment can be modified, beyond which cost can escalate exponentially. While insufficient data exist to accurately quantify this limit, indications are that for the typical piece of Life Science equipment (LSLE, Skylab) this limit is in the 20 to 40 percent range, and certainly before the 50 percent modification point is reached. Experience from earlier programs indicates that there is a strong tendency to stay with a "buy and modify" decision beyond the point of practically. Periodic review of the modification status by other than the point source of the "buy" decision is highly desirable. A make-or-buy decision must consider a number of issues unique to space flight operations and NASA. Buy decisions ususally have a beneficial impact on schedule and budget. Make decisions can result in improved levels of reliability and safety, and may lead to technology breakthroughs.

5.4 AUTOMATION VERSUS CREW UTILIZATION

This study developed both cost and benefit matrices which can be used to determine the most cost effective automation level for a particular SBI hardware item, and in fact, a dollar value can be derived for both the cost and benefit of automating any specific piece of hardware. From these values, the return on investment (ROI) can be calculated. ROI = Benefits gained ($)/Cost to automate ($). The ROI is satisfactory from a cost point of view if it is equal to or greater than one. If it is less than one, than the level of automation being considered is too high and the process should be iterated at a lower level of automation. For practical consideration, cost savings realized through automation are not usually found in the initial cost of design and development, but are in the

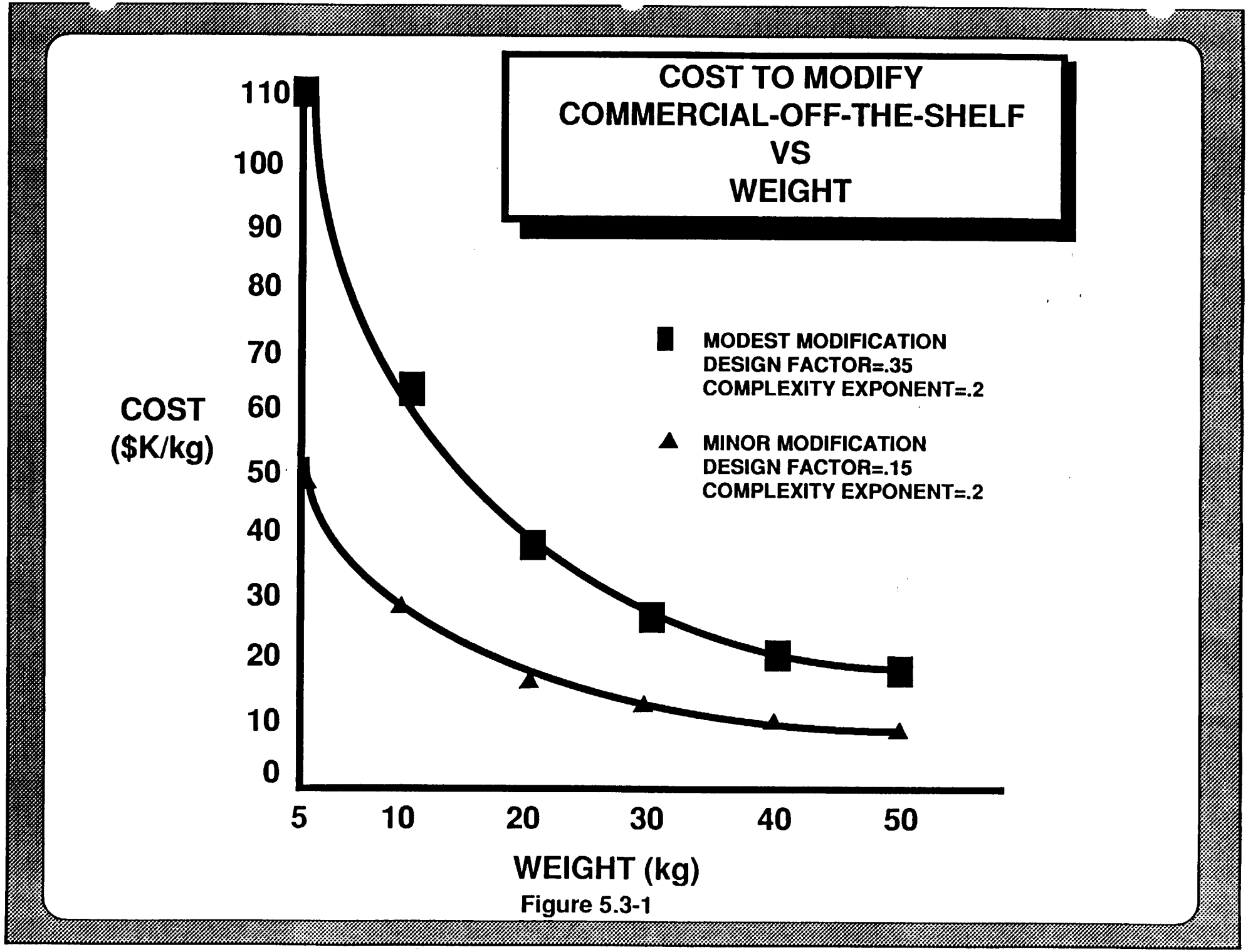

COST TO MODIFY
COMMERCIAL-OFF-THE-SHELF
VS
WEIGHT
MODEST MODIFICATION
DESIGN FACTOR=.35
COMPLEXITY EXPONENT=.2
MINOR MODIFICATION
DESIGN FACTOR=.15
COMPLEXITY EXPONENT=.2
COST
($K/kg)
110
100
90
80
70
60
50
40
30
20
10
0
5
10
20
30
40
50
WEIGHT (kg)

Figure 5.3-1

downstream costs of ownership and operation. These savings become apparent when the cost of crew training, and crew utilization time is quantified. There is historic data from earlier programs that quantifies Internal Vehicular Activity (IVA) and External Vehicular Activity (EVA) crew time cost for these programs. Savings are also realized through increased equipment utilization, and a high level of accurate repeatability in both physical and data domains. Highly structured task processes are more suitable to automation than unstructured ones. Four levels of automation can be considered for any piece of equipment, i.e., manual, semi-automatic, automatic, and independent. The greatest cost savings will be found in automating to the semi-automatic and automatic levels. Before automating to the independent level, an in-depth analysis should be made, as study data shows that a "saturation factor" often limits the cost effectiveness of this step.

5.5 HARDWARE MINIATURIZATION VERSUS COST

Study results indicate that miniaturization will add to the cost of acquisition, unless the component or assembly in question will enjoy a long production run. Normally, SBI hardware does not require such production runs. There is insufficient data on the items that comprise life cycle costs to do a full analysis on the effects of miniaturization, however, there is an indication that life cycle costs, particularily the cost of transportation, (reduced weight and volume), could be favorably impacted by miniaturization. Figure 5.5-1 shows that the large increase in cost incurred in the redesign necessary to miniaturize can in favorable cases be partly or wholly recouped by the savings in life cycle costs. However, in the best case curve, this crossover point is far downstream in the useful life of the item, and in less favorable examples it may never occur. Equipment that requires crew handling for operation, calibration, adjustment, etc. should not be miniaturized to the extent that it becomes difficult for a crew member to handle. For this reason, equipment that is to be automated is often a good candidate for miniaturization. Cost savings are possible if the hardware is automated and miniaturized concurrently.

5.6 SPACE STATION FREEDOM/SPACELAB MODULE COMPATIBILITY

This study examined the physical, electrical, thermal, fluid, video, and data interfaces between the three laboratory modules on the Space Station, the Spacelab, and the Shuttle Orbiter. At the present time, the three modules on the SSF are not designed to provide the user with common experiment-to-rack interfaces. This fact alone implies the scope of the problem. Standardized interfaces appear to provide commonality with little or no weight and volume penalty. The benefits of standardization should lower life cycle costs. However, to realize the optimum benefits from standardized interfaces, they should be enforced "across the board", not only for the U.S. designed and built modules, but also for the European Columbus and the Japanese Joint Experiment Module (JEM). The international cooperation and coordination necessary to attain this level of standardization cannot be effectively addressed at the program level, but should be addressed at the policy level.

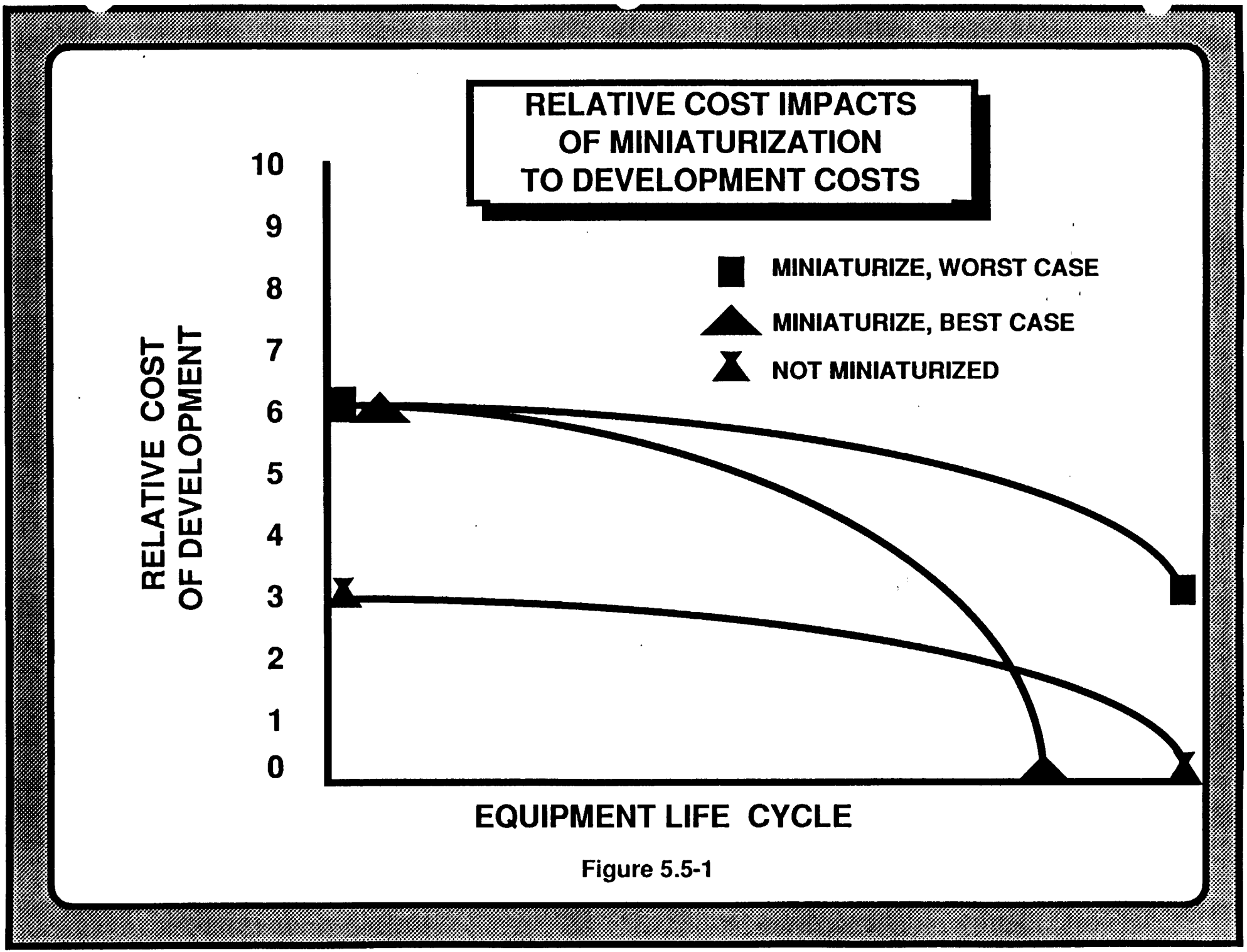

RELATIVE COST IMPACTS
OF MINIATURIZATION
TO DEVELOPMENT COSTS
MINIATURIZE, WORST CASE
MINIATURIZE, BEST CASE
NOT MINIATURIZED
RELATIVE COST
OF DEVELOPMENT
10
9
8
7
6
5
4
3
2
1
0
EQUIPMENT LIFE CYCLE

Figure 5.5-1

5.7 PROTOTYPE UTILIZATION

Unless an existing piece of hardware that is already space qualified meets all requirements for a piece of SBI equipment, each piece of SBI equipment is likely to undergo some form of prototype testing. This can range from protoflighting, where one piece of hardware fulfills all program requirements, to the use of two or three prototypes for multiple purposes, to specific prototypes for each required prototype function, i.e., breadboard, brassboard, proof of concept, pre-production, mockup, design/verification/test, training unit, qualification unit, engineering model, and thermal test article. Usually one unit fullfills more than one of these requirements.

6.0 RECOMMENDATIONS

6.1 INTEGRATION OF STUDIES

The interrelationship between automation, prototyping, modularization, and miniaturization becomes very apparent when these six studies are viewed as a whole. These functions, in turn, also impact hardware modification and compatibility. For these reasons a systems engineering study that would develop methodology which integrates the effects of automation, commonality, modularity, miniaturization, etc., is strongly recommended. Such a study should be conducted prior to freezing the design of SBI equipment in order to realize optimum benefits from it.

6.2 APPLICATION TO OTHER PROGRAMS

While these studies are specifically concerned with hardware for the Space Biology Initiative program, the study principles and methodology would certainly have application to other programs, such as Crew Health Care System, and other scientific payloads to be flown on the Space Transportation System and Space Station Freedom.

6.3 LOW COST SYSTEMS OFFICE

In 1973 a Low Cost Systems Office was established at NASA Headquarters. The purpose of this office was to reduce the cost of space hardware. This office was in existence for four years and during that time it investigated many cost saving avenues, some of them closely related to these studies. The effectivity of this office was a subject of controversy within NASA during and after its existence. It is not the intent of this summary to resolve that controversy, but in retrospect the concept of a Low Cost Systems Office appears to be sound. This office was in operation during the Apollo/Soyuz Test Program in the 1973-76 timeframe, and available data indicates a savings in excess of 20% over the November 1972 projected program costs, see Figure 6.3-1, which shows the planned versus actual run-out costs of the Apollo / Soyuz Test Program. It is recommended that a "lessons learned" study be conducted and a Low Cost Systems Office that incorporates those lessons be established for SBI

equipment and possibly all Office of Space Science and Applications, (OSSA) payloads.

6.4 SPACE STATION FREEDOM / SPACELAB MODULE COMPATIBILITY

Experiment to rack interfaces, and rack to module interfaces should be standardized. Standardization will benefit experiment location flexibility, changeout ability, checkout and verification, flight testing, and result in significant cost reduction. It will simplify experiment design, and the experiment integration process. It will significantly increase the efficiency and utilization of the SBI equipment, and increase the amount of work that can be performed per mission. There are no technical or economic negatives to standardization. It should be implemented, and all international partners should be included in the implementation process. The International Air Transport Association (IATA), a regulating organization for the world's airlines, has successfully standardized many systems and aspects of commercial transport aircraft, including the packaging and installation of avionic equipment in racks that are built to the same standards by the free world's aircraft manufacturers. The methodology used by IATA to accomplish this standardization would be a valuable assist in equipment and rack standardization for space flight. It is recommended that a study to define the necessary infrastructure to accomplish this standardization be conducted.

6.5 MINIATURIZATION

The miniaturization study indicates that cost savings should not be a major driver to miniaturize. A piece of hardware can benefit from miniaturization when:

- The article is too large and cumbersome to be used in space efficiently.
- The article is to be automated and therefore the man-machine interface is reduced or eliminated
- Technology advancements allow the application of new and smaller elements, i.e., highly integrated electronic devises.

6.6 MODULARITY AND COMMONALITY

Modularity and commonality cost savings are potentially significant. Such savings are large enough to justify analyzing each piece of SBI hardware for applications of commonality and modularity. The use of a module in two or three applications will result in cost reductions of 25 to 40%, therefore it is not necessary to find multiple applications to realize significant cost benefits.

ASTP PROGRAM
PLANNED COST vs. ACUTAL COST

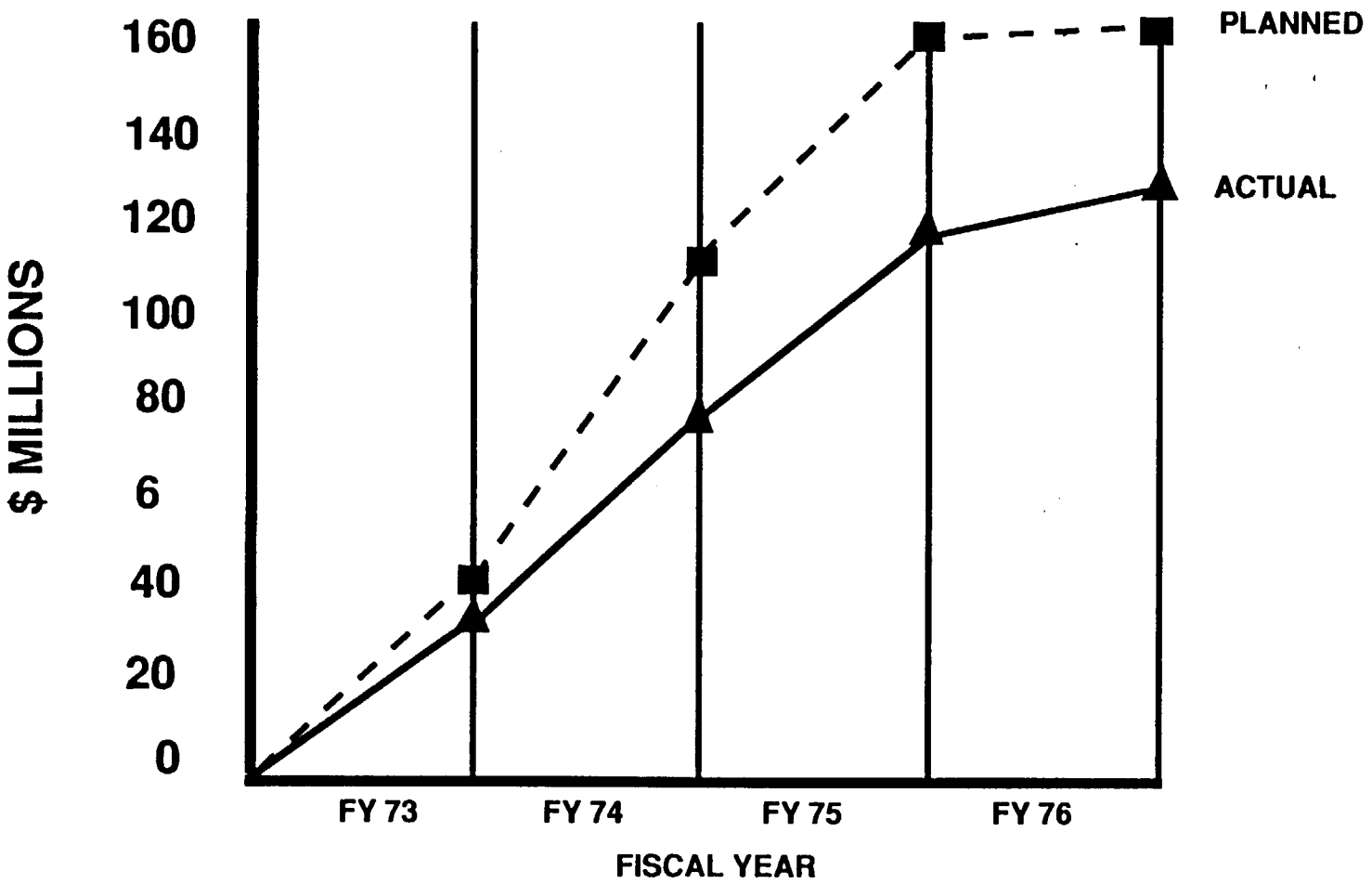


Figure 6.3-1

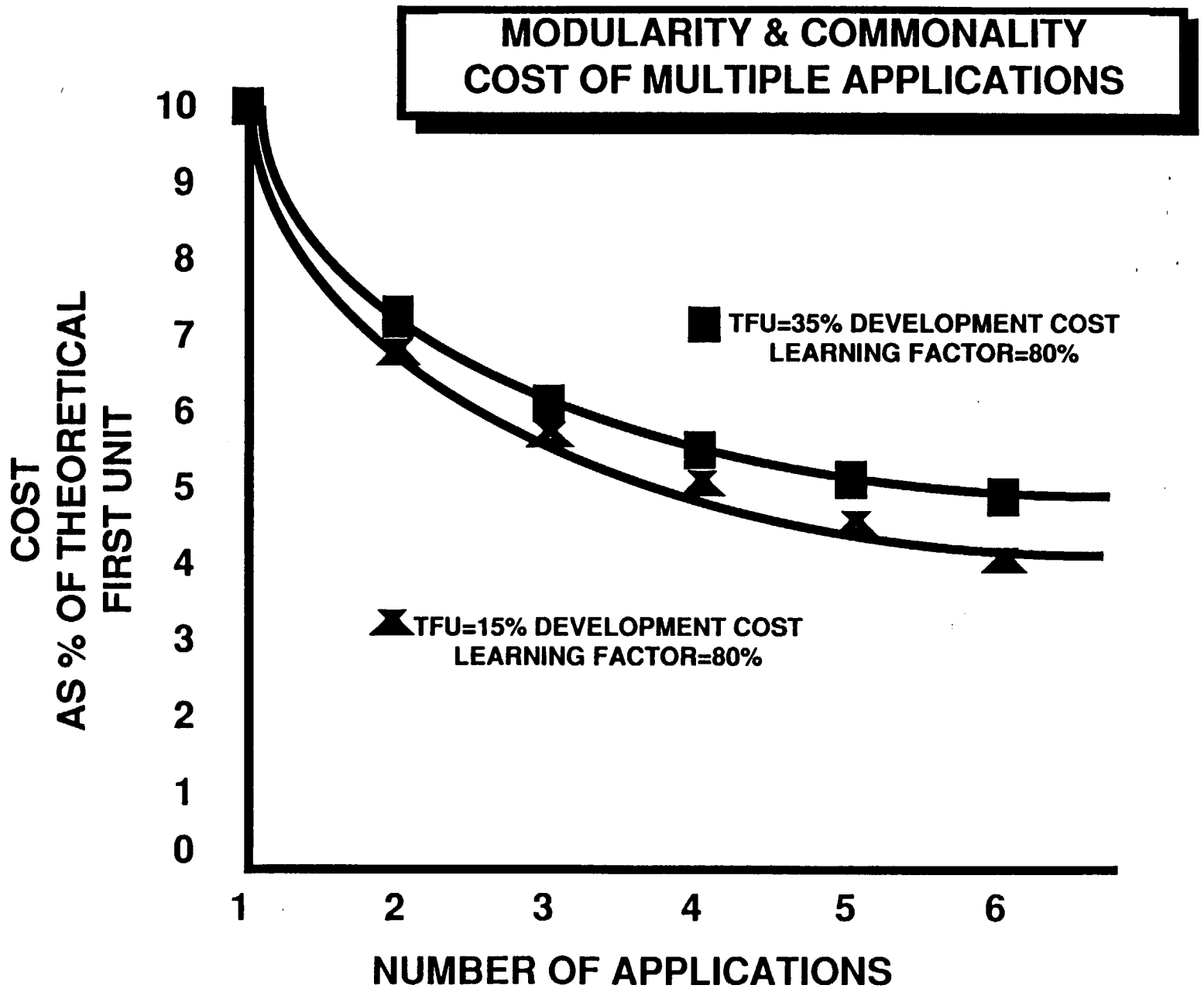

MODULARITY & COMMONALITY
COST OF MULTIPLE APPLICATIONS
COST
AS % OF THEORETICAL
FIRST UNIT
10
9
8
7
6
5
4
3
2
1
0
TFU=35% DEVELOPMENT COST
LEARNING FACTOR=80%
TFU=15% DEVELOPMENT COST
LEARNING FACTOR=80%
1
2
3
4
5
6
NUMBER OF APPLICATIONS

Figure 6.6-1

Logistics support functions and other elements of life cycle costs benefit from the use of modular systems. Modularization and commonality applications can be accomplished early in the design phase with little or no adverse weight impact. Figure 6.6-1 illustrates the benefits to be derived from the use of a common module in two or more applications. Using Theortical First Unit (TFU) cost as a percentage of total development cost, and accepted learning curve data, the cost of the second unit can be 65 - 75% of the first, and additional applications can bring the per unit cost down in to the 40 - 50% range.

6.7 USE OF COMMERCIAL OFF-THE-SHELF HARDWARE (COTS) VERSUS NEW DESIGN

Use of existing hardware, especially if already space qualified, can yield significant cost savings. However, that hardware which requires modification must be carefully evaluated to determine the extent of modification required. Hardware requiring major modification (40 - 50%) is generally not a good candidate for COTS use. Periodic review of the modification process is essential to prevent rapid cost escalation resulting from extensive modification.

6.8 AUTOMATION VERSUS CREW UTILIZATION

A significant emphasis upon automation within the Space Biology Initiative hardware appears justified to conserve crew labor and crew training effort. The study characterized the automation opportunities into two broad technology groups: (1) Information handling and decision making, and (2) Material handling and processing. The volume of experiments performed and the quality of results obtained will be increased by the use of automatic data acquisition, expert systems, robots, and machine vision. The automation described will also facilitate efforts to miniaturize and modularize the large array of SBI hardware identified to date.

SBI equipment specifiers and designers can use automation cost trend guidelines to determine the level of automation that should be attempted, and its impact on the overall cost of the SBI system. Additional study is recommended to definitize the impact of the generic forms of automation upon crew labor cost savings and crew training cost savings.

Previous program experience and this study strongly support the theorm that each upgrade in the level of automation (manual to semi-automatic, semi automatic to automatic, etc.), reduces the crew involvement by a factor of two. Data gathered from previous programs has priced Internal Vehicular Activity (flight crew labor cost) at $29,483.00 per hour, and Extra Vehicular Activity at $84,237.00 per hour. These per hour costs are taken from the JSC Optional Services Pricing Manual, NSTS JSC 20109, October 1984. It is obvious that the savings realized by the use of automation can be dramatic, particularly when going from manual to semi-automatic to automatic. SeeFigure 6.8-1.

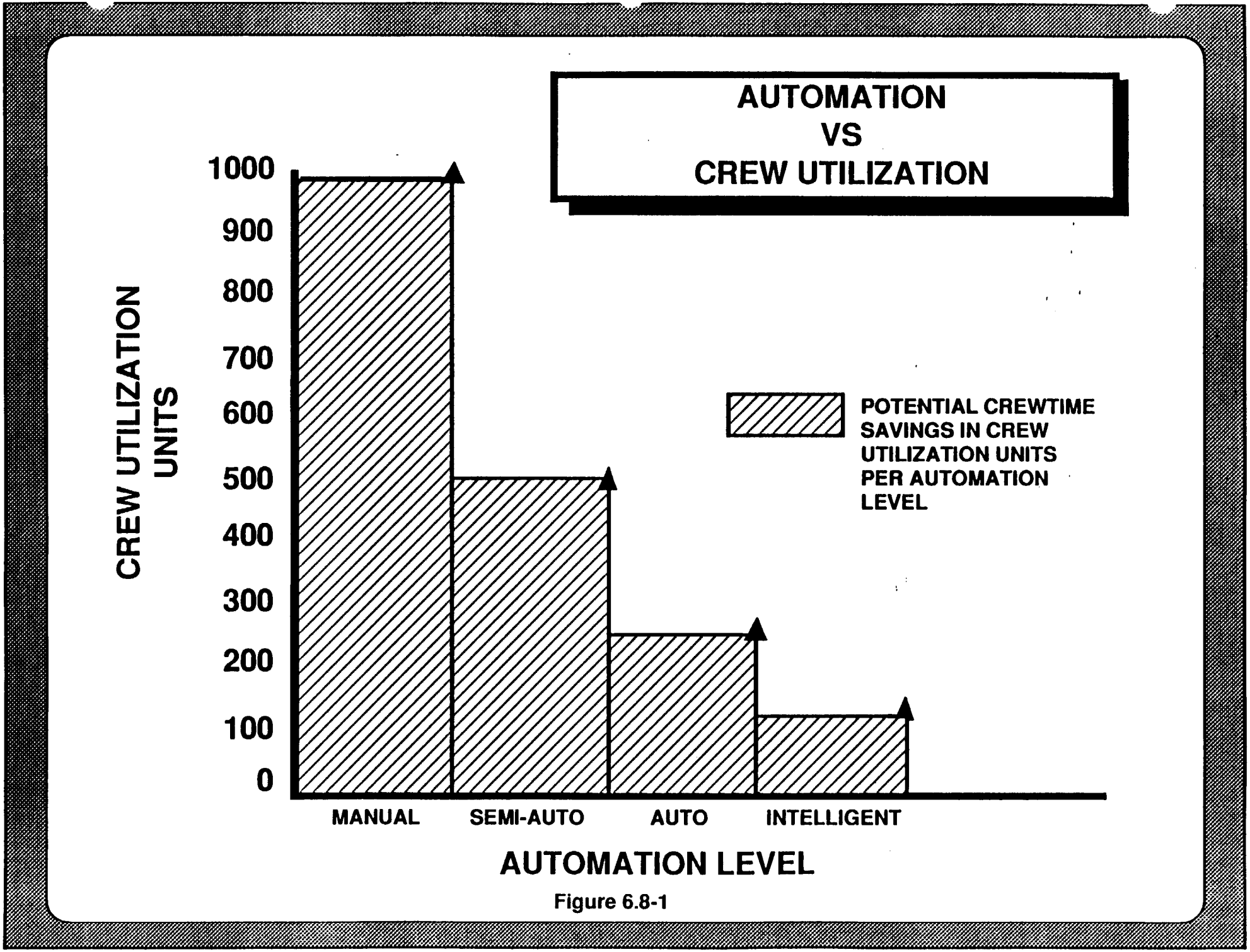

AUTOMATION
VS
CREW UTILIZATION
CREW UTILIZATION UNITS
1000
900
800
700
600
500
400
300
200
100
0
POTENTIAL CREWTIME SAVINGS IN CREW UTILIZATION UNITS PER AUTOMATION LEVEL
MANUAL
SEMI-AUTO
AUTO
INTELLIGENT
AUTOMATION LEVEL

Figure 6.8-1

6.9 PROTOTYPE UTILIZATION

Prototypes are used to:

- Keep cost down and under control
- Provide the necessary degree of reliability
- Prove the required functional capability
- Facilitate the development process
- Confirm interface compatibility

Prototypes are useful in both the design and development of new hardware and the modification of existing hardware. Prototypes are required in varying degrees in all hardware and software development programs, although they may not be a contractual delivery requirement. Automation, miniaturization, modularization and modification of hardware can benefit from a well planned and executed prototyping process. Each activity may be conducted in parallel, but they must all be integrated into prototype elements used in the program.

Prototypes are very cost effective in assisting designers to meet the variety of interface requirements encountered in the design and development of modules that have multiple applications, i.e., amplifiers, sensors, power supplies, etc.

Due to the rigorous SRM&QA demands on new SBI hardware, a basic prototyping activity should be baselined for all but the most elementary hardware items. The number of prototypes could be scaled up or down according to program drivers. In some cases a single unit could be used to fill several prototyping requirements.

MODIFICATION OF EXISTING HARDWARE VS NEW HARDWARE BUILD COST ANALYSIS

TRADE STUDIES

JOHNSON SPACE CENTER
HOUSTON, TEXAS
77058

SPACE BIOLOGY

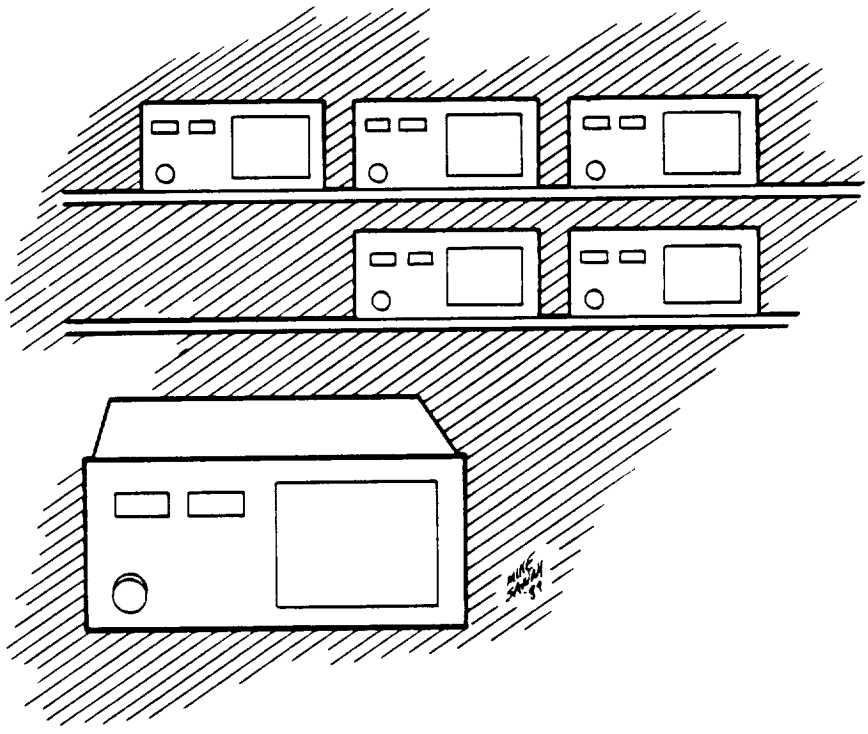
INITIATIVE

Space Biology Initiative
Program Definition Review

Lyndon B. Johnson Space Center
Houston, Texas 77058

HORIZON AEROSPACE

Modification of Existing Hardware vs. New Hardware Build Cost Analysis



FINAL REPORT

June 1, 1989

HORIZON AEROSPACE

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• HOUSTON, TEXAS, USA 77058 • (713) 333-5944
• TELEFAX (713) 333-3743

SPACE BIOLOGY INITIATIVE
PROGRAM DEFINITION REVIEW

TRADE STUDY 5

MODIFICATION OF EXISTING HARDWARE (COTS)
vs
NEW HARDWARE BUILD
COST ANALYSIS

FINAL REPORT

Prepared by:

HORIZON AEROSPACE

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T. Sutton

Prepared for:

GE GOVERNMENT SERVICES
Houston, Texas
Contract No. G966016-J45

June 1, 1989

Foreword

The "Modification of Existing Hardware Versus New Hardware Build" was performed as part of the Space Biology Initiative (SBI) Definition Trade Studies Contract which is a NASA activity intended to develop supporting data for JSC use in the Space Biology Initiative Definition (Non-Advocate) Review with NASA Headquarters, Code B, scheduled for the June-July 1989 time period. The task personnel researched, acquired, recorded, and analyzed information pertaining to a Make-or-Buy analysis of space biology equipment. The study data provides parametric information indicating the factors which influence the cost and design for categories and functions of SBI hardware.

This effort is one of four separate trade studies performed by Eagle Engineering, Inc. (EEI). Although the four trade studies address separate issues, the subject of SBI Hardware, the objectives to document the relative cost impacts for the four separate issues, and the intended audience are common for all four studies. Due to factor beyond control of the study management organizations, the trade studies were required to be completed in approximately one half of the originally planned time and with significantly reduced resources. Therefore, EEI immediately decided to use two proven time-and-resource-saving principles in studying these related SBI issues. The first principle employed was commonality. The study methodology was standardized where appropriate, the report formats were made the same where possible, a common database was developed, and the cost analysis techniques development and consultation was provided by a common team member. An additional benefit of this application of commonality with standardized material is to facilitate the assimilation of the study data more easily since the methods and formats will become familiar to the reader. The second principle employed was the phenomenon of the "vital few and trivial many" or sometimes known as the "Pareto principle" (see SBI #96). These are terms which describe the often observed phenomenon that in any population which contributes to a common effect, a relative few of the contributors account for the bulk of the effect. In this case, the effect under analysis was the relative cost impact of the particular SBI issue. If the phenomenon was applicable for the SBI hardware, EEI planned to study the "vital few" as a method of saving time and resources to meet the limitations of the study deadlines. It appears the "vital few and trivial many" principle does apply and EEI adopted the Principle to limit the number of hardware items that were reviewed.

The study was performed under the contract direction of Mr. Neal Jackson, Horizon Aerospace Project Manager. Mr. Mark Singletary, GE Government Services, Advanced Planning and Program Development Office, provided the objectives and policy guidance for the performance of the trade study. The direct study task personnel include:

EEI Project Manager:	Mr. W.L. Davidson (Bill)
Trade Study Manager:	Ms. Carolyn Blacknall
Cost Analysis Techniques Leader:	Mr. James W. Bilodeau (Jim)
Visual Materials Support:	Mr. J.M. Stovall (Mike)
Information Management Leader:	Mr. Terry Sutton (Eagle Technical Services)

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List of Abbreviations and Acronyms

AI	Artificial Intelligence
APM	Attached Pressurized Module
ARC	Ames Research Center
ASTP	Apollo - Soyuz Test Program
BmRP	Biomedical Research Project (Human/Crew Members)
BRP	Biological Research Project (Non-Human/Rodents, primates or plants)
BSHF	Biological Specimen Holding Facility
CELSS	Closed Ecological Life Support System
CER	Cost Estimating Relationship
CHeC	Crew Health Care
COTS	Commercial Off-The-Shelf
DDT&E	Design, Development, Test and Evaluation
DF	Design Factor
DFI	Development Flight Instrumentation
DMS	Data Management System
ECF	Exercise Countermeasure Facility
ECLSS	Environmental Control and Life Support System
EDCO	Extended Duration Crew Operations
EEI	Eagle Engineering, Inc.
EHS	Environmental Health System
EPDS	Electrical Power Distribution System
ESA	European Space Agency
FDA	Food and Drug Administration
FSU	Functional Support Unit
HMF	Health Maintenance Facility
HQUL	Hardware Quantity and Usage List
HRF	Human Research Facility
HW	Hardware
IOC	Initial Operating Capability
ISS	International Space Station
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KG	Kilogram
LAN	Local Area Network
LSCO	Low Cost Systems Office
LSE	Laboratory Support Equipment
LSFEP	Life Sciences Flight Experiment Program
LSLE	Life Sciences Laboratory Equipment
LSRF	Life Science Research Facility
MATSCG	Management and Technical Service Company
MDE	Mission Dependent Equipment
MDU	Medical Development Unit
MLI	Multi-Layer Insulation
MOB	Make or Buy

MRDB	Mission Requirements Data Base
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NIO	New Initiatives Office
NSTS	NASA Space Transportation System
OTS	Off-The-Shelf
PI	Principal Investigator
PMC	Permanent Manned Capability
POCC	Payload Operations Control Center
PSI	Pounds/Square Inch
QA	Quality Assurance
RMOAD	Reference Mission Operational Analysis Document
SAIS	Science & Applications Information System
SBHB	Space Biology Hardware Baseline
SBI	Space Biology Initiative
SLM	Science Laboratory Module
SSF	Space Station Freedom
SSFP	Space Station Freedom Program
SSIS	Space Station Information Systems
STS	Space Transportation System
TDRSS	Tracking and Data Relay Satellite System
TFU	Theoretical First Unit
US	United States
WAN	Wide Area Network
WG	Working Group

Glossary and Definitions

Assembly

An accumulation of subassemblies and/or components that perform specific functions within a system. Assemblies can consist of subassemblies, components, or both.

Buy, or Purchase

Equipment which will be purchased commercially and then modified, as necessary, for use in space.

Certification

The process of assuring that experiment hardware can operate under adverse Space Station Freedom environmental conditions. Certification can be performed by analysis and/or test. The complete SSFP definition follows. Tests and analysis demonstrate and formally document that all applicable standards and procedures were adhered to in the production of the product to be certified. Certification also includes demonstration of product acceptability for its operational use. Certification usually takes place in an environment similar to actual operating conditions.

Certification test plan

The organized approach to the certification test program which defines the testing required to demonstrate the capability of a flight item to meet established design and performance criteria. This plan is reviewed and approved by cognizant reliability engineering personnel. A quality engineering review is required and comments are furnished to Reliability.

Commercial Off-The-Shelf (COTS), Off-The-Shelf (OTS)

Equipment which is, or is expected to be, commercially available for purchase.

Component

An assembly of parts, devices, and structures usually self-contained, which perform a distinctive function in the operation of the overall equipment.

Experiment

An investigation conducted on the Space Station Freedom using experiment unique equipment, common operational equipment of facility.

Experiment Developer

Government agency, company, university, or individual responsible for the development of an experiment/payload.

Experiment unique hardware

Hardware that is developed and utilized to support the unique requirements of an experiment/payload.

Facility

Hardware/software on Space Station Freedom used to conduct multiple experiments by various investigators.

Flight Increment

The interval of time between shuttle visits to the Space Station Freedom. Station operations are planned in units of flight increments.

Flight increment planning

The last step in the planning process. Includes development of detailed resource schedules, activity templates, procedures and operations supporting data in advance of the final processing, launch and integration of payloads and transfer of crew.

Ground operations

Includes all components of the Program which provide the planning, engineering, and operational management for the conduct of integrated logistics support, up to and including the interfaces with users. Logistics, sustaining engineering, pre/post-flight processing, and transportation services operations are included here.

Increment

The period of time between two nominal NSTS visits.

Interface simulator

Simulator developed to support a particular Space Station Freedom or NSTS system/subsystem interface to be used for interface verification and testing in the S&TC and/or SSPF.

Integrated logistics support

Includes an information system for user coordination, planning, reviews, and analysis. Provides fluid management, maintenance planning, supply support, equipment, training, facilities, technical data, packaging, handling, storage and transportation. Supports the ground and flight user requirements. The user is responsible for defining specific logistics requirements. This may include, but not be limited to resupply return in term of frequency, weight, volume, maintenance, servicing, storage, transportation, packaging, handling, crew requirements, and late and early access for launch site, on-orbit, and post-mission activities.

Integrated rack

A completely assembled rack which includes the individual rack unique subsystem components. Verification at this level ensures as installed component integrity, intra-rack mechanical and electrical hookup interface compatibility and mechanisms operability (drawer slides, rack latches, etc.).

Integration

All the necessary functions and activities required to combine, verify, and certify all elements of a payload to ensure that it can be launched, implemented, operated, and returned to earth successfully.

Make, Made, Build, or New Build

Equipment which is designed and built "from scratch" specifically for use in the micro-gravity environment of space.

Modified Off-The-Shelf

Commercially available equipment which has been modified to adhere to NASA's standards for use in space. Most SBI hardware will require modifications if purchased commercially because of NASA's high standards for safety and reliability.

Orbital replaceable unit (ORU)

The lowest replaceable unit of the design that is fault detectable by automatic means, is accessible and removable, (preferably without special tools and test equipment or highly skilled/trained personnel), and can have failures fault-isolated and repairs verified. The ORU is sized to permit movement through the Space Station Freedom Ports.

Payload integration activities

Space Station Freedom payload integration activities will include the following:

Pre-integration activities shall include receiving inspection, kitting, GSE preps and installation, servicing preps and servicing, post deliver verification, assembly and staging (off-line labs), rack and APAE assembly and staging, alignment and post assembly verification.

Experiment integration activities shall include experiment package installation into racks, deck carriers, platforms, etc., and payload to Space station interface verification testing. When the Freedom element is available on the ground, Space Station Freedom integration activities (final interface testing) shall include rack or attached payload installation into Freedom element (e.g., pressurized element, truss structure, platform) and shall include payload-to-element, interface verification, followed by module, truss, or platform off-loading of experiments, as required, for launch mass for follow-on increments, Space Station Freedom integration activities shall include rack or attached payload installation into the logistics element and verification of the payload-to-logistics element interface.

Integration activities (final interface testing) shall include: rack or attached payload installation into Space Station Freedom element (e.g., lab module, truss structure, platform) on the ground, when available, and shall include payload to element interface verification, configure and test for station to station interface verification, followed by module, truss or platform off-loading of experiments, as required, for launch mass.

Launch package configuration activities shall include configuring for launch and testing station to NSTS interfaces, (if required), stowage and closeout, hazardous servicing, (if required), and transport to the NSTS Orbiter.

NSTS Orbiter integrated operations activities shall include insertion of the launch package into the orbiter, interface verification (if required), pad operations, servicing, closeout, launch operations, and flight to Space Station Freedom.

On-orbit integration activities shall include payload installation and interface verification with Space Station Freedom.

Hardware removal that includes rack-from-module and experiment-from-rack removal activities.

Payload life cycle

The time which encompasses all payload activities from definition, to development through operation and disbursement.

Permanent manned capability (PMC)

The period of time where a minimum of capabilities are provided, including required margins, at the Space Station Freedom to allow crews of up to eight on various tour durations to comfortably and safely work in pressurized volumes indefinitely. Also includes provisions for crew escape and EVA.

Physical integration

The process of hands-on assembly of the experiment complement; that is, building the integrated payload and installing it into a standard rack, and testing and checkout of the staged payload racks.

Principal Investigator

The individual scientist/engineer responsible for the definition, development and operation of an experiment/payload.

Rack staging

The process of preparing a rack for experiment/payload hardware physical integration: encompasses all pre-integration activities.

Space Station Freedom

The name for the first Unites States permanently manned space station. It should always be interpreted as global in nature, encompassing all of the component parts of the Program, manned and unmanned, both in space and on the ground.

Subassembly

Two or more components joined together as a unit package which is capable of disassembly and component replacement.

Subsystem

A group of hardware assemblies and/or software components combined to perform a single function and normally comprised of two or more components, including the supporting structure to which they are mounted and any interconnecting cables or tubing. A subsystem is composed of functionally related components that perform one or more prescribed functions.

Verification

The process of confirming the physical integration and interfaces of an experiment/payload with systems/subsystems and structures of the Space Station Freedom. The complete SSFP definition follows. A process that determines that products conform to the design specification and are free from manufacturing and workmanship defects. Design consideration includes performance, safety, reaction to design limits, fault tolerance, and error recovery. Verification includes analysis, testing, inspection, demonstration, or a combination thereof.

1.0 Introduction

1.1 Background

The JSC Life Sciences Project Division has been directly supporting NASA Headquarters, Life Sciences Division, in the preparation of data from JSC and ARC to assist in defining the Space Biology Initiative (SBI). GE Government Services and Horizon Aerospace have provided contract support for the development and integration of review data, reports, presentations, and detailed supporting data. An SBI Definition (Non-Advocate) Review at NASA Headquarters, Code B, has been scheduled for the June-July 1989 time period. In a previous NASA Headquarters review, NASA determined that additional supporting data would be beneficial to determine the potential advantages in modifying commercial off-the-shelf (COTS) hardware for some SBI hardware items. In order to meet the demands of program implementation planning with the definition review in late spring of 1989, the definition trade study analysis must be adjusted in scope and schedule to be complete for the SBI Definition (Non-Advocate) Review.

1.2 Task Statement

This study compares the relative costs of modifying existing commercial off-the-shelf (COTS) hardware to fabricating new hardware. This study surveys and identifies a historical basis for new build versus modifying COTS to meet current NMI specifications for Manned Space Flight hardware. This study will also identify selected SBI hardware as potential candidates for off-the-shelf modification and provide statistical estimates on the relative cost of modifying COTS versus new build.

1.3 Application of Trade Study Results

The SBI cost definition is a critical element of the JSC submission to the SBI Definition (Non-Advocate) Review and the results of this trade study are intended to benefit the development of the SBI costs. It is anticipated that the GE PRICE cost estimating model will be used to assist in the formulation of the SBI cost definition. The trade study results are planned to be produced in the form of factors, guidelines, rules of thumb, and technical discussions which provide insight on the effect of modifying commercial off-the-shelf equipment versus new build on the relative cost of the SBI hardware. The SBI cost estimators are required to define input parameters to the PRICE model which control the cost estimating algorithms. These trade study results can be used as a handbook of make-or-OTS-buy cost effects by the SBI cost estimators in developing and defining the required PRICE input parameters.

This study examines the list of reference biology equipment in the Space Biology Hardware Baseline and lists the hardware which will have a significant cost savings if modified from commercial off-the-shelf equipment. In addition, this study identifies historical make-or-OTS-buy costs and develops statistical cost analysis methods based on this historical data. This information can then be used to assist in performing a make-or-OTS-buy analysis on other reference SBI hardware or actual equipment.

1.4 Scope

The space biology hardware to be investigated has been defined and baselined in Appendix A, Space Biology Hardware Baseline (SBHB). By study contract direction, no other space biology hardware has been considered. The complexity and importance of the subject could warrant an extensive study if unlimited time and resources were available. However, due to the practical needs of the real program schedule and budget, the depth of study has been adjusted to satisfy the available resources and time. In particular, cost analyses have emphasized the determination of influential factors and parametric relationships rather than developing detailed, numerical cost figures. While program objectives and mission definitions may be stable in the early program phases, hardware end item specifications are evolving and usually change many times during the design phase. For this reason, the trade study analyses have focused on the category and function of each hardware item (Table 1.4) rather than the particular, current definition of the item. In the process of acquiring trade study data, certain information could be considered a snapshot of the data at the time it was recorded for this study. The data have been analyzed as defined at the time of recording; no attempt has been made to maintain the currency of acquired trade study data.

1.5 Methodology

The methodology used in performing the Make-or-OTS-Buy Trade Study is shown in Figure 1.5. It consists of the initial, important phase of search and acquisition of related data; followed by a period of data integration and analysis; and, finally, the payoff phase where candidate items and implementation factors are identified including relative cost reduction assessment for SBI hardware that can be implemented using existing OTS equipment.

1.5.1 Data And Documentation Survey

A literature review and database search were conducted immediately upon study initiation. In establishing criteria for make-or-OTS-buy decisions for SBI hardware, historical situations were reviewed. Decisions to modify off-the-shelf hardware or develop it from scratch have been made in Mercury, Gemini, Apollo, ASTP, medical, and in other scientific areas. These decisions are currently underway in several areas of the Space Station Freedom Program.

1.5.2 Database Development

An analysis of the trade study data needs was performed to provide an understanding of the logical database design requirements. Based on the knowledge gained in the database analysis, the trade study data structures were developed and implemented on a computer system. The pertinent information collected from the data and documentation survey was input to the trade study database.

1.5.3 Costing Techniques Summary

Costing techniques used in previous projects were surveyed and historical cost factors were collected for review of applicability to this trade study. The applicable data were identified for

use in cost analysis to demonstrate relative cost impacts of modifying commercial off-the-shelf hardware equipment.

1.5.4 Survey Data Integration

The reference Space Biology Hardware Baseline (SBHB) was reviewed for a make-or-OTS-buy assessment of potential candidate hardware. The technical data collected from the survey was integrated with the Space Biology Hardware Baseline and a list of considerations affecting a make-or-OTS-buy analysis was compiled. The initial survey data analysis was performed to select a sample of the SBHB items which could be potential candidates for implementation using modified COTS equipment. With limited study time and a SBHB of 93 items, a method was needed to separate the items which could have the most cost impact and were worthy of study resource application. The "vital few and trivial many" method (SBI #96) was used. This method applies the principle that in any population which contributes to a common effect (cost), a relative few of the contributors account for the bulk of the effect (cost). All SBHB items were listed in descending order of probable acquisition cost. Weight was used as an indication of probable acquisition cost based on historical experience in previous space programs. It was found that 34 percent of the items (32 items) accounted for 93 percent of the mass or probable cost (Table 5.7). Therefore, consideration was immediately limited to these 32 items. The make-or-OTS-buy candidate sample set was chosen from Table 5.7 based on amenability to use of modified COTS equipment.

The sample set was then subjected to a more detailed analysis to determine important factors relative to make-or-OTS-buy and to select the most representative candidate for final analysis. By this process, a reasonable effort could be devoted to the analysis of candidates for a possible make, OTS-buy, or for either a make or OTS buy decision.

1.5.5 Cost Analysis

Historical costs for both new build hardware and modified commercial off-the-shelf equipment were analyzed for several NASA programs. Design, development, test and evaluation (DDT&E) cost estimating relationships between new build and modified off-the-shelf were then established. The 32 most significant items of the Space Biology Hardware Baseline in terms of weight were then individually analyzed for make-or-OTS-buy potential. The method for this analysis is shown in Section 5.8, Make-or-OTS-Buy Cost Impact Analysis. The percentage of off-the-shelf hardware was estimated for each of the 32 SBHB items. Using the developed cost estimating relationships, the relative potential cost reduction for each item was estimated and entered in Table 5.7.2-1.

1.6 Definitions

The following definitions have been established for the purpose of this trade study:

Commercial Off-The-Shelf (COTS), Off-The-Shelf (OTS):
Equipment which is or is expected to be commercially available for purchase.

Modified Off-The-Shelf:

Commercially available equipment which has been modified to adhere to NASA's standards for use in space.

Make, Made, Build, or New Build:

Equipment which is designed and built "from scratch" specifically for use in the micro-gravity environment of space.

Buy, or OTS-Buy:

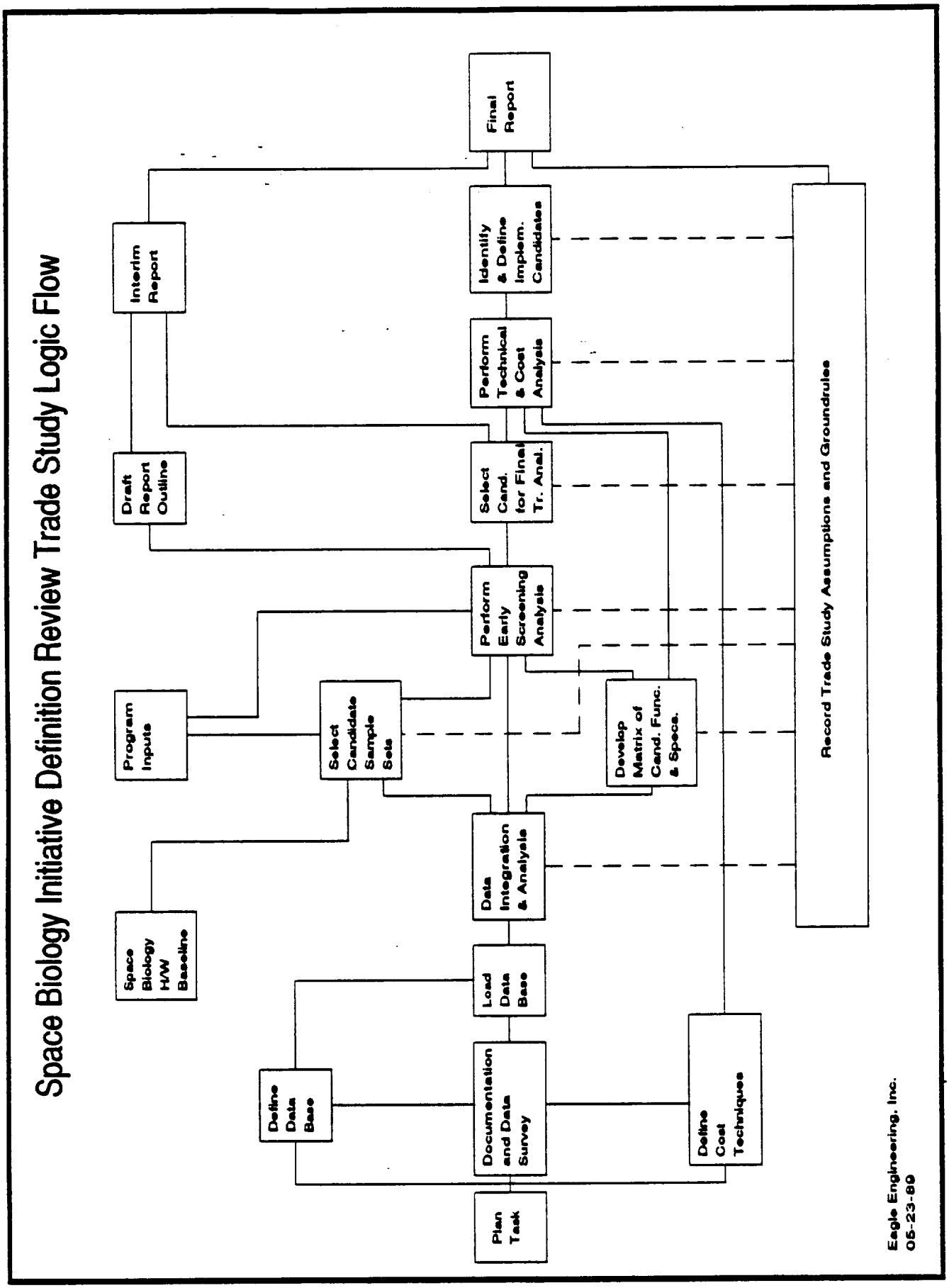
Off-the-shelf equipment which will be purchased commercially and then modified, as necessary, for use in space. Most SBI hardware will require modifications if purchased commercially because of NASA's high standards for safety and reliability.

CAUTION: In many industry make-or-buy plans, "make" refers to an in-house new build and "buy" refers to subcontracted new build. These definitions must be taken into consideration when comparing plans. In this trade study, only the stated definitions have been used.

Table 1.4 SBI Hardware Categories and Functions

SBI HARDWARE CATEGORIES	FUNCTIONS(Applicable to each Category)
Cardiovascular	Analysis
Cytology	Calibration
Environmental Monitoring	CELSS
Exobiology	Collection
Hematology	Health Maintenance
Histology	Measurement
Logistics	Preparation
Miscellaneous	Stowage
Neurophysiology	
Plant Sciences	
Pulmonary	
Surgical Science	
Urology	

Figure 1.5 Space Biology Initiative Definition Review Trade Study Logic Flow



2.0 Executive Summary

2.1 Assumptions And Groundrules

In the process of performing the subject trade study, certain data or study definition was not available or specified. Assumptions and groundrules have been established to document, for the purposes of this trade study, the definition of important information which is not definite fact or is not available in the study time period. Major assumptions and groundrules which affect the four EEI trade studies are provided in a list common to all of the studies (Table 2.1-1). The assumptions which primarily affect the COTS modification study are documented in a separate list (Table 2.1-2).

2.2 Make-or-OTS-Buy Analysis Summary

2.2.1 SBI Hardware Vital to Program Cost Impact Analysis

The baseline candidate list of 93 SBI hardware items is shown in Appendix A with an "S" by each item. Space flight history has established that project costs are most significantly affected by space equipment weight. To determine which SBI hardware warranted the most study resources, the SBI hardware list was prioritized by mass (Table 2.2-1 from data base printout on Table 5.7) this table shows the top 32 items which represent 93% of the mass, 87% of the volume, and 82% by power (watts) of the total 93 SBI items.

2.2.2 Make-or-OTS-Buy Assessment Review for Sample Selection

The 32 hardware items in Table 2.2-1 were broken down by assembly and analyzed for the potential of substituting with off-the-shelf equipment. According to the guidelines determined in this study, only off-the-shelf equipment which required modifications less than or equal to 40 percent of the item (by weight) were considered as potential OTS candidates. Hardware assemblies which would greater than a 40 percent modification if purchased OTS were calculated as new build, since these assemblies have little, if any, potential as an OTS purchase. (see Table 2.2-2 Make-or-OTS-Buy Assessment Review for Sample Selection). The following are definitions of the columns of Table 2.2-2:

Item Number Prioritized by Mass:

> This column lists the hardware cost impact order to the total SBI program in terms of the hardware's weight. Since weight has been found to be the major indicator of cost based on historical experience in previous space programs, this factor was used to establish priority.

Hardware Item Number:

> This column gives the hardware identification number from the Space Biology Hardware Baseline (SBHB) listed in Appendix A.

Hardware Item Name:

This column gives the hardware Item name from the Space Biology Hardware Baseline (SBHB) listed in Appendix A.

% Buy:

The percentage of each piece of hardware which could be commercially obtained was estimated by assembly. The total percentage of this hardware which could be used from OTS equipment was placed in the "% Buy" column.

Sufficient Data Available:

This column marks with a "no" the hardware items for which sufficient data was not available for a make-or-OTS-buy analysis.

% Mod to Buy:

The modifications which would be required to the new commercial hardware chosen in the % Buy column for space applications were then calculated. The percent of modifications to the new hardware were placed in the "% Mod to Buy" column. NOTE: The numbers in the "% Mod to Buy" column represent the amount of modification needed by the commercial hardware, located in the "% Buy" column. These numbers do not represent the percentage of modifications to the entire piece of equipment.

Confidence Level:

This column indicates the confidence of the evaluators in the buy and modification estimates based on the depth and detail of hardware and historical information.

2.2.3 SBI Hardware OTS-Buy Candidates Selection

Table 2.2.2 was examined for potential candidates for modified OTS-buy. Those items marked with a "no" under the column Sufficient Data Available were eliminated from consideration. Those candidates which were estimated to have no potential for OTS buy were also eliminated. The remaining SBI hardware items which are potential OTS-buy candidates are listed in Table 2.2.3 SBI Hardware OTS-Buy Candidates.

2.3 Relative Cost Impacts

This trade study examines and compares the development cost of new build versus modified off-the-shelf hardware. Of the 32 items from the vital list of space biology hardware, 23 were found to have a potential to be acquired as modified off-the-shelf hardware. Total costing considerations should also consider operational and life cycle costs.

Table 2.2.3, SBI Hardware Potential Cost Savings for Modified OTS Buy, examines the SBI hardware items in Table 2.2.2 and determines the % OTS and Potential % Cost Savings. The following are columns of Table 2.2.3:

% OTS:

This column shows the percentage of COTS hardware that does not require modification for each item of SBI hardware. The formula for this column is:
% OTS = % Buy - (% Mod to Buy * % Buy)/100.

This figure gives the total percentage OTS for costing purposes. For example, if 100% of an item is purchased OTS, but 30% is modified, then only 70% is considered OTS for costing.

% Cost Savings:

The percentage cost savings for each piece of SBI hardware is given in this column. OTS costs are taken as 15% of the cost of new build hardware, based on historical cost data information. The discussion of this estimate is developed in Section 5.2.

2.3.1 Potential Percentage Cost Savings Derivation

The potential percentage cost savings was derived as follows:

a. The percentage of hardware to be flown without modification is costed at 15% of new design.

b. The portion of OTS to be modified is estimated to cost 50% as much as a new design.

The cost of the modified OTS is then calculated as:

Modified Item Cost = (% unmodified) * .15 + (% modified) * .50

Potential Cost Savings = 100% - Modified Item Cost

An example may serve to illustrate. Assume that a given item is 60% modified and 40% unmodified. Then the cost is given at:

Cost Modified Item = .40 * .15 + .60 * .50
= .06 + .30 = .36

Savings = 1.00 - .36 = .64 or 64%

If one varies the numbers and assumes 60% is modified and the modification cost is equal to the new design cost then:

Cost of modified item = .60 * 100% + .40 * .15
= .60 + .06 = 66%

Potential Cost Savings = 100 - 66 = 34%

2.3.2 Potential Cost Savings Summary

Based upon the assumptions that OTS costs 15% as much as new hardware and that modification costs are 50% as much as all new design, the figures in the Potential % Cost Savings column of Table 2.3 were compiled. As the table illustrates, the potential savings in using modified off-the-shelf hardware items are very substantial.

2.4 Future Work

2.4.1 Make-or-OTS-Buy Analysis of All SBI Hardware

This trade study analyzed only the 32 SBI hardware items which have the greatest cost impact in terms of weight induced cost. Of these items, 23 were found to have a potential to be acquired as off-the-shelf hardware and modified to satisfy the SBI hardware definitions. Based on this early analysis, purchasing these items off-the-shelf would result in significant savings to the program. However, all items of SBI hardware would benefit from a make-or-OTS-buy analysis.

2.4.2 Make-or-OTS-Buy Comparisons for Other Life Sciences Hardware

In the course of research for this study, it was noticed that some similarity exists between SBI medical equipment and medical equipment used for Crew Health Care (CHeC) in Space Station Freedom and Extended Duration Crew Operations (EDCO). A future study might compare make-or-OTS-buy plans for SBI equipment with those of CHeC and other Life Sciences equipment. Additionally, this study could see if any similar equipment is being considered by the Space Station international partners.

2.4.3 Trade-Off Between Reliability and Cost

The trade-off between reliability and cost may be a significant factor in hardware design. For instance, light weight low-cost commercial quality equipment could be placed into orbit and should a failure occur, it could be returned for repair. In-flight maintenance is possible and a trade-off can be established between crew time and hardware cost. Mean-time-between-failure (MTBF) could be used to select hardware items for flight use. Modular instruments such as those with card-cage mounted PC boards could be easily repaired on-orbit if spare parts kits are included. For general purpose laboratory equipment which is to remain on-orbit for extended periods of time, trade-offs must be established between initial hardware cost and reliability, balanced with the use of in-flight maintenance and change-out schedules for calibration or refurbishment.

2.4.4 Other Cost Analysis Techniques

Additional cost analysis techniques were developed in Section 3.3 of Appendix C. Comparisons of the costs of modifying commercial off-the-shelf hardware are calculated in Table 3-7 for a system complexity factor of 2, and in Table 3-8 for a system complexity factor of 4. A future task might use this cost analysis method for OTS-buy costs.

2.5 Conclusion Summary

This study encountered examples of make-or-OTS-buy decisions from past NASA programs. It would be an oversimplification to group hardware items by classification or function and use this information to make a make-or-buy decision on other hardware. This study concluded that all pieces of SBI hardware should be individually analyzed for make-or-OTS-buy potential. However, the indications from this study all point to the fact that SBI can be developed using a significant percentage of modified COTS or OTS and save substantial amounts of money in the process.

Based upon the assumption that modification design costs are 50% as much as an all new design and that purchase costs are 15% of a new design, the potential cost savings for each SBHB make-or-buy candidate were calculated and presented in Table 2.3.

Two definite conclusions can be drawn from this trade study.

a. Each actual SBI hardware item must be analyzed by assembly for potential as a modified OTS purchase, once the actual hardware has been baselined and chosen. Then each item must be costed separately based upon a careful evaluation of the modification cost required and the cost of the basic unit compared to a new design.

b. The potential for cost savings by purchasing and modifying OTS hardware wherever possible is substantial even where the modification costs are high.

Table 2.1-1 Common SBI Trade Study Assumptions and Groundrules

1) Where project, hardware, and operations definition has been insufficient, detailed quantitative analysis has been supplemented with assessments based on experienced judgement of analysts with space flight experience from the Mercury Project through the current time.

2) Space flight hardware cost is primarily a function of weight based on historical evidence.

3) The effects of interrelationships with space biology and life science hardware and functions other than the SBI baseline hardware are not considered in the trade study analyses.

4) Trade study information, once defined during the analysis for the purpose of establishing a known and stable baseline, shall not be changed for the duration of the trade study.

5) Hardware life cycle costs cannot be studied with quantitative analyses due to the unavailability of definition data on hardware use cycles, maintenance plans, logistics concepts, and other factors of importance to the subject.

6) The SBI hardware as identified is assumed to be designed currently without any special emphasis or application of miniaturization, modularity, commonality, or modified commercial off-the-shelf adaptations.

7) It is assumed that the required hardware performance is defined in the original equipment specifications and must be satisfied without regard to implementation of miniaturization, modularization, commonality, or modified commercial off-the-shelf adaptations.

Table 2.1-2 COTS Modification Trade Study Assumptions and Groundrules

1) COTS modification costs are 50% less than new build costs.

2) Commercial off-the-shelf hardware costs 15% as much as new build hardware.

3) Due to the high level of cost required to modify and certify hardware for spaceflight use, the original cost of COTS equipment is assumed to be relatively low and not significant in cost impact analysis.

4) Some off-the-shelf hardware may require such substantial modifications that changes will not be cost effective. A goal of this study will be to determine the maximum amount of recommended COTS hardware modifications.

Item Prioritized by Mass	Hardware Item #	Hardware Item Name	Mass		Power		Volume	
			Kg	Accumul.	(Watts)	Accumul.	M^3	Accumul.
1	168	CELSS	1000	1000	1300	1300	1.92	1.92
2	169	Gas Grain Simulator	800	1800	1500	2800	1.92	3.84
3	84	Soft Tissue Imaging System	300	2100	800	3600	.96	4.80
4	77	Hard Tissue Imaging System	136	2236	300	3900	.29	5.09
5	126	Scintillation Counter	90	2326	500	4400	.24	5.33
6	74	Force Resistance System	70	2396	100	4500	.40	5.73
7	145	Automated Microbic System	70	2466	110	4610	.20	5.93
8	155	Total Hydrocarbon Analyzer	70	2536	250	4860	.20	6.13
9	161	Inventory Control System	70	2606	500	5360	.20	6.33
10	162	Lab Materials Pack & Hand. Equip.	70	2676	500	5860	.20	6.53
11	163	Test/Ckout/Calibration Instrumentation	70	2746	200	5860	.20	6.73
12	106	Neck Baro-Cuff	45	2791	145	6205	.13	6.86
13	113	Blood Gas Analyzer	45	2836	250	6455	.13	6.99
14	61	Mass Spectrometer	41	2897	200	6655	.09	7.08
15	112	Plant HPLC Ion Chromatograph	40	2917	200	6855	.12	7.2
16	147	Head Torso Phantom	32	2949	0	6855	.12	7.32
17	63	Pulmonary Gas Cylinder Assem.	30	2979	0	6855	.09	7.41
18	110	Plant Gas Chromatograph/Mass Spectrometer	25	3004	100	6955	.20	7.61
19	115	Chemistry System	23	3027	100	7055	.08	7.69
20	138	Hematology	23	3050	200	7255	.07	7.76
21	34	Sample Preparation Device	22	3072	150	7405	.17	7.93
22	165	Experiment Control Computer System	20	3092	400	7805	.05	7.98
23	62	Pulmonary Function Equip Stor. Assem.	20	3112	0	7805	.05	8.03
24	82	Motion Analysis System	20	3132	100	7905	.05	8.08
25	99	Animal Biotelemetry System	20	3152	100	8005	.05	8.13
26	100	Blood Pressure & Flow Instrumentation	20	3172	200	8205	.06	8.19
27	109	Venous Pressure Transducer/Display	20	3192	100	8305	.05	8.24
28	129	Cell Handling Accessories	20	3212	50	8355	.05	8.29
29	57	Bag-in-Box	19	3231	0	8355	.15	8.44
30	111	Plant Gas Cylinder Assem.	19	3250	0	8355	.09	8.53
31	119	Gas Cylinder Assembly	19	3269	50	8405	.09	8.62
32	130	Cell Harvester	19	3288	50	8455	.06	8.68

93 SBI H/W Items 89 Items have 3535 kg mass 10.0M^3 of volume 10,359 watts of power 4 Items are TBD (all are small)

Table 2.2-1 List of SBI Hardware Vital to Program Cost Impact Analysis

Item # Prioritized by Mass	Hardware Item #	Hardware Item Name	Sufficient Data Available	% Buy	% Mod to Buy	Assessment Confidence Level	
						Low	High
1	168	CELSS		20	30		X
2	169	Gas Grain Simulator Facility		33	30		X
3	84	Soft Tissue Imaging System	no				
4	77	Hard Tissue Imaging System	no				
5	126	Scintillation Counter		95	30		
6	74	Force Resistance System		95	25		X
7	145	Automated Microbic System		95	40	X	
8	155	Total Hydrocarbon Analyzer		100	30	X	
9	161	Inventory Control System		95	15		X
10	162	Lab Materials Pack & Hand. Equip.		0	0		X
11	163	Test/Ckout/Calibration Instrumentation		50	20		X
12	106	Neck Baro-Cuff		95	30		X
13	113	Blood Gas Analyzer	no				
14	61	Mass Spectrometer		95	35		
15	112	Plant HPLC Ion Chromatograph	no				
16	147	Head Torso Phantom		3	35		X
17	63	Pulmonary Gas Cylinder Assem.		95	10		X
18	110	Plant Gas Chromatograph/Mass Spec.		95	35	X	
19	115	Chemistry System		95	30		X
20	138	Hematology		95	40	X	
21	34	Sample Preparation Device		0	0		X
22	165	Experiment Control Computer System		80	30		X
23	62	Pulmonary Function Equip Stor. Assem.		0	0		X
24	82	Motion Analysis System		90	20		X
25	99	Animal Biotelemetry System		95	20		X
26	100	Blood Pressure & Flow Instrumentation		85	250		X
27	109	Venous Pressure Transducer/Display		85	20		X
28	129	Cell Handling Accessories		0	0		X
29	57	Bag-in-Box		80	20	X	
30	111	Plant Gas Cylinder Assem.		95	10		X
31	119	Gas Cylinder Assembly		95	10		X
32	130	Cell Harvester		0	0	X	

Table 2.2-2 Make-or-OTS Buy Assessment Review for Sample Selection

Hardware Item #	Hardware Item Name
168	CELSS
169	Gas Grain Simulator Facility
126	Scintillation Counter
74	Force Resistance System
145	Automated Microbic System
155	Total Hydrocarbon Analyzer
161	Inventory Control System
163	Test/Ckout/Calibration Instrumentation
106	Neck Baro-Cuff
61	Mass Spectrometer
147	Head Torso Phantom
63	Pulmonary Gas Cylinder Assem.
110	Plant Gas Chromatograph/Mass Spec
115	Chemistry System
138	Hematology
165	Experiment Control Computer System
82	Motion Analysis System
99	Animal Biotelemetry System
100	Blood Pressure & Flow Instrumentation
109	Venous Pressure Transducer/Display
57	Bag-in-Box
111	Plant Gas Cylinder Assem.
119	Gas Cylinder Assembly

Table 2.2-3 SBI Hardware OTS Buy Candidates

Hardware Item #	Hardware Item Name	Mass (kg)	% Buy	% Mod to Buy	% OTS	Potential % Cost Savings
168	CELSS	1000	20	20	14	15
169	Gas Grain Simulator Facility	800	33	30	23	25
126	Scintillation Counter	90	95	30	67	71
74	Force Resistance System	70	95	25	71	72
145	Automated Microbic System	70	95	40	57	67
155	Total Hydrocarbon Analyzer	70	100	30	70	74
161	Inventory Control System	70	95	15	81	76
163	Test/Ckout/Calibration Instrumentation	70	50	20	40	39
106	Neck Baro-Cuff	45	95	30	66	71
61	Mass Spectrometer	41	70	35	45	51
147	Head Torso Phantom	32	3	35	2	2
63	Pulmonary Gas Cylinder Assem.	30	95	10	85	77
110	Plant Gas Chromatograph/Mass Spec	25	70	35	46	53
115	Chemistry System	23	50	30	35	38
138	Hematology	23	50	30	35	38
165	Experiment Control Computer System	20	80	30	56	60
82	Motion Analysis System	20	90	20	72	70
99	Animal Biotelemetry System	20	95	20	76	74
100	Blood Pressure & Flow Instrumentation	20	85	20	68	67
109	Venous Pressure Transducer/Display	20	85	20	68	67
57	Bag-in-Box	19	80	20	64	62
111	Plant Gas Cylinder Assem.	19	95	10	86	77
119	Gas Cylinder Assembly	19	95	10	86	77

Table 2.3 SBI Hardware Potential Cost Savings for Modified OTS Buy

3.0 Trade Study Database

The trade study database has been implemented on the dBase IV program by Ashton-Tate. The database definition including a database dictionary is provided in Appendix D.

3.1 Database Files

Four types of dBASE IV files were created for the Space Biology Initiative (SBI) Trade Studies database. These files are database files, index files, report files and view files. Database files have the file name extension dbf. A database file is composed of records and records comprise fields which contain the data. Index files have the file name extension ndx. Index files are used to maintain sort orders and to expedite searches for specific data. Report files have the file name extension frm. Report files contain information used to generate formatted reports. View files contain information used to relate different database (dbf) files. View files link different database files into a single view file.

3.2 Database Management

The development of the SBI Trade Studies database consist of two major steps, logical database development and physical database development. Defining attributes and relationships of data was the major emphasis of the logical database development. The attributes and relationships of the data were determined after analysis of available data and consultation with other SBI team members. Based on the knowledge from the logical database development, the physical structure of the database was developed and implemented on a computer. Setting up the database on a computer was the second major development process. The first step of this process was to determine how to store the data. dBASE IV allows data to be stored as character, numeric, date or logical data types. The second step was to create the database files. After the database files were created, the actual data was entered. For a complete listing of the database structures see Appendix D.

3.3 Database Use

To the maximum extent possible, data generated in performance of this trade study was stored in the database. This approach not only facilitated analysis and comparison of trade data, but also enabled the efficient publication and editing of tables and figures in the study report. In addition, the data are available in the database for future evaluation using different screening logic and report organization.

4.0 Documentation Survey

A literature review and database search were conducted immediately upon study initiation. In establishing criteria for make-or-OTS-buy decisions for SBI hardware, historical situations were reviewed. Decisions to modify off-the-shelf hardware or develop it from scratch have been made in Mercury, Gemini, Apollo, ASTP, medical, and in other scientific areas. These decisions are also currently underway in several areas of the Space Station Freedom Program. Library searches were make using titles, authors, key words, acronyms, phrases, synonyms, time periods and any possible (both in-person and by telephone) having knowledge of the study subject activities. Interviews with personnel were made throughout the initial portion of the study.

4.1 Documentation Sources

4.1.1 Complete SBI Trade Study Bibliography

The complete list of all references used in the four Eagle Engineering, Inc. trade studies is provided in Appendix B. A unique EEI SBI reference index number has been assigned to each information source.

4.1.2 Make-Or-Buy Trade Study Bibliography

Particular reference information from Appendix B that is of special importance to modification of COTS hardware is repeated in Table 4.1.2. The literature was searched for reference to make-or-OTS-buy analysis and historical comparison costs.

4.2 Historical Make-Or-OTS-Buy Cases

4.2.1 Life Sciences Laboratory Equipment (LSLE) Experiences

In the Spacelab 4 mission, the decision was made to fly a commercial echocardiograph. NASA life sciences managers decided that it is impractical for complex instruments such as the LSLE echocardiograph to be fully developed by NASA when commercial technology is readily available. The Life Sciences Study for the Space Station, SBI #94, suggested that many items identified for use in the Health Maintenance Facility (HMF) will lend themselves to the modified commercial hardware approach.

NASA life sciences managers decided that candidate equipment which could be developed by modification of commercial hardware would include general purpose laboratory equipment such as computers, TV/video systems, oscilloscopes, chromatography systems, and certain specialized medical equipment such as a defibrillator, anesthesia apparatus and a blood analyzer.

Lessons learned from the design and development of LSLE are directly applicable to the SBI program. Jim Evans, of JSC, in interview SBI #70, had several comments on LSLE hardware development which are applicable to SBI equipment in the life sciences discipline.

In modifying commercial off-the-shelf equipment, sometimes unexpected problems arise which add greatly to the complexity of the modifications. However, where the decision has already

been made to "OTS-buy", modification continues even though it would be reasonable to stop and redesign the hardware as a new build. No one wants to admit a mistake in judgement. Mr. Evans suggests having a modification policy which states that, every time a major modification requirement is encountered, the advantages and disadvantages of modifying be again compared against new build. This policy would encourage the examination of both "make" and "OTS-buy" options even though some cost was already spent examining modifications.

Mr. Evans stated that there can be no absolute make-or-OTS-buy policy for all hardware; i.e., some hardware is best as new build and some is best as modified COTS. Each hardware item must be examined individually in a make-or-OTS-buy analysis and items with very similar functions could result in different approaches. Mr. Evans comments were included in the Make-or-OTS-Buy criteria in Section 5.3.

4.2.2 Apollo Soyuz Test Program Experience

The Apollo Soyuz Test Program (ASTP) used the cost saving techniques of modularity, commonality, modifying commercial OTS equipment, and reducing paperwork suggested by the Low Cost Systems Office. Figure 4.2.2 shows the results of cost saving methods on this program (SBI #22, SBI #24).

4.2.3 Skylab: Beware of Off-The-Shelf Hardware

In the Skylab program, the $6 million S071/72 experiment had to do with mice and gnats living in an environmental package. All test animals died due to a failure caused by poor packaging of a commercial off-the-shelf invertor (SBI #97. Three off-the-shelf invertors were bought for the Skylab program at a cost of about $300 each. These invertors had the company inspector's stamp on them and were acceptance tested to reasonable requirements.

In NASA tests, one invertor was subjected to several thermal vacuum mission profiles and was judged ready to fly. Subsequent to failure test and analysis, which pointed to the invertor, the two remaining invertors were opened up for inspection. Conductors in several places were very close to being exposed and, in those places where wires were exposed (i.e. insulation missing), a piece of tape was used to provide insulation from the metal case. In several areas, there were signs of charring caused by arcing from the conductors to the case even though the invertors had passed all tests.

In a memo entitled "Beware of Off-the-Shelf Hardware" written in October 1973 (SBI #97), Donald Arabian states:

> "There is a lesson to be learned; off-the-shelf items should be taken apart and visually inspected with the "eyeball" as part of the evaluation. Know what you are buying. Reliance on the inspector stamp and reliance on acceptance tests are not sufficient. I have seen off-the-shelf items that have very good design, superb packaging, choice inspection, and which I would stage against the elegance in quantity and inspection of space hardware. On the other hand, I have seen the opposite to be true, as in this case. We should make darn sure that we look into the guts of off-the-shelf items and not solely depend on credentials of the component. The cost of doing this is peanuts. In this case,

the mice would have been put to good use and the $6 M would have produced some scientific data."

4.2.4 Make-or-OTS-Buy Examples From Other NASA Programs

This study encountered examples of make-or-OTS-buy decisions from past NASA programs. It would be an oversimplification to group hardware items by some classification or function and use this information to make a make-or-OTS-buy decision on other hardware. However, information and "lessons learned" from past programs can be extremely useful for those responsible for the decision to make or buy hardware. The following list provides known items of NASA equipment previously considered for make-or-OTS-buy implementation and identifies the resulting decision:

Hardware	Program	Make-or-Buy
DFI Telemetry	Apollo	Mod OTS
Lunar Comm RY	Apollo	New Build
AF Tape Player	Apollo	Mod OTS
TV Systems	Apollo, STS	New Build
Signal Process	STS	New Build
Teleprinter	STS	Mod OTS
Cabin Leak Detector	STS	Mod OTS
Sir-C Payload	STS	International Dev

Richard Whitlock of the JSC Cost Analysis Office was also interviewed (SBI #64). He also advised caution and reconsideration of a "buy" choice if the amount of modification could be greater than 30 to 40 percent. Mr. Whitlock's suggestions were included in the make-or-OTS-Buy Criteria in Section 5.2.

4.2.5 Crew Health Care

An in-house make versus subcontractor make analysis was performed for each element of the CHeC program by McDonnell Douglas Astronautics Company (SBI #38). This study was made in accordance with their Make-or-Buy plan (DR MR-08, Report No. MDC H4013) dated February 1988. The process used is shown in Figure 4.2.5. The decision was made to buy almost all CHeC items from subcontractors because of the high dollar value, technical risk, degree of subcontract interface, contractual complexity, or schedule criticality required or the application of specific techniques in the preparation, consummation, and administration of the contractual arrangements. Table 4.2.5 lists these subcontract items. The items were given to subcontractors making similar equipment; however, the actual amount which can be considered off-the-shelf is not known.

Even though the "make-or-buy" terms used in CHeC vary from the "make-or-OTS-buy" idea of this report, an investigation of MDAC's CHeC make-or-buy analysis is beneficial to the understanding of the SBI make-or-OTS-buy decision.The analysis of the CHeC hardware divided the items into the following categories: 1) must make, 2) can make or buy, 3) must buy, or 4) must buy from a major subcontractor (in this case, either IBM or Honeywell). An

examination of the make-or-OTS-buy philosophy for CHeC items may be useful in considering alternatives for SBI hardware. Appendix E contains the Make-or-Buy Analysis for CHeC.

4.2.6 Low Cost Systems Office

The Low Cost Systems Office was established at NASA Headquarters in 1973. Its broad mandate was to facilitate significant reductions in the costs of developing, producing, launching, and acquiring spacecraft systems and subsystems. In its four years of existence, this office examined cost saving methods such as modularity and commonality, modifying commercial off-the-shelf equipment, reducing paperwork, and listing standardized components, such as batteries, for use in several space hardware items (SBI #22, SBI #24). Figure 4.2.2 shows the cost savings benefits of the Low Cost Systems Office approach on the Apollo Soyuz Test Program.

4.2.7 Industry Make-or-OTS-Buy Plans

Major commercial industries have investigated the relative merits of new build hardware versus modifying existing equipment. Many of these companies have documented a Make-or-OTS-Buy plan. However, the information in these documents is considered proprietary and access to the documents is often restricted. These documents may contain historical cost relation information which could benefit further make-or-buy studies of SBI hardware. However, care must be taken with industry definitions of make-or-buy since "make" often refers to an in house build and "buy" often refers to a new build by a subcontractor.

Table 4.1-2 Bibliography for COTS vs New Hardware

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI04	Shannon, J.	Business Practice Low Cost System Activity		NASA JSC		Houston, TX.	11/12/75
SBI22	LMSC	Low-Cost Program Practices For Future NASA Space Programs		LMSC	LMSC-D387518	Sunnyvale, CA.	05/30/74
SBI23	Steward, GMiller, L	Biomedical Equipment Technology Assesment For The Science Laboratory Module		Management and Technical Services Company		Houston, TX.	08/01/86
SBI50	MDAC	Crew Health Care	1	MDAC	MDC H3924	Houston, Texas	11/01/88
SBI57	Rockwell Intl.	Space Shuttle Management Proposal	II	Rockwell Intl.	SD 72-SH-50-2		05/12/72
SBI58	LMSC	Space Shuttle Management Proposal	II	LMSC	LMSC-D157364		05/12/72
SBI59	MDAC	Space Shuttle Program Management Proposal		MDAC	E0600		05/12/72
SBI68	Hamaker, Joe	Telephone interview relating to MSFC history and techniques for cost estimating.		Cost Analysis Branch Chief MSFC		Huntsville, Al.	04/27/89
SBI70	Evans, Jim	Personal Interview		Life Science Project Division JSC		Houston, TX.	04/19/89
SBI71	Heberlig, Jack	Telephone interview relating to make-or-buy lessons learned from Apollo		International Business Machines (IBM)		Houston, TX.	03/10/89
SBI72	Loftus, Joe	Telephone interview relating to make-or-buy history		Assistant Director (Plans) JSC		Houston, TX.	03/14/89
SBI73	Christy, Neil	Telephone interview relating to hardware development student experiments, and make-or-buy				Houston, TX.	03/15/89

Table 4.1-2 Bibliography for COTS vs New Hardware

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SB174	McAllister,Fred	Telephone Interview		Man-System Division, JSC		Houston,TX	03/14/89
SB175	Trowbridge, John	Interview relating to CHeC make-or-buy		McDonnell Douglas		Houston,TX.	03/17/89
SB176	Trowbridge, John	Personal interview relating CHeC experience to miniaturization, modularity and make-or-buy		McDonnell Douglas		Houston, TX.	03/29/89
SB177	Nagel, John	Personal Interview relating to LSLE make-or-buy experience		Eagle Technical Services		Houston, TX	03/27/89
SB178	McFadyen, Gary	Personal Interview relating to life science hardware background at JSC		Southwest Research Institute		Houston, TX.	04/10/89
SB192		Spacelab Payloads Accomodations Handbook		NASA MSFC	SLP/2104	Huntsvillle, Al.	08/16/85
SB194		Life Sciences Study for the Space Station		Management and Technical Services Co.		Houston, TX.	08/01/84
SB197	Arabian, D.	Beware Off-the-Shelf Hardware		NASA JSC		Houston, TX.	10/17/73
SB198	SB198NASA JSC	Experimenting with Baroceptor Reflexes	12	NASA Tech Briefs	No. 11	New York, NY	12/01/88

NASA-S-75-1029C

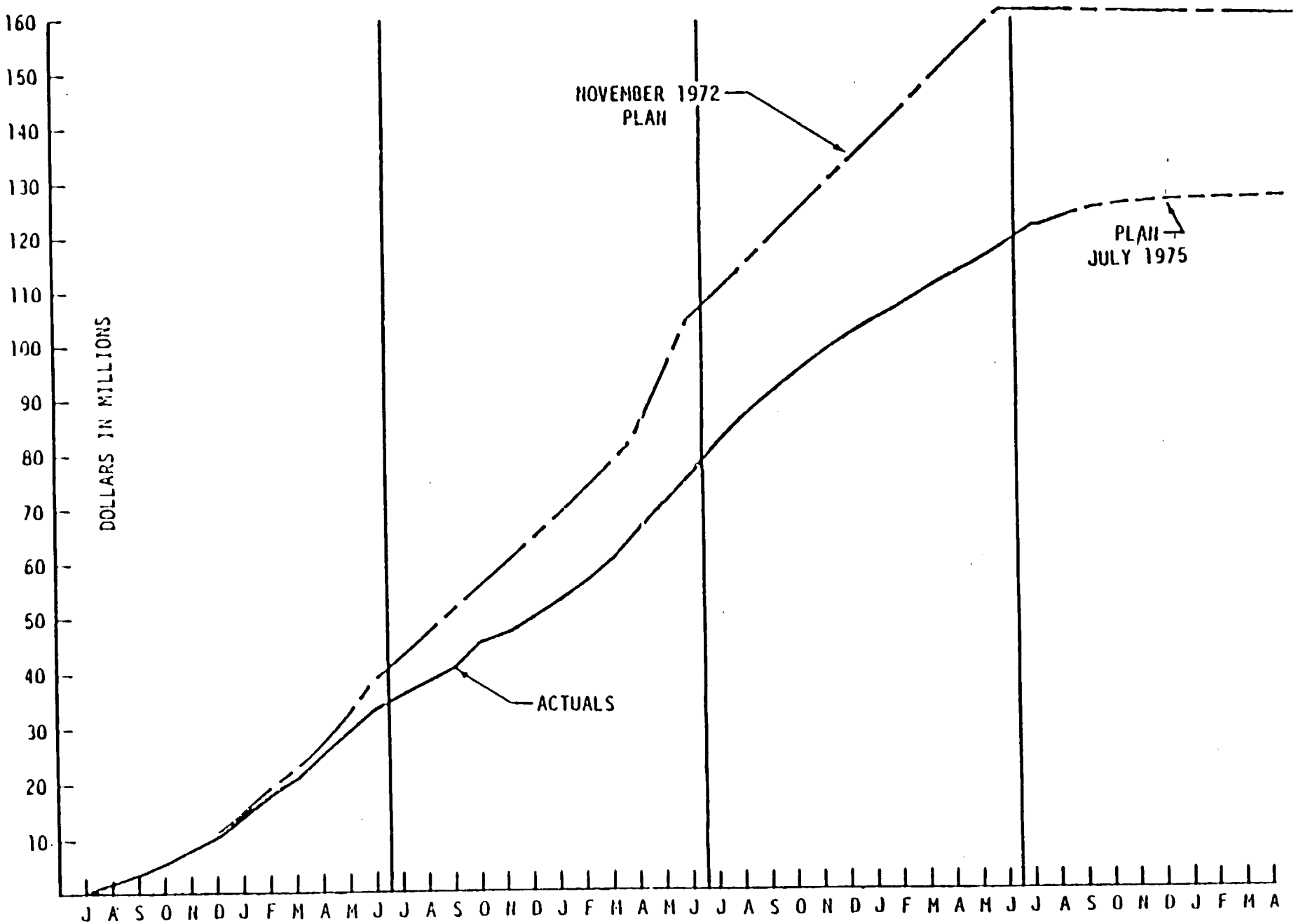


Figure 4.2.2 JSC - ASTP COST PLAN VS ACTUAL COST

Figure 4.2.5 Make-or-Buy (MOB) Plan for CHeC

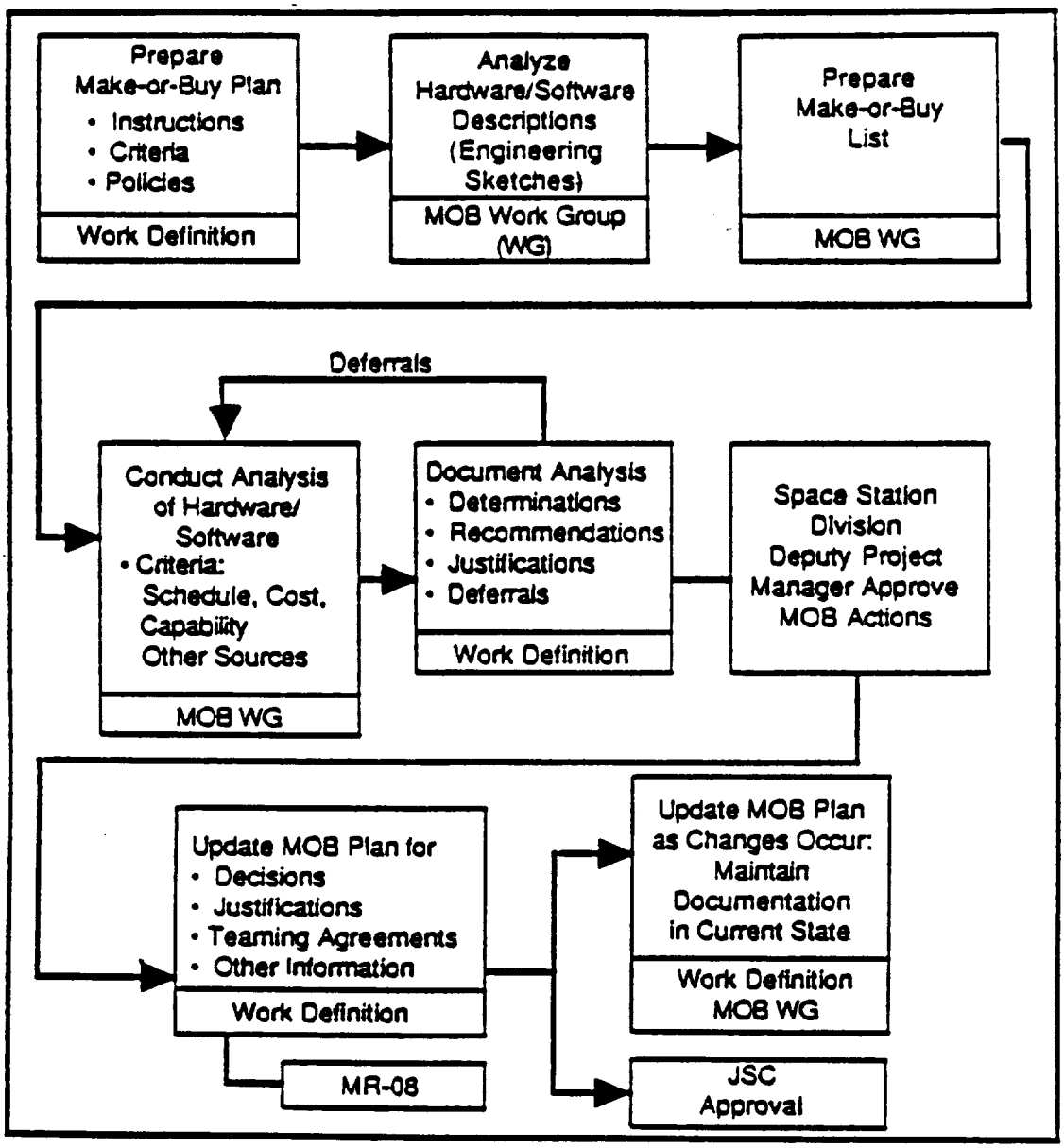


Table 4.2.5 Buy Items To Be Subcontracted For CHeC

Aerometer
Archival Particulate Sampler
Auto Microbial Identification Sys.
BCC
Bike/Rowe
Bioimpedance Analyzer
Blood Gas Analyzer
Blood Pressure Monitor
Body Mass Measuring Device
Cassette Processor/Tape Backup
Cautery Device
Centrifuge
Charged Particle Telescope Sensor & Electronics (EV)
Clinical Chemistry Analyzer
Compound Specific Analyzers
DCC
Defibrillator
Dental Camera
Dental Power Hand Tool
Dental X-Ray Collimator
Display Monitor
Dynamic Environment Mea. Sys.
ECG Monitor
EDP-1
Fluid Bags
Gas Chromotograph/Mass Spectrometer
Graphics
Heat and Moisture Exchanger
Hematology Analyzer
Incubator
Infusion Pumps
Interface Hardware Kit
Ion Chromotograph
Ion Specific Electrodes
Line Vacuum Air/Fluid Separator
Mass Storage Unit (MSU)
MDAC I/O
Medical Local Bus Controller
Metabolic Gas Monitor
Metal Aerosol Analyzer
Microbial Air Sampler System
Microbial Detoxification/Disposal System
Monochrome Raster Display Monitor
MPAC Processor (Modified)
Multiplexer/Demultiplexer
Multivariable Monitor Graphics
NIU (Special for X-ray)
Osmometer
Passive Thermoluminescent Detectors (TLD)
Portable Air Compressor
Portable Air/Fluid Separator
Portable Compressed Gas Tracks
Portable MPAC
Portable Total Hydrocarbon Analyzer
Pressure Regulator
Pulse Oximeter
Real Time Particulate Counter & Data Logger
Remote Network Interface Unit (RNIU)
Resistive Exercise Device
SDP-4B
SDP-X
Secondary Power Unit
Slide Staining System
Sound Level Monitor and Recorder
Spectrophotometer (UV-VIS)
Sterile Water for Injection System
Task Lighting
Tissue Equivalent Proportional Counter
Anneal and Storage
Total Organic Carbon Analyzer
Transport Monitor
Treadmill
Turbidity Meter
Utility Interface Panel
Ventilator
Vibration Isolation Device
Volatile Organics Analyzer (GC/MS)
Volatile Organics Sampler
Warm Blood Collection System
X-Ray Source/HV Generator

5.0 Trade Study

5.1 Considerations For Make-Or-OTS-Buy Analysis

There are many issues which must be considered in determining a make-or-OTS-buy decision. These factors must be considered in the design and development of equipment or in the analysis of commercially available hardware for modification.

5.1.1 Gravity Dependence

The impacts of a micro-gravity environment on commercial medical equipment must be considered. Plans and schematics must be reviewed to eliminate gravity dependance.

Devices which rely on gravity for their operation on Earth may have to be completely redesigned for operation in space. Fluid handling will be one of the problems encountered when performing life science research in a micro-gravity environment. Because a great majority of analytical biomedical equipment requires some degree of fluid handling during sample preparation, sample analysis and clean up procedures, this problem must be addressed.

5.1.2 Electromagnetic Interference

There is a significant risk of Electromagnetic Interference (EMI) among the various pieces of biomedical hardware. This could lead to erroneous results that could be difficult to detect. Major SBI equipment must also be checked for possible EMI with the NSTS and Space Station Freedom.

5.1.3 Toxicology

Modifications to commercial biomedical equipment may be required due to environmental toxicology constraints. Many of the plastics found in current biomedical hardware, along with many common disinfectants and reagents, will not be allowed aboard Space Station Freedom since they have potential toxic effects at certain atmospheric concentrations. Many compounds will not be allowed in the closed environment of the Space Station even at a sea level pressure of 14.7 PSI. A study to assess the impact of toxicology regulations on candidate biomedical equipment should, therefore, be done for all make-or-OTS-buy candidate equipment. Toxicology considerations include contamination from outgassing and the restrictions of dangerous materials such as mercury. Materials such as glass must also be avoided because of crew safety.

5.1.4 Crew Interfaces

Safety requirements include review of vehicle and crew interfaces to eliminate hazards to the crew and hazards which might damage the vehicle. This includes elimination of sharp edges and corners, stress analysis of mounting points, and proper fusing and grounding. Latches, levers, cranks, hooks and controls that can catch/retain equipment should be designed and located to prevent gaps, overhangs, and/or snags. In addition, latches should be designed to prevent

inadvertent actuation. All dials, controls, and gauges must be easy for the crew to read and operate.

5.1.5 Weight And Fit

Commercial equipment must be examined for excessive weight or size. If either of these are high, then a study should be made to investigate miniaturization and weight reduction capabilities if designed from scratch.

5.1.6 Servicing

Another issue is the frequency with which commercially available biomedical equipment needs to be serviced. Both routine calibrations and preventive maintenance, as well as unexpected breakdowns, are common occurrences in commercial labs. Without modifications, this servicing frequency can only be expected to increase in a micro-gravity environment. Modifications enhancing reliability are essential both to the collection of the science data and the reduction of crew time for maintenance and service. Designs which allow for modular replacement parts should be considered in reducing SBI equipment servicing. The added initial cost for increasing reliability will be compensated for by the reduced long-term costs for replacement storage and on-board crew time.

5.1.7 Medical Certification

One issue that needs to be addressed in any make-or-OTS-buy decision is medical certification. Any commercial medical equipment which can be potentially dangerous to humans must undergo severe testing by the Food and Drug Administration (FDA). However, modifications to this equipment, even to the housing or structure, could potentially nullify any FDA certification. In a make-or-OTS-buy analysis of complex medical equipment such as a tissue imaging system, the amount of time for medical approval and certification on made or modified equipment must be considered.

5.1.8 Flammability

Off-the-shelf products must be evaluated for flammability and the possible catalytic combination of materials. Some pieces of commercial medical equipment already meets requirements for safety in oxygen-rich environments such as operating rooms.

5.1.9 Standardization

Commercial medical equipment may contain non-standard parts without quality checks or traceability. Commercial units are not necessarily identical with each other. Documentation of commercial equipment may be poor.

5.1.10 Power Requirements

The power requirements of commercial off-the-shelf equipment must meet those of the NASA supplier. Cables and connectors must interface with NASA spacecraft.

5.1.11 Extra Features

Commercial off-the-shelf hardware may provide extra features and functions which may, on inspection, prove to be unnecessary to SBI equipment users. Taking out these extra features may reduce weight or volume and may be advisable except in cases where the total system is so complex that these changes require extra certification and inspection.

5.1.12 Batch Procurement

After make-or-OTS-buy decisions have been completed, a listing can be made of SBI hardware to be purchased. Examination of this list will determine the efficiency of grouping some hardware under a single subcontract. Batch procurement can lower contract management manpower and costs.

5.1.13 License Agreements

Some hardware requires license agreements to ensure that sufficient rights are available to allow the production of modified equipment meeting program requirements. During the evaluation phase, contract managers initiate extensive industry surveys to establish appropriate licenses with potential suppliers. NASA must be able to obtain access to any information, such as source codes and wiring diagrams, needed for equipment performance and testing. Equipment with information limited as "proprietary" may not be acceptable.

5.1.14 Increased Status Reviews and Reports

Periodic status reviews are necessary to monitor and assess the progress of SBI hardware development. Reviews may be accomplished at the subcontractor's facility when necessary to ensure open and effective communication. Subcontractors developing complex equipment items are reviewed often while routine items are reviewed as necessary based on progress. For example, an image digitizing system represents advanced technology and high risk; this system would undergo several formal reviews. During critical stages of development, on-site technical representation ensures that all system requirements have been addressed. Detailed reporting of cost, schedule, and technical milestones enhances monitoring of SBI hardware development.

5.2 Make-or-Buy Criteria

A more in-depth make-or-OTS-buy analysis would group SBI equipment hardware into one of these categories: 1) Must OTS-buy, 2) Must make, 3) Can make or OTS-buy. The requirements for these categories were developed from the McDonnell Douglas Astronautics Company (MDAC) make-or-buy decisions for Crew Health Care SBI #48). Examination of these guidelines would be useful in a detailed make-or-OTS-buy analysis of SBI hardware.

5.2.1 Must-OTS-Buy Considerations

The following must-OTS-buy considerations were developed from the MDAC make-or-OTS-buy analysis for CHeC. However, these considerations are of value in determining factors necessary to consider in an SBI make-or-OTS buy analysis. Must-OTS-buy decisions can be based on the following criteria:

A. The item involves development that has been already completed by an outside source on prior similar programs and it is not cost or schedule effective to duplicate such development effort on the new program.

B. An outside source possessed unique processes, tooling, facility, relative technical superiority, or exclusive franchises for a given item or task.

C. When the financial or technical risks are not involved, a buy decision can be made if comparative capabilities, schedules, and costs favor a buy recommendation. In evaluating suppliers, the relative competence, ability, experience, size, and location (small business, small disadvantage business, or labor surplus areas) of suppliers must be considered. Supplier proximity (or the logistics involved in coordination, delivery or assembly of supplier parts), supplier accessibility, prior performance, parts replacement, and warranties are also evaluation factors.

5.2.2 Must-Make Considerations

Based on the information of the MDAC make-or-buy analysis for CHeC, must-make decisions should take the following criteria into consideration:

A. An item could be developed and produced without requiring additional facilities at equal or lower cost than if purchased.

B. An item was, or is being made cost-effectively by NASA on other similar space biology programs.

C. Certain complex items or those with critical interfaces, determined to involve quality, cost, schedule, or technical risks, warranted "must make" recommendation to ensure maximum management attention to and control of these items to minimize such risks.

D. In a make-or-buy situation, where the successful development of a complex item depends in large measure on close interface control and rapid adaptation to changing in-house design conditions or interface requirements, a make decision was warranted even though the item or task could be competitively purchased in terms of comparable costs and performance.

E. When certain new assemblies or schedule-critical components required close management or engineering surveillance during the development process in order to ensure meeting program need dates, a make decision was made.

5.2.3 Make-or-OTS-Buy Considerations

Either make-or-buy conditions occurred in the CHeC analysis where neither a strong make-or-buy recommendation existed. Other factors considered by MDAC in the make-or-buy analysis for CHeC, include:

A. Make-or-OTS-buy tradeoff factors which include the relative availability of specialized personnel, material, or processes for a given program; capacity considerations, such as the impact on plant workloads; facility changes and costs; laboratory, manufacturing, or manpower resources; new business and future production requirements; and market conditions.

B. New technology or product lines and future technological innovations must be assessed to determine whether to embark on the new product line in-house or to solicit and support outside development of the item.

5.3 Benefits of Make

The following are advantages of new build hardware:

New build may be the only way to construct unique hardware.

Can specify extremes of reliability and safety if needed.

Ability to incorporate miniaturization, commonality, modularity, or other special features.

Possibility of reduced operational maintenance cost due to modularity.

5.4 Benefits of Buy

The following are advantages of modified OTS hardware:

Possibility of significantly less DDT&E and production cost.

Possibility of significantly less DDT&E time.

Vendor's design and production expertise utilized.

Spare parts usually available in future.

Technology updates available in future.

Significant cost reduction.

5.5 Knowledge of Commercial Technologies

It is imperative that a thorough search of existing and planned commercial technologies be performed before any decision is made to design a product from scratch. For example, fluid handling will be one of the problems encountered when performing life science research in a micro-gravity environment. Because a great majority of analytical biomedical equipment requires some degree of fluid handling during sample preparation, sample analysis and clean up procedures, this problem must be addressed. A capability for fluid transfer in a microgravity environment might be considered non-existent in the commercial market; however, an in-depth survey could reveal that equipment to perform these tasks exists commercially.

For example, current laboratory techniques for diluting, dispensing, pipeting and titration of fluids usually rely on gravity-dependent processes. However, a survey of commercial capabilities done by Management and Technical Services Company (MATSCO) and published in "Biomedical Equipment Technology Assessment for the Science Laboratory Module" (SBI #23) found that some sample preparation devices are currently being manufactured which could work in micro-gravity. These systems can provide for fluid handling, reduce crewtime requirements, and reduce the volume of reagents and samples necessary because of eliminated waste and higher accuracy. One such system is the Beckman Accu-Prep. It uses positive displacement rather than peristaltic pumps to transfer fluid and should, therefore, work fine in micro-gravity regardless of cabin pressure. An additional advantage of the Accu Prep is its built-in microcomputer which is able to store up to 50 separate sample preparation protocols, thereby eliminating the need for hardcopy or uplinked Payload Crew Activity Plans. Further studies could then be done to investigate the feasibility of modifying this equipment for use in space.

5.6 Uniformity of Design Requirements

Uniformity of design requirements needs to be established between the design organization and the flight agency (NASA) certifying quality assurance. Uniform criteria for application of reliability standards, materials requirements and requirements, to the many classes of hardware to be developed must be established. The Management and Technical Services Company (MATSCO) in preparing the Life Sciences Study for the Space Station, SBI #94, learned that testing done by the manufacturer of commercial equipment may exceed spacecraft requirements, see Table 5.6. Information on the Spacelab requirements was obtained from the Spacelab Payload Accommodation Handbook, SBI #92.

5.7 Hardware Make-or-OTS-Buy Analysis

5.7.1 SBI Hardware Vital to Program Costs

The Space Biology Hardware Baseline list is shown in Appendix A. This list has 169 hardware items, however, only 93 of these items are categorized for SBI functions. This list was based-lined December 1988 and then updated 23 March 1989. Many of these items are in the conceptional phase, however, some are existing hardware items that are in existence today.

This list is a reference list only. There will more than likely be future additions and deletions to this baseline list.

The initial survey data analysis was performed to select a sample of the SBHB items which could be potential candidates for make-or-OTS-buy. With limited study time and a SBHB of 93 items, a method was needed to separate items which could have large cost impact and were worthy of study resource application. The following method was used. All SBHB items were listed in descending order of probable acquisition cost. Weight was used as an indication of probable acquisition cost based on historical experience in previous space programs. It was found that 34 percent of the items (32 items) accounted for 93 percent of the mass or probable cost (see Table 5.7, Database Listing for SBI Hardware Vital to Program Cost Impact Analysis). The accumulated volume (8.68 M^3) of the 32 items represents 87% of the total volume. The accumulated power (8455 watts) represents 82% of total power requirements. Thus these 32 items account for the majority of the cost of SBI hardware.

5.7.2 SBI Hardware Sample Selection

The prioritized list of "vital" hardware items was considered for as a sample set of candidates for buy. This list was further examined for those items which could be obtained from modified COTS hardware. The 32 hardware items in Table 5.7 were broken down by assembly and analyzed for the potential of substituting with off-the-shelf equipment. According to the guidelines determined in this study, only off-the-shelf equipment which required modifications less than or equal to 40 percent of the item (by weight) were considered as potential OTS candidates. Hardware assemblies which would require greater than a 40 percent modification if purchased OTS were calculated as new build, since these assemblies have little, if any, potential as an OTS purchase. This list was developed using all available resources within the constraints of this study. This assessment of possible candidates is based upon the best knowledge of the SBI hardware items at the time of this study. The items for which estimates were left blank in this table ("No" under Sufficient Data) indicates that these items are still in a conceptual phase and sufficient data was not available for assessment. (See Table 5.7-1, Database Listing for Make-or-OTS-Buy Sample Selection Assessment.)

5.7.3 SBI OTS-Buy Candidates Selection

The hardware items in Table 5.7-1 were examined for potential off-the-shelf buy candidates. Items of SBI hardware for which sufficient data was unavailable for breakdown and analysis be assembly were eliminated for consideration. Those hardware items judged to have no potential for OTS-buy were also eliminated. The remaining SBI hardware items were judged to have a potential for use as modified commercial off-the-shelf equipment items. These OTS-buy candidates are listed in Table 5.7-2, Database Listing for Make-or-Buy Candidate Sample Set and summarized in Table 2.2.3.

5.8 Make-or-OTS-Buy Cost Impact Analysis

Table 5.7-2 lists the % Buy, % Mod to Buy, and % OTS of the most important pieces of SBI hardware. The potential percentage cost savings were then calculated for each item, using the following method:

The potential percentage cost savings was derived as follows:

a. The percentage of hardware to be flown without modification is costed at 15% of new design.

b. The portion of OTS to be modified is estimated to cost 50% as much as a new design.

The cost of the modified OTS is then calculated as:

Modified Item Cost = (% unmodified) * .15 + (% modified) * .50

Potential Cost Savings = 100% - Modified Item Cost

An example may serve to illustrate. Assume that a given item is 60% modified and 40% unmodified. Then the cost is given at:

Cost Modified Item = .40 * .15 + .60 * .50
= .06 + .30 = .36

Savings = 1.00 - .36 = .64 or 64%

If one varies the number and assumes 60% is modified and the modification cost is equal to the new design cost then:

Cost of modified item = .60 * 100% + .40 * .15
= .60 + .06 = 66%

Potential Cost Savings = 100 - 66 = 34%

5.8.1 Neck Baro-Cuff Make-or-OTS-Buy Example

The 32 items accounting for 94 percent of the mass of SBI hardware were examined for the possibility of purchase as commercial off-the-shelf equipment, with modifications for use in the micro-gravity environment of space. Each of these 32 pieces of SBI hardware was broken down into major components and the components analyzed for make-or-buy recommendations. The Neck Baro-Cuff, SBHB item #106, is shown as an example of this process.

The Neck Baro-Cuff, also known as the Carotid Sinus Baroreceptor Stimulator, is a chamber strapped to the neck of a human subject which applies pressure or suction of controlled magnitude and duration to the carotid arteries. The Baro-Cuff was designed to study the blood pressure reflex responses of astronauts in space. A Neck Baro-Cuff drawing, which appeared in NASA Tech Briefs, Dec. 1988 (SBI #98), is shown in Figure 5.2.

The Neck Baro-Cuff was broken down into the following components:

Neck chamber and umbilical tube

Pressure sensor
Bellows
Stepping motor
Electronic system

The Baro-Cuff Neck Chamber is modified uniquely to fit the front of the subject's neck so that it provides a seal for both positive and negative pressures. The seal leaks so little that a bellows can be used instead of a pump to change the pressure in the chamber. The bellows, driven by a stepping motor, is smaller and quieter than a pump and uses less power. The electronic system contains a microprocessor chip which controls the stepping motor and collect the data. Erasable, programmable, read-only memory chips store custom software for the microprocessor. Instruments measure and display the pressure in the chamber and the subject's electrocardiogram and respiration.

5.8.2 Neck Baro-Cuff Make-or-OTS-Buy Analysis

Each of the Baro-Cuff components were analyzed for possible off-the-shelf purchase. The neck chamber was immediately eliminated since it must be designed and fitted to conform to the test subject. However, the pressure sensor, bellows, stepping motor, and electronic system were found to all have the potential for off-the-shelf purchase followed by modifications for use in space. These items were judged to account for 95 percent of the weight of the Baro-Cuff system. Each of these items was then analyzed for the amount of modifications which would be required. The percentage of OTS that must be modified was estimated to be 30%. This means 66% is OTS with no modification required and 29% is OTS which must be modified. Modification costs are then estimated to be 50% as much as a new design and OTS cost taken as 15% the cost of new design. The result is a net savings on the baro-cuff of 70% compared to all new design. Had the modification cost been taken as equal to the cost of new design, and the OTS cost taken as 25% of a new design, the net savings would be reduced to 49%.

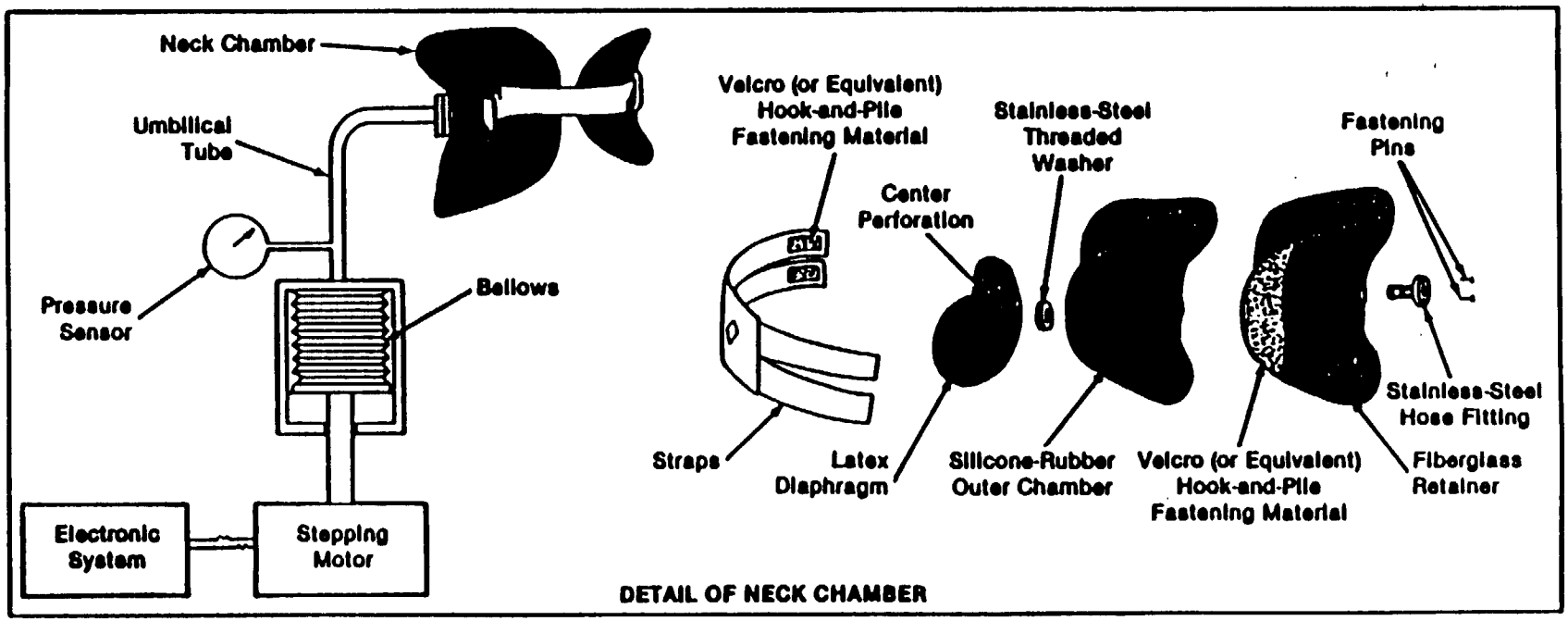


Figure 5.2-1 Make-or-Buy Cost Impact Analysis Example

Table 5.6 Comparison of Environmental Standards Between a Commercial Company and Spacelab

	HEWLETT-PACKARD	SPACELAB REQUIREMENT
TEMPERATURE:	-40°C to 75°C (Non Operating) -20°C to 65°C (Operating)	-10°C to +55°C
HUMIDITY:	40°C 5-95% RH 65°C 90% RH (Non Operating)	Test Not Required
VIBRATION:	5 - 55 - 5 Hz .015 IN 1 Min/Octave	Vibration Spectrum Defined in SPAH*
SHOCK:	30g 11MS 18 Shocks	20g 11MSs 18 Shocks
BENCH HANDLING:	Per MIL-T-28800A Paragraph 4.5.5.4.4 (4" Drop Test)	Test Not Required
EMI:	Radiated-Conducted- Electrostatic Discharge Power Line Transients Susceptibility Magnetic Fields	Radiated Only Per MSFC Spec 521
STRIFE:	Temperature Cycling for 1 Month	168 HR 55°C Burn-In
PRESSURE:	Low Pressure Test to Qualify for Air Transport Shipment	Not required

Table 5.7 Database Listing of SBI Hardware Vital to Program Cost Impact Analysis

ITEM # PRIORITIZED BY MASS	HW ITEM #	HARDWARE ITEM NAME	ACCUM % OF ITEMS	MASS (kg)	ACCUM MASS	ACCUM MASS PERCENT	ACCUM POWER PERCENT	ACCUM VOLUME PERCENT
1	168	CELSS Test Facility	1	1000.0	1000	28	13	19
2	169	Gas Grain Simulator	2	800.0	1800	51	27	38
3	84	Soft Tissue Imaging System	3	300.0	2100	59	35	48
4	77	Hard Tissue Imaging System	4	136.0	2236	63	38	51
5	126	Scintillation Counter	5	90.0	2326	66	42	53
6	74	Force Resistance System	6	70.0	2396	68	45	57
7	145	Automated Microbal System	8	70.0	2466	70	46	59
8	155	Total Hyrdocarbon Analyzer	9	70.0	2536	72	48	61
9	161	Inventory Control System	10	70.0	2606	74	53	63
10	162	Lab Materials Packaging & Handling Equipment	11	70.0	2676	76	58	65
11	163	Test/Checkout/Calibration Instrumentation	12	70.0	2746	78	60	67
12	106	Neck Baro-Cuff	13	45.2	2791	79	61	69
13	113	Blood Gas Analyzer	14	45.0	2836	80	63	70
14	61	Mass Spectrometer	15	40.7	2877	81	65	71
15	112	Plant HLPC Ion Chromatograph	16	40.0	2917	83	67	72
16	147	Head/Torso Phantom	17	32.0	2949	83	67	73
17	63	Pulmonary Gas Cylinder Assembly	18	30.0	2979	84	67	74
18	110	Plant Gas Chromatograph/Mass Spectrometer	19	25.0	3004	85	68	76
19	115	Chemistry System	20	23.0	3027	86	69	77
20	138	Hematology System	22	23.0	3050	86	71	78
21	34	Sample Preparation Device	23	22.0	3072	87	73	79
22	165	Experiment Control Computer System	24	20.1	3092	87	77	80
23	62	Pulmonary Function Equipment Stowage Assembly	25	20.0	3112	88	77	80
24	82	Motion Analysis System	26	20.0	3132	89	77	81
25	99	Animal Biotelemetry System	27	20.0	3152	89	78	81
26	100	Blood Pressure and Flow Instrumentation	28	20.0	3172	90	80	82
27	109	Venous Pressure Transducer/Display	29	20.0	3192	90	81	82
28	129	Cell Handling Accessories	30	20.0	3212	91	82	83
29	57	Bag-in-Box	31	19.0	3231	91	82	84
30	111	Plant Gas Cylinder Assembly	32	19.0	3250	92	82	85
31	119	Gas Cylinder Assembly	33	19.0	3269	92	82	86
32	130	Cell Harvestor	34	19.0	3288	93	82	87

NOTES:

1. Total number of SBI hardware items = 93.
2. 89 items have 3535 kg mass, 10,359 Watts power, and 10 cubic meters volume.
3. 4 items are not currently defined, but all are small.

Table 5.7-1 Database Listing for Make-or-Buy Sample Selection Assessment

Item # Prioritized by Mass	HW Item #	Hardware Item Name	Sufficient Data Available	% Buy	% Mod to Buy	Assessment Confidence Level
1	168	CELSS Test Facility	YES	20	30	HIGH
2	169	Gas Grain Simulator	YES	33	30	HIGH
3	84	Soft Tissue Imaging System	NO	0	0	
4	77	Hard Tissue Imaging System	NO	0	0	
5	126	Scintillation Counter	YES	95	30	HIGH
6	74	Force Resistance System	YES	95	25	HIGH
7	145	Automated Microbal System	YES	95	40	LOW
8	155	Total Hyrdocarbon Analyzer	YES	100	30	LOW
9	161	Inventory Control System	YES	95	15	HIGH
10	162	Lab Materials Packaging & Handling Equipment	YES	0	0	HIGH
11	163	Test/Checkout/Calibration Instrumentation	YES	50	20	HIGH
12	106	Neck Baro-Cuff	YES	95	30	HIGH
13	113	Blood Gas Analyzer	NO	0	0	
14	61	Mass Spectrometer	YES	70	35	LOW
15	112	Plant HLPC Ion Chromatograph	NO	0	0	
16	147	Head/Torso Phantom	YES	3	35	HIGH
17	63	Pulmonary Gas Cylinder Assembly	YES	95	10	HIGH
18	110	Plant Gas Chromatograph/Mass Spectrometer	YES	70	35	LOW
19	115	Chemistry System	YES	50	30	LOW
20	138	Hematology System	YES	50	30	LOW
21	34	Sample Preparation Device	YES	0	0	HIGH
22	165	Experiment Control Computer System	YES	80	30	HIGH
23	62	Pulmonary Function Equipment Stowage Assembly	YES	0	0	HIGH
24	82	Motion Analysis System	YES	90	20	HIGH
25	99	Animal Biotelemetry System	YES	95	20	HIGH
26	100	Blood Pressure and Flow Instrumentation	YES	85	20	HIGH
27	109	Venous Pressure Transducer/Display	YES	85	20	HIGH
28	129	Cell Handling Accessories	YES	0	0	HIGH
29	57	Bag-in-Box	YES	80	20	LOW
30	111	Plant Gas Cylinder Assembly	YES	95	10	HIGH
31	119	Gas Cylinder Assembly	YES	95	10	HIGH
32	130	Cell Harvestor	YES	0	0	LOW

Table 5.7-2 Database Listing for Make-or-Buy Candidate Sample Set

HW Item #	Hardware Item Name	Mass (kg)	% Buy	% Mod to Buy	% OTS	Assessment Confidence Level
168	CELSS Test Facility	1000.0	20	30	14	HIGH
169	Gas Grain Simulator	800.00	33	30	23	HIGH
126	Scintillation Counter	90.000	95	30	67	HIGH
74	Force Resistance System	70.000	95	25	71	HIGH
145	Automated Microbal System	70.000	95	40	57	LOW
155	Total Hyrdocarbon Analyzer	70.000	100	30	70	LOW
161	Inventory Control System	70.000	95	15	81	HIGH
163	Test/Checkout/Calibration Instrumentation	70.000	50	20	40	HIGH
106	Neck Baro-Cuff	45.200	95	30	66	HIGH
61	Mass Spectrometer	40.700	70	35	45	LOW
147	Head/Torso Phantom	32.000	3	35	2	HIGH
63	Pulmonary Gas Cylinder Assembly	30.000	95	10	85	HIGH
110	Plant Gas Chromatograph/Mass Spectrometer	25.000	70	35	46	LOW
115	Chemistry System	23.000	50	30	35	LOW
138	Hematology System	23.000	50	30	35	LOW
165	Experiment Control Computer System	20.100	80	30	56	HIGH
82	Motion Analysis System	20.000	90	20	72	HIGH
99	Animal Biotelemetry System	20.000	95	20	76	HIGH
100	Blood Pressure and Flow Instrumentation	20.000	85	20	68	HIGH
109	Venous Pressure Transducer/Display	20.000	85	20	68	HIGH
57	Bag-in-Box	19.000	80	20	64	LOW
111	Plant Gas Cylinder Assembly	19.000	95	10	86	HIGH
119	Gas Cylinder Assembly	19.000	95	10	86	HIGH

6.0 Conclusion

In this study, a make-or-OTS-buy analysis was made from the Space Biology Hardware Baseline (SBHB). Of the 32 SBHB items accounting for 93 percent of the mass, 23 were found to have a potential to be acquired as modified off-the-shelf. The percentages (by weight) of these 32 SBHB items which could be acquired as modified off-the-shelf were then found and listed in Table 5.7.-1.

This study encountered many examples of make-or-OTS-buy decisions from past NASA programs. It would be an oversimplification to group hardware items by some classification or function and use this information to make a make-or-OTS-buy decision on other hardware. This study concluded that all pieces of SBI hardware should be individually analyzed for make-or-OTS-buy potential. However, the indications from this study all point to the fact that SBI can be developed using a significant percentage of modified COTS or OTS and save substantial amount of money in the process.

There are two conclusions which can be drawn from this relative cost evaluation.

a. After the final selection of SBI hardware items, each individual item must be costed separately based upon a careful evaluation of the modification cost required and the cost of the basic unit compared to a new design.

b. The potential for cost savings or cost avoidance is very substantial even where the modification costs are high. Appendix C, Table 3-7 and Table 3.8 contain estimated dollar cost per kilogram for modification cost over a range of design factors, df.

Based upon the assumption that modification design costs are 50% as much as an all new design and that purchase costs are 15% of a new design, the potential cost savings for each SBHB make-or-OTS-buy candidate were calculated and presented in Table 5.7-2 and 2.2.3.

As space operations and research becomes more accessible, the need become more pronounced for using equipment routinely found in medical facilities/research labs on the ground. Decisions on whether to develop hardware or modify commercial hardware will become extremely significant in terms development times and costs.

Appendix A - Space Biology Hardware Baseline

LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

December 1988
UpDated 23 Mar 1989

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
1.8 METER CENTRIFUGE FACILITY (1)					
	SPECIMEN SUPPORT GROUP (1A)				
1	1.8 M Centrifuge	C	2.40	1100	1500
2	Equipment Washer/Sanitizer	W	0.96	320	2500
3	Life Sciences Glove Box (Copy 1 of 2)	W	0.96	350	800
4	Modular Habitat Holding System	C	0.48	200	500
5	Plant Growth Module	C	0.10	50	550
6	Primate Module	C	0.10	50	220
7	Rodent Module	C	0.07	40	230
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2)					
	BIOWASTE COLLECTION & MONITORING GROUP (2A)				
8	Fecal Monitoring System (24 Hr)	E	0.12	25	50
9	Urine Monitoring System (24 Hr)	E	0.20	60	50
	BIOLOGICAL SAMPLE STORAGE GROUP (2B)				
10	Freeze Dryer	W	0.07	19	140
11	Freezer (-20 deg. C)	W	0.48	120	300
12	Freezer (-70 deg. C)	W	0.48	120	300
13	Freezer Cryogenic (-196 deg. C) w/ Snap Freezer	W	0.09	20	0
14	Radiation Shielded Locker (Copy 1 of 2)	W	0.20	80	0
15	Refrigerator (4 deg. C)	W	0.48	120	300

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2), (con't)					
	SAMPLE COLLECTION AND PROCESSING GROUP (2C)				
16	Animal Tissue Biopsy Equipment	S	0.03	8	0
17	Blood Collection System	S	0.02	1	0
18	Centrifuge Refrigerated	W	0.15	40	450
19	Centrifuge Standard Lab	E	0.09	26	200
20	Digital Thermometer	W	0.01	2	34
21	Drug Administration Equipment	E	0.01	1	0
22	Electrofusion Device	S	0.06	TBD	TBD
23	Fixation Unit	S	0.02	4	0
24	Fluid Handling Tools/System	W	0.48	80	100
25	Laboratory Sciences Workbench	W	0.96	300	700
26	Life Sciences Glove Box (Copy 2 of 2)	W	0.96	350	800
27	Microscope System (Stereo Macroscope Subset, Copy 2	W	0.25	80	200
28	Muscle Biopsy Equipment	S	0.01	1	0
29	Perfusion & Fixation Unit	S	0.01	2	0
30	Plant Care Unit	S	0.05	10	50
31	Plant Harvest/Dissection Unit	S	0.01	4	20
32	Radioimmunoassay Prep Device	E	0.01	2	0
33	Saliva Collection Unit	S	~~0.01~~ .001	~~1~~ .2	0
34	Sample Preparation Device	S	0.17	22	150
35	Shielded Isotope Container	E	0.02	22	0
36	Specimen Labeling Tools/Device	W	0.01	4	20
37	Surgery/Dissection Tools	W	0.06	20	0
38	Sweat Collection Device	S	~~0.01~~ .005	~~TBD~~ 5.05	~~0~~ .15

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2), (con't)					
	RODENT SUPPORT GROUP (2D)				
39	CO2 Administration Device	S	0.01	3	0
40	Rodent Blood Collection System	S	0.03	10	50
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S	0.01	2	50
42	Rodent Guillotine	S	0.01	4	0
43	Rodent Restraint	S	0.01	3	0
44	Rodent Surgery Platform	S	0.01	3	0
45	Rodent Surgery/Dissection Unit	S	0.01	3	0
46	Rodent Urine Collection System	S	0.03	10	50
47	Rodent Veterinary Unit	S	0.03	10	0
	PRIMATE SUPPORT GROUP (2E)				
48	Primate Blood Collection System	S	0.05	2	140
49	Primate Handling Equipment	S	0.01	1	0
50	Primate LBNP Device	S	0.05	3	140
51	Primate Surgery Platform	S	0.04	5	0
52	Primate Surgery/Dissection Unit	S	0.02	5	0
53	Primate Urine Collection System	S	0.01	10	14
54	Primate Veterinary Unit	S	0.03	10	0
55	Small Primate Restraint	S	0.05	2	0

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (3)					
PULMONARY ANALYSIS GROUP (3A)					
56	Bag Assembly	S	0.01	1	0
57	Bag-in-Box	S	0.15	19	0
58	Doppler Recorder	E	0.01	1	0
59	Electronics Control Assembly	S	0.08	13	100
60	Mask/Regulator System	S	0.01	3	30
61	Mass Spectrometer	S	~~0.02~~ .087	~~10~~ 40.7	~~100~~ 200
62	Pulmonary Function Equipment Stowage Assembly	S	~~0.39~~ .051	20	0
63	Pulmonary Gas Cylinder Assembly	S	0.09	30	0
64	Rebreathing Assembly	S	0.02	1	0
65	Spirometry Assembly	S	0.01	1	0
66	Syringe (3 Liter Calibration)	S	0.01	2	0
PHYSICAL MONITORING GROUP (3B)					
67	Accelerometer And Recorder	S	0.04	16	35
68	Anthropometric Measurement System	S	0.02	~~TBD~~ 1	0
69	Cameras	W	0.15	50	150
70	Compliance Volumometer	S	~~0.06~~ .015	~~TBD~~ 16	~~TBD~~ 130
71	Electroencephalomagnetogram (EEMG)	S	0.06	~~TBD~~ 2	TBD
72	Electromyograph (EMG)	E	0.01	2	20
73	Force Measurement Device	E	0.01	1	10
74	Force Resistance System	S	0.40	70	~~100~~ 220
75	Fundus Camera	S	~~0.03~~ .003	~~TBD~~ 2	~~TBD~~ Bat. of
76	Goniometer And Recorder	E	0.01	2	25

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (con't)					
	PHYSICAL MONITORING GROUP (3B) (con't)				
77	Hard Tissue Imaging System	S	0.29	136	300
78	Mass Calibration Unit	S	0.01	2	0
79	Mass Measurement Device-Body	E	0.65	35	15
80	Mass Measurement Device-Micro	W	0.08	17	15
81	Mass Measurement Device-Small	W	0.08	17	15
82	Motion Analysis System	S	0.05	20	100
83	Plethysmograph Measuring System	S	0.01	3	30
84	Soft Tissue Imaging System	S	0.96	300	800
85	Tonometer	S	~~0.01~~.0002	~~TBD~~-06	~~0~~ Bat OP
86	Video System	E	0.10	30	300
	NEUROPHYSIOLOGICAL ANALYSIS GROUP (3C)				
87	EEG Cap	S	0.01	2	0
88	EEG Signal Conditioner	S	0.01	2	20
89	Electrode Impedance Meter	E	0.01	1	0
90	Electro-oculograph (EOG)	E	0.01	2	20
91	Neurovestibular ECDI	E	0.09	11	120
92	Neurovestibular Helmet Interface Box	E	0.01	2	20
93	Neurovestibular Helmet Assembly	E	0.04	13	110
94	Neurovestibular Helmet Restraint	E	0.01	2	20
95	Neurovestibular Optokinetic Stimulus	E	0.01	2	20
96	Neurovestibular Rotating Chair	E	0.12	38	220
97	Subject Restraint System	E	0.05	18	0
98	Visual Tracking System	S	0.01	2	20

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (con't)					
	CARDIOVASCULAR GROUP (3D)				
99	Animal Biotelemetry System	S	0.05	20	100
100	Blood Pressure And Flow Instrumentation	S	0.06	20	200
101	Cardiodynamic Monitor	S	0.02	4	150
102	Electrocardiograph (ECG)	S	0.01	2	20
103	Holter Recorder	S	0.01	2	0
104	Human Biotelemetry System	E	0.05	17	140
105	LBNP Device	E	0.16	20	55
106	(Neck Baro-Cuff) ← CAROTID SINUS BARORECEPTOR STIMULATOR	S	~~0.10~~ .132	~~TBD~~ 45.2	~~TBD~~ 145
107	Physiological Hemodynamic Assess Device	E	0.05	18	100
108	Ultrasonic Imaging System	W	0.20	70	600
109	Venous Pressure Transducer/Display	S	0.05	20	100
	PLANT MONITORING GROUP (3E)				
110	Plant Gas Chromatograph/Mass Spectrometer	S	0.20	25	100
111	Plant Gas Cylinder Assembly	S	0.09	19	0
112	Plant HPLC Ion Chromatograph	S	0.12	40	200

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
	ANALYTICAL INSTRUMENTS FACILITY (4)				
	BIOLOGICAL SAMPLE ANALYSIS GROUP (4A)				
113	Blood Gas Analyzer	S	0.13	45	250
114	Chemistry Analysis System	E	0.10	30	200
115	Chemistry System	S	0.08	23	100
116	Continuous Flow Electrophoresis Device	S	0.06	TBD	TBD
117	ELISA Reader	E	0.02	6	100
118	Gas Chromatograph/Mass Spectrometer	W	0.20	25	100
119	Gas Cylinder Assembly	S	0.09	19	0
120	High Performance Liquid Chromatograph	W	0.12	40	100
121	Incubator (35-65 deg C Copy 1 of 2)	W	0.16	50	400
122	Osmometer	E	0.02	5	20
123	pH Meter/Ion Specific Analyzer	W	0.02	7	5
124	Qualitative Reagent Strip And Reader	S	0.03	10	100
125	Radioimmunoassay	E	0.05	20	0
126	Scintillation Counter	S	0.24	90	500
127	Spectrophotometer (UV/VIS/NIR)	W	0.11	40	300
128	Urine Analysis System	E	0.16	55	400
	CELL ANALYSIS GROUP (4B)				
129	Cell Handling Accessories	S	0.05	20	50
130	Cell Harvestor	S	0.06	19	50
131	Cell Perfusion Apparatus	S	0.06	TBD	TBD
132	Centrifugal Incubator (5% CO2 @37 deg C Copy 1 of 2)	E	0.16	40	300
133	Centrifugal Incubator (5% CO2 @37 deg C Copy 2 of 2)	E	0.16	40	300

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
ANALYTICAL INSTRUMENTS FACILITY (4) (con't)					
	CELL ANALYSIS GROUP (4B) (con't)				
134	Centrifuge Hematocrit	S	0.01	2	20
135	Chromosomal Slide Preparation Device	S	0.01	2	20
136	Fluoromeasure Probe	S	0.05	TBD	TBD
137	Flow Cytometer	E	0.24	36	500
138	Hematology System	S	0.07	23	200
139	Image Digitizing System	S	~~0.25~~ .03	~~70~~ 11.4	500
140	Microscope System (Optical & Stereo Macroscope Subsets)	W	0.40	100	400
141	Mitogen Culture Device	E	0.01	2	20
142	Skin Window Device	S	0.01	2	0
143	Slide Preparation Device	E	0.01	2	20

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
LAB SUPPORT EQUIPMENT FACILITY (5)					
	ENVIRONMENTAL MONITORING & CONTROL GROUP (5A)				
144	Accelerometer Subsystem	W	0.10	30	200
145	Automated Microbic System	S	0.20	70	500 110
146	Dosimeter, Passive	W	0.09	35	0
147	Head/Torso Phantom	S	0.12	~~TBD~~ 32	0
148	Incubator (35-65 deg C Copy 2 of 2)	W	0.16	50	400
149	Microbial Preparation System	S	0.01	2	~~20~~ 110
150	Radiation Shielded Locker (Copy 2 of 2)	W	0.20	80	0
151	Reuter Microbiology Air Sampler	S	~~0.01~~ .005	~~+~~ 1.45	0
152	Solid Sorbent Air Sampler	S	0.01	5	0
153	Spectrometer (Proton/Heavy Ion)	S	0.03	10	20
154	Tissue Equivalent Proportional Counter	S	~~0.01~~ .001	~~TBD~~ 2	0
155	Total Hydrocarbon Analyzer	S	0.20	70	250
	HARDWARE MAINTENANCE GROUP (5B)				
156	Battery Charger	W	0.03	10	100
157	Camera Locker	W	0.30	100	0
158	Cleaning Equipment	W	0.20	70	500
159	Digital Multimeter	W	0.06	20	50
160	General Purpose Hand Tools	W	0.10	30	0
	LOGISTICS CONTROL GROUP (5C)				
161	Inventory Control System	S	0.20	70	500
162	Lab Materials Packaging & Handling Equipment	S	0.20	70	500
163	Test/Checkout/Calibration Instrumentation	S	0.20	70	200

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
	CENTRALIZED LIFE SCIENCES COMPUTER FACILITY (6)				
	LIFE SCIENCES DATA GROUP (6A)				
164	Digital Recording Oscilloscope	W	0.03	10	100
165	Experiment Control Computer System	S	0.05	20	400
166	Multichannel Data Recorder	E	0.09	30	150
167	Voice Recorder	S	~~0.01~~ .003	~~1~~ .26	~~0~~ Bat CP
	CLOSED ECOLOGICAL LIFE SUPPORT FACILITY (7)				
	FEAST GROUP (7A)				
168	CELSS Test Facility	S	1.92	1000	1300
	EXOBIOLOGY FACILITY (8)				
	GAS/GRAIN GROUP (8A)				
169	Gas Grain Simulator	S	1.92	800	1500

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM Ele...

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H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
16	Animal Tissue Biopsy Equipment	S	0.03	8	0				A
17	Blood Collection System	S	0.02	1	0				J
22	Electrofusion Device	S	0.06	TBD	TBD				J
23	Fixation Unit	S	0.02	4	0				A*J
28	Muscle Biopsy Equipment	S	0.01	1	0				A
29	Perfusion & Fixation Unit	S	0.01	2	0				A
30	Plant Care Unit	S	0.05	10	50				A
31	Plant Harvest/Dissection Unit	S	0.01	4	20				A
33	Saliva Collection Unit	S	0.01	1	0	0.001	0.2	0	J
34	Sample Preparation Device	S	0.17	22	150				J*A
38	Sweat Collection Device	S	0.01	TBD	0	0.005	5.05	15	J
39	CO2 Administration Device	S	0.01	3	0				A
40	Rodent Blood Collection System	S	0.03	10	50				A
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S	0.01	2	50				A
42	Rodent Guillotine	S	0.01	4	0				A
43	Rodent Restraint	S	0.01	3	0				A
44	Rodent Surgery Platform	S	0.01	3	0				A
45	Rodent Surgery/Dissection Unit	S	0.01	3	0				A
46	Rodent Urine Collection System	S	0.03	10	50				A
47	Rodent Veterinary Unit	S	0.03	10	0				A
48	Primate Blood Collection System	S	0.05	2	140				A
49	Primate Handling Equipment	S	0.01	1	0				A
50	Primate LBNP Device	S	0.05	3	140				A
51	Primate Surgery Platform	S	0.04	5	0				A
52	Primate Surgery/Dissection Unit	S	0.02	5	0				A
53	Primate Urine Collection System	S	0.01	10	14				A
54	Primate Veterinary Unit	S	0.03	10	0				A
55	Small Primate Restraint	S	0.05	2	0				J
56	Bag Assembly	S	0.01	1	0				J
57	Bag-In-Box	S	0.15	19	0				J
59	Electronics Control Assembly	S	0.08	13	100				J
60	Mask/Regulator System	S	0.01	3	30				J
61	Mass Spectrometer	S	0.02	10	100	0.087	40.7	200	J
62	Pulmonary Function Equipment Stowage Assembly	S	0.39	20	0	0.051	20	0	J
63	Pulmonary Gas Cylinder Assembly	S	0.09	30	0				J
64	Rebreathing Assembly	S	0.02	1	0				J
65	Spirometry Assembly	S	0.01	1	0				J
66	Syringe (3 Liter Calibration)	S	0.01	2	0				J
67	Accelerometer And Recorder	S	0.04	16	35		16.06		J

A=ARC, J=JSC, *=Prime

Updated: 3/22/89

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
68	Anthropometric Measurement System	S	0.02	TBD	0		1		J
70	Compliance Volumometer	S	0.06	TBD	TBD	0.0152	16	130	J
71	Electroencephalomagnetogram (EEMG)	S	0.06	TBD	TBD		2		J
74	Force Resistance System	S	0.40	70	100			220	J
75	Fundus Camera	S	0.03	TBD	TBD	0.003	2	Battery Op	J
77	Hard Tissue Imaging System	S	0.29	136	300				J
78	Mass Calibration Unit	S	0.01	2	0				J
82	Motion Analysis System	S	0.05	20	100				J
83	Plethysmograph Measuring System	S	0.01	3	30				J
84	Soft Tissue Imaging System	S	0.96	300	800				J
85	Tonometer	S	0.01	TBD	0	0.000226	0.06	Battery Op	J
87	EEG Cap	S	0.01	2	0				J
88	EEG Signal Conditioner	S	0.01	2	20				J
98	Visual Tracking System	S	0.01	2	20				J
99	Animal Biotelemetry System	S	0.05	20	100				A
100	Blood Pressure And Flow Instrumentation	S	0.06	20	200				AJ'
101	Cardiodynamic Monitor	S	0.02	4	150				J
102	Electrocardiograph (ECG)	S	0.01	2	20				J
103	Holter Recorder	S	0.01	2	0				J
106	Neck Baro-Cuff	S	0.10	TBD	TBD	0.132	45.2	145	J
109	Venous Pressure Transducer/Display	S	0.05	20	100				J
110	Plant Gas Chromatograph/Mass Spectrometer	S	0.20	25	100				A
111	Plant Gas Cylinder Assembly	S	0.09	19	0				A
112	Plant HPLC Ion Chromatograph	S	0.12	40	200				A
113	Blood Gas Analyzer	S	0.13	45	250				J
115	Chemistry System	S	0.08	23	100				J
116	Continuous Flow Electrophoresis Device	S	0.06	TBD	TBD				J
119	Gas Cylinder Assembly	S	0.09	19	0				J
124	Qualitative Reagent Strip And Reader	S	0.03	10	100				J
126	Scintillation Counter	S	0.24	90	500				J
129	Cell Handling Accessories	S	0.05	20	50				A'J
130	Cell Harvestor	S	0.06	19	50				A'J
131	Cell Perfusion Apparatus	S	0.06	TBD	TBD				AJ'
134	Centrifuge Hematocrit	S	0.01	2	20				AJ'
135	Chromosomal Slide Preparation Device	S	0.01	2	20				J
136	Fluoromeasure Probe	S	0.05	TBD	TBD				J
138	Hematology System	S	0.07	23	200				J
139	Image Digitizing System	S	0.25	70	500	0.03	11.4		J
142	Skin Window Device	S	0.01	2	0				J

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
145	Automated Microbic System	S	0.20	70	500	0.2	70	110	J
147	Head/Torso Phantom	S	0.12	TBD	0		32		J
149	Microbial Preparation System	S	0.01	2	20	0.01	2	110	J
151	Reuter Microbiology Air Sampler	S	0.01	1	0	0.005	1.45		AJ*
152	Solid Sorbent Air Sampler	S	0.01	5	0				J
153	Spectrometer (Proton/Heavy Ion)	S	0.03	10	20				J
154	Tissue Equivalent Proportional Counter	S	0.01	TBD	0	0.001	2	0	J
155	Total Hydrocarbon Analyzer	S	0.20	70	250				J
161	Inventory Control System	S	0.20	70	500				AJ*
162	Lab Materials Packaging & Handling Equipment	S	0.20	70	500				A*J
163	Test/Checkout/Calibration Instrumentation	S	0.20	70	200				AJ*
165	Experiment Control Computer System	S	0.05	20	400				J*A
167	Voice Recorder	S	0.01	1	0	0.003	0.26	Battery Op	J
168	CELSS Test Facility	S	1.92	1000	1300				A
169	Gas Grain Simulator	S	1.92	800	1500				A

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI01	Kozarsky, D.	MUS Inputs		Lockheed Life Sciences Program Office	Lockheed Memo	Washington, DC	01/19/89
SBI02	Kozarsky, D.	Latest Space Station Rack Studies		NASA MSFC		Huntsville, AL.	02/02/89
SBI03	Holt, A.	PMWG-SS Freedom Assly. Seq. Trial Pyl. Manifest		Payload Manifest Working Group (PMWG)		Reston, VA.	12/09/88
SBI04	Shannon, J.	Business Practice Low Cost System Activity		NASA JSC		Houston, TX.	11/12/75
SBI05	NASA	Off-the-Shelf Hardware Procurement		NASA JSC	NASA MEMO HB/73-M286	Houston, TX.	05/16/73
SBI06	NASA	OTS Technology Use For Space Shuttle Program		NASA JSC	NASA MEMO	Houston, TX.	11/20/73
SBI07	NASA	Proposed Space Shuttle Directive On OTS HW.		NASA JSC	NASA MEMO NB/74-L149	Houston, TX.	06/20/74
SBI08	NASA	Cancellation Of Space Shuttle Directive On OTS		NASA JSC		Houston, TX.	10/01/74
SBI09	NASA	Agency Balloon Pyl. Util. of Avail. Equip. & Exper		NASA JSC	NASA PLAN 323-50-XX-71	Houston, TX.	05/25/76
SBI10	NASA	Space Shuttle Program DTO/DSO Noncritical Requirements Document		Flight Support Equipment Office - JSC	NSTS 21096	Houston, TX.	08/01/88
SBI11	NASA	Reference Mission Operational Analysis Document (RMOAD) For The Life Sciences Research Facilities.		NASA JSC	NASA TM 89604	Houston, TX.	02/01/87
SBI12	Breiling, R.	Cost Risk Analysis Using Price Models		RCA Price Systems		Mooreston, NJ.	09/01/87
SBI13	Fogleman, G.Schwart, D.Fonda, M.	Gas Grain Simulation Facility: Fundamental Studies of Particle Formation And Interactions	1	NASA Ames Research Center	NASA ARC/SSS 88-01	Moffet Field, CA.	08/31/87

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SBI14	JPL	Flight Projects Office Payload Classification Product Assurance Provisions		JPL	JPL D-1489 Rev. A	Pasadena, CA.	04/30/87
SBI15	PRC Systems	Cost Estimate For The Search for Extraterrestrial Intelligence (SETI) Revised		PRC Systems Services		Huntsville, AL.	06/15/87
SBI16	NASA SSPO	Space Station Commonality Process Requirements Rev.B		NASA SSPO	SSP 30285 Rev. B	Reston, Virgina	09/15/88
SBI17	Webb, D.	Technology Forecasting Using Price - H		Rockwell International		Anaheim, CA.	04/17/86
SBI18	NASA	Classification Of NASA Office Of Space Science And Applications (OSSA) Space Station Payloads		NASA JSC		Houston, TX.	/ /
SBI19	NASA	Life Science Research Objectives And Representative Experiments For The Space Station (Green Book)		NASA Ames Life Science Division		Moffet Field, CA.	01/01/86
SBI20	NASA	Medical Requirements Of An In-Flight Medical System For Space Station		NASA JSC	JSC 31013	Houston, TX.	11/30/87
SBI21	TRW	A Study Of Low Cost Approaches To Scientific Experiment Implementation For Shuttle Launched And Serviced Automated Spacecraft		TRW Systems Group	Contract NASW - 2717	Redondo Beach, CA.	03/19/89

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SBI22	LMSC	Low-Cost Program Practices For Future NASA Space Programs		LMSC	LMSC-D387518	Sunnyvale, CA.	05/30/74
SBI23	Steward, GMiller, L	Biomedical Equipment Technology Assesment For The Science Laboratory Module		Management and Technical Services Company		Houston, TX.	08/01/86
SBI24	General Electric	WP-3 Commonality Plan		General Electric	NAS5-32000	Philadelphia, PA	04/22/88
SBI25	NASA	Microbiology Support Plan For Space Station		NASA JSC	JSC-32015	Houston, TX.	09/01/86
SBI26	NASA	Concepts And Requirements For Space Station Life Sciences Ground Support And Operations		NASA JSC	LS-70034	Houston, TX.	04/11/88
SBI27	NASA	Spacelab Mission 4 Integrated Payload Requirements Document		NASA JSC	SM-SE-03	Houston, TX.	06/01/83
SBI28	General Dynamics	Life Sciences Payload Definition And Integration Study	IV	General Dynamics	CASD-NAS-74-046	San Diego, CA.	08/01/74
SBI29	General Dynamics	Life Sciences Payload Definition and Integration Study - Executive Summary	1	General Dynamics	CASD-NAS-74-046	San Diego, CA.	08/01/74
SBI30	NASA	SL-3 Ames Research Center Life Sciences Payload Familiarization Manual		Ames Research Center	ADP-81-50-001	Moffet Field, CA.	02/01/81
SBI31	Rockwell Intl.	EMS Data Data Package 2.3A S4200.2 Methodology Definition - Commonality Analysis Trade Study		Rockwell Internation	SSS 85-0168	Downey, Ca.	10/04/85

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SBI32	Rockwell Intl.	EMS Data Data Package 2.2B S4201.2, Module Commonality Analysis		Rockwell International	SSS 85-0137	Downey, CA	09/06/85
SBI33	General Electric	Space Station Work Package 3 Definition And Preliminary Design Commonality Candidates		General Electric Space Systems Division	DRD - 19	Philadelphia, PA	05/10/85
SBI34	Rockwell Intl.	EMS Data Data Package 2.3A S4203.2, Module Outfitting/System Commonality Analysis		Rockwell International	SSS 85-0158	Downey, CA	10/28/85
SBI35	NASA JSC	Space Station Freedom Human-Oriented Life Sciences Research Baseline Reference Experiment Scenario		JSC- Medical Sciences Space Station Office	Blue Book	Houston, TX.	10/01/88
SBI36	NASA SSPO	Space Station Approved Electrical Electronic, And Electromechanical Parts List		Space Station Program Office	SSP 30423 Rev. A	Reston, Virgina	11/15/88
SBI37	NASA SSPO	Space Station Program Design Criteria and Practices		Space Station Program Office	SSP 30213 Rev. B	Reston, Virgina	07/30/88
SBI38	MDAC	Manufacturing Management Plan		McDonnel Douglas	DR MU-01	Houston, TX	/ /
SBI39	NASA JSC	July 1988 Pogress Report On Experiment Standard User Interfaces Study		JSC - Life Sciences Project Division		Houston, TX.	07/01/88
SBI40	Rockwell Intl.	EMS Data Data Package 2.3A S4207.2, BSE Commonality Analysis		Rockwell International	SSS 85-0099	Downey, CA	10/04/85
SBI41	NASA OSSA	Life Sciences Space Station Planning Document: A Reference Payload For The Life Sciences Research Facility		Office of Space Science and Applications	NASA TM 89188	Washington, D.C.	01/01/86

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SBI42	Buroni, A.Pascucci, B	The OBDH test equipment and its goals		ESA		Milan, Italy	10/01/78
SBI43	Shiokari, A.	Standarization and Program Effect Analysis - Final Report	111	Aerospace Corporation		El Segundo, CA	01/01/75
SBI44	Huffstetler, W.	Skylab Biomedical Hardware Development		AIAA 20th Annual Meeting		Los Angeles, CA	08/22/74
SBI45	Powell, A.	Commonality Analysis For The NASA Space Station Common Module - 36 IAF Meeting, October 7-12 1985		Pergamon Press		New York, NY	10/07/85
SBI46	Anderson, A.	Progressive Autonomy - For Space Station Systems Operation		AIAA		New York, NY	06/05/84
SBI47	NASA JSC	Life Sciences Research Laboratory (LSRL) Human Research Facility forSpace Station Initial Operating Configuration (IOC) Science Reqts.		NASA JSC	JSC 20799	Houston, TX	10/01/85
SBI48	MDAC	Crew Health Care System (CHec) Development Plan		Mcdonnell Douglas Space Station Co.		Houston, TX.	01/28/89
SBI49	Minsky, M.	Engines of Creation		Anchor Press		New York, NY	01/10/86
SBI50	MDAC	Crew Health Care	1	MDAC	MDC H3924	Houston, Texas	11/01/88
SBI51	NASA JSC	Columbus Reference Configuration Report		NASA JSC	RP 1213800000	Houston, TX.	05/31/88
SBI52	NASA HQ	Shuttle/Payload I/F Definition Document for Middeck Accomodations		NASA HQ	NSTS 21000	Washington, DC	03/01/88

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI53		Rack Accomodations Users Manual					/ /
SBI54	NASA JSC	Mission Integration Plan		NASA JSC	SSP 30000 Appendix D	Houston, TX.	04/30/86
SBI55	Pacheo	Analyzing Commonality in a System		Boeing	NASA STI Facility	Baltimore, MD.	03/01/88
SBI56	NASA MSFC	Spacelab Configurations					/ /
SBI57	Rockwell Intl.	Space Shuttle Management Proposal	II	Rockwell Intl.	SD 72-SH-50-2		05/12/72
SBI58	LMSC	Space Shuttle Management Proposal	II	LMSC	LMSC-D157364		05/12/72
SBI59	MDAC	Space Shuttle Program Management Proposal		MDAC	E0600		05/12/72
SBI60	MSFC	MSFC Space Station CER's Report		MSFC	PRC D-2185-H		12/01/82
SBI61	NASA JSC	CERV Target Costs for Benchmark and Reference Configurations		JSC CERV Office		Houston, TX.	06/15/88
SBI62	CBO	Cost Estimating For Air Missles		Congressional Budget Office		Washington, D.C.	01/01/83
SBI63	Evans, Jim	Meeting with Jim Evans Technical Assistant, NASA Space and Life Sciences		Eagle Engr.		Houston, TX.	04/19/89
SBI64	Whitlock, R.	JSC Cost Analysis Office		Eagle Engr.		Houston, TX.	04/11/89
SBI65	PRICE	PRICE Users Newsletter	12				10/01/88
SBI66	General Electric	PRICE H Reference Manual					01/01/88
SBI67	NASA JSC	Satellite Services Workshop	1&2	NASA JSC	JSC 20677	Houston, TX.	11/06/85

Appendix B - Complete SBI Trade Studies Bibliography

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI68	Hamaker, Joe	Telephone interview relating to MSFC history and techniques for cost estimating.		Cost Analysis Branch Chief MSFC		Huntsville, Al.	04/27/89
SBI69	Booker, Clef	Personal Interview		Man-Systems Division JSC		Houston, TX.	04/04/89
SBI70	Evans, Jim	Personal Interview		Life Science Project Division JSC		Houston, TX.	04/19/89
SBI71	Heberlig, Jack	Telephone interview relating to make-or-buy lessons learned from Apollo		International Business Machines (IBM)		Houston, TX.	03/10/89
SBI72	Loftus, Joe	Telephone interview relating to make-or-buy history		Assistant Director (Plans) JSC		Houston, TX.	03/14/89
SBI73	Christy, Neil	Telephone interview relating to hardware development student experiments, and make-or-buy				Houston, TX.	03/15/89
SBI74	McAllister, Fred	Telephone Interview		Man-System Division, JSC		Houston, TX	03/14/89
SBI75	Trowbridge, John	Interview relating to CHeC make-or-buy		McDonnell Douglas		Houston, TX.	03/17/89
SBI76	Trowbridge, John	Personal interview relating CHeC experience to miniaturization, modularity and make-or-buy		McDonnell Douglas		Houston, TX.	03/29/89
SBI77	Nagel, John	Personal Interview relating to LSLE make-or-buy experience		Eagle Technical Services		Houston, TX	03/27/89
SBI78	McFadyen, Gary	Personal Interview relating to life science hardware background at JSC		Southwest Research Institute		Houston, TX.	04/10/89

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SB179	Booker, Clef	Personal Interview - Minaturization on amplifiers, computers and modularity		NASA JSC/SP 341 Man-System Division		Houston, TX.	04/04/89
SB180	McFadyen	Bioengineering on SBI hardware		Southwest Research Institute		San Antonio, TX.	04/06/89
SB181	Allen, Joe	Personal interview - S.S. Life Science AIAA Meeting		Space Industries		Houston, TX.	04/07/89
SB182	Averner, Maurice	Personal interview on CELSS		NASA HQ. CELSS Coordinator		Washington, DC.	04/07/89
SB183	Fogleman, G. PhD	Personal interview relating to Gas Grain Simulation Facility		NASA AMES		Moffet Field, CA.	04/06/89
SB184	White. Bob	Personal Interview relating to modularity and commonality		NASA JPL		Pasadena, CA.	04/10/89
SB185	Grumm, Richard	Personal interview relating to SBI hardware		NASA JPL		Pasadena, CA.	04/11/89
SB186	Boeing	U.S. Lab Review Workshop					/ /
SB187	McGillroy,B.	Personal Interview on CELSS		NASA AMES		Moffet Field, CA	05/05/89
SB188	NASA JSC	Life Science Flight Experiments Program Life Sciences Laboratory Equipment (LSLE) Descriptions		NASA JSC	JSC-16254-I	Houston, TX.	09/01/86
SB189	Boeing	Space Station Program Commonality Plan Draft 3		Boeing	D683-10112-1		10/31/88
SB190	GE Govt.Services	Life Sciences Hardware List for the Space Station Freedom Era - Baselined December 1988 Updated 3/22/89		GE Government Services		Houston, TX.	03/22/89

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI91		NASDA Standard Rack Envelope Study Status		NASDA			/ /
SBI92		Spacelab Payloads Accomodations Handbook		NASA MSFC	SLP/2104	Huntsvillle; Al.	08/16/85
SBI93		Station Interface Accomodations for Pressurized and Attached Payloads		NASA			02/01/89
SBI94		Life Sciences Study for the Space Station		Management and Technical Services Co.		Houston, TX.	08/01/84
SBI95	Crenshaw, John	Personal Interview with John Crenshaw - Discussion of standarized avoins (mounted on racks) in airlines.				Houston, TX.	05/16/89
SBI96	Juran, J.M.	The Non-Pareto Principle Mea Culpa					/ /
SBI97	Arabian, D.	Beware Off-the-Shelf Hardware		NASA JSC		Houston, TX.	10/17/73
SBI98	SBI98NASA JSC	Experimenting with Baroceptor Reflexes	12	NASA Tech Briefs	No. 11	New York, NY	12/01/88

Appendix C - Cost Assessment Techniques Summary

1.0 Introduction

1.1 Relative Cost Impact Analysis Task

JSC and GE Government Services are developing the SBI hardware cost estimate to be presented to NASA Headquarters. The cost related task in these trade studies is to develop and present factors which assist the cost estimators in using tools to develop the effect of the trade study specialty area (miniaturization, modularity and commonality, and Modified COTS) on SBI cost estimates. The life cycle costs are most important in judging the long term benefits of a new project. However, consideration of life cycle costs requires knowledge of the probable project life, operational use time lines, maintenance concepts, and logistics relationships. These data are not available at the time of these initial trade studies. Therefore, the trade studies address primarily the relative cost impact analysis of the design and development phase of the SBI. Life cycle costs are dealt with on a comparative, subjective basis in order to illustrate the influence of life cycle cost factors on the various trade study subjects.

1.2 Documentation Approach

The application of cost methods as applied to SBI trade studies involves some methods common to all of the studies and others that apply uniquely to a specific trade subject. Therefore, the selected approach to the problem is to deal with cost methods and cost trends in this appendix that is to be a part of each study report. In the cost appendix, subsequent sections of Section 1.0 deal with various methods examined for the trade studies, Section 2.0 defines the cost estimating relationship (CER's) and their factors and sensitivities, and Section 3.0 deals with specific variations and parameters of interest with respect to each trade study. Sections 4, 5 and 6 provide brief discussions of testing, SE&I and project management costs, Section 7.0 life cycle effects, and Section 8.0 summarizes the conclusions.

1.3 Cost Method Overview

Cost methods considered and evaluated in the course of this effort include the basic types listed below:

a. Detailed cost build-up method. The detailed cost estimate is compiled using estimates from specialists in the various design disciplines and is constructed from a spread of hours required in design, labor rates, overhead and other factors affecting the cost of DDT&E.

b. General Electric PRICE. The PRICE H model is a sophisticated cost modeling program requiring a variety of inputs including weight, manufacturing complexities, and design complexity plus secondary factors.

c. Cost estimating relationship (CER's). The simplest cost estimating tools are empirical relationships based primarily on system weight and derived to match past experience on previous programs.

d. Cost impact analysis methods. Parametric studies to establish and/or to quantify cost drivers and cost trend effects.

The choice between the foregoing alternatives was narrowed to options c and d which are used in combination as described in the balance of this report. Initial SBI cost estimates will be developed in a separate effort using PRICE H. Therefore, the task in the trade studies is to provide data and/or factors which will be helpful in assisting cost estimators in the use of the tools from which the actual estimates will be formulated. A secondary purpose is to develop parametric trend data that will help the reader understand the potential impact of the various trade study subjects on cost, i.e. miniaturization, commonality, and the use of commercial products (COTS) in lieu of new design.

Empirical cost relationships use system weight as the primary factor in deriving development and theoretical first unit (TFU) costs. A series of such relationships can be used to reflect the inherent complexity of different types of space-borne systems, i.e., one relationship for structural or mechanical systems, a second for packaged electronics, and a third for complex distributed hybrid systems. This approach has its roots in past program experience in that the end results are usually compared with past program actual costs and the relationships adjusted to match what has happened on similar system development during their life cycle. References SBI No. 60 and SBI No. 61 were used as a data source for CER's. Also, a discussion was held with the cost analysis specialist at JSC and MSFC (ref. SBI No. 64 and No. 68) as part of the effort to determine whether or not other cost work has been accomplished on the SBI trade study subjects.

As will be seen in the ensuing sections and in the trade studies proper, the results and trends also employ second order effects such as the amount of new design required, the impact of sophisticated technology and alternate materials.

Regardless of how one approaches the subject of cost development or cost trends there are three fundamental principles are involved in evaluating costs, cost drivers and cost trends (ref. SBI No. 65). These are as follows:

1. Estimates require reasoned judgments made by people and cannot be automated.

2. Estimates require a reasonably detailed definition of the project hardware that must be acquired or developed before estimates can be made.

3. All estimates are based upon comparisons. When we estimate, we evaluate how something is like or how it is unlike things we have seen before.

The SBI Program estimates are particularly challenging because the definition of the hardware items and the data that will permit comparisons is not detailed and complete. We are dealing with some items in their earliest conceptual phase of definition.

A couple of study principles should also be mentioned because they may help us understand the validity of the results we obtain. These are:

1. The sensitivity that study results show to variations in assumption provides an indication as to the fundamental nature of the assumption. If results are highly sensitive to variations in assumption then the assumption should be used with caution. Extrapolations are particularly hazardous in such instances. On the other

hand if results are not highly sensitive, then scaling over a wide range may be feasible, although extrapolations of cost values can yield misleading results in any event and should always be applied carefully.

2. Parametric approaches may be necessary in order to understand trends due to the absence of specific data for use in the study. Parametric in the sense used here means the arbitrary variation of a given parameter over a range of expected values, while holding other values constant.

The costing relationships used in SBI trade studies are applicable to space systems and are founded on past programs as described in references SBI No. 60 and No. 61. The only questions, therefore, are whether or not they can be used on SBI hardware (which does use subsystems similar in nature to other manned space systems) and how accurately they can be scaled to fit the range of SBI sizes. Insofar as practical, these questions have been circumvented by means of reporting cost trends in lieu of cost values.

2.0 General Development Cost Methods

2.1 Empirical Methods

As stated in Section 1.3 CER's are empirical cost estimating relationships that express expected costs on the basis of past program experience. Empirical cost estimating requires some sort of systems definition plus good judgement in the selection of the constants, and exponents. The nature of a system element or assembly, and the size/weight of the item are primary cost drivers. The most predominant variable is the exponent of the weight term in the following generalized equation:

$$\text{Cost} = df * (C_1 (Wt)^n) + C_2 (Wt)^a$$

Where wt = weight of the system, module or assembly

n = an exponent selected on the basis of system complexity

df = a factor reflecting the amount of new design required (design factor)

C_1 = constant selected to establish the cost trend origin

C_2 = a constant to reflect special requirements such as tooling - can be zero

Adjustments to the weight exponent and the constants yields values which show dramatic cost increases as a function of weight but decreasing cost per pound as the weight is increased. Cost relationships always show these trends when applied to launch vehicles, spacecraft, or payloads. Therefore, it is assumed that they apply to biology equipment (for space) as well. Economies of scale are present in all such systems. The larger the system, assembly, or component, the lower its cost per pound. There is, however, a limitation to the applicability of CER's to SBI hardware

due to size limitations. All CER's have a range of applicability and produce consistent results in terms of cost per pound over that range. The limitation comes into play when extrapolating outside the range of applicability, particularly where the size is small. Unfortunately, this limitation may be a factor in SBI hardware elements and assemblies due to their size being relatively small compared to manned spacecraft systems. Therefore, when a CER yields costs in a very high range, on the order of $100,000/lb. or $220,000/Kg, or higher, caution and judgement are necessary to avoid the use of misleading results.

2.2 System Complexity Exponents (n)

Past experience in estimating costs with empirical methods suggests that the exponent, n, increases with increasing system complexity and as a function of the degree to which a system is distributed. For example, relatively simple, structure or packaged power modules may be represented by n = 0.2. The cost of more complex mechanical systems and structures which are comprised of a variety of components and assemblies can be represented by an exponent, n = 0.4 and the most complex distributed electronics call for an exponent on the order of 0.5 to 0.6. Inasmuch as the SBI systems involve all the foregoing elements plus sophisticated sensors, it may be necessary to use exponents that are as high as 0.8 or 1.0 to represent cost trends of parts of the SBI systems. Reference No. 60 uses an exponent, n, equal to .5 for development when historical data are not available. This value has been used in SBI Reference No. 60 for displays and controls, instrumentation and communications, all of which are comprised of distributed electronics and is consistent with the range recommended here (.5 to .6).

The dramatic effect of the system complexity exponent is illustrated by Figure 2-1. Figure 2-1 is a plot of cost per pound vs. complexity exponent, n, for a range of values of n between 0.1 and 1.0. As can be seen from the figure, 1000 units of weight costs 0.2% per unit weight as much at n = 0.1 compared to the cost at n = 1.0. The point is that care must be exercised in making a proper selection of exponent in order to achieve reasonable accuracy in estimating actual costs.

The historical use of lower exponents for simple, packaged systems, and the use of higher values for complex distributed systems matches common sense expectations. To express it another way, one can safely assume that the cost of a system will be influenced dramatically by the number of different groups involved in the design, by the number of interfaces in the system, and by the complexity of the design integration effort required. Distributed power and data systems invariably cost more (per pound) to develop than do packaged elements. However, the degree to which this applies to SBI is not clear due to the fact that biological systems tend to be more packaged and less distributed than do other space systems.

2.3 Design Factors (df)

Figure 2-2 defines the design factors that represent the degree of new design required in a development. On the low side is the factor representing the use of existing designs that require very little modification, integration or testing. For all new current state-of-the-art designs which involve no new technology, the design factor is 0.9 to 1.0. The factor for new design requiring advancement in technology is expressed as greater than unity and can be as high as 2 or 3 for efforts that dictate a multiple design path approach to achieve the desired goals. Price H refers to this type of factor as the engineering complexity factor and uses design values similar to those

in Figure 2-2. However, Price H varies the experience of the design team as well as the complexity and the difficulty of the design.

2.4 Method Summary

The SBI trade studies will all require a definition of system element size, complexity and degree of new design. These factors may have to be varied over a range of probable values to evaluate trends, but they will all come into play in costing comparisons.

FIGURE 2-1
Effect of Exponent "n" on Cost

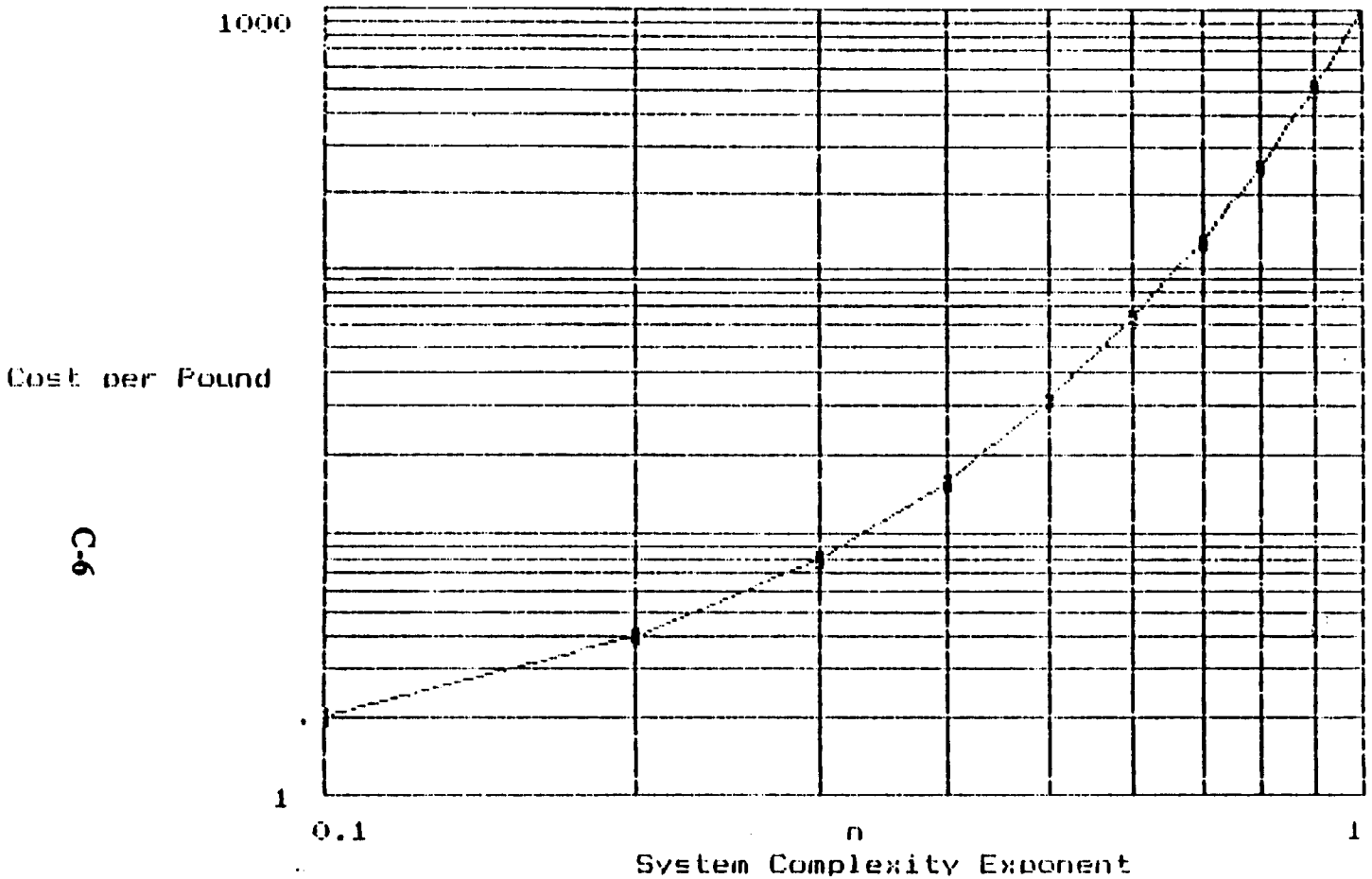


Figure 2-2 Design Factors

Design Factor	Description of the Design Task
.1 to .2	Off-The-Shelf. Minor design modifications and little or no qualification testing required
.3 to .4	Design Exists. Some new design drawings required Minimum integration costs involved
.5 to .6	Design exists but requires significant modification. On the order of 40% to 50% to existing drawings.
.7 to .8	Similar designs exist but mostly new drawings required No new technology involved in electronics, structure etc.
.9 to 1.0	New design with all new drawings. Little or no new technology required
1.0 to 3.0	All new design, new technology required. May require multiple attack on new technology problems

3.0 Cost Methods Applicable to Specific Trade Studies

Three of the four studies are discussed separately in this section although there are common elements associated with them that were not covered in Section 2.0. The intent is to examine the prime cost drivers that come into play with the subjects of miniaturization, modularity and commonality, use of COTS, and compatibility between spacecraft. Rack compatibility is covered in Section 7.4 under life cycle costs.

3.1 Hardware Miniaturization Cost Drivers

Fundamentally the variables of system (or component) weight, system complexity, and difficulty of design all influence miniaturization cost trends. For the purposes of this section weight and design difficulty will be varied, while system complexity will be treated as a series of constants, each being evaluated separately. Materials changes will not be dealt with even though it is valid to assume that the use of titanium, graphite, steel or composites will adversely affect cost. In fact, the dense materials (titanium and steel) will adversely affect cost due to weight and cost due to manufacturing complexity as well.

Given the foregoing exclusions, the miniaturization cost trends have been dealt with by parametric variation of the system size, and the degree of new design needed to achieve a given degree of miniaturization. The selected values of miniaturization vary between 10% and 90% in increments of 10%. In other words, if an unminiaturized system size is treated as 100%, Tables 3-1 through 3-4 show the effect on cost of weight reduction between zero and 90% on the first line. In order to include the effect of system complexity, Tables 3-1 through 3-4 are provided for values of n = 0.2, 0.4, 0.6, and 0.8.

The columns in the tables vary the design difficulty between a minimum change (.1 to .2 on Figure 2-2) and an all new design (0.9 to 1.0 on Figure 2-2). However, Tables 3-2 through 3-4 show the minimum design change as unity for reasons of simplifying the numbers. Thus the minimum design change number becomes 1.0 in lieu of 0.15 and the all new design becomes 6.0 which represents a relative value, compared to the minimum change value, i.e. 0.90 /0.15 = 6.0.

The use of Tables 3-1 through 3-4 is simple. Numbers less than 1.0 indicate a cost reduction and the degree of same, while numbers above 1.0 represent cost increases and the relative size of the increase. For example, using a 50% size reduction, and miniaturization requiring an all new design (df = 6) for n = 0.4, table 3-2 shows that the cost will be on the order of 4 1/2 times the cost for an unmodified item that is not miniaturized. In like manner, one can deduce that the cost of an all new design that achieves a 90% reduction in size (was 20 lbs., is 2.0 lbs.) will cost approximately 2 1/2 (2.4 from Table 3-2) the amount of an unmodified design.

Figure 3-1 is included to illustrate the cost trends for various systems complexity factors between n = .2 and n = .8. The curves all use a design factor df = 1.0 and all have been normalized so that the unminiaturized weight is unity. The purpose of Figure 3-1 is to show the effect of complexity factors on cost as weight is reduced. No design modification effects are included in Figure 3-1 so the curves indicate complexity trends only. To generate an estimate of the relative cost of miniaturization including redesign effects, one must multiply the cost factor (Figure 3-1) by a design factor as is done in Tables 3-1 through 3-4.

Table 3-1
Miniaturization Guide Chart
n=.2

% Miniat. / df	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.98	.96	.93	.90	.87	.83	.79	.73	.63
Significant Modification Req'd (30%)	2.00	1.96	1.92	1.86	1.80	1.74	1.66	1.58	1.46	1.26
Major Modification Req'd (50%)	3.00	2.94	2.88	2.79	2.70	2.61	2.49	2.37	2.19	1.89
All New Design	6.00	5.88	5.76	5.58	5.40	5.22	4.98	4.74	4.38	3.78

Table 3-2
Miniaturization Guide Chart
n=.4

% Miniat. / df	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.96	.92	.87	.82	.76	.69	.62	.53	.40
Significant Modification Req'd (30%)	2.00	1.92	1.84	1.74	1.64	1.52	1.38	1.24	1.06	.80
Major Modification Req'd (50%)	3.00	2.88	2.76	2.61	2.46	2.28	2.07	1.86	1.59	1.20
All New Design	6.00	5.76	5.52	5.22	4.92	4.56	4.14	3.72	3.18	2.40

Table 3-3
Miniaturization Guide Chart
n=.6

% Miniat. / dl	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.94	.86	.81	.74	.66	.58	.49	.38	.25
Significant Modification Req'd (30%)	2.00	1.88	1.72	1.62	1.48	1.32	1.16	.98	.76	.50
Major Modification Req'd (50%)	3.00	2.82	2.58	2.43	2.22	1.98	1.74	1.47	1.14	.75
All New Design	6.00	5.64	5.16	4.86	4.44	3.96	3.48	2.94	2.28	1.50

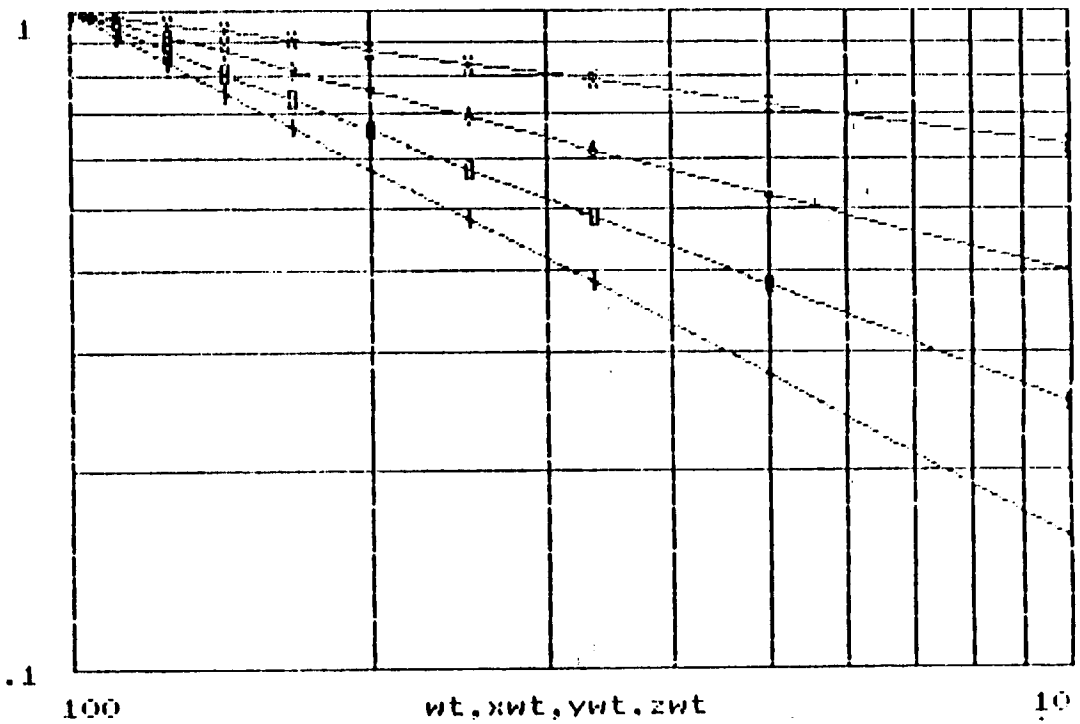
Table 3-4
Miniaturization Guide Chart
n=.8

% Miniat. / dl	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.92	.84	.75	.67	.57	.48	.38	.28	.16
Significant Modification Req'd (30%)	2.00	1.84	1.68	1.50	1.34	1.14	.96	.76	.56	.32
Major Modification Req'd (50%)	3.00	2.76	2.52	2.25	2.01	1.71	1.44	1.14	.84	.48
All New Design	6.00	5.52	5.04	4.50	4.02	3.42	2.88	2.28	1.68	.96

Cost Factor from Tables 3-1 thru 3-4
cost(wt,xwt,ywt,zwt)=df*(wt)^n/wt

Figure 3 -1

Variation of Cost as a Function of Weight



X = Normalized Cost for n =.2
V = Normalized Cost for n =.4
0 = Normalized Cost for n =.6
+ = Normalized Cost for n =.8

The examples are not meant to suggest that certain combinations of miniaturization and design difficulty are more rational than others, but were selected simply to demonstrate table usage. It is conceivable that a modest degree of miniaturization is achievable with modest design (df = 2).

Caution is advised! for several reasons:

1. Some items cannot be reduced in size.

2. Some items should not be reduced in size.

3. Significant size reductions may require technology breakthroughs in materials, electronics, displays, etc. that could complicate the SBI development task.

4. Substitute materials will often negate weight reductions and raise costs even higher than estimated by the tables.

Notwithstanding all the adverse possibilities, one could conceivably reduce size and cost by miniaturizing an item or an assembly.

3.2 Modularity and Commonality

Common system modules, assemblies or components can have a profound impact upon development cost because of the potential savings associated with the use of a common module in more than one SBI hardware item. The following examples serve to illustrate this fact.

Table 3-5 shows the impact of using learning to reduce costs. For example, consider the case where sixteen units are to be constructed for a given SBI application of a system rack or drawer, but the item in question can be used in four applications rather than in only a single place. If the system is to be produced in small quantities, exotic tools and automation are not cost effective and the item is normally assembled using piece parts. Such systems usually have learning factors of 80%, i.e., each time the number of units is doubled (SBI Ref. No. 68), the cost of the nth unit is 80% of the previous cycle's end product cost. To be specific, the 2nd unit costs .8 times the first unit, the 4th unit .8 times the second, etc. See Table 3-5. In the case of a built-up drawer or rack which is used in four places, 16 units for prototypes, test, flight hardware, etc., becomes 64. As can be seen from Table 3-5, the cost of the 64th unit is 26.2% of the 1st unit and 64% of the 16th unit. The average cost for 64 items is reduced to 37.4% of the first unit cost compared to 55.8% of the first unit cost for 16 items. The lower the learning, the less dramatic the unit cost reduction, but for any item that is fabricated by other than completely automated processes, there is a cost reduction to be realized by common use in more than one application.

If one considers the programmatic input of multiple applications, there also exists the opportunity to avoid duplicate design and development efforts. For the sake of simplicity, we will confine this discussion to D&D plus fabrication and assume that four separate developments each require a test program. This being the case, we can treat a single, dual, triple and quadruple application in terms of the D&D effort and include the effect of reduced costs due to learning as well.

D&D = Design and Development Cost
TFU = Theoretical First Unit Cost
L.F. = .80
Number of articles required per application = 16

Then:

Let CP_1 = Cost of a single program,
Let 35% D&D = TFU Cost

$C.P_1$ = 1.0 $D\&D_{cost}$ + [.35 D&D * L.F.] 16

= 1.0 D&D + [.35 D&D * .558] 16

$C.P_1$ = 1.0 D&D + 3.1248 D&D = 4.1248 D&D

Normalized cost = C.P./4.1248 D&D

In a similar manner, the cost of 2, 3 and 4 applications can be calculated which yields the data in Table 3-6.

TABLE 3-5
Learning Factor Table
All First Articles are 100%

Quantity		2	4	8	16	24	32	64
Learning Factor								
0.95	N^{th}	95.0%	90.3%	85.7%	81.5%	79.0%	77.4%	73.5%
	Aver.	97.5%	94.4%	90.8%	87.0%	84.65	83.0%	79.1%
0.90	N^{th}	90.0%	81.0%	72.9%	65.6%	61.7%	59.0%	53.1%
	Aver.	95.0%	88.9%	82.2%	75.2%	71.3%	68.5%	62.0%
0.85	N^{th}	85.0%	72.3%	61.4%	52.2%	47.5%	44.4%	37.7%
	Aver.	92.5%	83.6%	74.2%	64.9%	59.7%	56.2%	48.3%
0.80	N^{th}	80.0%	64.0%	51.2%	41.0%	35.9%	32.8%	26.2%
	Aver.	90.0%	78.6%	69.3%	55.8%	49.8%	45.9%	37.4%

)tes:

1. N^{th} refers to the 2^{nd}, 4^{th} etc article in the fabrication of identical articles by the same process

2."Aver.", refers to the average cost of the 1^{st} through the N^{th} article under the same conditions

3. The External Tank learning factor has been estimated at 80% (0.80) due to the relatively large amount of manual labor that goes into the fabrication process. In general the more manual the process, the greater the learning and the smaller is the number from the table that applies.

4. As the learning factors approach unity the reduction in cost for each succeeding cycle is reduced and 1.0 represents a fully automated process wherein the first article and the N^{th} article cost is the same.

5. For the purposes of the SBI trade studies we can use the guidelines that the manual fabrication and assembly processes of sheet metal have learning factors of 80% to 90% while the more automated and repetitive processes range between 90% and 95% or even as high as 97%. There probably won't be any automated processes where the costs of a number of articles remains the same as the first article cost.

Table 3-6
Cost of Multiple Applications

Applications	D&D Cost	Production Cost	Normalized Total Cost Per Application
1	1.0 (D&D)	3.1248 (D&D)	1.00
2	.50 (D&D)	5.1408 (D&D)	.744
3	.33 (D&D)	6.7704 (D&D)	.628
4	.25 (D&D)	8.3776 (D&D)	.568
5	.20 (D&D)	9.785 (D&D)	.523

Figure 3-2 is a linear plot of the foregoing information based upon a theoretical first unit (TFU) cost of 35% * (DD), Figure 3-3 is based on a TFU of 15% * (DD). Figures 3-2 and 3-3 illustrate two facts. The first is that a significant cost reduction result from the use of hardware in more than a single application. The second is that the point of diminishing cost return occurs rapidly beyond the third application.

Modularity, although similar to commonality in some respects, offers other advantages as well. However, one must acknowledge that modular designs may cost more initially than non-modular designs due to the tendency for them to require added weight for packaging and more design integration due to an increase in the number of interfaces present in the system. Nevertheless, such systems have lower life cycle costs because of simplicity in assembly, repair, replacement, problem diagnosis and upkeep in general. Also there are the advantages of being able to upgrade individual modules with new technology and/or design improvements without impacting the rest of the system and without complicated disassembly and assembly to affect a module changeout.

Thus, if modules can be made common, the system possesses the attributes of modularization and offers potential cost savings from the multiple use of various system modules. The long and short of it is that the system cost can be reduced and the system flexibility and life cycle attributes improved. Common elements in modular designs should be a major, high priority goal in all SBI systems.

3.3 Modification of Existing Hardware (COTS) vs. New Hardware Build

Commercial off-the-shelf (COTS) hardware has been used for space applications sporadically since the early days of manned space flight and it poses the same cost-related challenges today as it did 25 years ago. The variables involved are the cost of the item, the cost of modification to meet space flight requirements, and the cost of demonstrating the hardware's reliability in qualification testing.

Past experience indicates that the cost of hardware modification is normally the primary cost factor of the cost elements listed. In an effort to assign an order of magnitude to modification costs, the weight of the COTS, the degree of modification (design factor, df), and the nature of the system (weight and system complexity, n) are used as prime cost drivers. Table 3-6 and 3-7 show the cost of modification against size (wt), and for systems with complexity factors (n) of .2 and .4. The higher order complexity factors are assumed to be not applicable on the basis that COTS is usually procured as modules or assemblies and then integrated into a larger system as necessary.

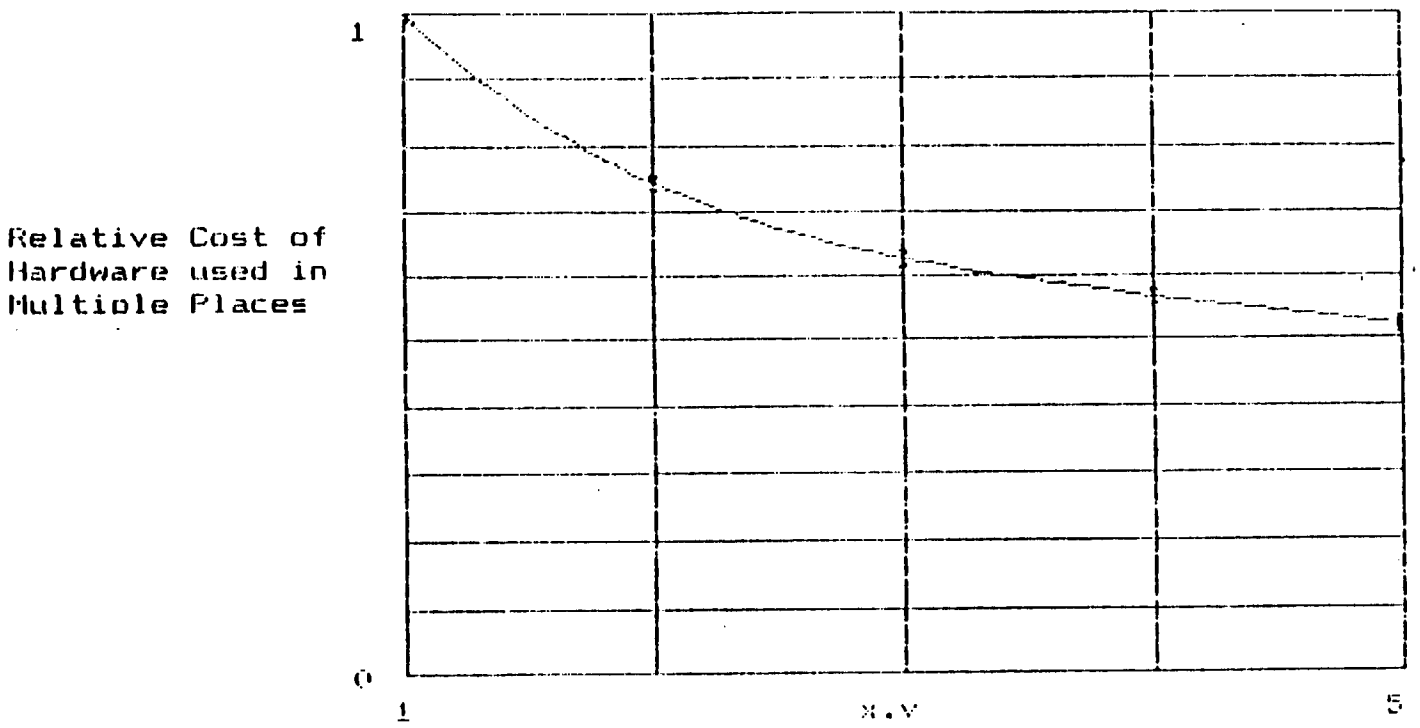
The costs shown in Tables 3-7 and 3-8 are based upon the assumption that COTS modifications are approximately the same cost as are redesigns to existing systems. The degree of modification (or redesign) is reflected in the design factor, df. The degree of system complexity is reflected by the system complexity factor, n. The range of weights over which these parameters are varied was selected on the basis that few items to be modified would be heavier than 50 Kg and that the small items less than 5 Kg would be procured as components or small assemblies which would be used in the design of a new system. The assumed size limit can be modified if necessary but were made to keep the number of weight variables in a reasonable size range with modest increments between each one. Here, again, caution is needed when applying CER type relationships to small items and to items where the portion of a hardware element being modified is small. See paragraph 2.1 for a discussion of scaling limitations.

Specific modifications to COTS may be simple enough to invalidate the assumption that modifications and redesign costs are similar. If so, alternate COTS modification cost methods will be required and will reflect greater savings. Thus, the foregoing assumption degrades gracefully because it is conservative from a cost point of view.

A popular viewpoint today is that modified COTS is always less costly than is a new design. This belief is reflected in the emphasis on "make or buy" in recent NASA RFP's and also in recent cost seminars held by major aerospace companies. Nonetheless, some cost specialists express the opinion that modifications to COTS greater than 30-35% probably makes a new design preferable. The COTS vs. new design trade study deals with these subjects so this part of the report will be confined to cost trends only. From the viewpoint of modification costs alone it appears straightforward that COTS has great cost reduction potential and should be seriously considered whenever a commercially available system element exists that can be utilized in SBI.

In order to illustrate the cost trends for modification costs and modification cost per pound, Figure 3-4 and 3-5 are included. Figure 3.4 represents minor modifications (df = .15) and n = .2, and, therefore, shows the lowest cost per pound of any of the cases in Tables 3-7 and 3-8. Figure 3-5 is for the case of substantial modifications and n = .4, df = .55 and thus represents a high side cost case. The figures both show the trends that are typical for the values presented in the tables.

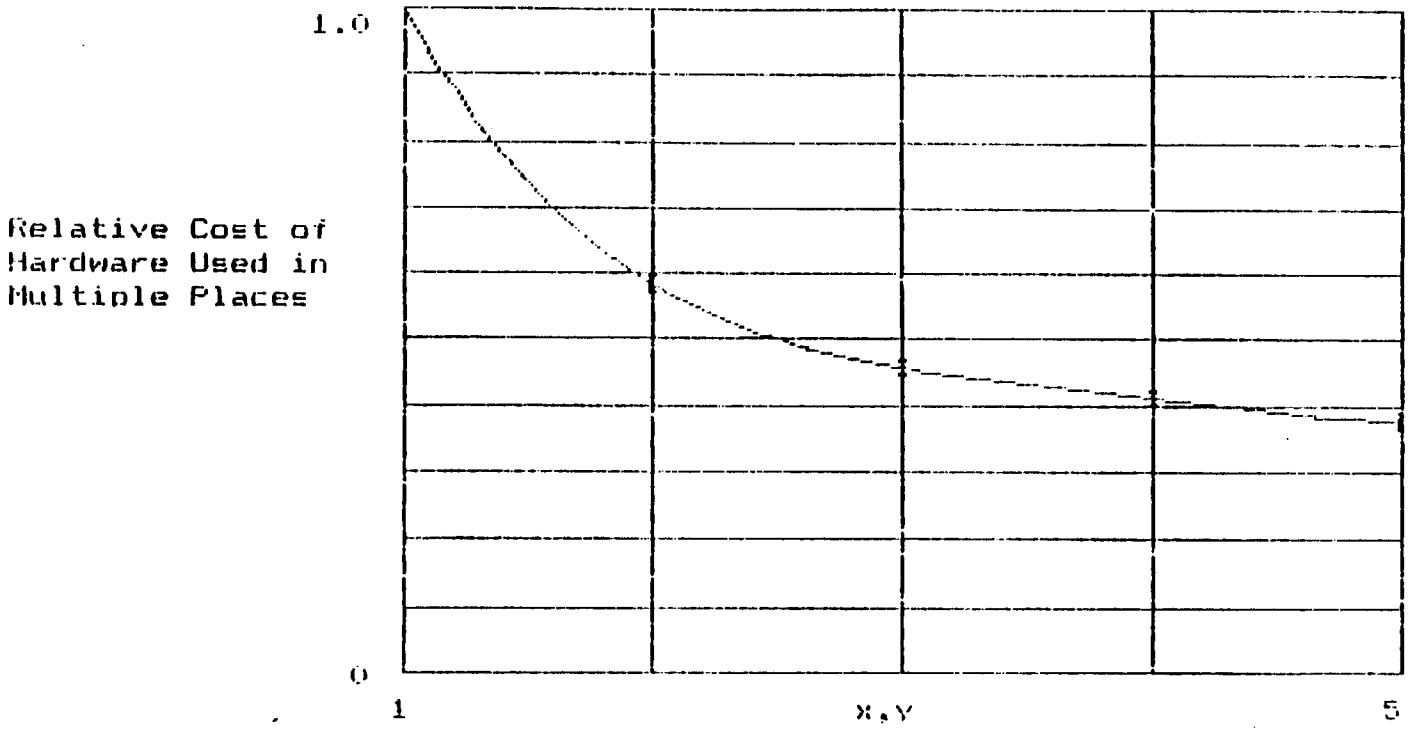
Figure 3-2
Effect on Cost of Multiple
Applications of Hardware



First Unit Cost (TFU) = .35*(Dev. Cost)

Learning Factor = 80%

Figure 3-3
Effect on Cost of Multiple
Applications of Hardware



First Unit Cost (TFU) = .15*(Dev.Cost)

Learning Factor = 80%

Table 3-7 Cost of Modifying Commercial Off-the Shelf Hardware

System Complexity Factor (n) =.2

Weight of Part Modified \ Design Factor	Minor Mods df=.15		Modest Mods df=.35		Substantial Mods df=.55		Major Mods df=.75	
	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg
Weight =5 kgs	242.3	48.46	565.4	113.1	888.5	177.7	1212	242.3
Weight = 10 kgs.	278.3	27.83	649.5	64.95	1021	102.1	1392	139.2
Weight = 20 kgs.	319.7	15.99	746.0	37.3	1172	58.62	1599	79.93
Weight = 30kgs.	346.7	11.56	809.1	26.97	1271	42.38	1734	57.79
Weight = 40 kgs.	376.0	9.182	857.0	21.42	1347	33.67	1836	45.91
Weight = 50 kgs.	384.0	7.681	896.1	17.92	1408	28.16	1920	38.40

Notes: 1) All costs are in thousands of dollars

Table 3-8 Cost of Modifying Commercial Off-the Shelf Hardware

System Complexity Factor (n) =.4

Weight of Part Modified \ Design Factor	Minor Mods df=.15		Modest Mods df=.35		Substantial Mods df=.55		Major Mods df=.75	
	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg
Weight =5 kgs.	391.4	78.28	913.3	182.7	1435	287.0	1957	391.4
Weight = 10 kgs.	516.5	51.65	1205	120.5	1894	189.4	2582	258.2
Weight = 20 kgs.	681.5	34.08	1590	79.51	2499	148.5	3408	170.4
Weight = 30 kgs.	801.5	26.72	1870	62.34	2939	97.96	4008	133.6
Weight = 40 kgs.	899.3	22.48	2098	52.46	3297	82.43	4496	112.4
Weight = 50 kgs.	983.2	19.66	2294	45.88	3605	72.10	4916	98.32

Notes: 1) All costs are in thousands of dollars

Figure 3 - 4
Variation of Cost & Cost/kg for COTS Mods
df=.15 n=.2

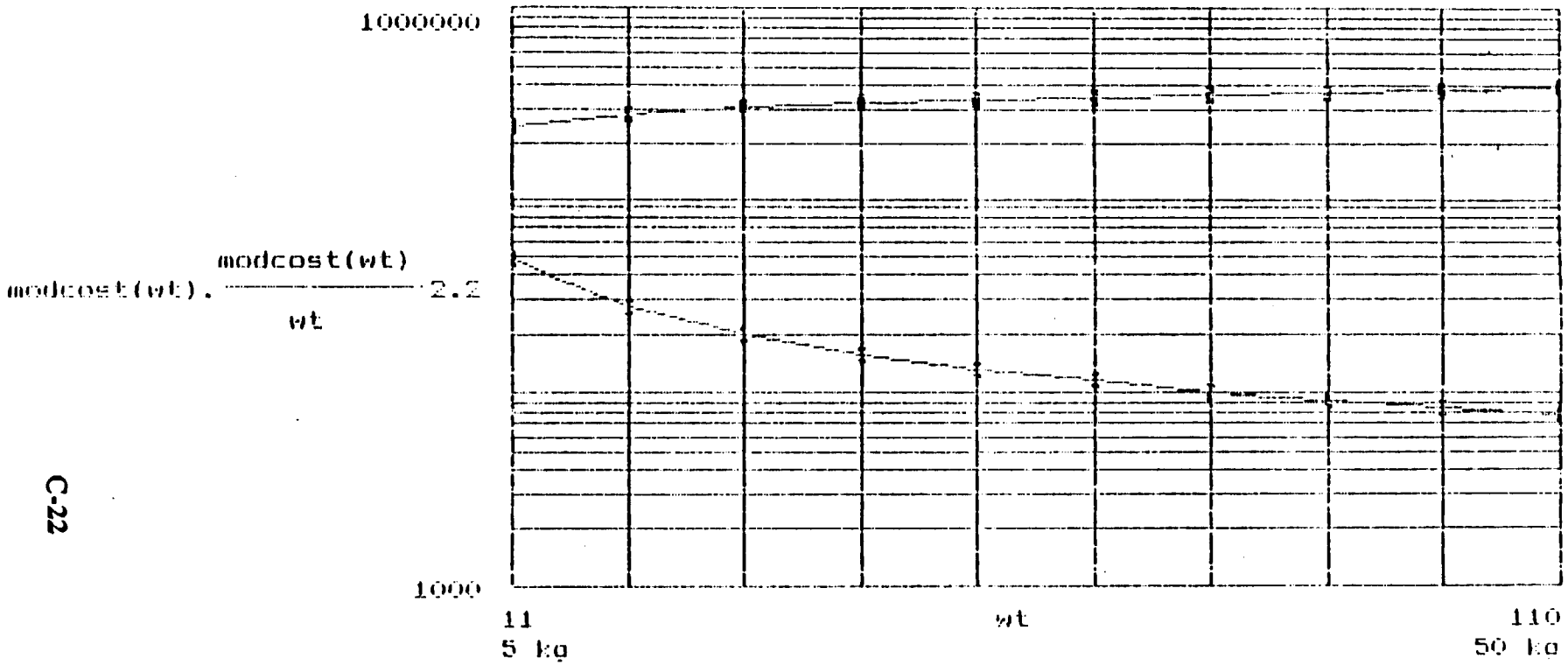
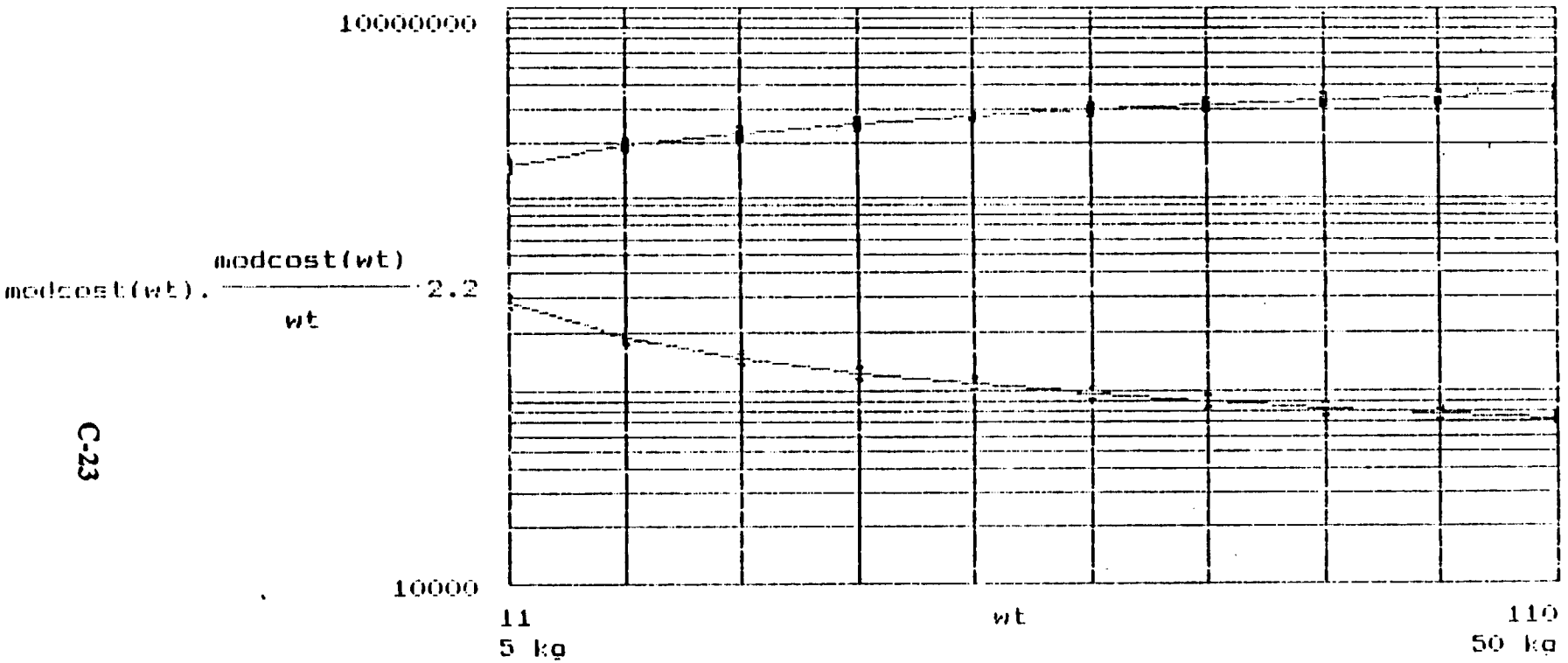


Figure 3 - 5
Variation of Cost & Cost/kg for COTS Mods
df=.55 n=.4



4.0 Testing Costs

A cursory treatment of testing costs is presented so as to make the cost picture as complete as possible. However, the applicability of test costs to SBI has not been validated and the guidelines presented should be applied with care only where a similarity exists between SBI elements and/or subsystems, and other manned spacecraft systems.

4.1 Test Hardware

Test hardware costs in past manned programs have included the cost of labor and materials for major test articles used to verify design concepts. However, test hardware cost relationships exclude element tests, component tests, qualification and certification tests. The cost of labor and material for the design, procurement, installation, checkout and operation of the instrumentation system on major test articles is included and as one might expect, these factors drive the cost of test hardware up to a value greater than the first unit cost.

The CER's examined put the cost of test hardware at 30% more than the theoretical first unit (TFU) cost, i.e. 1.3 * TFU. It should be noted that this cost is to demonstrate and to verify the operation of the designed hardware and should not be construed to include experimentation and testing to acquire biological information of an experimental or research character.

4.2 Integration Assembly and Checkout (IACO)

This factor is most commonly estimated as a function of TFU costs or test hardware costs. It will generally run on the order of 10 - 20% of test hardware costs for manned systems, but care must be exercised in applying such a rough rule of thumb to SBI. Therefore, a simple CER is suggested in cases where PRICE H estimates have not yet been formulated. The CER is as listed below:

$$IACO = .3\ (1.3\ TFU)^{0.7}$$

The resulting estimate can only be generated when all other hardware costs are available.

4.3 Test Operations

Test operations CER's indicate that costs generally run on the order of 20% to 30% of the cost of test hardware plus integration, assembly and checkout costs. However, as is the case with other test related items of cost, the applicability to SBI hardware has not been validated. Nonetheless, the order of magnitude could be used for SBI estimates pending specific definition of test requirements for the various experiments.

Examination of the SBI hardware list (Ref.SBI No. 87) and the Life Science Laboratory Equipment description (Ref. SBI No.88) suggests that test operations could vary from little or nothing all the way up to the level indicated in CER's and approximated above.

5.0 SE&I Costs

SE&I cost for the design and development phase are generally expressed as a function of the DDT&E + Systems Test Hardware + IACO + Test Operations + GSE costs. However, the lower end of the validity range is almost $1.0 billion of DDT&E costs and the applicability to SBI is extremely doubtful. For that reason, it is recommended that the preliminary SBI SE&I cost be taken as 10% to 15% of the SBI total system development cost until a detailed estimate or a PRICE H value is generated.

6.0 Program Management Costs

Program management costs usually run 5% of the total of all other costs, i.e., 5% of the sum of DDT&E + IACO + Test Hardware + Test Operations + GSE + SE&I (for DDT&E) costs. Inasmuch as there is no basis to assume that SBI program management cost is any more or any less than other types of programs, it seems reasonable to use a very preliminary value of this order of magnitude for budgetary estimating purposes.

7.0 Life Cycle Costs

As noted previously in this appendix, life cycle cost information is not available and therefore only a subjective treatment of the subject is possible. Nonetheless, Table 7-1 provides some worthwhile insights concerning all the SBI trade study subjects being addressed by Eagle. Taken singly, these subjects reveal the following probable life cycle impacts.

7.1 Study No. 3 - Miniaturization

The possible reduction of cost due to the impact of weight reduction is more theoretical than achievable. Indications are fairly clear that most attempts to miniaturize will cost rather than save money. Therefore, one must conclude that the reason for attempting size reductions is other than cost savings. It is beyond the scope of this write-up to postulate or to speculate further.

7.2 Study No. 4 - Modularity and Commonality

If the SBI program-wide support can be mobilized to support modular design and the development of hardware for common application to a number of SBI experiments and/or facilities, the cost benefit should be very significant. All the factors noted in Table 7-1 tend to substantiate this conclusion and only the programmatic direction and support has any identifiable cost or problem related to it.

Modular designs and common equipment should be a top priority requirement, goal and objective of SBI effort.

7.3 Study No. 5 - COTS vs. New Hardware

COTS should be regarded as a slightly trickier subject than commonality due to the potential pitfalls and cost penalties that can be incurred in its application to spaceflight. Nonetheless, the potential cost savings are large enough so that judicious use of COTS where it fits with the SBI program appears to be a cost-wise approach which could yield tremendous cost benefits for only nominal technical risk. Technical risk which can be offset by care in selecting, testing, and screening the procured items.

The use of modified COTS in lieu of a new design appears to pay off until the modification cost approaches the cost of an optimized new piece of hardware. The cut-off point has not been defined but would make an interesting and worthwhile follow-on study. Intuitively one would expect to find a series of cut-off points that are a function of the hardware complexity, and therefore, the cost and complexity of the modification program.

7.4 Study No. 6 - Rack Compatibility

To a greater degree than the other SBI trade studies, this subject seems to defy analysis that could give cost trend indications or life cycle cost indicators. Nevertheless, if one assumes that the inter-program coordination of rack compatibility can be accomplished with a reasonable effort, there exists the possibility to lower cost, to reduce the cost of data normalizing and

comparison, and improved scientific data return might possibly be a companion benefit to lower experimentation costs.

The entire spectrum of life cycle costs beyond the design and program management phase that would accrue due to compatibility all appear to be very positive and beneficial. Logistics, ground processing, pre-flight checkout, operations, repair and replacement all would be impacted in a beneficial way by this approach. A comparable achievement that comes to mind is the establishment of standard equipment racks by the International Air Transport Association (IATA). The benefits apply to a large number of items (commercial transports) and of course the impact is greater, but the concept has been a true bonanza to all the world's commercial airlines. Rack compatibility is potentially a smaller sized cousin to IATA's achievement.

Table 7 -1 Life Cycle Cost

Phase \ Study	Study No. 3 Hardware Miniaturization	Study No. 4 Modularity and Commonality	Study No. 5 COTS vs. New Hardware	Study No. 6 Rack Compatibility
Design	Design change always required. Cost of redesign may be partially offset by size & weight reduction.	Requires programmatic support and some allowance for increased weight and cost in design phase.	Dependent upon availability and suitability of commercial modules and/or elements for SBI system application.	Requires inter-program coordination/communication and direction which is very difficult to achieve.
Development	Fabrication may be complicated due to size reduction.	Development, manufacture or procurement is facilitated by modularity. Commonality cost impacts all positive.	Modified COTS appears to have significant potential advantage. Requires sound make or buy anlysis & eval.	Common source would be highly desireable but will be hard to do due to specification differences & organiz. barriers
Test and Evaluation	Test costs may increase due to difficulty in set-up and trouble shooting.	Module testing, integrated testing and test trouble shooting are simplified and cost savings result.	Testing impact appears to be negative due to need for extra qualification tests and periodic retest (screening).	Should have only minor impact which stems from differences in test requirements.
Sustaining Engineering	No significant impact pro or con is apparent.	Individual engineering groups can operate with less sytems integration effort.	Should be automatically supported by vendor's program. Generally positive. Mods could pose problems.	Responsibility may be difficult to establish and to identify. Problem potential is small due to type of hardware.
Technology Upgrade	May be less likely due to absence of alternate hardware availability.	Facilitated and made easier by modular design.	Not predictable. Experience indicates that it can vary from easy and to very painful and awkward.	Should be possible within a rack or module. Compatibili will reduce the overall cost of inserting new tech. upgrades
Maintenance and Operations	Possible adverse impact on maintenance due to small size. Operation should not be affected.	Common module impacts on maintenance, logistics and operations are all positive & highly significant.	Maintenance of unmodified portion could pose problem. Operation not affected if reliability is adequate.	Design for long life should mean small scale preventive maintenance is all that is required.
Replacement	May be less costly due to size and favorable impact on logistics.	Can be accomplished in planned phases and/or steps with minimum disruption to system operation.	COTS use suggests that low cost replacements are available. Advantage can erode with age.	Standard interfaces can only work to reduce the cost of replacement. Fewer spares, standard procedures etc.
Overall Life Cycle Cost Impact	Tends to look negative. The need to miniaturize must be based upon reasons other than cost.	Life cycle cost impacts are all highly favorable except for design phase coordination & possible weight penalties.	Very significant life cycle cost advantage inherent in COTS. However, initial selection and mod program must be prudent.	Whatever the cost of inter-program coordination, ICD's etc., the impact on overall NASA cost is very beneficial

8.0 Recommendations

1. Perform a follow-on effort to generate a designer's "John Commonsense" manual for cost avoidance and/or reduction. The manual should be a series of simple groundrules and guidelines to help reduce Space Biology Initiative Program costs. Where possible, a series of tables or curves to help assess the potential cost gain should be included.

2. Mount an effort to accumulate an SBI historical cost data base. The objective should be at least two-fold. First, identify the breakpoint for various cost trade-offs. Examples are presented in Figures 3-2 and 3-3 which show that commonality soon reaches a point of diminishing return insofar as it pertains to development and manufacturing. Given such breakpoints, explore the possibility of additional life cycle cost benefits which result from reduced sparing, simplified logistics, reduced maintenance, etc. Second, obtain enough historical cost information to permit the development of CER's that are properly scaled for the range of sizes in question. Existing CER's have limitations that may invalidate their use on SBI. Therefore, actual cost data from ongoing SBI efforts would provide a valuable asset to future work of a similar nature.

3. Consider a follow-on program to develop a rule-based or expert system that could be used for quick cost estimates and cost comparisons. Such an effort can only proceed in parallel with item 2, above, but the development time is such that it should begin as soon as practical.

4. Generate a comprehensive compendium of cost estimating relationships and apply them to SBI. Subsequently, make comparisons with other cost estimating methods in an attempt to remove the existing programmatic skepticism about the voodoo and black magic of cost predictions.

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Appendix D - Database Definition

Appendix D - Database Definition

The database files for the SBI trade Studies were developed using dBASE IV. The database files consist of dbf, ndx, and frm files. The dbf files are dBASE IV database files. NDX files are the index files for the dbf (database) files. The frm files are report files for the trade study candidate and bibliography reports. The SBI trade study database consist of 4 database files with 78 fields of information. A complete listing of the database structure and dictionary is included in this database definition.

Database Structure For SBI Trade Studies

Structure for database: W:hardware.dbf
Number of data records: 93
Date of last update : 05/30/89

Field	Field Name	Type	Width	Dec
1	HW_ID	Character	3	
2	HW_NAME	Character	50	
3	HW_DESCRTN	Character	254	
4	HW_FACILIT	Character	55	
5	INFO_SOURC	Character	250	
6	HW_MASS	Numeric	6	3
7	HW_VOLUME	Numeric	8	6
8	HW_POWER	Numeric	4	
9	HW_VOLTAGE	Numeric	6	
10	HW_HEIGHT	Numeric	6	
11	HW_WIDTH	Numeric	6	
12	HW_DEPTH	Numeric	8	
13	REMARKS	Character	50	
14	RECORD_DAT	Date	8	
15	GROUP	Character	50	
16	CATEGORY	Character	50	
17	FUNCTION	Character	60	
18	FAC_ID	Character	4	
19	GROUP_ID	Character	4	
20	MIN_LEVEL	Character	5	
21	CONFIDENCE	Character	5	
22	SUFFIC_DAT	Character	4	
23	PRIORITY	Character	2	
24	MIN_LV_POT	Character	6	
25	MIN_EST_CF	Character	6	
26	MOD_LV_POT	Character	6	
27	MOD_EST_CF	Character	6	
28	COM_LV_POT	Character	6	
29	COM_EST_CF	Character	6	
30	SYS_COMPLX	Character	6	
31	DSN_COMPLX	Character	6	
32	BUY_LV_POT	Numeric	4	
33	BUY_MOD_LV	Numeric	4	
34	BUY_EST_CF	Character	4	
35	BUY_OTS_PT	Numeric	4	
36	BUY_DAT_AV	Character	4	
37	MOD_CAN	Logical	1	
** Total **			968	

```
Structure for database: W:biblo.dbf
Number of data records:      98
Date of last update    : 05/26/89
Field  Field Name  Type        Width     Dec
    1  BB_ID       Character       5
    2  AUTHOR_NO1  Character      16
    3  AUTHOR_NO2  Character      12
    4  AUTHOR_NO3  Character      12
    5  ART_TITLE   Character     135
    6  BOOK_TITLE  Character     100
    7  VOLUME_NO   Character       3
    8  PUBLISHER   Character      42
    9  PUBL_LOC    Character      32
   10  DATE        Date            8
   11  PAGE_NOS    Character       4
   12  ABSTRACT    Character     100
   13  ACQUIRED    Character      20
   14  COST        Numeric         6
   15  LOANED      Character       4
   16  REP_DOC_NO  Character      22
   17  MOD         Logical         1
   18  MIN         Logical         1
   19  COTS        Logical         1
   20  RACK        Logical         1
** Total **                     526

Structure for database: W:rack_com.dbf
Number of data records:     166
Date of last update    : 05/26/89
Field  Field Name  Type        Width     Dec
    1  IF_ITEM     Character      38
    2  UNITS       Character       8
    3  UNIT_SYS    Character       1
    4  ITEM_TYPE   Character      12
    5  VALUE       Character      50
    6  MODULE      Character      25
** Total **                     135


Structure for database: W:comm_mod.dbf
Number of data records:     153
Date of last update    : 05/30/89
Field  Field Name  Type        Width     Dec
    1  HW_ID       Character       3
    2  COMM_MOD    Character      30
    3  COUNT       Numeric         1
    4  COST_DECSC  Numeric         4       2
    5  MASS        Numeric         4       2
** Total **                      43
```

Appendix D - Database Dictionary for Space Biology Initiative Trade Studies

Hardware.dbf **This is the database file for SBI hardware.**

Field 1	HW_ID	Unique identification number for each hardware item
Field 2	HW_NAME	Hardware name
Field 3	HW_DESCRTN	Hardware description
Field 4	HW_FACILIT	Facility where SBI hardware is used
Field 5	INFO_SOURC	Information source for SBI hardware data
Field 6	HW_MASS	Hardware mass
Field 7	HW_VOLUME	Hardware volume
Field 8	HW_POWER	Hardware power requirement
Field 9	HW_VOLTAGE	Hardware voltage requirements
Field 10	HW_HEIGHT	Hardware height
Field 11	HW_WIDTH	Hardware width
Field 12	HW_DEPTH	Hardware depth
Field 13	REMARKS	Remarks concerning SBI hardware equipment
Field 14	RECORD_DAT	Update of last record
Field 15	GROUP	Hardware group
Field 16	CATEGORY	Hardware category
Field 17	FUNCTION	Hardware function
Field 18	FAC_ID	Hardware facility ID number
Field 19	GROUP_ID	Hardware group ID number
Field 20	MIN_LEVEL	Miniaturization level for hardware
Field 21	CONFIDENCE	Confidence level for miniaturization
Field 22	SUFFIC_DAT	Is there sufficient data to make a decision of hardware miniaturization?
Field 23	PRIORITY	Priority level for hardware item based on mass
Field 24	MIN_LV_POT	Miniaturization level potential for the hardware item
Field 25	MIN_EST_CF	Confidence level for miniaturization
Field 26	MOD_LV_POT	Modularity potential for hardware item
Field 27	MOD_EST_CF	Confidence level for modularity estimate
Field 28	COM_LV_POT	Commonality potential for hardware item
Field 29	COM_EST_CF	Confidence level for commonality estimate
Field 30	SYS_COMPLX	System complexity for hardware item
Field 31	DSN_COMPLX	Design complexity for hardware item
Field 32	BUY_LV_POT	Percent Buy for Hardware Item
Field 33	BUY_MOD_LV	Percent modification to Buy Hardware Item
Field 34	BUY_EST_CF	Confidence Level for Make-or-Buy Estimate
Field 35	BUY_OTS_PT	Percentage of COTS hardware that does not require modification
Field 36	BUY_DAT_AV	Is sufficient data available for make-or-buy estimate
Field 37	MOD_CAN	Logical field can the hardware item be modularized Y or N

biblo.dbf **This is the database for bibliography information.**

Field 1	BB_ID	Identification number for the reference
Field 2	AUTHOR_NO1	First author
Field 3	AUTHOR_NO2	Second author
Field 4	AUTHOR_NO3	Third author
Field 5	ART_TITLE	Title of article
Field 6	BOOK_TITLE	Title of book
Field 7	VOLUME_NO	Volume number
Field 8	PUBLISHER	Publisher
Field 9	PUBL_LOC	Publisher's address
Field 10	DATE	Date of publication
Field 11	PAGE_NOS	Page number of reference
Field 12	ABSTRACT	Abstract
Field 13	ACQUIRED	Where the reference was acquired
Field 14	COST	Cost of reference
Field 15	LOANED	Where the reference was loaned from
Field 16	REP_DOC_NO	Report or document number
Field 17	MOD	Was this reference used on the modularity trade study? y or n
Field 18	MIN	Was this reference used on the miniaturization trade study? y or n
Field 19	CUTS	Was this reference used on the make-or-buy trade study? y or n
Field 20	RACK	Was this reference used on the rack compatibility trade study? y or n

rack_com.dbf **This is the database file for the rack comparison study.**

Field 1	IF_ITEM	I/F item being compared, i.e. power converters
Field 2	UNITS	Units of comparison, i.e. inches
Field 3	UNIT_SYS_	Unit system, i.e. metric
Field 4	ITEM_TYPE	Functional Grouping of IF Item i.e. Data Mgmt.
Field 4	VALUE	Value of the comparison
Field 5	MODULE	Module, i.e. U.S. Lab

comm_mod.dbf **This is the design modularity and commonality database**

Field 1	HW_ID	Unique identification number for each hardware item
Field 2	COMM_MOD	Modularity function/assembly
Field 3	COUNT	Used to total hardware items in COMM_MOD Field
Field 4	COST_DECSC	Cost description
Field 5	MASS	Mass of hardware item

Appendix E - Make-or-Buy Analysis for CHeC

Appendix E - MAKE-OR-BUY ANALYSIS FOR CHeC

This appendix contains brief descriptions of the Make-or-Buy categories developed by McDonnell Douglas Astronautics Company (MDAC) for Crew Health Care (CHeC). This information was obtained from MDC H3924, CHeC Volume 1, Narrative, November 1988.

The items in Category 1 (must make) are of two types. The first type consists of items that are either identical to or similar to Space Station items that are being designed for reasons other than CHeC. Examples are compartment assemblies. The second type of Category 1 item is software. We believe that we must design the software associated with Data Management System (DMs) in order to ensure compatibility with the rest of the DMS.

Items that are considered to be in Category 2 (can make or buy) are of seven types: First, there are instruments that are primarily electronic in nature. We chose to buy these in most cases because many companies are available that can develop and produce such instruments at competitive prices. The second Category 2 type consists of containers, such as those used for kits. We have chosen to design these in Houston, and have them fabricated by small businesses in the Houston area. The third type consists of simple fabricated items as a specialized nature, and the fourth consists of complex fabricated items of a specialized nature. We plan to design both of these types in Houston; the simple ones will be fabricated locally by small businesses; the complex ones will be fabricated in-house in Huntington Beach. The fifth Category 2 type consists of wire harnesses; the sixth of plumbing. We plan to design both harness and plumbing in Houston. Both will be fabricated in Huntington Beach to take advantage of the availability of specialized equipment and experienced personnel. The seventh Category 2 type consists of low fidelity mockups. We plan to design and fabricate these in Houston. Fabrication of these noncritical items can safely be accomplished there, since specialized equipment and specially trained personnel are not required.

Category 3 (must buy) items are of four types. The first consists of instruments that involve more than just electronics, and other specialized flight equipment. We normally buy these items because certain companies have experienced and specialized equipment that makes them better qualified sources than our own company. There are two exceptions, where we decided that specialized flight equipment falls in Category 2 (can make or buy). These are the incubator and the glove box, where our company has directly applicable specialized experience. We plan to design the glove box in Houston, and fabricate it in Huntington Beach. The incubator is planned to be bought, but could be designed and built by a St. Louis division of our company. The second Category 3 type is the contents of kits. The third Category 3 is supplies. For both of these types of items, we expect that existing off-the-shelf items will be suitable for the CHeC requirements. The fourth category 3 type consists of items requiring specialized technology that is available only in certain companies. Examples are surgery drapes and task lighting.

Category 4 (must buy from major subcontractor) consists of those items that are identical to or similar to items normally supplied by our major subcontractors for Space Station. Examples are a Multipurpose Application Console (MPAC) processor and a modified Network Interface Unit (NIU) (less the bedside communications controller), both of which will be supplied by IBM.

In addition to the four categories discussed above, there is a GSE category. This has been used for items normally provided to us by the government because they are produced as part of another work package contract.

AUTOMATION COST VS CREW UTILIZATION

TRADE STUDIES

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SPACE BIOLOGY

INITIATIVE

Space Biology Initiative
Program Definition Review

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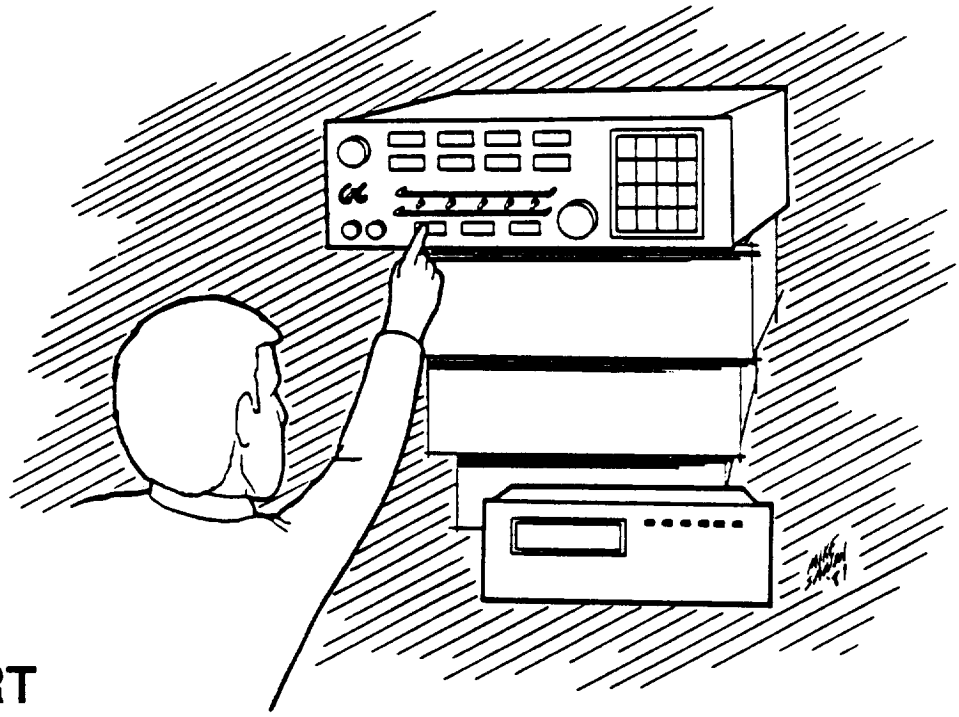
Automation Costs vs. Crew Utilization



FINAL REPORT

June 1, 1989

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SPACE BIOLOGY INITIATIVE
PROGRAM DEFINITION REVIEW

TRADE STUDY 1

AUTOMATION COSTS
vs.
CREW UTILIZATION

FINAL REPORT

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June 1, 1989

SBI Program Definition Review

Trade Study 1

Automation vs. Crew Utilization

EXECUTIVE SUMMARY

Executive Summary

A significant emphasis upon automation within the Space Biology Initiative hardware appears justified in order to conserve crew labor and crew training effort. Two generic forms of automation have been identified: automation of data and information handling and decision making and the automation of material handling, transfer and processing. The use of automatic data acquisition, expert systems, robots and machine vision will increase the volume of experiments and quality of results. The automation described in this report may also influence efforts to miniaturize and modularize the large array of SBI hardware identified to date.

The cost and benefit model developed in this study appears to be a useful guideline for SBI equipment specifiers and designers. Additional refinements would enhance the validity of the model.

Two NASA automation pilot programs, "The Principal Investigator in a Box" and "Rack Mounted Robots" have been investigated and found to be quite appropriate for adaptation to the SBI program. There are other in-house NASA efforts that provide technology that may be appropriate for the SBI program.

Important data is believed to exist in advanced medical labs throughout the US, Japan and Europe. The information and data processing in medical analysis equipment is highly automated and future trends reveal continued progress in this area. However, automation of material handling and processing has progressed in a limited manner because the medical labs are not affected by the power and space constraints that Space Station medical equipment is faced with. Therefore, NASA's major emphasis in automation will require a lead effort in the automation of material handling to achieve optimal crew utilization.

AUTOMATION VS CREW UTILIZATION

1.0 INTRODUCTION

1.1 Background

The history of Life Science Biology experimentation dates long before the birth of the National Aeronautic and Space Administration (NASA). The first documented flight carrying a living payload was a V-2 rocket in 1948, which was launched by the Navy. On this flight, a primate, "Albert", was carried in a specially designed nose cone [reference 1]. The Blossum missions (1948 - 1950) were the first to carry a biological or medical payload. Starting with a rhesus monkey as the first biological payload, several cynomolgus monkeys and later a mouse were sent on the missions. Later, the Army joined in carrying out life science experiments using ballistic rockets as a means of carrying the experiments.

The Aerobee missions (1951 - 1952) followed the Blossom missions. These launched more capuchin and rhesus monkeys into flight. The monkeys and mice were recovered alive and showed no ill effects from flight.

The Mouse-In-Able missions (1958) carried mice into sub-orbital flight in a nose cone, monitoring ECG signals and pulse rate. These missions lasted typically on the order of 20 minutes.

The Army Medical Sounding Rocket (1958 - 1959) carried for the first time various biological specimens including sea urchin eggs.

From this point on, NASA began taking the lead in space biology research. The Mercury Project (1961 - 1963) placed several chimpanzees into orbital flight. Mercury 3 carried the first American, Alan B. Shepard, Jr. into space opening the gateway to manned space flights and human experimentation. The flight duration was extended to 34 hours (Mercury Atlas 9) and cardiovascular data gathered on this mission included orthostatic intolerance and dizziness on standing, dehydration due to weight loss and hemoconcentration.

The Gemini Program (1965 - 1966) conducted and evaluated physiological tests to demonstrate feasibility of earth orbital flights of up to two weeks duration.

During the five year span of the Apollo Program (1967 - 1972), biomedical studies were essentially limited to the pre-flight and post-flight mission phases, with in-flight monitoring and observations. The biomedical findings in the Apollo Program confirmed the Gemini results of post-flight dehydration and weight loss, post-flight reduction in exercise capacity and decrease in red cell mass and plasma volumes. The last Apollo mission, Apollo XVII lasted 301 hours and 51 minutes.

The Skylab Program (1973 - 1974) resulted in a major contribution towards understanding man in his new space environment. Individual experiments were developed to study the cardiovascular, musculoskeletal, hematological, vestibular and metabolic systems in the body. The last Skylab mission, Skylab 4, lasted 84 days in space.

The Space Shuttle era (1981 - present) has experienced the culmination of a wide range of biological experiments to better understand the long-term effects of zero gravity on plant, animal and human physiology and pathology. However, the short duration of the shuttle flights limited the use of the shuttle to experiments that must be completed in approximately 7 - 12 days.

The proposed space station will overcome this limitation by establishing a Permanent Manned Capability (PMC) in space. One of the major efforts in support of the space station is the Space Biology Initiative (SBI). The objective of the SBI is to study the effects of prolonged weightlessness on humans, animals and plants. In addition the experimental data would augment the safety and efficiency of the crew members, especially during longer flight duration. To carry out this objective, a series of biological experiments were devised to study the performance of these systems when subjected to micro gravity. The ultimate goal of the SBI program is to have a permanent or at least long duration (0 - 15 years) space life station laboratory that will be equipped with the latest technology hardware items to serve mankind in the best possible way to achieve permanent manned capability (PMC) in space. The PMC is expected to be realized around the year 2000.

A look at the evolution of life science experiments performed during the space flight missions reveals four trends: First, the increase in complexity of the experimental data and associated data collection and interpretation ranging from carrying a rhesus monkey into space (1948) to elaborate human physiological testing (1989). Second, the increase in length of mission duration, ranging from 20 minutes (1958) to 84 days (Skylab 4). Third, the lack of automation in life science experiments increased the burden on the crew time, thus forcing the crew to perform many of the time consuming experimental set up and calibration, which in turn decreased the number of different types of experiments that could possibly be performed during a mission. Fourth, the lack of automation resulted in post flight analysis of experimental data that was collected on flight. For example, during the early Apollo - Soyuz mission, electrophoresis columns were frozen and later analyzed post flight. The advent of automation in life science experiments has to a great extent positively influenced the complexity, nature and duration of experiments performed in space. For example, computer aided automated processing made it possible for Skylab 4 crew members to stay in space for over 84 days and perform in excess of 700,000 biochemical analysis of food, blood, urine and fecal samples [reference 2]. More then 18,000 minutes of blood pressure determinations and 12,000 minutes of electrocardiographic data were analyzed.

This is ample evidence that automation will play a significant role in fulfilling the objectives and ultimate goal of the SBI program. This study will analyze the benefits and cost impacts of automation on the SBI program. This study will define specific "rules of thumb" to identify the best candidates for automation of hardware items in the SBI program. An analysis of the impacts of automation on in-orbit crew utilization, crew training, hardware diagnostics, repair and equipment accuracy is also presented.

1.2 Purpose

The main contribution of this trade study is the proposed methodology and scoring mechanism. This study does not stress the actual quantitative analysis because of its subjective nature.

The main purpose of this trade study is to provide the designer or hardware engineer with a handbook of general "rules of thumb" that will aid in making the following decisions:

- Identify functional elements of life science hardware that are good candidates for automation. When and what realistic level of automation should be incorporated in a specific SBI hardware unit?

- What are the impacts of each level of automation on the following:

  i) crew time utilization
  ii) equipment performance
  iii) crew training time
  iv) hardware diagnostics and maintenance
  v) hardware repair

-What are the cost impacts of the different levels of automation in order to estimate the total cost for an automated hardware item?

In addition, this study will also identify the advantages of automated hardware versus non-automated hardware designs.

1.3 Scope

The scope of this study is limited to the hardware items that were chosen to be specifically used for the SBI program [reference 3]. The hardware items in reference 3 designated with an "E" (EDCO - Extended Duration Crew Orbital) or a "W" (WP - 01 Work Package) or a "C" (Centrifuge) are not considered in this study. The hardware items labelled with a "S" (SBI) are the only ones that have been investigated for this study.

A detailed and accurate study and automation analysis of a hardware unit is to a great extent dependent on its use in a given experiment protocol or procedure. The steps taken to successfully perform an experiment will determine actual labor utilization of the hardware item, crew training time and crew utilization, which in turn can aid in determining the level of automation to incorporate, as well as estimate the cost.

Since the experiment protocols or procedures were not available for this study, we have based our study on past experience with hardware equipment similar to the ones designated to be used for the SBI program. This includes direct working knowledge of most of the SBI hardware units obtained by SwRI staff members with work experience at NASA -JSC. The assumptions and guesses made were also based on the information contained in references 4, 5, 6, 7, 8.

Efforts have been made to formulate the guidelines and "rules of thumb" given in this document in as general terms as possible, in order to make them applicable to a wide range of automation studies.

It is again stressed that the quantitative analysis made in this study is subjective and is based on experience with the hardware items. However, general rules of thumb are provided to enable the reader to interpret the scoring and fine tune them to match personal knowledge level and expertise.

1.4 Methodology

The first task was to define the evolution of automation. The evolution of automation is typically categorized in terms of the level of mechanization, the level of software and electronics complexity, the level of self autonomy and finally the level of intelligent autonomy. Progressive levels of automation can be scored using an alphanumeric code with the lowest code corresponding to no automation and the highest code corresponding to full automation. Details on the alphanumeric code is described in section 2.2.3.

Generally, the system automation of an SBI hardware unit can be characterized from two perspectives or domains. These domains are the Data Domain and the Physical Domain. The Data domain essentially deals with the acquisition, interpretation and display of the data, or information transformation. The Physical domain relates to the amount of physical labor involved in the change, manipulation and movement of physical objects or material transformation. Each of the aforementioned domains can be independently alphanumericaly classified from zero level of automation (totally manual) to full automation (totally independent). The weighted average of the data domain and the physical domain indicates the total level of system automation of the man-machine hardware unit. The weighting factors depend to a large extent on the individual hardware unit itself, since in some cases, the data domain may be more predominant than the physical domain and the vice versa may be true for others. General "rules of thumb" to associate a hardware unit with a particular alphanumeric code are given in section 2.2.3.

The alphanumeric scheme described above was used to determine the current known level of automation for every individual SBI hardware item of reference 3. In addition, the realistic level of automation that can be conceived in an appropriate schedule coordinated with IOC (Initial Orbital Configuration) was also rated. Finally, the maximum available level of automation was determined for each individual SBI hardware item of reference 3. Each hardware unit was also graded on the basis of crew knowledge and crew skill required to operate successfully. The labor utilization of the hardware items was assessed on the basis of the crew time required for a particular hardware item and experiment.

All the above information is displayed in the form of charts, to enable identification of potential candidates for automation, their current level of automation, their realistic level of automation and finally the maximum possible level of automation. The hardware items were sorted with respect to

their levels of automation, beginning with those items with least possible automation and ending with those with the highest level of automation.

The cost impacts of automation were determined by first classifying the hardware items into functional groups based on the main purpose or function of the hardware item. Six different functional groups were identified. Then generic components of hardware items that most positively affect the cost were determined and it was found that any SBI hardware item can be broken down into five main generic components. Some items may have only one generic item represented in them, while others may have most or all of the generic components. Following the definition of the generic components, we identified a list of five major mission benefits that will result from automation. After selecting one representative hardware item from each functional group, a cost model was developed by determining the number of units that each generic component will increase as a function of automation level. The same was done with the mission benefits to develop the benefits model. This information is represented in the form of a matrix, showing characteristic cost, benefit and return on investment trends. Cost and benefit graphs are then presented for each functional group.

A tree flow chart is given to represent the entire methodology proposed in this study to assess the cost, benefits and return of investment of automation for SBI hardware.

2.0 Trade Study

2.1 Historical Basis

NASA has in the past and still continues to conduct a wide spectrum of IOC feasibility studies and requirement definitions for space station automation and its implementation. The historical basis for advancing automation in the space station has been primarily:

o Automation offers the potential to relieve the crew member of routine tasks [reference 9], thus increasing crew utilization. In addition, logically/physically complex and skill intensive tasks can be easily automated, reducing crew training time.

o Automation technology can be used to decrease crew dependence on mission control, thus enhancing autonomy during long periods of flight [reference 10]. In addition, the crew involvement in system operation is reduced.

o Automation advancement in space has produced spin-off technology that has benefited terrestrial applications [reference 11].

o Automation provides progressive upward compatibility for the space station in areas such as new autonomous subsystems, implementation of fault identification and recovery, on board machine access to data bases and increased productivity [reference 11].

o Automation promotes crew safety, assures a better and more uniform control of system elements and relieves the crew of tedious constant monitoring of the operation of space station components [reference 9, 10].

o Automation strongly supports the operations philosophy for the space station [reference 12].

o Automation of experimental hardware equipment increases the quality of results, as well as the repeatability of experimental data.

o Automation supports a short turn-around time from experiment selection to analysis of experimental results [reference 13]. Past space programs have required on the order of four to five years from experiment selection to post-flight analysis. This long turn-around period is incompatible with a progressive research program. Therefore automation must be used to reduce turn around time to its minimum.

o Automation may have a direct impact on the accommodation of the principal investigator/scientist of an experiment by providing an expert system which makes available the knowledge of the principal investigator/scientist without the scientist being physically present in the space station or data-linked with mission control [reference 13].

2.2 Automation Analysis for SBI Hardware

Figure 1 summarizes the methodology proposed in this study to evaluate automation for the SBI program and determine the most optimal cost effective level of automation for a SBI equipment. The first step in this methodology is to identify the current level of automation, the SBI realistic level of automation and the maximum level of automation that the item can possibly progress to. The reason for determining all the aforementioned levels of automation is primarily to identify the range of possible progressive levels of automation that can be considered for the hardware item. The rules of thumb to perform the first step is explained in section 2.2.3.

The second step in the methodology is to identify the functional group to which the hardware item being considered belongs to. This is necessary because each functional group has different characteristics. The rules of thumb to perform the second step is explained in section 2.3.1.

The third step is to identify the generic components that constitute the hardware item. This is done for the cost analysis. The rules of thumb describing the third step is given in section 2.3.2.

The fourth step is to choose the desired level of automation to which the hardware item is required to progress. The desired level of automation may also be the level of automation for which an automation - crew utilization analysis must be performed. The desired level of automation must naturally be between the current level and maximum level of automation for the hardware item in question.

The fifth step is to determine the total cost for the level of automation being analyzed from the cost model described in section 2.3.2.

The sixth step in the proposed methodology is to determine the total benefits gained from the benefit model described in section 2.3.3.

The seventh step is to determine the return on investment (section 2.3.4) for the level of automation being analyzed. If the return on investment is satisfactory, the analysis is complete and the level of automation being considered is cost effective. If the return on investment is not satisfactory, then this is indicative of the fact that the chosen level of automation is not cost effective. Therefore, the desired level of automation chosen in step 4 must be reduced and a reiteration through the cost and benefit model is required until a satisfactory return on investment is obtained.

The proposed methodology is general enough to enable the designer or

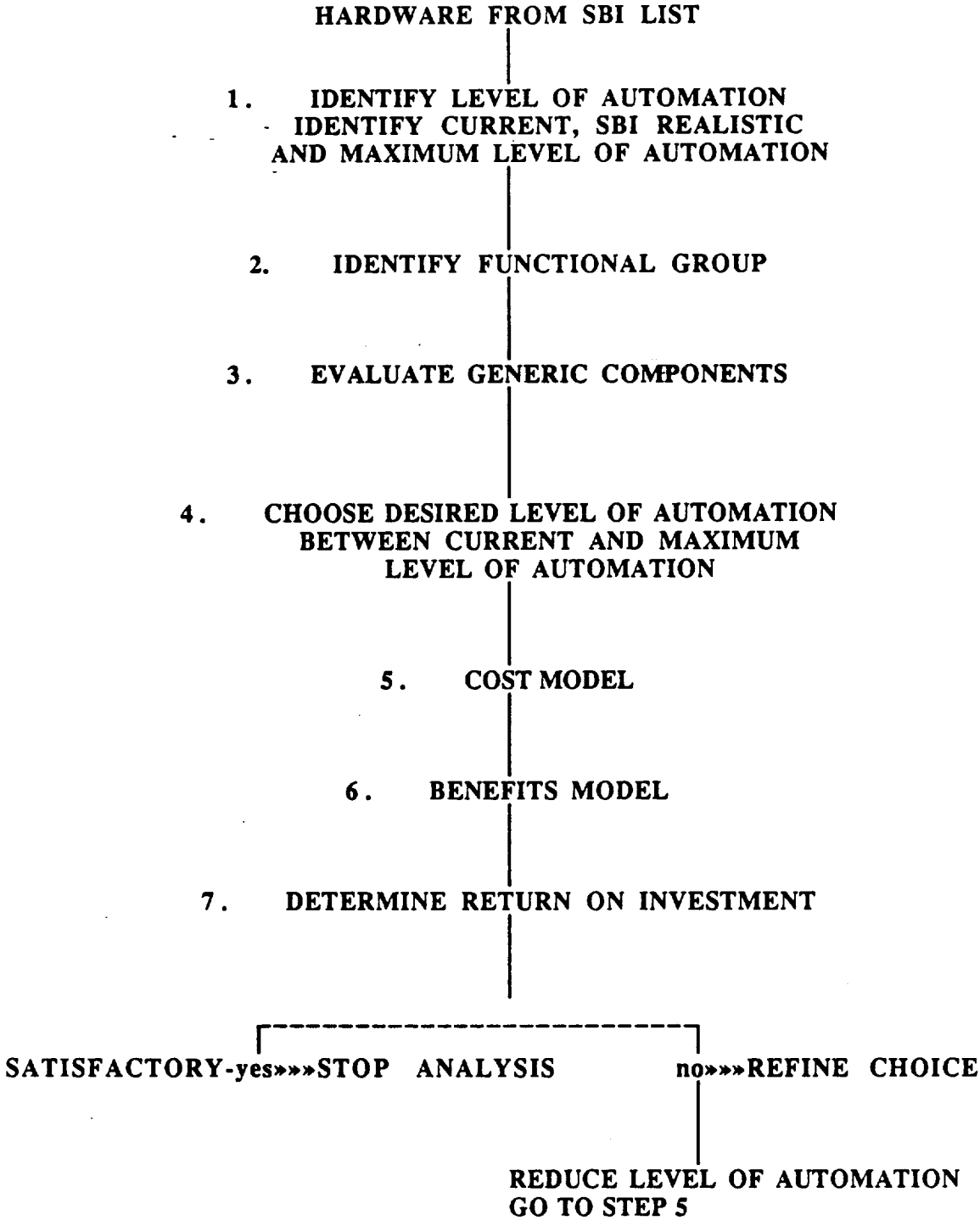

Figure 1 A Flow diagram to illustrate the methodology to determine the most cost effective automation level

hardware engineer to evaluate an SBI hardware unit in terms of:

o Current concept (Item described in documentation): An evaluation of the item based upon descriptions received in the source information documentation received for this study [references 4 to 8].

o SBI realistic target (Item practical for SBI use): An evaluation of the item based upon expert technical opinion of what is realistic and achievable within space operation constraints (volume, mass, power, microgravity, finite resources, limited manpower).

o Maximum available technology (item possible with the maximum available technology): An evaluation of the item based upon expert technical opinion of what exists or is technologically possible in a terrestrial (Earth-bound) environment. Space operation constraints such as volume, mass, power,microgravity, finite resources and limited manpower are not considered

The methodology will also enable the identification of good candidates of automation and the impacts of automation on cost and mission benefits.

In the following sections, each step in the methodology proposed in Figure 1 is analyzed in more detail and generic rules of thumb are presented. Sections 2.2.1 to 2.2.7 describe the methodology proposed in this study.

2.2.1 Evolution of Automation

A literature survey of automation reveals that a number of references are available for the history of automatic controllers, software/hardware automation, manufacturing automation, but very little or practically no work has been done in the development of a technique that will help identify the evolution of automation in a most general manner. In order to classify the SBI hardware items with respect to levels of automation, it was necessary to first develop an evolution chart of automation from its most primitive form (manual) to the highest known level of automation.

The evolution of automation can be classified into four main groups, namely:

i) Manual/Mechanized operation
ii) Semi-automatic operation
iii) Automatic operation
iv) Independent operation

Each of the above four groups can be progressively scored into sub-levels of automation form an M1 (totally manual) to an I3 (totally independent). This scoring mechanism is described in detail in section 2.2.3. In the manual/mechanized level of automation, the human controls and performs all steps of the task. In the semi-automatic level of automation, the machine assists the human in performing the task. In the automatic level of automation, the human assists the machine in performing the task. In the independent level of automation, the machine is intelligent enough to

perform all the steps of the task autonomously. Each sub-level of automation is identified by one example of an SBI hardware item. Figure 2 shows an evolution of automation.

2.2.2 Basis of Evaluation and Assumptions

The source of information and the basis of evaluation is described as follows:

Syymmdd: NASA data sheet with detail sheet dated yymmdd. Usually describes an overview of what an equipment is and how it operates.

NDSnodate: NASA data sheet with detail sheet but not dated. Usually describes an overview of what an equipment is and how it operates.

NDSonly: NASA data sheet, no detail sheet. Usually describes onlywhat an equipment is.

LSHWBL: Life Science Hardware Basic List, version 1.00 (13 pages).Describes only what an equipment is.

ARC/SSS: NASA document pre-print # NASA ARC/SSS 88-01, Gas Grain Simulation Facility: Fundamental Studies of Particle Formation and Interactions, Volume 1. Describes the Gas Grain Simulation equipment and how it operates.

The hardware item status is described as follows:

New: New design item. Space qualified version does not exist.
Mod: Modification required to an existing equipment.
OATS: Off-the shelf item.
COTS: Commercial off-the shelf item.
as is: Item exists and may be used without change.
LSLE: Item exits and has been space qualified in previous flights. "LSLE" is an item catalog number prefix.
SLS-1: Item exists and will be used for SLS-1 mission.

The main assumptions made in this study are as follows:

a) We assume that the main contribution of this trade study will be firstly the methodology presented and secondly the general rules of thumb described in this study. The actual quantitative

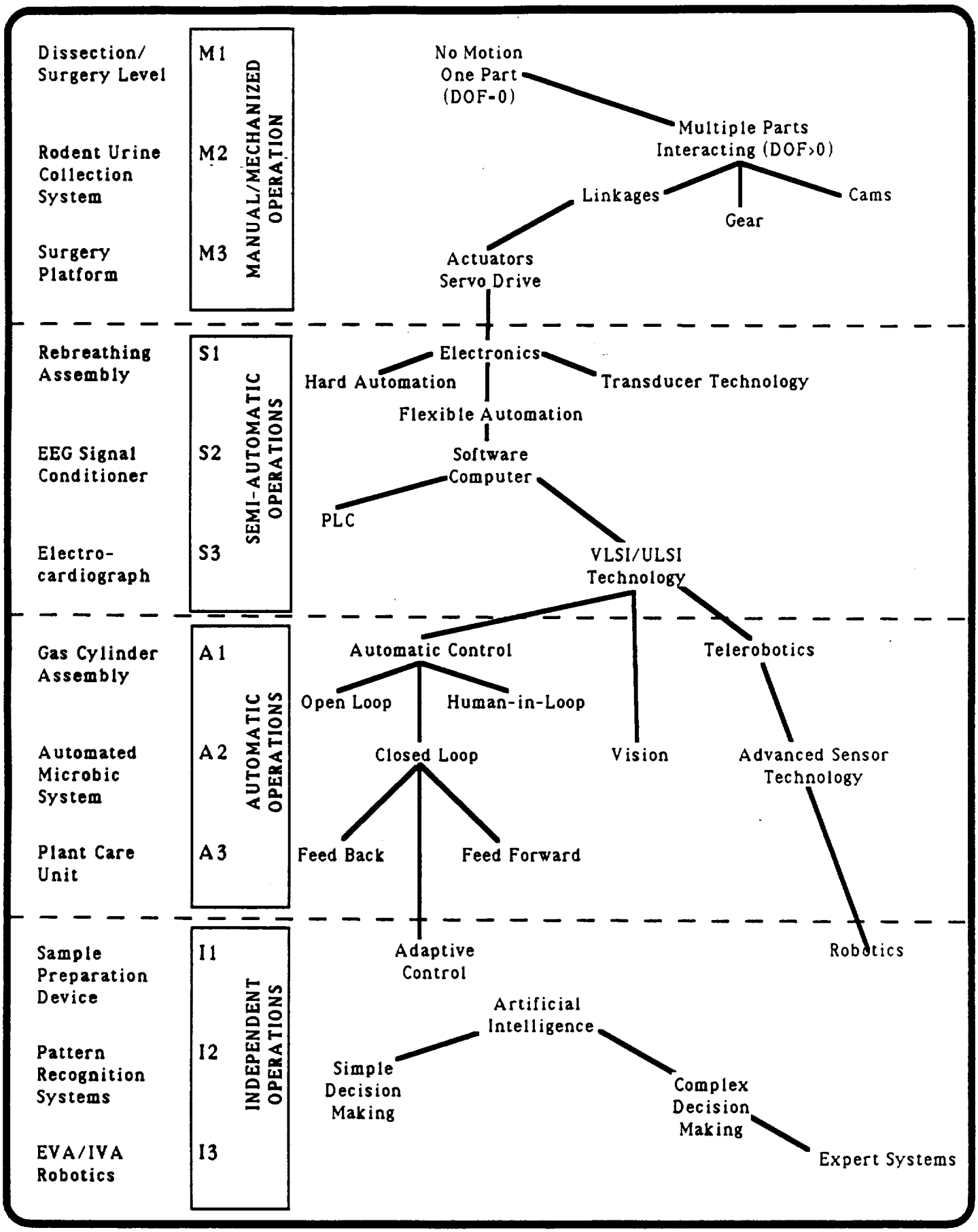

Figure 2 EVOLUTION OF AUTOMATION

analysis is subjective based on experience of a few experts at SwRI. The subjective nature of the quantitative analysis was mainly due to the unavailability of data on the SBI hardware items. Although, the absolute scores may not bear much importance, the relative trends are noteworthy.

b) For the purpose of this study, it was assumed that the data furnished in the available NASA sheets was accurate and projected NASA's point of the view of the hardware item.

c) Each hardware item in the Life Science Hardware Basic List was regarded as a separate entity and the evaluation was done assuming stand-alone operation without the item of concern physically connected or interfaced with other items of the aforementioned list. Although, this assumption does not hold true for an integrated Life Science Module where several items are interconnected to run a particular experiment, this assumption was necessary due to lack of information on the exact type of equipment, protocol of experiments and layout within the module.

d) In the determination of good candidates for automation, we have only considered the current level of automation and the SBI realistic target for automation. Thus the maximum level of automation is not considered for the selection of good candidates for automation because the maximum level of technology will extend beyond the time frame of the SBI program. In addition, the evaluation of the maximum available technology is based on ground operation and not subject to space constraints. A separate study will have to be initiated to analyze the maximum level of technology.

e) The cost ranges of the generic components (section 2.3.2) in the cost model are based on experience with commercially available off the shelf items. Thus, research and development costs as well as cost to space qualify an item is not included.

f) It is assumed that both physical and data domains of all SBI hardware items have equal weight. This is not necessarily true for all SBI items.

Additional assumptions are highlighted for the levels of automation analysis as well as the cost and benefit model. These are described in the individual sections.

2.2.3 Levels of Automation

The basis for investigating the different levels of automation for the SBI hardware was driven by the fact that it provides an indicator to assist in the choice of good candidates for automation. An alphanumeric scoring scheme was developed to classify the hardware in terms of level of automation. Man-machine automated hardware equipment can be broadly characterized in two domains, namely: Physical Domain and the Data Domain.

In the Physical domain, the target of automation is material. The automation level is scored from a physical perspective, by considering the

interaction and importance of skills and actions in task performance. Thus Physical Automation is equivalent to skills and actions.

In the Data domain, the target of automation is information. The automation is scored from a data perspective, by considering the interactions and importance of knowledge and decisions in task performance. Thus Data automation is equivalent to knowledge and decisions.

Items like the dissection units, biopsy equipment or syringes with a low automation index will typically have only a Physical domain and no Data domain, since only physical material is being handled or transferred. Other equipment like the blood collection system or the isokinetic measuring device with a higher automation index will have both a Physical domain automation as well as a Data domain automation. Thus the automation level of a man-machine system is a conservative weighted average of the Data automation score as well as the Physical automation score. The determination of the weights depends on the ratio of importance of one domain to the other for a particular hardware item. As mentioned in section 2.2.2, we assign an equal weight to both domains for all hardware equipment. Thus system automation = (Physical automation + Data automation)/2.

The following definitions provide an intuitive understanding of the automation levels and the relative relationships to each other with respect to performing a task. A task consists of two or more discrete steps that are performed in sequence. The task may be completely defined by a network of steps. The human and machine, as components of the human-machine system, use their respective skills and knowledge together to complete each step of the task. The human and machine make decisions and take actions that are under their respective control to follow a path of steps to successfully complete a task. The following scoring mechanism is used to score the Physical, the Data and the System automation of a hardware item. The descriptions of the scores are general enough to be regarded as rules of thumb to be used to classify a hardware item with a level of automation. Examples are given for each level of automation in order to further understand and apply the given rules of thumb.

The adjectives "large", "average", "small","more or less" ,"more complex" are subjective but the reader can get a better quantitative feel after reviewing some hardware items within the classes.

M: Manual Operation = " Human does." The human performs all steps of the task. Task completion relies almost exclusively on the human. The machine in this category is regarded as a tool, capable of no decisions or actions by itself.

M1: The following rules of thumb apply to classify the automation level of a hardware item in the M1 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as M1 :

- It requires a human with expert knowledge gained by advanced education during a period of years or months to successfully operate the hardware.

o It requires a human with expert skill gained by special experience during a period of years or months to operate the hardware unit.

o The machine is a tool which is not capable of performing any steps in a task without human assistance.

Examples: Rodent surgery/dissection unit, Primate surgery/dissection unit

M2: The following rules of thumb apply to classify the automation level of a hardware item in the M2 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as M2 :

o It requires a human with special knowledge gained by education during a period of weeks or days to successfully operate the hardware.

o It requires a human with special skill gained by special experience during a period of weeks or days to operate the hardware unit.

Example: Head/Torso Phantom, Anthropometric measurement system.

M3: The following rules of thumb apply to classify the automation level of a hardware item in the M3 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as M3 :

o It requires a human with basic knowledge gained by education during a period of hours to successfully operate the hardware.

o It requires a human with basic skill gained by special experience during a period of hours to operate the hardware unit.

o The machine is a tool that is more capable and can thusperform some steps without human supervision.

Example: Saliva collection unit, Rodent Guillotine.

S: Semiautomatic operation = "Human does, Machine Assists." The machine performs a task of two or more step "groups". Human controls task at each decision "check point" between groups. The task completion relies on the human, with the machine assisting the human. The machine is a device capable of predefined decisions and fixed actions by itself.

S1: The following rules of thumb apply to classify the automation level of a hardware item in the S1 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as S1 :

o There are a large number of groups and checkpoints in the hardware item in order to successfully complete a task.

- There are a small number of steps in each group (minimum 2)

- The task network of the hardware item is small

- The hardware item is a less sophisticated device, although it can perform a series of predefined actions.

Example: Blood collection system, Mask/regulator system.

S2: The following rules of thumb apply to classify the automation level of a hardware item in the S2 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as S2 :

- There are an average number of groups and checkpoints in the hardware item in order to successfully complete a task.

- There are a average number of steps in each group.

Example: EEG cap, CO2 administration device.

S3: The following rules of thumb apply to classify the automation level of a hardware item in the S3 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as S3 :

- There are a small number of groups (minimum 2) and checkpoints (minimum 1) in the hardware item in order to successfully complete a task.

- There are a large number of steps in each group.

- The task network of the hardware item is large.

- The hardware item is a more sophisticated device.

Example: Sweat collection device, Electronics control assembly.

A: Automatic Operation = "Machine Does, Human Assists." The machine performs the task steps from start to finish. Task performance relies on machine with human assisting machine. The assistance can be in the form of supplying to the machine the required specimens or imputing required critical decisions. Machine is a system capable of procedural decisions and programmed actions by itself.

A1: The following rules of thumb apply to classify the automation level of a hardware item in the A1 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as A1 :

- There are a small number of steps in the task but larger than S3.

- The task network of the hardware item is larger than S3.

- The hardware item does not recognize error conditions, i.e. on error, the machine will have to be reprogrammed to continue execution.

- The human has to actively supervise the machine's task performance, in order to successfully complete a task.

- The machine is a less complex system.

Example: Pulmonary gas cylinder assembly, motion analysis system.

A2: The following rules of thumb apply to classify the automation level of a hardware item in the A2 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as A2 :

- There are an average number of steps in the task.

- The machine recognizes predefined error conditions, i.e. on error, the machine will call for and wait for human intervention and supervision.

- The human has to periodically supervise the machine's task performance, in order to successfully complete a task.

Example: Soft tissue imaging system, fixation unit

A3: The following rules of thumb apply to classify the automation level of a hardware item in the A3 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as A3 :

- There are a large number of steps in the task.

- The task network of the hardware item is large.

- The hardware item recognizes and acts on predefined error conditions, i.e. on error, the machine will perform predefined error handling routines.

- The human is only required to passively supervise the machine's task performance, in order to successfully complete a task.

- The machine is a more complex system.

Example: Mass spectrometer, plant HPLC ion chromatograph

I: Independent Operation = "Machine Does." Machine controls and performs all steps of the task. Task performance relies almost exclusively on machine. The machine is intelligent and autonomous, capable of reasoned decisions (expert system technology) and flexible actions (robotic system technology) by itself.

I1: The following rules of thumb apply to classify the automation level of a hardware item in the I1 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as I1 :

- o The machine is capable of performing low levels of decisions, reasoning and flexible action
- o The machine is capable of performing only fixed reasoning in unchanging scenarios.
- o The machine requires well defined and structured environment to perform reasoning and decision making.
- o The machine is fairly intelligent and autonomous.

Example: Sample preparation devise, inventory control system.

I2: The following rules of thumb apply to classify the automation level of a hardware item in the I2 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as I2 :

- o The machine is capable of performing decisions, reasoning and flexible action of medium level of complexity.
- o The machine is capable of performing adjustable reasoning in changing scenarios.
- o The machine can learn and extend its knowledge base.

Example: None in the SBI hardware list.

I3: The following rules of thumb apply to classify the automation level of a hardware item in the I3 class. If any of the following rules apply, then the automation level of the hardware item of concern can be classified as I3 :

- o The machine is capable of performing high levels of decisions, reasoning and flexible actions.
- o The machine is capable of performing adaptable reasoning and flexibility even for changing scenarios.
- o The machine does not require a well defined and structured environment to perform reasoning and decision making. It has the capability of learning and adapting in new unplanned scenarios.
- o The machine is more intelligent and autonomous.

Examples: None in the SBI hardware list.

2.2.4 Evaluation of Crew Training

The amount of pre-flight crew training time required to successfully operate a machine in-flight is another prime indicator in the decision of picking good candidates for automation, since this will directly affect crew utilization. A general rule of thumb would be if the hardware item being considered requires an excessive amount of crew training time in order to run an experiment, then the excessive crew training time can be reduced by introducing more automation than presently available in the equipment. This reduction in crew training time results not only in dollar savings but also relieves the crew from lengthy, often intensive training. In the following, the word "training" is equivalent to pre-flight crew training. Conceptually, training required to operate an equipment consists of two types, namely:

i) Knowledge education: Training concentrating on having the crew member acquire data domain expertise, particularly factual and procedural knowledge.

ii) Skill experience: Training concentrating on having the crew member acquire physical domain expertise, particularly hand-eye coordination and body movement skills.

Both the knowledge education and skill experience can be subjectively quantified by a "training expert" using the following rules of thumb:

1: The training is given a score of 1 if a low level of training effort is required to operate the hardware equipment.

2: The training is given a score of 2 if a low to medium level of training effort is required to operate the hardware equipment.

3: The training is given a score of 3 if a medium level of training effort is required to operate the hardware equipment.

4: The training is given a score of 4 if a medium to high level of training effort is required to operate the hardware equipment.

5: The training is given a score of 5 if a high level of training effort is required to operate the hardware equipment.

2.2.5 Evaluation of Crew Utilization

The crew utilization is another important factor to consider when selecting good candidates for automation. Better crew utilization results in more productivity for the life science module. The crew utilization can be quantified with a crew utilization index value, which is defined as the percentage of machine operation time during which a crew member must interact with the machine to provide the machine with knowledge, skills, decisions and actions that it does not internally possess. The human interaction with the machine is requisite for the machine to continue with its operation.

The following rules of thumb will quantify the crew utilization by defining an index as follows:

The crew utilization index has a value of 1 if the crew member must monitor the machine for 0% to 20% of the machine operation time to complete a task.

The crew utilization index has a value of 2 if the crew member must monitor the machine for 20% to 40% of the machine operation time to complete a task.

The crew utilization index has a value of 3 if the crew member must monitor the machine for 40% to 60% of the machine operation time to complete a task.

The crew utilization index has a value of 4 if the crew member must monitor the machine for 60% to 80% of the machine operation time to complete a task.

The crew utilization index has a value of 5 if the crew member must monitor the machine for 80% to 100% of the machine operation time to complete a task.

2.2.6 Additional Factors to Consider for Automation

The following is a list of additional factors and general rules of thumb that a design/hardware engineer will have to consider to aid in deciding whether to automate or not to automate a particular experiment or hardware item. These factors will also aid in deciding which kinds of experiments are better candidates for automated equipment and the level of automation to be applied.

o The duration of the experiment may be considered an indicator for automating or not automating the hardware item. As a general rule of thumb, experiments that are lengthy in time or require a high percentage of crew time may more readily justify automated equipment then those which are short.

o Experiments that are routine and mundane may call for automation as opposed to those that require supervision of multiple variables and intelligent decision making. The astronauts time is better spent supervising more complicated experiments than controlling mundane repetitive experiments.

o The complexity of the experiments is a possible precursor for automation. Experiments can be classified as a function of complexity. Complex (requiring constant supervision from the astronaut), moderate (requiring occasional supervision) and simple (requiring practically no supervision from the astronaut). The more simple experiments can be automated while the more intensive experiments may be partially automated requiring some astronaut intervention, thus keeping the human in the loop for major decision making. In other word, if an experiment requires

intensive human intervention or supervision for successful completion, then it is more desirable to only automate to a level where the crew will still perform the critical items.

o Time required to successfully train an astronaut to perform the experiment (see section 2.2.4). Automation can reduce actual time required to train an astronaut to successfully perform the experiments, e.g. time-consuming calibration procedures.

o Sensitivity and importance of the experiments. Sensitive experiments whose results are dependent on the environment and other unknown factors are best performed manually, since unpredicted conditions may have serious effects on the performance and results of the experiments. The level of future technology will not support automation to the level of making it as adaptable as humans. Thus, sensitive experiments are better performed manually.

o Can unexpected radiation or microbes hazardous to human life be produced during an experiment? If so, higher levels of automation must be used in the experiments to increase crew safety.

o Maintainability of automated hardware for the experiments. If the automated hardware is susceptible to constant maintenance and repair due to increased electro-mechanical complexity, then the process/experiment to be performed by that particular hardware item should not be fully automated. The tasks requiring complex decision making can be performed by the astronaut.

o Repairability issues. Should the hardware malfunction, can the astronaut easily repair the unit or will terrestrial help be required, which would inevitably cause long/costly delays in the execution of the experiments ?

o Equipment accuracy and dependability will definitely affect the choice for automation. Automated equipment produce more accurate and repeatable experimental results than non-automated equipment.

o Availability of hardware to automate experiments. The available technology may not support the desirable level of automation. In such cases, such high levels of automation should not be considered.

o Do the required modules and units exist or are they still in prototype stage? When considering prototypes for the space station, the issues of reliability, maintainability and repairability become important.

o Are there certain experiments that the astronaut would prefer not to perform, for example, fecal and urine tests? Those experiments may prove to be good candidates for automation. In this context, it should be noted that the astronauts performing the experiments must be included in the process of choosing the best candidates for automation. The crew should be interviewed about their preferences, experiences, ideas and opinions. Automated equipment must keep the crew member within the operational loop. In other words, automated equipment and crew members should complement each other.

o The volumetric size, mass and power consumption should also be considered when deciding whether to automate or not to automate a hardware item. Increased automation may lead to oversized hardware which may violate space module constraints of power and space.

o Can a set of experiments be performed by the same automated hardware item? If so, then this would better utilize the available volume, power and crew time.

o Delicate sample handling and preparation are best performed using some level of automation, since the handling and preparation are extremely important to the success and results of the experiments.

o Automation should be considered in tasks that become difficult to perform because of the lack of gravity in space.

o Tasks which have a well defined protocol with little deviations from the norm, eg Inventory Control System or data collection, are good candidates for automation.

o The data communication process is a good candidate for automation since this will relieve the astronaut from having to decide what relevant information/data to send and receive from ground control. The delay in transmission time dictates the requirement that minimum data be exchanged between the ground and Space station.

o For longer durations in space, automation will have higher payoffs. Therefore, experiments which will be running for a longer duration should be considered for automation.

o Automation can relieve the astronaut from having to plan ahead all the details required to perform the experiments.
The crew time is more effectively utilized by leaving the micro-management and details to automation.

o Experiments requiring labor intensive preparation and adjustments should be automated since this would reduce the possibility of experimental errors, resulting in better repeatability and accuracy of the results.

2.2.7 Common Operational and Performance Questions that Lead to AutomationSolutions

The following is a list of common operational and performance questions that lead to automation solutions:

1. How efficient is the operation and is there room for improvement?

2. What is the net worth and net profit?

3. Can new materials be used effectively?

4. Will new product designs be producible?

5. Will new processes and methods be effective?

6. Can the operations effectively use new equipment designs?

7. How can costs be cut and scrap reduced?

8. What is the plant capacity in terms of surge production for anyparticular product?

9. Can new product lines be added without increasing floor space?

10. How much improvement can be made in terms of process flow andequipment rearrangement?

11. Can quality and production problems be adequately analyzed andsolved ?

12. Can labor situations be avoided?

13. Where are the process choke points?

14. Where are the health, safety and hygiene problem areas?

15. What is the ranking of improvements that can be implemented?

Although some of these questions are specific to a manufacturing scenario, most of the above questions are applicable to the SBI program.

2.2.8 SBI Candidates for Automation

The scoring mechanism described in sections 2.1.2 to 2.1.4 was used to evaluate each individual hardware item in reference 3. Based on the scores given to each of the Physical and Data domains(see section 2.1.2), the current level of automation of the entire human-machine system was determined by taking a simple average of the two domains. In addition to the current level of automation, the realistic level of automation for the SBI program as well as the maximum possible level of automation that can be achieved was also

determined. The crew training (section 2.1.3) and crew utilization index (section 2.1.4) are based on the information that was made available to us during the course of this study [references 4,5,6,7,8]. In cases where no information was available at all, educated guesses were made based on experience and direct working knowledge with similar types of equipment. The results of this evaluation using the methodology described in sections 2.2.1 to 2.2.5 are shown in sections 3.2 to 3.7. This detailed evaluation of all the hardware items of the SBI list was performed to determine those items most suitable for automation. As additional knowledge and information about particular experiments become available, the quantitative scores given to the hardware item may change. However, the methodology for making the decision to automate or not to automate should remain the same.

The following conclusions about good SBI candidates for automation can be drawn from the results presented in sections 3.2 to 3.7:

o Hardware equipment in the M class (M1 to M3) are usually not suitable choices for automation. The reasons is the infeasibility of introducing automation from a technological point of view. However, if the technology to cost-effectively automate becomes available, then these items should be considered for automation because these equipment are typically characterized by a high crew utilization index. Some examples are: rodent surgery/dissection units, primate surgery/dissection units, animal tissue biopsy equipment, pulmonary function equipment stowage assembly.

The anthropometric measurement system, whose current automation level is M2 and SBI realistic automation level is S1, is an example to the above rule of thumb. This hardware item can be considered for automation because the technology is available to automate limb and joint measurements. This will benefit both the crew and the mission.

o The initial choice of good SBI candidates for automation begin in the S class. The current automation level and the SBI realistic level of automation of some candidates in the S1 class are identical, indicating that an increase in automation is not possible from a technological point of view or indicating a possible violation of the space constraints. It is not beneficial to consider automation for such items. Some examples are: Rodent restraint, mask regulator system, the rodent blood collection system, blood collection system.

On the other hand, there are several items in the S class whose current level and SBI realistic level of automation span a range of possible progressive levels of automation. These items deserve more consideration for automation, especially if the range is relatively large and the crew training time and the crew utilization index value is reduced. For example, the current automation level of the electrofusion device is S2 and can progress to A1 in the SBI realistic level. The benefits include reduction of crew training time as well as crew utilization index value by a unit each, resulting in $ savings.

Thus a rule of thumb would be to recommend items for automation in the following priority:

o Items with the largest range of possible progressive levels of automation and the largest reduction of crew training time and crew

utilization index value deserve the highest priority for consideration to automate because these items will result in the largest benefits.

- o The items with a medium range of possible progressive levels of automation but large reduction of crew training time and crew utilization index value.

- o The items with a small range of possible progressive levels of automation with a medium reduction of crew training time and crew utilization index value.

- o The items with a small range of possible progressive levels of automation with a small reduction of crew training time and crew utilization index value.

- o The items with a zero range of possible progressive levels of automation, i.e. the current level of automation is identical to the SBI realistic level of automation, should be the last to be considered for automation.

The following rules of thumb can be made about hardware items in the A and I class of automation:

- o The higher the current state of automation of a hardware item, the less are the benefits of advancing to the next progressive level of automation. In other words, the cost to advance to the next level of automation outweighs the benefits. Thus, the current level of automation is identical to the SBI realistic level of automation for the most of the items in the A (A1 to A3) and I1 class.

- o The range of possible progressive levels of automation steadily decreases for hardware items in the A class and is zero for hardware items in the I class of automation. For example, there are only five hardware items in the A class which are beneficial to automate to the next level of automation, namely: The accelerometer and recorder, the force resistance system, the chemistry system, the chromosal slide preparation device and the spectrometer. This is again indicative of the fact that hardware items in the A and I class should not be the first in the priority list of automation because the cost to automate to a higher level of automation outweighs the benefits especially for items with current level of automation approaching the I class of automation.

- o Figure 3 shows the range of possible automation levels versus automation level. It is most cost beneficial to automate hardware items in the S class, then it is for any other class of automation. The crew training time saved and crew utilization index value is the largest for items in the S class.

The following rule of thumb can be formulated for data automation versus physical automation:

- o Data automation will have a higher precedence over physical automation because it is more flexible and easier to implement and maintain. Data automation is mainly concerned with the transfer of data (in the form of bits).

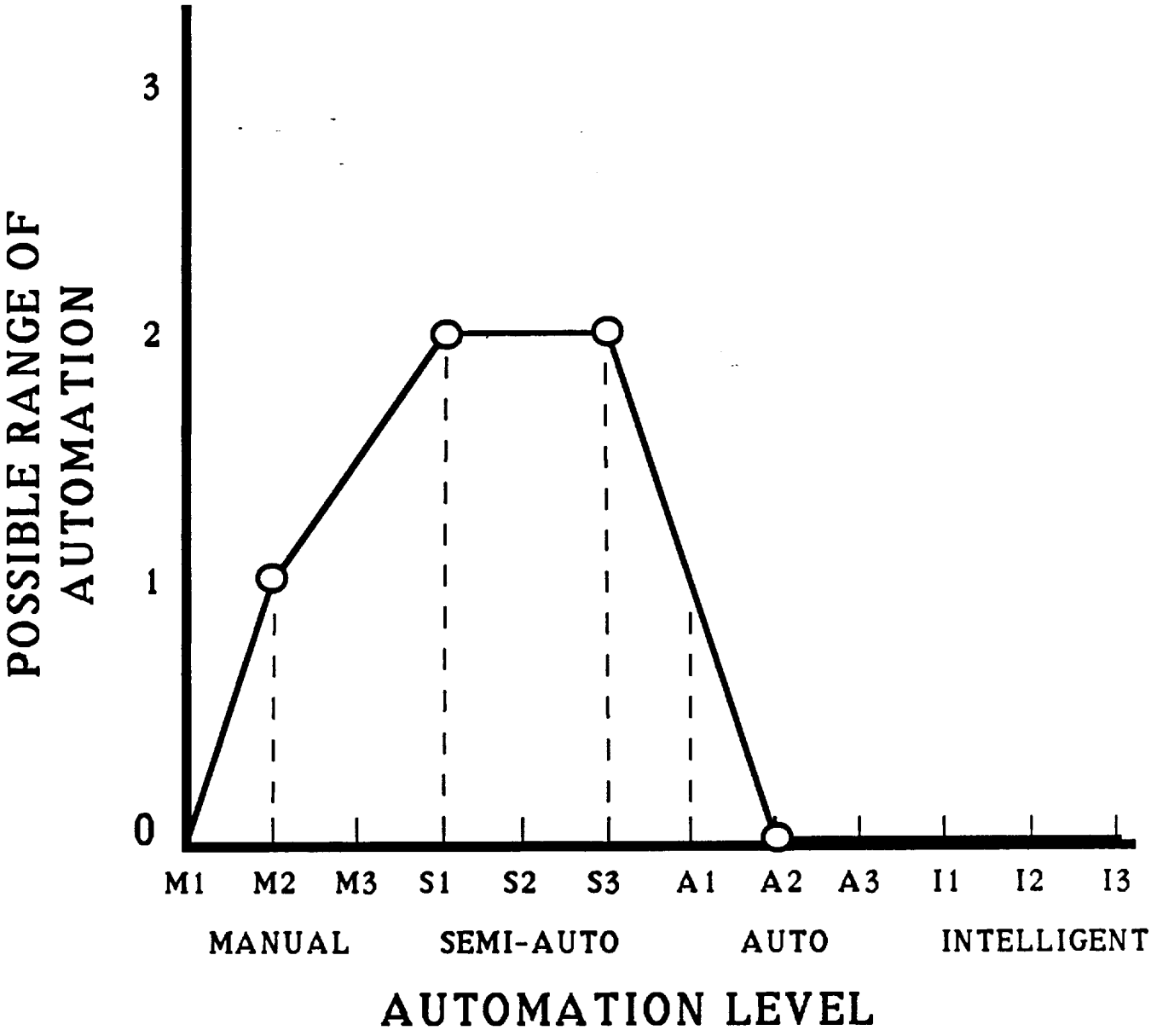

Figure 3
Range of
Possible Automation Levels
vs.
Automation Levels

Since data will be transferred over a data bus, sharing and use of a common data bus defined for the space station becomes more readily feasible. Higher levels automation can be realized with more advanced microelectronics and specialized chips. The low cost and advanced state of present electronic technology will make data automation more feasible and cost effective than physical automation.

On the other hand, physical automation is mainly concerned with the transfer of material. The type of automation is dependent on the material being transferred and on the environment. Since many kinds of material (solid, liquid, gas) will be used on the space station, it is almost impossible to share automation resources between hardware items. Physical automation will have to be tailored for each individual application. This places it in keen competition for the limited space, payload launch capability and power constraints of the space station. Physical automation will generally be costlier to implement and maintain compared to data automation.

2.3 Cost Impacts of Automation

The following factors affect the total cost of a hardware item in an earth-bound laboratory:

a) Cost of preparing a valid specification and/or requirements analysis.
b) System purchase and/or development.
c) Installation (including cabling).
d) Laboratory integration into operations.
e) Continuing operation and maintenance.
f) Insurance liability costs.
g) Staff training
h) Equipment spares.

If the system is modest and stand-alone, then only the acquisition cost (b) will be the most significant. If the system is large and expensive then all above factors will have to be considered. The laboratory integration (d) includes equipment interface to hardware, integrated software and integrated testing and was estimated at 50% of the total equipment cost [reference 14]. For a nominal ten year program, the cost of Laboratory maintenance (e) is estimated to be 50% of the total equipment cost. For a nominal ten year program, the equipment spares (h) are estimated to be 200% of unit equipment cost based on 50% of unit cost for initial spares and 15% of unit cost per year thereafter [reference 14].

In this study, in order to define a general cost - benefit model, the hardware items were first classified into six main functional groups, namely:

i) Biological specimen support.
ii) Physiological measurement/monitoring.
iii) Chemistry systems.
iv) Material preparation/handling.
v) Large scale systems.
vi) Facility support.

Five main generic components of SBI hardware items were also identified, namely:

i) Specimen handling/preparation.
ii) Sensor/transducer.
iii) Electronics.
iv) Software.
v) Computer.

Five main mission benefits were identified resulting from automation, namely:

i) Decrease in crew training time.
ii) Decrease in crew involvement time.
iii) Increase in quality of results.
iv) Decrease in crew risk.
v) Increase in mission productivity.

Upon defining the functional groups, the generic components and mission benefits, a representative item was selected from each class and the number of units that each generic component will be required to increase as well as the benefits gained as a function of the automation level was determined and represented in matrix form.

2.3.1 Functional Groups

The SBI hardware items can be broadly classified into six main groups. The six groups are restated as follows:

i) Biological specimen support.
ii) Physiological measurement/monitoring.
iii) Chemistry systems.
iv) Material preparation/handling.
v) Large scale systems.
vi) Facility support.

The following define rules of thumb that aid in identifying an item with a specific group.

Biological specimen support: The equipment that can be identified with this group are primarily used in support of the SBI experiments. These items are primarily manual, some can be semi-automated and only a few are automated with low power requirements in the range of 0 to 145 watts. Some typical examples for this group are: the plant care unit, the rodent caudal vertebrae thermal device (CVTD), rodent guillotine, rodent restraint, rodent surgery platform, surgery/dissection units and neck baro-cuff.

Physiological Measurement/Monitoring: These items are primarily electronic. Items in this group measure, analyze and display signals. They require crew interaction and have medium power requirements in the range of 0 to 800 watts. Some typical examples are: Bag assembly, bag in box, mask-regulator system, electroencephalomagnetogram and soft tissue imaging system.

Chemistry systems: These items analyze materials (specimen samples). Some form of material handling or processing is usually required before these items can be used. These items include analytical as well as clinical chemistry. Some typical examples are: mass spectrometer, plant gas chromatograph, blood gas analyzer, qualitative reagent strip, scintillation counter and hematology system.

Material preparation/handling: All items in this group primarily collect or process material samples for analysis. Currently, many items in this class are only in the concept design stage. Some items are completely manual, e.g. the saliva collection device or fully automatic or independent, e.g. the sample preparation device.

Large-scale systems: Only two items were found to belong to this group, namely the CELSS (Closed Ecological Life Support System) test facility and the gas grain simulator. These items are special systems designed to support a wide variety of experiments in a specialized area. These items are in the conceptual design stage and are envisioned by NASA to be fully automated and independent.

Facility support: These items primarily support SBI equipment and, with exception of the mass calibration unit (manual), are automatic or independent. Most of these items consume an average of 500 watts and have a large amount of electronics and software. Some typical items are: Inventory control system, lab materials packaging and handling equipment, experimental control computer and voice recorder.

2.3.2 Mission Cost Model

The major cost drivers of SBI hardware items are primarily:

i) Increase in complexity of hardware.
ii) Increase in complexity of electronics.
iii) Increase in software effort.
iv) Increase in engineering complexity.
v) Increase in new design.

The above mentioned individual cost drivers result from the cost effects of specific components of the hardware item. Therefore, the identification of hardware components that affect the major cost drivers will lead to a fairly robust cost model. Five generic hardware components have been identified which most strongly affect the above mentioned cost drivers.
These are:

i) Specimen handling/preparation.
ii) Sensor/transducer.
iii) Electronics.
iv) Software.
v) Computer.

Any SBI hardware can be broken down into the above mentioned generic components. Some items like the surgery dissection units will only have the

specimen handling/preparation component, while other more complicated equipment like the sample preparation device will have all the generic components. The specimen handling/preparation component will relate directly to the increase in complexity of hardware, the sensor/transducer component will relate to the increase in engineering complexity, the electronic component will relate to the increase in the amount and complexity of electronics, the software component will relate to the increase in software effort, while all the generic components in combination will relate to the increase in new design. Upon selecting a hardware item from the SBI list, a cost model can be defined by determining the number of units of each generic component required in order for the equipment in question to progress to the next level of automation. Thus, general trends can be observed, and used to predict the increase in hardware complexity, electronics, software, engineering complexity and new design as a function of the levels of automation. For this purpose, all the above generic components are quantified and given a score from 0 to 5 using the following rules of thumb. A score of 0 implies the generic component is not applicable to the item being analyzed. In addition, each score is given a cost range in $ to aid in the evaluation of approximate cost values for a generic component.

Specimen Handling/Preparation:

The specimen handling/preparation component is scored in function of complexity.

The score 0 implies no specimen handling/preparation component.

The score 1 implies low complexity of the specimen handling/preparationsystem. The cost range is $0 - $500.

The score 2 implies low to medium complexity of the specimen handling/preparation system.The cost range is $500 - $1000.

The score 3 implies medium complexity of the specimen handling/preparation system.The cost range is $1000 - $5000.

The score 4 implies medium to high complexity of the specimen handling/preparation system.The cost range is $5000 - $10,000.

The score 5 implies high complexity of the specimen handling/preparation system.The cost range is over $10,000.

Sensor/Transducer

The sensor/transducer component is scored in function of complexity of the unit.

The score 0 implies no sensor/transducer component.

The score 1 implies low complexity of the sensor/transducer system.The cost range is $0 - $250.

The score 2 implies low to medium complexity of the sensor/transducer system. The cost rage is $250 - $1000.

The score 3 implies medium complexity of the sensor/transducer system. The cost range is $1000 - $2500.

The score 4 implies medium to high complexity of the sensor/transducer system. The cost range is $2500 - $5000.

The score 5 implies high complexity of the sensor/transducer system. The cost range is over $5000.

Electronic

The electronics component comprises of all the electrical components including power supply. The electronic component is scored in function of the average number of integrated chips in the electronics. The cost presented for the electronics include hermetic packaging and schematic documentation.

The score 0 implies no electronic/electrical components and no powersupply or battery. In other words a score 0 implies totally manual operation.

The score of 1 implies the presence of predominantly discretecomponents like transistors, resistors and capacitors and a small number of SSI (Small Scale Integration) chips. The cost range is $0 to $50.

The score of 2 implies the presence of predominantly SSI chips and afew MSI (Medium Scale Integration) chips. The cost range is $50 to $500.

The score of 3 implies the presence of predominantly MSI chips with a few LSI (Large Scale Integration) chips. The cost range is $500 to $2000.

The score of 4 implies the presence of predominantly LSI chips with some VLSI (Very Large Scale Integration) chips. The cost range is $2000 to $5000.

The score of 5 implies the presence of predominantly VLSI chips along with ULSI (Ultra Large Scale Integration) chips. The cost range is over $5000.

Software

The software component is scored in function of the lines of code. A good rule of thumb for average software cost is approximately $10 per debugged line of code. This cost was determined from software experience within the Robotics Department at SwRI.

The score of 0 implies no software (code) present.

The score of 1 implies 0 to 1000 lines of code.

The score of 2 implies 1000 to 10,000 lines of code.

The score of 3 implies 10,000 to 50,000 lines of code.

The score of 4 implies 50,000 to 100,000 lines of code.

The score of 5 implies more than 100,000 lines of code.

Computer

The computer component is scored in function of the complexity of the Central Processing Unit (CPU).

The score of 0 implies no computer component present.

The score of 1 implies a 4 bit CPU architecture. Non-programmable calculators and the Motorolla 14100 CPU chip would be assigned this score. The cost range is $0 - $500.

The score of 2 implies a 8 bit CPU architecture. An IBM PC with a 8088CPU chip and the Motorolla 6800 CPU chip would be assigned this score.The cost range is $500 - $1500.

The score of 3 implies a 16 bit CPU architecture. An IBM PC-AT witha 80286 CPU chip and the Motorolla 6809 CPU chip would be assigned this score. The cost range is 1500$ - 10,000$.

The score of 4 implies a 32 bit CPU architecture. An IBM PC-AT with a 80386 CPU chip and the Motorolla 68020/68030 CPU chip would be assigned this score. The cost range is 10,000$ - 100,000$.

The score of 5 implies a 64 bit CPU and/or multiple processors in anetwork of massively parallel processors (MPP). A supercomputer like the CRAY and the MPP CONNECTION machine would be assigned this score. The cost range is over 100,000$.

Based on the rules of thumb developed in section 2.2.1, a representative hardware item was selected from each functional group and the increase in all the generic components as a function of the automation was determined. The above rules of thumb were used to determine the increase in generic components as a function of automation. The results are presented in the following. "N/A" means the entry is not applicable.

Functional group: Biological Specimen Support
Representative Hardware Item: Primate Handling device

Generic Component	Level of automation			
	M	S	A	I
Specimen handling/preparation	1	2	3	N/A
Sensor/Transducer	0	0	1	N/A
Electronics	0	1	3	N/A
Software	0	0	0	N/A
Computer	0	0	0	N/A

The scores in all columns are absolute ranging from a score of 0 to 5. For example, at the M level of automation, the primate handling device has only 1 unit of a specimen handling/preparation component. To progress to a S level

of automation, the specimen handling/preparation component is increased by a factor of 2 and 1 unit of electronics is required. To progress to an A level of automation, the specimen handling/preparation unit is increased by a factor of 1.5, 1 unit of sensor component is required and the electronic component is increased by a factor of 3. It is not feasible to progress to an I level of automation for the primate handling devise.

Similar rules of thumb and relative trends from one level of automation to the other can be made from the cost matrices presented in the following.

Functional group: Physiological Measurement/Monitoring
Representative Hardware Item: Electrocardiogram (ECG)

Generic Component	Level of automation			
	M	**S**	**A**	**I**
Specimen handling/preparation	0	0	0	0
Sensor/Transducer	1	1	2	3
Electronics	1	2	3	4
Software	0	0	1	3
Computer	0	0	1	2

Functional group: Chemistry Systems
Representative Hardware Item: Qualitative Reagent Strip Reader

Generic Component	Level of automation			
	M	**S**	**A**	**I**
Specimen handling/preparation	1	2	4	5
Sensor/Transducer	1	2	3	3
Electronics	0	1	3	3
Software	0	0	1	3
Computer	0	0	1	2

Functional group: Material Preparation/Handling
Representative Hardware Item: Cell Harvester

Generic Component	Level of automation			
	M	**S**	**A**	**I**
Specimen handling/preparation	1	2	4	5
Sensor/Transducer	0	1	3	5
Electronics	1	2	4	5
Software	0	0	1	3
Computer	0	0	1	2

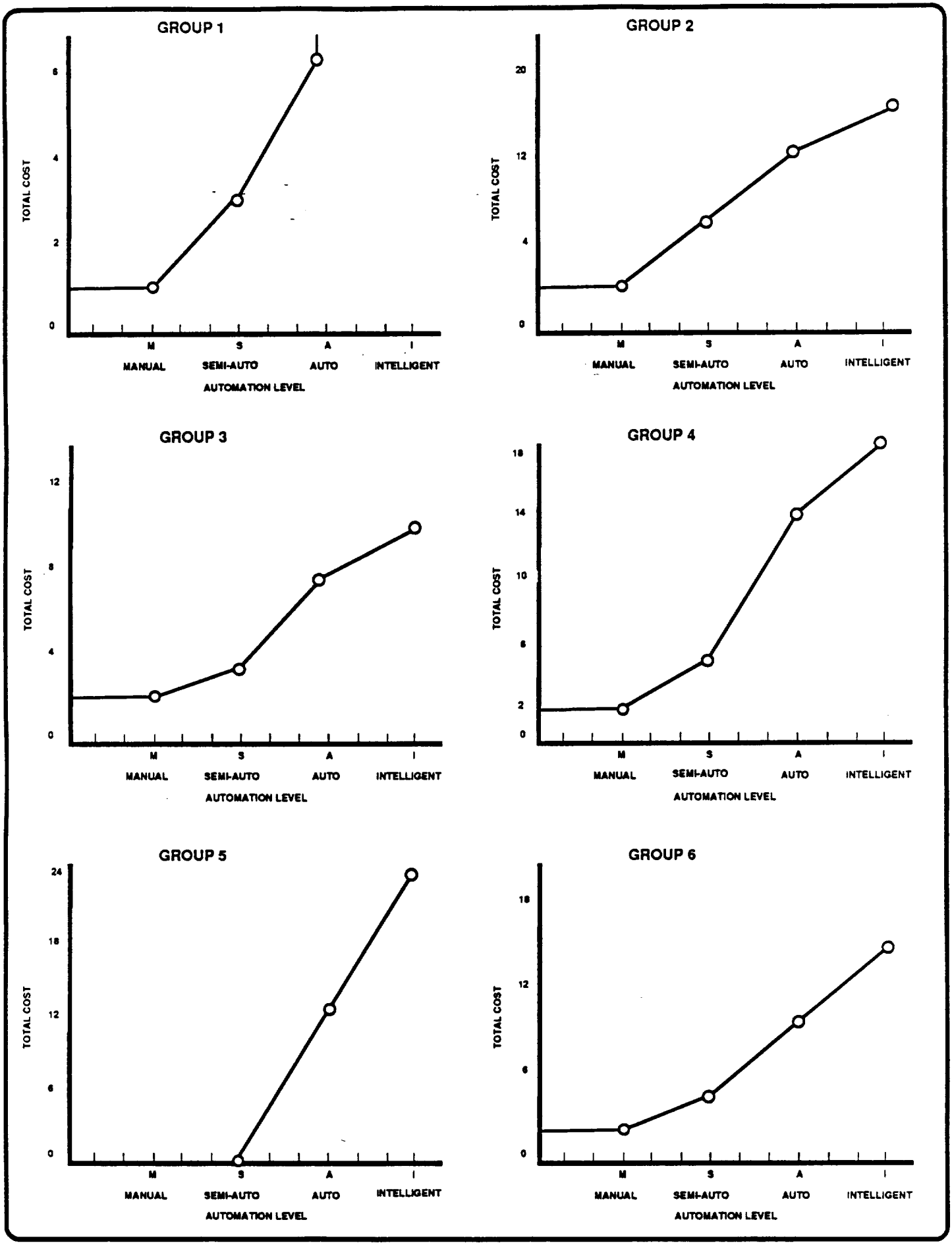

Figure 4 Total Cost vs. Automation Level for Each Functional Group

Functional group: Large-scale System.
Representative Hardware Item: CELSS

Generic Component	Level of automation			
	M	S	A	I
Specimen handling/preparation	N/A	N/A	4	5
Sensor/Transducer	N/A	N/A	3	5
Electronics	N/A	N/A	3	5
Software	N/A	N/A	2	5
Computer	N/A	N/A	2	5

Functional group: Facility Support
Representative Hardware Item: Calibration instrument

Generic Component	Level of automation			
	M	S	A	I
Specimen handling/preparation	0	0	0	0
Sensor/Transducer	1	2	4	5
Electronics	1	2	4	4
Software	0	0	1	4
Computer	0	0	1	2

For each functional group, every unit of generic component can be assigned a $ value. In this study, it was assumed that the total cost of progressing to a level of automation is equal to the sum of the generic components in the corresponding column. The reason for not assigning a specific $ value to each generic component was mainly because they varied as a function of the functional group which would complicate the cost model. In our opinion, the cost model would be more accurate if a $ value was assigned to each generic component after the performance specifications of the hardware item became available.

Figure 4 shows the total cost as a function of automation level for each of the different groups described in section 2.2.1. The following rules of thumb can be postulated for the cost model:

o For hardware items in the functional group of biological specimen support, the total cost increases with level of automation. The gradient (slope) or the cost per automation is greatest for the A level automation range, while the cost per automation of the S level automation is moderate.

o For hardware items in the other functional groups, excluding those in the biological specimen support group, the cost per automation of the cost curve is greatest for the A level automation hardware. Unlike the previous rule of thumb, items at the I level reveal a smaller or same cost per automation as items at the A level of automation. The cost per automation of items at the S level is approximately 50% that of items at the A level and 30% that of items at the I level of automation. Thus from a cost point of view, it is

least expensive to upgrade to a S level of automation, and it is most expensive to upgrade to an A level of automation.

The above rules of thumb and the cost matrices of this section constitute the cost model.

2.3.3. Mission Benefits Model

Five main mission benefits were identified for the SBI program as a result of introducing automation, namely:

i) Reduction of crew training time.
ii) Reduction of crew involvement time.
iii) Increase in quality of results.
iv) Decrease in crew risk.
v) Increase in crew productivity.

The crew involvement time is defined as the time that the crew member has to interact or supervise the equipment in order to perform the experiment. Upon selecting a hardware item from the SBI list, a benefit model can be defined by determining the number of units that each mission benefit will increase by when the equipment in question progresses to the next level of automation. Thus, general trends can be observed which will predict and quantify the increase in benefits as a function of the levels of automation. For this purpose, all the above mission benefits are quantified and given a score from 1 to 5. The following rules of thumb were used to score the individual benefits.

Crew Training Time:

The crew training time is scored as a function of the number of total hours spent to train the crew member on the ground.

The score 1 implies 0 hours to 10 hours of total training time.

The score 2 implies 10 hours to 25 hours of total training time.

The score 3 implies 25 hours to 50 hours of total training time.

The score 4 implies 50 hours to 100 hours of total training time.

The score 5 implies greater than 100 hours of total training time.

Crew Involvement Time:

The crew involvement time is scored as a function of the percentage of the total machine operation time that a crew member must monitor an equipment in order to perform a task.

A score of 1 implies that the crew member must monitor the machine for 0% to 20% of the total machine operation time.

A score of 2 implies that the crew member must monitor the machine for 20% to 40% of the total machine operation time.

A score of 3 implies that the crew member must monitor the machine for 40% to 60% of the total machine operation time.

A score of 4 implies that the crew member must monitor the machine for 60% to 80% of the total machine operation time.

A score of 5 implies that the crew member must monitor the machine for 80% to 100% of the total machine operation time.

Quality of Results

The quality of results is scored from low quality to high repeatable results.

A score of 1 implies low quality of results which will generally showa statistically significant variability.

A score of 2 implies a low to a medium quality of results. Theseresults are characterized by a significantly large statistical variability.

A score of 3 implies medium quality of results which will generallyhave an average statistical variability.

A score of 4 implies medium to high quality of results which willgenerally have a small statistical variability.

A score of 5 implies a high quality of results which will generallyhave a negligible statistical variability.

Crew Risk

The crew risk is scored from low risk to high risk to crew health or presence.

A score of 1 implies low crew risk.

A score of 2 implies low to medium crew risk.

A score of 3 implies medium crew risk.

A score of 4 implies medium to high crew risk.

A score of 5 implies high crew risk.

Productivity

The productivity is scored as a function of the number of experiments performed for a fixed mission duration.

A score of 1 implies a low number of experiments performed for a fixed mission duration.

A score of 2 implies a low to medium number of experiments for a fixed mission duration.

A score of 3 implies a medium number of experiments for a fixed mission duration.

A score of 4 implies a medium to high number of experiments for a fixed mission duration.

A score of 5 implies a high number of experiments for a fixed mission duration.

The hardware items selected in section 2.2.2 to develop the cost model were also selected for developing the benefits model. The above mentioned benefits were analyzed as a function of automation level and presented in matrix form. The matrices were derived based on the above rules of thumb.

Functional group: Biological Specimen Support
Representative Hardware Item: Primate Handling

Mission Benefits	Level of automation			
	M	S	A	I
Crew Training Time	5	3	2	N/A
Crew Involvement Time	5	3	1	N/A
Results Quality	1	3	4	N/A
Crew Risk	5	4	2	N/A
Productivity	1	2	4	N/A

For example, the primate handling hardware at the manual level of automation requires five units of crew training units, five units of crew utilization, produces one unit of quality in results, five units in crew risk and results in one unit of crew mission productivity. By increasing the automation to a S level, the crew training time is reduced by 2 units, the crew involvement is reduced by 2 units, the quality of the results is increased by 2 units, the crew risk is reduced by one unit and the productivity is increased by 2 units.

Thus the following rule of thumb can be derived from the above benefit matrix for equipment belonging to the biological specimen support group:

o If the hardware item is progressed from a M level to a S level of automation, the crew training time is reduced by a factor of 2, the crew involvement time is reduced by a factor of 2, the quality of results is increased by a factor of 3, the crew risk is reduced by a factor of 20% and the productivity is doubled. Similar rules of thumb and trends can be made for equipment progressing from a S level to an A level of automation.

Functional group: Physiological Measurement/Monitoring
Representative Hardware Item: Electrocardiogram (ECG)

Mission Benefits	Level of automation			
	M	S	A	I
Crew Training Time	3	2	2	1
Crew Involvement Time	3	3	2	1
Results Quality	1	2	3	5
Crew Risk	1	1	1	1
Productivity	1	2	3	5

Functional group: Chemistry Systems
Representative Hardware Item: Qualitative Reagent Strip Reader

Mission Benefits	Level of automation			
	M	S	A	I
Crew Training Time	3	2	2	1
Crew Involvement Time	3	3	2	1
Results Quality	1	2	4	5
Crew Risk	3	2	1	1
Productivity	1	2	4	5

Functional group: Material Preparation/Handling
Representative Hardware Item: Cell Harvester

Mission Benefits	Level of automation			
	M	S	A	I
Crew Training Time	4	3	2	1
Crew Involvement Time	5	4	2	1
Results Quality	1	2	4	5
Crew Risk	5	4	2	1
Productivity	1	2	4	5

Functional group: Large Scale Systems
Representative Hardware Item: CELSS

Mission Benefits	Level of automation			
	M	S	A	I
Crew Training Time	N/A	N/A	2	1
Crew Involvement Time	N/A	N/A	2	1
Results Quality	N/A	N/A	4	5
Crew Risk	N/A	N/A	1	1
Productivity	N/A	N/A	4	5

Functional group: Facility Support
Representative Hardware Item: Calibration instrument

Mission Benefits	Level of automation			
	M	S	A	I
Crew Training Time	5	4	3	2
Crew Involvement Time	5	4	2	1
Results Quality	1	2	4	5
Crew Risk	4	3	2	1
Productivity	1	2	4	5

Figure 5 summarizes the results of the benefits matrix presented above. The following rule of thumb can be derived from Figure 5:

o Automation is most beneficial in the S and lower A level of automation. Increase in level of automation in hardware items of level I will reveal only a small increase in benefits because of a saturation effect. It is thus most beneficial to automate hardware items in the S class of automation followed by hardware items in the A class of automation.

The above rule of thumb and the benefit matrices presented in this section constitute the benefit model.

2.3.4 Return on Investment

For the purpose of this study, the return on investment (ROI) is defined as the dimensionless ratio of the total benefits gained expressed in $ divided by the total cost to automate expressed in $.

ROI = Total Benefits gained ($)/Total Cost to automate ($)

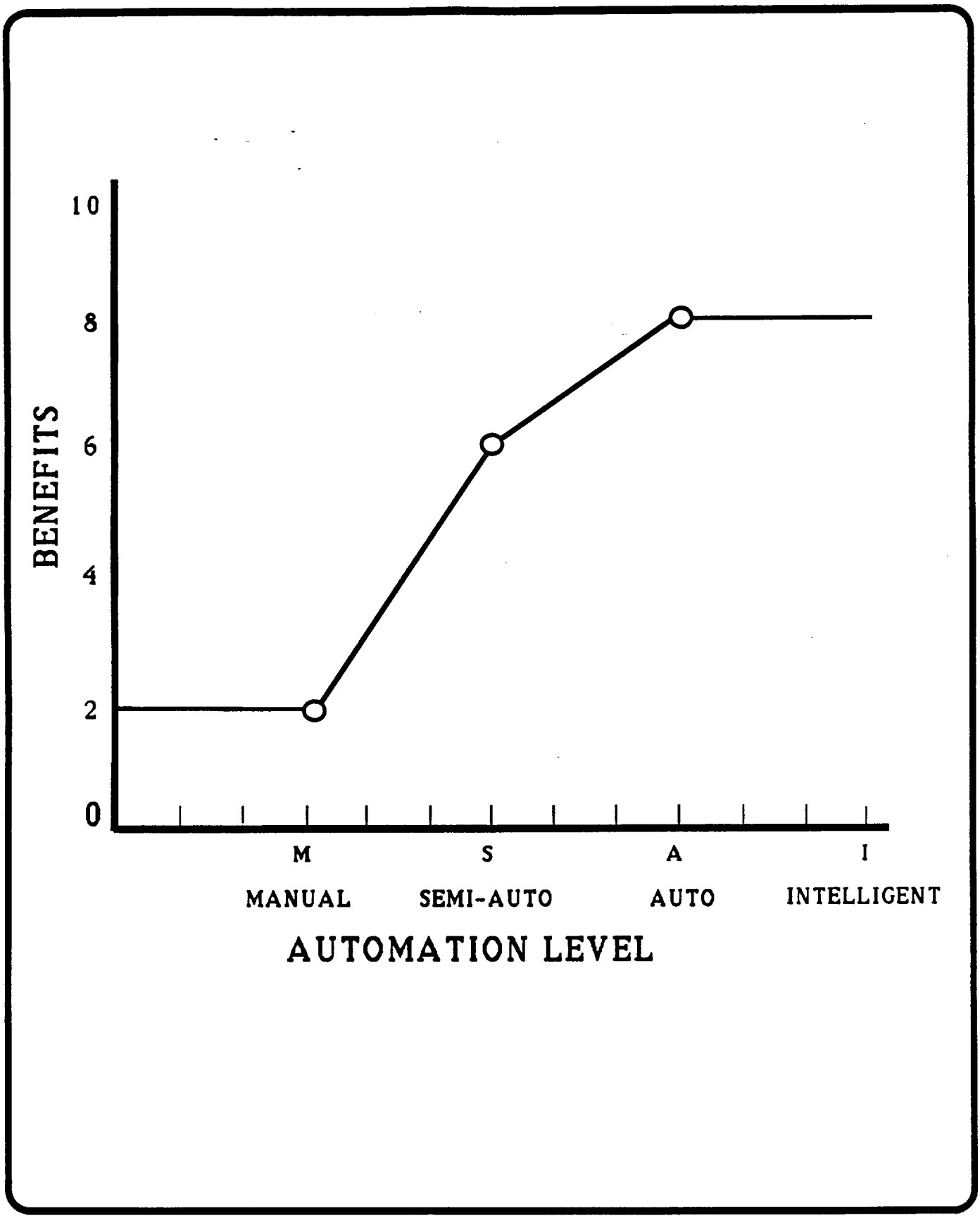

Figure 5
Benefits vs. Automation Level

The ROI value is satisfactory from a cost point of view if it is equal to or greater than one. In other words, if the total benefits gained over a certain period of time is equal to or greater than the total cost to automate, then automation is cost effective. The total cost is obtained from the cost model of section 2.3.2. In order to express the total cost in $, each generic component unit will need to be assigned a $ value and the methodology outlined in section 2.3.2 can then be used to approximate the total cost. The total benefit is obtained from the benefit model of section 2.3.3. The total benefit gained can be expressed in $ after assigning a $ value to each mission benefit unit.

In case the ROI is not satisfactory, then the level of automation being analyzed for the equipment in question is not cost effective. The methodology outlined in Figure 1 suggests refining the choice which essentially means that the automation must be reduced by a unit and the cost and benefit model must be repeated. Several iterations may be required to determine the most optimum level of automation for a particular hardware item.

3.0 Trade Study Data Base

3.1 Literature Bibliography Report

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NASA SBI EQUIPMENT INVENTORY - EVALUATION OF HARDWARE AUTOMATION LEVELS

COLUMN HEADER DEFINITIONS

COLUMN HEADER [Full Name]: Explanation	COLUMN VALUES: Meaning
HARDWARE IDENTIFICATION:	
SBI# [Space Biology Initiative Hardware List #]: Sequential number assigned to item by NASA in a document, Life Sciences Hardware List for the Space Station FREEDOM Era.	Numeric, selected values from 1 to 169: Unique identifier for item.
HW ITEM NAME [Hardware Item Name]: Descriptive name assigned to item by NASA.	Proper name: Alternate (reference) identifier for item.
CURRENT SBI HW CONCEPT INFO SOURCE: The basis on which the Current Concept item evaluation was performed.	Information Source Code Values: **Syymmdd**: NASA Data Sheet, with detail sheet dated yymmdd. Usually describes WHAT and HOW. **NDSnodate**: NASA Data Sheet, with detail sheet (not dated). Usually describes WHAT and HOW. **NDSonly**: NASA Data Sheet, no detail sheet. Usually describes WHAT. **LSHWBL**: Life Sciences Hardware Basic List, version 1.00 (13 pages). Only describes WHAT. **ARC/SSS**: NASA document, preprint # NASA ARC/SSS 88-01, Gas-Grain Simulation Facility: Fundamental Studies of Particle Formation and Interactions, Volume 1. Describes WHAT and HOW in detail. Item Status Code Values: **New**: New design item. Space-qualified version does not exist. **Mod**: Modification required of an existing item. **OTS**: Off-The-Shelf. **COTS**: Commercial OTS. **"as is"**: Item exists and may be used without change. **LSJE**: Item exists and has been space-qualified in previous flights. "LSJE" is a item catalog number prefix. **SLS-1**: Item exists and will be used for the SLS-1 mission.
WHT ["WHAT is item" data]: Summarizes conclusion reached on the amount and quality of data on-hand which describes the item's function.	*: Asterisk, appears where usable item function data was both available and adequate for evaluation purposes.
HOW ["HOW item works" data]: Summarizes conclusion reached on the amount and quality of data on-hand which describes the item's operation.	*: Asterisk, appears where usable item operation data was both available and adequate for evaluation purposes.

NASA SBI EQUIPMENT INVENTORY - EVALUATION OF HARDWARE AUTOMATION LEVELS

COLUMN HEADER DEFINITIONS

COLUMN HEADER [Full Name]: Explanation	COLUMN VALUES: Meaning

HW CHARACTERISTICS:

VOLUME: Space station volume, including packaging and storage material.	Numeric, units in cubic meters.
MASS: Orbital launch mass, including packaging and storage material.	Numeric, units in kilograms.
POWER: External electrical power (Space Station power) required to operate the item. Internal power (e.g., batteries) is not counted.	Numeric, units in watts.

EVALUATION GROUPS: The following three (3) groups contain the columns with the same headings. These three groups make up the actual evaluation. The evaluation methodology is repeated within each evaluation group.

CURRENT CONCEPT [Item Described in Documentation]: An evaulation of the item based upon descriptions received in the source information documentation received for this exercise.

SBI REALISTIC TARGET [Item Practical for SBI Use]: An evaulation of the item based upon expert technical opinion of what is realistic and achievable within space operation constraints (volume, mass, power, microgravity, finite resources, limited manpower).

MAX AVAIL TECHNOLOGY [Item Possible with the Maximum Available Technology]: An evaulation of the item based upon expert technical opinion of what exists or is technologically possible in a terrestrial (Earth-bound) environment.. Space operation constraints (volume, mass, power, microgravity, finite resources, limited manpower) are not considered.

NASA SBI EQUIPMENT INVENTORY - EVALUATION OF HARDWARE AUTOMATION LEVELS

COLUMN HEADER DEFINITIONS

COLUMN HEADER [Full Name]: Explanation

COLUMN VALUES: Meaning

EVALUATION COLUMNS IN EACH EVALUATION GROUP: The following evaluation columns make up each evaluation group.

LVL-ByDomain [Automation Level, By Domain]: A set of three (3) subjective indices estimating the automation level of an item envisioned in the evaluation group. The item's automation level is evaluated from two (2) domain perspectives: the Data Domain and the Physical Domain. The Man-Machine System Automation Score is derived form the Data Automation Score and the Physical Automation Score.

Data [Data Automation Score]: The target of automation is information. The automation level is scored from an data perspective, by considering the interaction and importance of knowledge and decisions in task performance.

Phys [Physical Automation Score]: The target of automation is material. The automation level is scored from an physical perspective, by considering the interaction and importance of skills and actions in task performance.

Syst [Man-Machine System Automation Score]: A conservative weighed average of the Data Automation Score and the Physical Automation Score. NOTE: The weights assigned to each domain in this evaluation are equal for all items.

Automation Level Index Values: These values are used to score **Data, Phys, and Syst**. The following definitions attempt to give an intuitive understanding of the automation levels and their relative relationship to each other with respect to performing a task.

M: Manual Operation = "Man Does." Man controls and performs all steps of the task. Task performance relies almost exclusively on Man. Machine is a tool, capable of no decisions or actions by itself.

- **M1**: Man w/Expert Knowledge = Education(Mns, Yrs).
  Man w/Expert Skill = Experience(Mns, Yrs).
  Machine is a less user-friendly tool.
- **M2**: Man w/Special Knowledge = Education(Dys, Wks).
  Man w/Specific Skill = Experience(Wks, Mns).
- **M3**: Man w/Basic Knowledge = Education(Hrs, Dys).
  Man w/Basic Skill = Experience(Dys, Wks).
  Machine is a more user-friendly tool.

S: Semiautomatic Operation = "Man Does, Machine Assists." Machine performs the task in a sequence of two or more step "groups". Man controls task at decision "checkpoints" between groups. Task performance relies on Man, with Machine assisting Man. Machine is a device, capable of predefined decisions and fixed actions by itself.

- **S1**: Large # of groups and checkpoints.
  Small # of steps in each group.
  Machine is a less sophisticated device.
- **S2**: Average # of groups and checkpoints.
  Average # of steps in each group.
- **S3**: Small # of groups (min. 2) and checkpoints (min. 1).
  Large # of steps in each group.
  Machine is a more sophisticated device.

NASA SBI EQUIPMENT INVENTORY - EVALUATION OF HARDWARE AUTOMATION LEVELS

COLUMN HEADER DEFINITIONS

COLUMN HEADER [Full Name]: Explanation

COLUMN VALUES: Meaning

A: Automatic Operation = "Machine Does, Man Assists." Machine performs the task steps from start to finish. Task performance relies on Machine, with Man monitoring Machine. Machine is a system, capable of procedural decisions and programmed actions by itself.

- A1: Small # of steps, decisions, and actions.
  Does not recognize error conditions.
  i.e., ON ERROR, ATTEMPTS TO CONTINUE.
  Man actively watches Machine's task performance.
  Machine is a less complex system.

- A2: Average # of steps, decisions, and actions.
  Recognizes predefined error conditions.
  i.e., ON ERROR, STOPS. May call for Man's attention.
  Man periodically checks Machine's task performance.

- A3: Large # of steps, decisions, and actions.
  Recognizes predefined error conditions.
  Executes predefined error handling routines.
  i.e., ON ERROR, DEFINED ERROR-HANDLING.
  Man passively monitors Machine's task performance.
  Machine is a more complex system.

I: Independent Operation = "Machine Does." Machine controls and performs all steps of the task. Task performance relies almost exclusively on Machine. Machine is intelligent/autonomous, capable of reasoned decisions (expert system technology) and flexible actions (robotic system technology) by itself.

- I1: Low level of decision reasoning, action flexibility.
  Requires well-defined and static boundary conditions.
  Machine is less intelligent/autonomous.

- I2: Medium level of decision reasoning, action flexibility.
  Can adjust its own reasoning and flexibility, within limits.
  Can learn and expand existing boundary conditions.

- I3: High level of decision reasoning, action flexibility.
  Can learn and expand new boundary conditions.
  Can adjust its own reasoning and flexibility, as required.
  Machine is more intelligent/autonomous.

NASA SBI EQUIPMENT INVENTORY - EVALUATION OF HARDWARE AUTOMATION LEVELS

COLUMN HEADER DEFINITIONS

COLUMN HEADER [Full Name]: Explanation	COLUMN VALUES: Meaning
TRNG [Training Required]: A subjective index estimating the level of effort in preflight (ground-based) training needed to enable a crewmember to perform the requisite task with the machine inflight. Conceptually, the training required consists of two (2) types:	**Training Level Index Values**: 1: Low level of training effort required. 2: Low-to-Medium level of training effort required. 3: Medium level of training effort required. 4: Medium-to-high level of training effort required. 5: High level of training effort required.
Knw [Knowledge Education]: Training concentrating on having the crewmember acquire data domain expertise, particularly factual and procedural knowledge.	
Skl [Skill Experience]: Training concentrating on having the crewmember acquire physical domain expertise, particularly hand-eye coordination and body movement skills.	
CwTim [Percent Crew Time Required]: A subjective index estimating the proportion of machine operation (use) time during which a human crew member must interact with the machine, to provide the machine with knowledge, skills, decisions, and actions that it does not possess. The human interaction is requisite for the machine to continue with its operation.	**Crew Utilization Index Values**: 1: 0% to 20% of the time. 2: 20% to 40% of the time. 3: 40% to 60% of the time. 4: 60% to 80% of the time. 5: 80% to 100% of the time.

3.2 SUMMARY TABLE - EVALUATION OF SBI HARDWARE AUTOMATION LEVELS

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	CURRENT SBI HW CONCEPT INFO SOURCE	CURRENT CONCEPT LVL-ByDomain DataPhysSyst			TRNG %Cw KnwSklTim			SBI REALISTIC TARGET LVL-ByDomain DataPhysSyst			TRNG %Cw KnwSklTim			MAX AVAIL TECHNOLOGY LVL-ByDomain DataPhysSyst			TRNG %Cw KnwSklTim		
16	Animal Tissue Biopsy Equipment	LSHWBL	M3	M3	M3	3	4	5	M3	M3	M3	3	4	5	S3	S3	S3	2	2	4
17	Blood Collection System	NDSnodate Mod	M3	S2	S1	2	3	5	M3	S2	S1	2	3	5	S3	S2	S2	1	2	4
22	Electrofusion Device	NDS890222 COT	S2	S2	S2	3	3	4	A2	A1	A1	2	2	3	I1	I2	I1	1	1	1
23	Fixation Unit	NDSonly New	A3	A2	A2	3	2	2	A3	A2	A2	3	2	2	I2	I1	I1	2	1	1
28	Muscle Biopsy Equipment	LSHWBL	M3	M3	M3	3	3	5	M3	M3	M3	3	3	5	S3	A2	A1	3	2	4
29	Perfusion and Fixation Unit	LSHWBL	A3	A2	A2	3	2	2	A3	A2	A2	3	2	2	I2	I1	I1	2	1	1
30	Plant Care Unit	LSHWBL	I1	A3	A3	2	1	1	I1	A3	A3	2	1	1	I3	I2	I2	1	1	1
31	Plant Harvest/Dissection Unit	LSHWBL	S3	S1	S2	3	3	4	S3	S1	S2	2	2	4	I1	A3	A3	1	2	3
33	Saliva Collection Unit	NDSnodate DSO	M3	M3	M3	1	1	5	M3	M3	M3	1	1	5	M3	M3	M3	1	1	5
34	Sample Preparation Device	NDS890302 New	I2	I1	I1	2	1	1	I1	A3	A3	3	2	2	I2	I2	I2	1	1	1
38	Sweat Collection Device	NDS890303 Mod	A1	S2	S3	2	1	2	A2	S3	A1	1	1	2	A3	A1	A2	1	1	1
39	CO2 Administration Device	LSHWBL	S1	S3	S2	2	2	1	S1	S3	S2	2	2	1	A3	A3	A3	1	1	1
40	Rodent Blood Collection System	LSHWBL	M3	S2	S1	2	3	5	M3	S2	S1	2	3	5	S3	S2	S2	1	2	4
41	Rodent Caudal Vertebrae Thermal	LSHWBL	S1	M3	M3	1	3	2	S1	M3	M3	1	3	2	S2	S2	S2	1	2	1
42	Rodent Guillotine	LSHWBL	M3	S1	M3	2	2	5	M3	S1	M3	2	2	5	S2	S3	S2	2	1	3
43	Rodent Restraint	LSHWBL	S1	S1	S1	2	3	3	S1	S1	S1	2	3	3	A1	S3	S3	2	2	2
44	Rodent Surgery Platform	LSHWBL	S1	M3	M3	2	2	2	S1	M3	M3	2	2	2	S3	A2	A1	2	1	2
45	Rodent Surgery/Dissection Unit	LSHWBL	M1	M2	M1	5	5	5	M1	M2	M1	5	5	5	M2	S2	M3	4	4	5
46	Rodent Urine Collection System	LSHWBL	M3	M2	M2	2	3	5	M3	M2	M2	2	3	5	S1	M3	M3	2	2	5
47	Rodent Veterinary Unit	LSHWBL	M2	S2	M3	4	3	4	M2	S2	M3	4	3	4	S2	S3	S2	3	3	4
48	Primate Blood Collection System	LSHWBL	M3	S2	S1	2	3	5	M3	S2	S1	2	3	5	S3	S2	S2	1	2	4
49	Primate Handling Equipment	LSHWBL	S1	M3	M3	2	2	3	S1	M3	M3	2	2	3	S3	S3	S3	2	2	2
50	Primate Lower Body Negative Pre	LSHWBL	S1	M3	M3	2	2	2	S1	M3	M3	2	2	2	S1	S1	S1	2	1	2
51	Primate Surgery Platform	LSHWBL	S1	M3	M3	2	2	2	S1	M3	M3	2	2	2	S2	A1	S3	2	1	2
52	Primate Surgery/Dissection Unit	LSHWBL	M1	M2	M1	5	5	5	M1	M2	M1	5	5	5	M2	S2	M3	4	4	5
53	Primate Urine Collection System	LSHWBL	M3	M2	M2	2	3	5	M3	M2	M2	2	3	5	S1	M3	M3	2	2	5
54	Primate Veterinary Unit	LSHWBL	M2	S1	M3	4	3	4	M2	S1	M3	4	3	4	S2	S3	S2	3	3	4
55	Small Primate Restraint	LSHWBL	S1	M3	M3	2	3	3	S1	M3	M3	2	3	3	S3	S3	S3	2	2	2
56	Bag Assembly	NDSnodate SLS	M3	M3	M3	1	1	1	M3	M3	M3	1	1	1	M3	M3	M3	1	1	1
57	Bag-in-Box	NDSnodate SLS	S2	A1	S3	1	1	1	S2	A1	S3	1	1	1	S2	A1	S3	1	1	1
59	Electronics Control Assembly	NDS890306 SLS	S3	A1	S3	2	1	1	S3	A1	S3	2	1	1	A1	A1	A1	2	1	1
60	Mask/Regulator System	NDSonly "as i	S1	S1	S1	1	1	1	S1	S1	S1	1	1	1	S1	S1	S1	1	1	1
61	Mass Spectrometer	NDSnodate New	A3	A3	A3	3	1	1	I1	A3	A3	2	1	1	I2	I2	I2	2	1	1
62	Pulmonary Function Equipment St	NDSonly "as i	M2	M3	M2	1	1	1	M2	M3	M2	1	1	1	M2	M3	M2	1	1	1
63	Pulmonary Gas Cylinder Assembly	NDS890306 SLS	A1	A1	A1	2	2	1	A1	A1	A1	2	2	1	A1	A2	A1	2	1	1
64	Rebreathing Assembly	NDSnodate SLS	M3	S3	S1	2	1	1	M3	S3	S1	2	1	1	S1	S3	S2	1	1	1
65	Spirometry Assembly	NDSnodate SLS	S3	S2	S2	2	1	1	A1	S2	S3	2	1	1	A2	S2	S3	1	1	1
66	Syringe (3 Liter Calibration)	NDS890303 SLS	M3	M2	M2	1	1	5	M3	M2	M2	1	1	5	S1	S1	S1	1	1	1
67	Accelerometer and Recorder	NDS890301 New	A3	S3	A1	2	1	1	I1	S3	A2	2	1	1	I1	A1	A2	1	1	1
68	Anthropometric Measurement Syst	NDSnodate COT	M2	M2	M2	2	3	4	S1	S1	S1	2	3	4	A3	S3	A1	2	1	3
70	Compliance Volumometer	NDS890221 New	A1	S1	S2	2	3	5	A2	S2	S3	1	3	5	A3	A3	A3	1	2	4
71	Electroencephalomagnetogram (EE	NDS890310 New	A3	S2	A1	3	3	2	I1	S2	A1	3	3	1	I2	S3	A2	2	2	1
74	Force Resistance System	NDS890310 Mod	A2	S3	A1	2	2	3	I1	A1	A2	2	2	2	I1	A3	A3	2	1	2
75	Fundus Camera	NDS890221 Mod	S3	M3	S1	3	2	5	A2	S1	S3	2	2	4	I1	S3	A2	1	1	4
77	Hard Tissue Imaging System	NDSonly New	I1	A1	A2	4	2	3	I1	A1	A2	4	2	3	I2	I1	I1	2	1	2
78	Mass Calibration Unit	NDSonly OTS	M3	M3	M3	1	1	5	M3	M3	M3	1	1	5	M3	M3	M3	1	1	5
82	Motion Analysis System	NDS890310 Mod	A3	S3	A1	2	2	5	I1	A1	A2	2	1	3	I2	I1	I1	1	1	1

SUMMARY TABLE - EVALUATION OF SBI HARDWARE AUTOMATION LEVELS

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	CURRENT SBI HW CONCEPT INFO SOURCE	CURRENT CONCEPT LVL-ByDomain	CURRENT CONCEPT DataPhysSyst	CURRENT CONCEPT TRNG	CURRENT CONCEPT KnwSklTim	CURRENT CONCEPT %Cw	SBI REALISTIC TARGET LVL-ByDomain	SBI REALISTIC TARGET DataPhysSyst	SBI REALISTIC TARGET TRNG	SBI REALISTIC TARGET KnwSklTim	SBI REALISTIC TARGET %Cw	MAX AVAIL TECHNOLOGY LVL-ByDomain	MAX AVAIL TECHNOLOGY DataPhysSyst	MAX AVAIL TECHNOLOGY TRNG	MAX AVAIL TECHNOLOGY KnwSklTim	MAX AVAIL TECHNOLOGY %Cw
83	Plethysmograph Measuring System	NDSonly New	A3	A2	3	2	4	A3	A2	3	2	4	I2	I1	2	1	3
84	Soft Tissue Imaging System	LSHWBL	I1	A1	4	2	3	I1	A1	4	2	3	I2	I1	2	1	2
85	Tonometer		A2	A1	2	1	5	A2	A1	2	1	5	I1	A3	3	2	1	3
87	EEG Cap	NDS890310 Mod	A2	M2	3	2	1	A3	M3	2	2	1	I1	S2	1	2	1	1
88	EEG Signal Conditioner	NDS890310 Mod	A1	M3	3	1	1	A2	S1	2	1	1	I1	S3	1	1	1	1
98	Visual Tracking System	LSHWBL	A3	A1	2	2	4	A3	A1	2	2	4	I2	I1	1	1	1	1
99	Animal Biotelemetry System	LSHWBL	A2	M3	2	2	1	A2	M3	2	2	1	I1	S2	1	2	1	1
100	Blood Pressure and Flow Instrum	NDSonly New	A2	M3	2	2	5	A2	M3	2	2	5	I1	S2	1	2	4	1
101	Cardiodynamic Monitor	NDSonly New	A3	S2	2	2	3	A3	S2	2	2	3	I1	S3	1	1	2	1
102	Electrocardiograph (ECG)	NDSonly "as i	A3	S1	2	2	3	A3	S1	2	2	3	I2	S3	1	1	2	1
103	Holter Recorder	NDSonly "as i	A2	A1	2	1	1	A2	A1	2	1	1	A3	A1	1	1	1	1
106	Neck Baro-Cuff	NDSnodate Mod	A2	A1	2	2	1	A2	A1	2	2	1	A3	A2	1	2	1	1
109	Venous Pressure Transducer/Disp	NDSnodate SLS	A3	M2	2	2	2	A3	M2	2	2	2	I1	S1	1	1	1	1
110	Plant Gas Chromatograph/Mass Sp	LSHWBL	I1	A3	3	1	2	I1	A3	3	1	2	I2	I2	2	1	1	1
111	Plant Gas Cylinder Assembly	LSHWBL	A1	A3	2	2	1	A1	A3	2	2	1	A3	A3	1	2	1	1
112	Plant HPLC Ion Chromatograph	LSHWBL	I1	A2	3	1	2	I1	A2	3	1	2	I2	I2	2	1	1	1
113	Blood Gas Analyzer	NDSonly New	A3	A3	3	1	2	A3	A3	3	1	2	I2	I2	2	1	1	1
115	Chemistry System	NDSnodate Mod	A3	S3	4	2	2	I1	A1	3	2	2	I2	I2	2	1	1	1
116	Continuous Flow Electrophoresis	NDS890222 Mod	A3	I1	3	2	2	I1	A3	2	2	2	I2	I2	2	1	1	1
119	Gas Cylinder Assembly	NDSonly "as i	A2	S3	2	2	1	A2	S3	2	2	1	A3	A3	1	2	1	1
124	Qualitative Reagent Strip and R	NDS890302 COT	S3	S3	3	1	2	I1	S3	2	1	1	I2	I2	2	1	1	1
126	Scintillation Counter	NDS890221 New	A3	A3	3	2	2	I1	A3	2	2	2	I2	I2	2	1	1	1
129	Cell Handling Accessories	NDSonly New	A3	A2	2	3	4	A3	A2	2	3	4	I1	I2	1	1	1	1
130	Cell Harvester	NDS890221 New	A3	A3	2	1	2	I1	A3	1	1	2	I2	I2	1	1	1	1
131	Cell Perfusion Apparatus	NDS890221 New	A3	A3	2	1	2	I1	A3	1	1	2	I2	I2	1	1	1	1
134	Centrifuge Hematocrit	NDSnodate LSL	S2	S2	2	1	3	S3	S2	2	1	3	A3	A3	1	1	1	1
135	Chromosomal Slide Prep Device	NDS890221 New	A3	A3	3	1	2	I1	A3	2	1	2	I2	I2	2	1	1	1
136	Fluoromeasure Probe		I1	A3	3	2	4	I1	A3	3	2	4	I2	I2	2	1	1	1
138	Hematology System	NDSonly Mod	A3	A3	3	2	2	A3	A3	3	2	2	I1	I1	2	1	1	1
139	Image Digitizing System	NDSnodate New	I1	A1	4	2	2	I1	A1	3	2	2	I2	I2	2	1	1	1
142	Skin Window Device	NDSnodate New	M3	S3	2	2	5	M3	A1	2	1	5	S1	A2	1	1	3	1
145	Automated Microbic System (AMS)	NDS890221 Mod	I1	S3	2	1	1	I1	A3	3	2	2	I2	I2	1	1	1	1
147	Head/Torso Phantom	NDSnodate COT	M2	M2	2	2	1	S1	M3	1	2	1	A1	S1	1	1	1	1
149	Microbial Preparation System	NDS890222 New	I2	I1	2	1	1	I1	A3	3	2	2	I2	I2	1	1	1	1
151	Reuter Microbiology Air Sampler	NDS890221 Mod	M3	S1	1	1	5	M3	S1	1	1	5	S1	S1	1	1	2	1
152	Solid Sorbent Air Sampler	LSHWBL	S1	S1	1	1	5	S1	S1	1	1	5	A1	A1	1	1	2	1
153	Spectrometer (Proton/Heavy Ion)	NDSnodate New	A3	A2	3	2	2	I1	A3	3	1	2	I2	I2	2	1	1	1
154	Tissue Equivalent Proportional		I1	A3	2	2	2	I1	A3	2	2	2	I2	I2	1	1	1	1
155	Total Hydrocarbon Analyzer	LSHWBL	I1	A3	2	1	2	I1	A3	2	1	2	I2	I2	2	1	1	1
161	Inventory Control System	NDSonly OTS	I2	I1	2	1	1	I2	I1	2	1	1	I3	I2	1	1	1	1
162	Lab Materials Packaging and Han	NDSonly New	I2	I1	2	1	1	I2	I1	2	1	1	I3	I2	1	1	1	1
163	Test/Checkout/Calibration Instr	LSHWBL	I1	A1	3	2	3	I1	A1	3	2	3	I2	A3	2	2	2	1
165	Experiment Control Computer Sys	NDSonly New	I1	S3	3	1	2	I2	S3	2	1	1	I3	A1	2	1	1	1
167	Voice Recorder	NDSnodate LSL	A2	S3	2	1	2	A2	S3	2	1	2	A3	A3	2	1	2	1
168	Closed Ecological Life Support	LSHWBL	I2	I1	2	1	1	I2	I1	2	1	1	I2	I2	1	1	1	1
169	Gas Grain Simulator	ARC/SSS New	I1	A2	4	3	1	I1	A2	4	2	1	I2	I1	3	2	1	1

3.3 TABLE I - SBI HARDWARE INFORMATION SOURCE & COMPLETENESS

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	CURRENT SBI HW CONCEPT INFO SOURCE	W H H O T W
16	Animal Tissue Biopsy Equipment	LSHWBL	*	
17	Blood Collection System	NDSnodate Mod (LSLE)	*	*
22	Electrofusion Device	NDS890222 COTS (BTX, Inc./German Space Agency)	*	*
23	Fixation Unit	NDSonly New	*	
28	Muscle Biopsy Equipment	LSHWBL	*	
29	Perfusion and Fixation Unit	LSHWBL	*	
30	Plant Care Unit	LSHWBL	*	
31	Plant Harvest/Dissection Unit	LSHWBL	*	
33	Saliva Collection Unit	NDSnodate DSO "as is"	*	*
34	Sample Preparation Device	NDS890302 New	*	*
38	Sweat Collection Device	NDS890303 Mod (John B. Pierce Foundation Laboratory)	*	*
39	CO2 Administration Device	LSHWBL	*	
40	Rodent Blood Collection System	LSHWBL	*	
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	LSHWBL	*	
42	Rodent Guillotine	LSHWBL	*	
43	Rodent Restraint	LSHWBL	*	
44	Rodent Surgery Platform	LSHWBL	*	
45	Rodent Surgery/Dissection Unit	LSHWBL	*	
46	Rodent Urine Collection System	LSHWBL	*	
47	Rodent Veterinary Unit	LSHWBL	*	
48	Primate Blood Collection System	LSHWBL	*	
49	Primate Handling Equipment	LSHWBL	*	
50	Primate Lower Body Negative Pressure (LBNP) Device	LSHWBL	*	
51	Primate Surgery Platform	LSHWBL	*	
52	Primate Surgery/Dissection Unit	LSHWBL	*	
53	Primate Urine Collection System	LSHWBL	*	
54	Primate Veterinary Unit	LSHWBL	*	
55	Small Primate Restraint	LSHWBL	*	
56	Bag Assembly	NDSnodate SLS-1 "as is" (U. of California, SD)	*	*
57	Bag-in-Box	NDSnodate SLS-1 "as is" (U. of California, SD)	*	*
59	Electronics Control Assembly	NDS890306 SLS-1 "as is"	*	*
60	Mask/Regulator System	NDSonly "as is"	*	
61	Mass Spectrometer	NDSnodate New (U. of Colorado Health Sciences Center)	*	*
62	Pulmonary Function Equipment Stowage Assembly	NDSonly "as is"	*	
63	Pulmonary Gas Cylinder Assembly	NDS890306 SLS-1 "as is"	*	*
64	Rebreathing Assembly	NDSnodate SLS-1 (U. of California, SD)	*	*
65	Spirometry Assembly	NDSnodate SLS-1 "as is"	*	*
66	Syringe (3 Liter Calibration)	NDS890303 SLS-1 "as is"	*	*
67	Accelerometer and Recorder	NDS890301 New (Kistler Instrument Corporation)	*	*
68	Anthropometric Measurement System	NDSnodate COTS	*	*
70	Compliance Volumometer	NDS890221 New (NASA)	*	*
71	Electroencephalomagnetogram (EEMG)	NDS890310 New (Biomagnetic Technologies, Inc.)	*	*
74	Force Resistance System	NDS890310 Mod (TORK PTY. LIMITED)	*	*
75	Fundus Camera	NDS890221 Mod (Kiwa Opthalmic Company)	*	*
77	Hard Tissue Imaging System	NDSonly New	*	
78	Mass Calibration Unit	NDSonly OTS	*	
82	Motion Analysis System	NDS890310 Mod (Ariel Dynamics)	*	*

TABLE I - SBI HARDWARE INFORMATION SOURCE & COMPLETENESS

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	CURRENT SBI HW CONCEPT INFO SOURCE	W/T	H/W
83	Plethysmograph Measuring System	NDSonly New	*	
84	Soft Tissue Imaging System	LSHWBL	*	
85	Tonometer			
87	EEG Cap	NDS890310 Mod (Skylab)	*	*
88	EEG Signal Conditioner	NDS890310 Mod (Skylab)	*	*
98	Visual Tracking System	LSHWBL	*	
99	Animal Biotelemetry System	LSHWBL	*	
100	Blood Pressure and Flow Instrumentation	NDSonly New	*	
101	Cardiodynamic Monitor	NDSonly New	*	
102	Electrocardiograph (ECG)	NDSonly "as is"	*	
103	Holter Recorder	NDSonly "as is"	*	
106	Neck Baro-Cuff	NDSnodate Mod (Virginia Commonwealth University)	*	*
109	Venous Pressure Transducer/Display	NDSnodate SLS-1 "as is" (UT Southwest Medical Center)	*	*
110	Plant Gas Chromatograph/Mass Spectrometer	LSHWBL	*	
111	Plant Gas Cylinder Assembly	LSHWBL	*	
112	Plant HPLC Ion Chromatograph	LSHWBL	*	
113	Blood Gas Analyzer	NDSonly New	*	
115	Chemistry System	NDSnodate Mod (Kodak/HMF)	*	*
116	Continuous Flow Electrophoresis Device	NDS890222 Mod (McDonnell Douglas Astronautics Co.)	*	*
119	Gas Cylinder Assembly	NDSonly "as is"	*	
124	Qualitative Reagent Strip and Reader	NDS890302 COTS (Ames Labs/Behring Diagnostics/JSC)	*	*
126	Scintillation Counter	NDS890221 New (Packard Instrument Co.)	*	*
129	Cell Handling Accessories	NDSonly New	*	
130	Cell Harvester	NDS890221 New (Cambridge Technology, Inc)	*	*
131	Cell Perfusion Apparatus	NDS890221 New (PhytoResource Research, Inc)	*	*
134	Centrifuge Hematocrit	NDSnodate LSLE#J016	*	*
135	Chromosomal Slide Prep Device	NDS890221 New	*	*
136	Fluoromeasure Probe			
138	Hematology System	NDSonly Mod	*	
139	Image Digitizing System	NDSnodate New (Krug Int'l/Perceptive Systems, Inc.)	*	*
142	Skin Window Device	NDSnodate New	*	*
145	Automated Microbic System (AMS)	NDS890221 Mod (JSC/Vitek)	*	*
147	Head/Torso Phantom	NDSnodate COTS	*	*
149	Microbial Preparation System	NDS890222 New	*	*
151	Reuter Microbiology Air Sampler	NDS890221 Mod (Reuter/ARC)	*	*
152	Solid Sorbent Air Sampler	LSHWBL	*	
153	Spectrometer (Proton/Heavy Ion)	NDSnodate New (Batelle Memorial Institute)	*	*
154	Tissue Equivalent Proportional Counter			
155	Total Hydrocarbon Analyzer	LSHWBL	*	
161	Inventory Control System	NDSonly OTS	*	
162	Lab Materials Packaging and Handling Equipment	NDSonly New	*	
163	Test/Checkout/Calibration Instrumentation	LSHWBL	*	
165	Experiment Control Computer System	NDSonly New	*	
167	Voice Recorder	NDSnodate LSLE#J013	*	*
168	Closed Ecological Life Support System Test Facility	LSHWBL	*	
169	Gas Grain Simulator	ARC/SSS New	*	

3.4 TABLE II - SBI CURRENT HARDWARE CONCEPT ESTIMATE

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	W H T	H O W	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT CONCEPT LVL-ByDomain Data	Phys	Syst	TRNG Knw	Skl	%Cw Tim
16	Animal Tissue Biopsy Equipment	*		0.030	8.0	0	M3	M3	M3	3	4	5
17	Blood Collection System	*	*	0.020	1.0	0	M3	S2	S1	2	3	5
22	Electrofusion Device	*	*	0.060	TBD	TBD	S2	S2	S2	3	3	4
23	Fixation Unit	*		0.020	4.0	0	A3	A2	A2	3	2	2
28	Muscle Biopsy Equipment	*		0.010	1.0	0	M3	M3	M3	3	3	5
29	Perfusion and Fixation Unit	*		0.010	2.0	0	A3	A2	A2	3	2	2
30	Plant Care Unit	*		0.050	10.0	50	I1	A3	A3	2	1	1
31	Plant Harvest/Dissection Unit	*		0.010	4.0	20	S3	S1	S2	3	3	4
33	Saliva Collection Unit	*	*	0.001	0.2	0	M3	M3	M3	1	1	5
34	Sample Preparation Device	*	*	0.170	22.0	150	I2	I1	I1	2	1	1
38	Sweat Collection Device	*	*	0.005	5.1	15	A1	S2	S3	2	1	2
39	CO2 Administration Device	*		0.010	3.0	0	S1	S3	S2	2	2	1
40	Rodent Blood Collection System	*		0.030	10.0	50	M3	S2	S1	2	3	5
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	*		0.010	2.0	50	S1	M3	M3	1	3	2
42	Rodent Guillotine	*		0.010	4.0	0	M3	S1	M3	2	2	5
43	Rodent Restraint	*		0.010	3.0	0	S1	S1	S1	2	3	3
44	Rodent Surgery Platform	*		0.010	3.0	0	S1	M3	M3	2	2	2
45	Rodent Surgery/Dissection Unit	*		0.010	3.0	0	M1	M2	M1	5	5	5
46	Rodent Urine Collection System	*		0.030	10.0	50	M3	M2	M2	2	3	5
47	Rodent Veterinary Unit	*		0.030	10.0	0	M2	S2	M3	4	3	4
48	Primate Blood Collection System	*		0.050	2.0	140	M3	S2	S1	2	3	5
49	Primate Handling Equipment	*		0.010	1.0	0	S1	M3	M3	2	2	3
50	Primate Lower Body Negative Pressure (LBNP) Device	*		0.050	3.0	140	S1	M3	M3	2	2	2
51	Primate Surgery Platform	*		0.040	5.0	0	S1	M3	M3	2	2	2
52	Primate Surgery/Dissection Unit	*		0.020	5.0	0	M1	M2	M1	5	5	5
53	Primate Urine Collection System	*		0.010	10.0	14	M3	M2	M2	2	3	5
54	Primate Veterinary Unit	*		0.030	10.0	0	M2	S1	M3	4	3	4
55	Small Primate Restraint	*		0.050	2.0	0	S1	M3	M3	2	3	3
56	Bag Assembly	*	*	0.010	1.0	0	M3	M3	M3	1	1	1
57	Bag-in-Box	*	*	0.150	19.0	0	S2	A1	S3	1	1	1
59	Electronics Control Assembly	*	*	0.080	13.0	100	S3	A1	S3	2	1	1
60	Mask/Regulator System	*		0.010	3.0	30	S1	S1	S1	1	1	1
61	Mass Spectrometer	*	*	0.087	40.7	200	A3	A3	A3	3	1	1
62	Pulmonary Function Equipment Stowage Assembly	*		0.051	20.0	0	M2	M3	M2	1	1	1
63	Pulmonary Gas Cylinder Assembly	*	*	0.090	30.0	0	A1	A1	A1	2	2	1
64	Rebreathing Assembly	*	*	0.020	1.0	0	M3	S3	S1	2	1	1
65	Spirometry Assembly	*	*	0.010	1.0	0	S3	S2	S2	2	1	1
66	Syringe (3 Liter Calibration)	*	*	0.010	2.0	0	M3	M2	M2	1	1	5
67	Accelerometer and Recorder	*	*	0.040	16.1	35	A3	S3	A1	2	1	1
68	Anthropometric Measurement System	*	*	0.020	1.0	0	M2	M2	M2	2	3	4
70	Compliance Volumometer	*	*	0.015	16.0	130	A1	S1	S2	2	3	5
71	Electroencephalomagnetogram (EEMG)	*	*	0.060	2.0	TBD	A3	S2	A1	3	3	2
74	Force Resistance System	*	*	0.400	70.0	220	A2	S3	A1	2	2	3
75	Fundus Camera	*	*	0.003	2.0	0	S3	M3	S1	3	2	5
77	Hard Tissue Imaging System	*		0.290	136.0	300	I1	A1	A2	4	2	3
78	Mass Calibration Unit	*		0.010	2.0	0	M3	M3	M3	1	1	5
82	Motion Analysis System	*	*	0.050	20.0	100	A3	S3	A1	2	2	5

TABLE II - SBI CURRENT HARDWARE CONCEPT ESTIMATE

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	W	H	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT CONCEPT LVL-ByDomain Data	Phys	Syst	TRNG %CW KnwSkl	Tim	
83	Plethysmograph Measuring System	*		0.010	3.0	30	A3	A2	A2	3	2	4
84	Soft Tissue Imaging System	*		0.960	300.0	800	I1	A1	A2	4	2	3
85	Tonometer			0.000	0.1	0	A2	A1	A1	2	1	5
87	EEG Cap	*	*	0.010	2.0	0	A2	M2	S2	3	2	1
88	EEG Signal Conditioner	*	*	0.010	2.0	0	A1	M3	S2	3	1	1
98	Visual Tracking System	*		0.010	2.0	20	A3	A1	A2	2	2	4
99	Animal Biotelemetry System	*		0.050	20.0	100	A2	M3	S2	2	2	1
100	Blood Pressure and Flow Instrumentation	*		0.060	20.0	200	A2	M3	S2	2	2	5
101	Cardiodynamic Monitor	*		0.020	4.0	150	A3	S2	A1	2	2	3
102	Electrocardiograph (ECG)	*		0.010	2.0	20	A3	S1	S3	2	2	3
103	Holter Recorder	*		0.010	2.0	0	A2	A1	A1	2	1	1
106	Neck Baro-Cuff	*	*	0.132	45.2	145	A2	A1	A1	2	2	1
109	Venous Pressure Transducer/Display	*	*	0.050	20.0	100	A3	M2	S2	2	2	2
110	Plant Gas Chromatograph/Mass Spectrometer	*		0.200	25.0	100	I1	A3	A3	3	1	2
111	Plant Gas Cylinder Assembly	*		0.090	19.0	0	A1	A3	A2	2	2	1
112	Plant HPLC Ion Chromatograph	*		0.120	40.0	200	I1	A2	A3	3	1	2
113	Blood Gas Analyzer	*		0.130	45.0	250	A3	A3	A3	3	1	2
115	Chemistry System	*	*	0.080	23.0	100	A3	S3	A1	4	2	2
116	Continuous Flow Electrophoresis Device	*	*	0.060	TBD	TBD	A3	I1	A3	3	2	2
119	Gas Cylinder Assembly	*		0.090	19.0	0	A2	S3	A1	2	2	1
124	Qualitative Reagent Strip and Reader	*	*	0.030	10.0	100	S3	S3	S3	3	1	2
126	Scintillation Counter	*	*	0.240	90.0	500	A3	A3	A3	3	2	2
129	Cell Handling Accessories	*		0.050	20.0	50	A3	A2	A2	2	3	4
130	Cell Harvester	*	*	0.060	19.0	50	A3	A3	A3	2	1	2
131	Cell Perfusion Apparatus	*	*	0.060	TBD	TBD	A3	A3	A3	2	1	2
134	Centrifuge Hematocrit	*	*	0.010	2.0	0	S2	S2	S2	2	1	3
135	Chromosomal Slide Prep Device	*	*	0.010	2.0	20	A3	A3	A3	3	1	2
136	Fluoromeasure Probe			0.050	TBD	TBD	I1	A3	A3	3	2	4
138	Hematology System	*		0.070	23.0	200	A3	A3	A3	3	2	2
139	Image Digitizing System	*	*	0.030	11.4	500	I1	A1	A2	4	2	2
142	Skin Window Device	*	*	0.010	2.0	0	M3	S3	S1	2	2	5
145	Automated Microbic System (AMS)	*	*	0.200	70.0	110	I1	S3	A2	2	1	1
147	Head/Torso Phantom	*	*	0.120	32.0	0	M2	M2	M2	2	2	1
149	Microbial Preparation System	*	*	0.010	2.0	110	I2	I1	I1	2	1	1
151	Reuter Microbiology Air Sampler	*	*	0.005	1.5	0	M3	S1	M3	1	1	5
152	Solid Sorbent Air Sampler	*		0.010	5.0	0	S1	S1	S1	1	1	5
153	Spectrometer (Proton/Heavy Ion)	*	*	0.030	10.0	20	A3	A2	A2	3	2	2
154	Tissue Equivalent Proportional Counter			0.001	2.0	0	I1	A3	A3	2	2	2
155	Total Hydrocarbon Analyzer	*		0.200	70.0	250	I1	A3	A3	2	1	2
161	Inventory Control System	*		0.200	70.0	500	I2	I1	I1	2	1	1
162	Lab Materials Packaging and Handling Equipment	*		0.200	70.0	500	I2	I1	I1	2	1	1
163	Test/Checkout/Calibration Instrumentation	*		0.200	70.0	500	I1	A1	A2	3	2	3
165	Experiment Control Computer System	*		0.050	20.0	400	I1	S3	A2	3	1	2
167	Voice Recorder	*	*	0.003	0.3	0	A2	S3	A1	2	1	2
168	Closed Ecological Life Support System Test Facility	*		1.920	1000.0	1300	I2	I1	I1	2	1	1
169	Gas Grain Simulator	*		1.920	800.0	1500	I1	A2	A3	4	3	1

3.5 TABLE III - SBI REALISTIC TARGET & MAXIMUM TECHNOLOGY ESTIMATES

SBI#	HARDWARE IDENTIFICATION -HW ITEM NAME	SBI REALISTIC TARGET LVL-ByDomain DataPhysSyst	SBI REALISTIC TARGET TRNG %Cw KnwSklTim	MAX AVAIL TECHNOLOGY LVL-ByDomain DataPhysSyst	MAX AVAIL TECHNOLOGY TRNG %Cw KnwSklTim
16	Animal Tissue Biopsy Equipment	M3 M3 M3	3 4 5	S3 S3 S3	2 2 4
17	Blood Collection System	M3 S2 S1	2 3 5	S3 S2 S2	1 2 4
22	Electrofusion Device	A2 A1 A1	2 2 3	I1 I2 I1	1 1 1
23	Fixation Unit	A3 A2 A2	3 2 2	I2 I1 I1	2 1 1
28	Muscle Biopsy Equipment	M3 M3 M3	3 3 5	S3 A2 A1	3 2 4
29	Perfusion and Fixation Unit	A3 A2 A2	3 2 2	I2 I1 I1	2 1 1
30	Plant Care Unit	I1 A3 A3	2 1 1	I3 I2 I2	1 1 1
31	Plant Harvest/Dissection Unit	S3 S1 S2	2 2 4	I1 A3 A3	1 2 3
33	Saliva Collection Unit	M3 M3 M3	1 1 5	M3 M3 M3	1 1 5
34	Sample Preparation Device	I1 A3 A3	3 2 2	I2 I2 I2	1 1 1
38	Sweat Collection Device	A2 S3 A1	1 1 2	A3 A1 A2	1 1 1
39	CO2 Administration Device	S1 S3 S2	2 2 1	A3 A3 A3	1 1 1
40	Rodent Blood Collection System	M3 S2 S1	2 3 5	S3 S2 S2	1 2 4
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S1 M3 M3	1 3 2	S2 S2 S2	1 2 1
42	Rodent Guillotine	M3 S1 M3	2 2 5	S2 S3 S2	2 1 3
43	Rodent Restraint	S1 S1 S1	2 3 3	A1 S3 S3	2 2 2
44	Rodent Surgery Platform	S1 M3 M3	2 2 2	S3 A2 A1	2 1 2
45	Rodent Surgery/Dissection Unit	M1 M2 M1	5 5 5	M2 S2 M3	4 4 5
46	Rodent Urine Collection System	M3 M2 M2	2 3 5	S1 M3 M3	2 2 5
47	Rodent Veterinary Unit	M2 S2 M3	4 3 4	S2 S3 S2	3 3 4
48	Primate Blood Collection System	M3 S2 S1	2 3 5	S3 S2 S2	1 2 4
49	Primate Handling Equipment	S1 M3 M3	2 2 3	S3 S3 S3	2 2 2
50	Primate Lower Body Negative Pressure (LBNP) Device	S1 M3 M3	2 2 2	S1 S1 S1	2 1 2
51	Primate Surgery Platform	S1 M3 M3	2 2 2	S2 A1 S3	2 1 2
52	Primate Surgery/Dissection Unit	M1 M2 M1	5 5 5	M2 S2 M3	4 4 5
53	Primate Urine Collection System	M3 M2 M2	2 3 5	S1 M3 M3	2 2 5
54	Primate Veterinary Unit	M2 S1 M3	4 3 4	S2 S3 S2	3 3 4
55	Small Primate Restraint	S1 M3 M3	2 3 3	S3 S3 S3	2 2 2
56	Bag Assembly	M3 M3 M3	1 1 1	M3 M3 M3	1 1 1
57	Bag-in-Box	S2 A1 S3	1 1 1	S2 A1 S3	1 1 1
59	Electronics Control Assembly	S3 A1 S3	2 1 1	A1 A1 A1	2 1 1
60	Mask/Regulator System	S1 S1 S1	1 1 1	S1 S1 S1	1 1 1
61	Mass Spectrometer	I1 A3 A3	2 1 1	I2 I2 I2	2 1 1
62	Pulmonary Function Equipment Stowage Assembly	M2 M3 M2	1 1 1	M2 M3 M2	1 1 1
63	Pulmonary Gas Cylinder Assembly	A1 A1 A1	2 2 1	A1 A2 A1	2 1 1
64	Rebreathing Assembly	M3 S3 S1	2 1 1	S1 S3 S2	1 1 1
65	Spirometry Assembly	A1 S2 S3	2 1 1	A2 S2 S3	1 1 1
66	Syringe (3 Liter Calibration)	M3 M2 M2	1 1 5	S1 S1 S1	1 1 1
67	Accelerometer and Recorder	I1 S3 A2	2 1 1	I1 A1 A2	1 1 1
68	Anthropometric Measurement System	S1 S1 S1	2 3 4	A3 S3 A1	2 1 3
70	Compliance Volumometer	A2 S2 S3	1 3 5	A3 A3 A3	1 2 4
71	Electroencephalomegnetogram (EEMG)	I1 S2 A1	3 3 1	I2 S3 A2	2 2 1
74	Force Resistance System	I1 A1 A2	2 2 2	I1 A3 A3	2 1 2
75	Fundus Camera	A2 S1 S3	2 2 4	I1 S3 A2	1 1 4
77	Hard Tissue Imaging System	I1 A1 A2	4 2 3	I2 I1 I1	2 1 2
78	Mass Calibration Unit	M3 M3 M3	1 1 5	M3 M3 M3	1 1 5
82	Motion Analysis System	I1 A1 A2	2 1 3	I2 I1 I1	1 1 1

TABLE III - SBI REALISTIC TARGET & MAXIMUM TECHNOLOGY ESTIMATES

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	SBI REALISTIC TARGET LVL-ByDomain DataPhysSyst		TRNG KnwSklTim			%Cw	MAX AVAIL TECHNOLOGY LVL-ByDomain DataPhysSyst		TRNG KnwSklTim			%Cw
83	Plethysmograph Measuring System	A3	A2	A2	3	2	4	I2	I1	I1	2	1	3
84	Soft Tissue Imaging System	I1	A1	A2	4	2	3	I2	I1	I1	2	1	2
85	Tonometer	A2	A1	A1	2	1	5	I1	A3	A3	2	1	3
87	EEG Cap	A3	M3	S3	2	2	1	I1	S2	A1	1	2	1
88	EEG Signal Conditioner	A2	S1	S3	2	1	1	I1	S3	A2	1	1	1
98	Visual Tracking System	A3	A1	A2	2	2	4	I2	I1	I1	1	1	1
99	Animal Biotelemetry System	A2	M3	S2	2	2	1	I1	S2	A1	1	2	1
100	Blood Pressure and Flow Instrumentation	A2	M3	S2	2	2	5	I1	S2	A1	1	2	4
101	Cardiodynamic Monitor	A3	S2	A1	2	2	3	I1	S3	A2	1	1	2
102	Electrocardiograph (ECG)	A3	S1	S3	2	2	3	I2	S3	A2	1	1	2
103	Holter Recorder	A2	A1	A1	2	1	1	A3	A1	A2	1	1	1
106	Neck Baro-Cuff	A2	A1	A1	2	2	1	A3	A2	A2	1	2	1
109	Venous Pressure Transducer/Display	A3	M2	S2	2	2	2	I1	S1	A1	1	1	1
110	Plant Gas Chromatograph/Mass Spectrometer	I1	A3	A3	3	1	2	I2	I2	I2	2	1	1
111	Plant Gas Cylinder Assembly	A1	A3	A2	2	2	1	A3	A3	A3	1	2	1
112	Plant HPLC Ion Chromatograph	I1	A2	A3	3	1	2	I2	I2	I2	2	1	1
113	Blood Gas Analyzer	A3	A3	A3	3	1	2	I2	I2	I2	2	1	1
115	Chemistry System	I1	A1	A2	3	2	2	I2	I2	I2	2	1	1
116	Continuous Flow Electrophoresis Device	I1	A3	A3	2	2	2	I2	I2	I2	2	1	1
119	Gas Cylinder Assembly	A2	S3	A1	2	2	1	A3	A3	A3	1	2	1
124	Qualitative Reagent Strip and Reader	I1	S3	A2	2	1	1	I2	I2	I2	2	1	1
126	Scintillation Counter	I1	A3	A3	2	2	2	I2	I2	I2	2	1	1
129	Cell Handling Accessories	A3	A2	A2	2	3	4	I1	I2	I1	1	1	1
130	Cell Harvester	I1	A3	A3	1	1	2	I2	I2	I2	1	1	1
131	Cell Perfusion Apparatus	I1	A3	A3	1	1	2	I2	I2	I2	1	1	1
134	Centrifuge Hematocrit	S3	S2	S2	2	1	3	A3	A3	A3	1	1	1
135	Chromosomal Slide Prep Device	I1	A3	A3	2	1	2	I2	I2	I2	2	1	1
136	Fluoromeasure Probe	I1	A3	A3	3	2	4	I2	I2	I2	2	1	1
138	Hematology System	A3	A3	A3	3	2	2	I1	I1	I1	2	1	1
139	Image Digitizing System	I1	A1	A2	3	2	2	I2	I2	I2	2	1	1
142	Skin Window Device	M3	A1	S2	2	1	5	S1	A2	S3	1	1	3
145	Automated Microbic System (AMS)	I1	A3	A3	3	2	2	I2	I2	I2	1	1	1
147	Head/Torso Phantom	S1	M3	M3	1	2	1	A1	S1	S2	1	1	1
149	Microbial Preparation System	I1	A3	A3	3	2	2	I2	I2	I2	1	1	1
151	Reuter Microbiology Air Sampler	M3	S1	M3	1	1	5	S1	S1	S1	1	1	2
152	Solid Sorbent Air Sampler	S1	S1	S1	1	1	5	A1	A1	A1	1	1	2
153	Spectrometer (Proton/Heavy Ion)	I1	A3	A3	3	1	2	I2	I2	I2	2	1	1
154	Tissue Equivalent Proportional Counter	I1	A3	A3	2	2	2	I2	I2	I2	1	1	1
155	Total Hydrocarbon Analyzer	I1	A3	A3	2	1	2	I2	I2	I2	2	1	1
161	Inventory Control System	I2	I1	I1	2	1	1	I3	I2	I2	1	1	1
162	Lab Materials Packaging and Handling Equipment	I2	I1	I1	2	1	1	I3	I2	I2	1	1	1
163	Test/Checkout/Calibration Instrumentation	I1	A1	A2	3	2	3	I2	A3	I1	2	2	2
165	Experiment Control Computer System	I2	S3	A2	2	1	1	I3	A1	A3	2	1	1
167	Voice Recorder	A2	S3	A1	2	1	2	A3	A3	A3	2	1	2
168	Closed Ecological Life Support System Test Facility	I2	I1	I1	2	1	1	I2	I2	I2	1	1	1
169	Gas Grain Simulator	I1	A2	A3	4	2	1	I2	I1	I1	3	2	1

3.6 SBI Hardware Functional Groups

GROUP 1 - BIOLOGICAL SPECIMEN SUPPORT

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT LVL-ByDomain Data	Phys	Syst	REALISTIC LVL-ByDomain Data	Phys	Syst	MAX AVAIL LVL-ByDomain Data	Phys	Syst
30	Plant Care Unit	0.050	10.0	50	I1	A3	A3	I1	A3	A3	I3	I2	I2
39	CO2 Administration Device	0.010	3.0	0	S1	S3	S2	S1	S3	S2	A3	A3	A3
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	0.010	2.0	50	S1	M3	M3	S1	M3	M3	S2	S2	S2
42	Rodent Guillotine	0.010	4.0	0	M3	S1	M3	M3	S1	M3	S2	S3	S2
43	Rodent Restraint	0.010	3.0	0	S1	S1	S1	S1	S1	S1	A1	S3	S3
44	Rodent Surgery Platform	0.010	3.0	0	S1	M3	M3	S1	M3	M3	S3	A2	A1
45	Rodent Surgery/Dissection Unit	0.010	3.0	0	M1	M2	M1	M1	M2	M1	M2	S2	M3
47	Rodent Veterinary Unit	0.030	10.0	0	M2	S1	M3	M2	S1	M3	S2	S3	S2
49	Primate Handling Equipment	0.010	1.0	0	S1	M3	M3	S1	M3	M3	S3	S3	S3
50	Primate Lower Body Negative Pressure (LBNP) Device	0.050	3.0	140	S1	M3	M3	S1	M3	M3	S1	S1	S1
51	Primate Surgery Platform	0.040	5.0	0	S1	M3	M3	S1	M3	M3	S2	A1	S3
52	Primate Surgery/Dissection Unit	0.020	5.0	0	M1	M2	M1	M1	M2	M1	M2	S2	M3
54	Primate Veterinary Unit	0.030	10.0	0	M2	S1	M3	M2	S1	M3	S2	S3	S2
55	Small Primate Restraint	0.050	2.0	0	S1	M3	M3	S1	M3	M3	S3	S3	S3
106	Neck Baro-Cuff	0.132	45.2	145	A2	A1	A1	A2	A1	A1	A3	A2	A2
	TOTAL	0.47	109.2	385									

GROUP 2 - PHYSIOLOGICAL MEASUREMENT/MONITORING

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT LVL-ByDomain Data	Phys	Syst	REALISTIC LVL-ByDomain Data	Phys	Syst	MAX AVAIL LVL-ByDomain Data	Phys	Syst
56	Bag Assembly	0.010	1.0	0	M3	M3	M3	M3	M3	M3	M3	M3	M3
57	Bag-in-Box	0.150	19.0	0	S2	A1	S3	S2	A1	A3	S2	A2	S3
59	Electronics Control Assembly	0.080	13.0	100	S3	A1	S3	S3	A1	S3	A1	A1	A1
60	Mask/Regulator System	0.010	3.0	30	S1	S1	S1	S1	S1	S1	S1	S1	S1
62	Pulmonary Function Equipment Stowage Assembly	0.051	20.0	0	M2	M3	M2	M2	M3	M2	M2	M3	M2
63	Pulmonary Gas Cylinder Assembly	0.090	30.0	0	A1	A1	A1	A1	A1	A1	A1	A2	A1
64	Rebreathing Assembly	0.020	1.0	0	M3	S3	S1	M3	S3	S1	S1	S3	S2
65	Spirometry Assembly	0.010	1.0	0	S3	S2	S2	A1	S2	S3	A2	S2	S3
66	Syringe (3 Liter Calibration)	0.010	2.0	0	M3	M2	M2	M3	M2	M2	S1	S1	S1
67	Accelerometer and Recorder	0.040	16.1	35	A3	S3	A1	I1	S3	A2	I1	A1	A2
68	Anthropometric Measurement System	0.020	1.0	0	M2	M2	M2	S1	S1	S1	A3	S3	A1
70	Compliance Volumometer	0.015	16.0	130	A1	S1	S2	A2	S2	S3	A3	A3	A3
71	Electroencephalomagnetogram (EEMG)	0.060	2.0	TBD	A3	S2	A1	I1	S2	A1	I2	S3	A2
74	Force Resistance System	0.400	70.0	220	A2	S3	A1	I1	A1	A2	I1	A3	A3
75	Fundus Camera	0.003	2.0	0	S3	M3	S1	A2	S1	S3	I1	S3	A2
77	Hard Tissue Imaging System	0.290	136.0	300	I1	A1	A2	I1	A1	A2	I2	I1	I1
82	Motion Analysis System	0.050	20.0	100	A3	S3	A1	I1	S3	A2	I2	A2	A3
83	Plethysmograph Measuring System	0.010	3.0	30	A3	A2	A2	A3	A2	A2	I2	I1	I1
84	Soft Tissue Imaging System	0.960	300.0	800	I1	A1	A2	I1	A1	A2	I2	I1	I1
85	Tonometer	0.000	0.1	0	A2	A1	A1	A2	A1	A1	I1	A3	A3
87	EEG Cap	0.010	2.0	0	A2	M2	S2	A3	M3	S3	I1	S2	A1
88	EEG Signal Conditioner	0.010	2.0	0	A1	M3	S2	A2	S1	S3	I1	S3	A2
98	Visual Tracking System	0.010	2.0	20	A3	A1	A2	A3	A1	A2	I2	I1	I1
99	Animal Biotelemetry System	0.050	20.0	100	A2	M3	S2	A2	M3	S2	I1	S2	A1
100	Blood Pressure and Flow Instrumentation	0.060	20.0	200	A2	M3	A1	A2	M2	S2	I1	S1	A1
101	Cardiodynamic Monitor	0.020	4.0	150	A3	S2	A1	A3	S2	A1	I1	S3	A2
102	Electrocardiograph (ECG)	0.010	2.0	20	A3	S1	S3	A3	S1	S3	I2	S3	A2
103	Holter Recorder	0.010	2.0	0	A2	A1	A1	A2	A1	A1	A3	A1	A2
109	Venous Pressure Transducer/Display	0.050	20.0	100	A3	M2	S2	A3	M2	S2	I1	S1	A1
139	Image Digitizing System	0.030	11.4	500	I1	A1	A2	I1	A1	A2	I2	I2	I2
147	Head/Torso Phantom	0.120	32.0	0	M2	M2	M2	M2	M3	M2	M2	M3	M2
154	Tissue Equivalent Proportional Counter	0.001	2.0	0	I1	A3	A3	I1	A3	A3	I2	I2	I2
TOTAL		2.66	775.52	2835									

GROUP 3 - CHEMISTRY SYSTEMS

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT LVL-ByDomain Data	Phys	Syst	REALISTIC LVL-ByDomain Data	Phys	Syst	MAX AVAIL LVL-ByDomain Data	Phys	Syst
61	Mass Spectrometer	0.087	40.7	200	A3	A3	A3	I1	A3	A3	I2	I2	I2
110	Plant Gas Chromatograph/Mass Spectrometer	0.200	25.0	100	I1	A3	A3	I1	A3	A3	I2	I2	I2
111	Plant Gas Cylinder Assembly	0.090	19.0	0	A1	A3	A2	A1	A3	A2	A3	A3	A3
112	Plant HPLC Ion Chromatograph	0.120	40.0	200	I1	A2	A3	I1	A2	A3	I2	I2	I2
113	Blood Gas Analyzer	0.130	45.0	250	A3	A3	A3	A3	A3	A3	I2	I2	I2
115	Chemistry System	0.080	23.0	100	A3	S3	A1	I1	A1	A2	I2	I2	I2
116	Continuous Flow Electrophoresis Device	0.060	TBD	TBD	A3	I1	A3	I1	A3	A3	I2	I2	I2
119	Gas Cylinder Assembly	0.090	19.0	0	A2	S3	A1	A2	S3	A1	A3	A3	A3
124	Qualitative Reagent Strip and Reader	0.030	10.0	100	S3	S3	S3	A3	S3	A1	I2	I2	I2
126	Scintillation Counter	0.240	90.0	500	A3	A3	A3	I1	A3	A3	I2	I2	I2
134	Centrifuge Hematocrit	0.010	2.0	0	S2	S2	S2	S3	S2	S2	A3	A3	A3
136	Fluoromeasure Probe	0.050	TBD	TBD	I1	A3	A3	I1	A3	A3	I2	I2	I2
138	Hematology System	0.070	23.0	200	A3	A3	A3	A3	A3	A3	I1	I1	I1
145	Automated Microbic System (AMS)	0.200	70.0	110	I1	S3	A2	I1	S3	A2	I2	I2	I2
153	Spectrometer (Proton/Heavy Ion)	0.030	10.0	20	A3	A2	A2	I1	A3	A3	I2	I2	I2
155	Total Hydrocarbon Analyzer	0.200	70.0	250	I1	A3	A3	I1	A3	A3	I2	I2	I2
	TOTAL	1.69	486.7	2030									

GROUP 4 - MATERIAL PREPARATION AND HANDLING

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT LVL-ByDomain Data	Phys	Syst	REALISTIC LVL-ByDomain Data	Phys	Syst	MAX AVAIL LVL-ByDomain Data	Phys	Syst
16	Animal Tissue Biopsy Equipment	0.030	8.0	0	M3	M3	M3	M3	M3	M3	S3	S3	S3
17	Blood Collection System	0.020	1.0	0	M3	S2	S1	M3	S2	S1	S3	S2	S2
22	Electrofusion Device	0.060	TBD	TBD	S2	S2	S2	A2	A1	A1	I1	I2	I1
23	Fixation Unit	0.020	4.0	0	A3	A2	A2	A3	A2	A2	I2	I1	I1
28	Muscle Biopsy Equipment	0.010	1.0	0	M3	M3	M3	M3	M3	M3	S3	S3	S3
29	Perfusion and Fixation Unit	0.010	2.0	0	A3	A2	A2	A3	A2	A2	I2	I1	I1
31	Plant Harvest/Dissection Unit	0.010	4.0	20	S3	S1	S2	S3	S1	S2	I1	A3	A3
33	Saliva Collection Unit	0.001	0.2	0	M3	M3	M3	M3	M3	M3	M3	M3	M3
34	Sample Preparation Device	0.170	22.0	150	I2	I1	I1	I1	A3	A3	I2	I2	I2
38	Sweat Collection Device	0.005	5.1	15	A1	S2	S3	A2	S3	A1	A3	A3	A3
40	Rodent Blood Collection System	0.030	10.0	50	M3	S2	S1	M3	S2	S1	S3	S2	S2
46	Rodent Urine Collection System	0.030	10.0	50	M3	M2	M2	M3	M2	M2	S1	M3	M3
48	Primate Blood Collection System	0.050	2.0	140	M3	S2	S1	M3	S2	S1	S3	S2	S2
53	Primate Urine Collection System	0.010	10.0	14	M3	M2	M2	M3	M2	M2	S1	M3	M3
129	Cell Handling Accessories	0.050	20.0	50	A3	A2	A2	A3	A2	A2	I1	I2	I1
130	Cell Harvester	0.060	19.0	50	A3	A3	A3	I1	A3	A3	I2	I2	I2
131	Cell Perfusion Apparatus	0.060	TBD	TBD	A3	A3	A3	I1	A3	A3	I2	I2	I2
135	Chromosomal Slide Prep Device	0.010	2.0	20	A3	A3	A3	I1	A3	A3	I2	I2	I2
142	Skin Window Device	0.010	2.0	0	M3	S3	S1	M3	A1	S2	S1	A1	S3
149	Microbial Preparation System	0.010	2.0	110	I2	I1	I1	I1	A3	A3	I2	I2	I2
151	Reuter Microbiology Air Sampler	0.005	1.5	0	M3	S1	M3	M3	S1	M3	M3	S1	M3
152	Solid Sorbent Air Sampler	0.010	5.0	0	S1	S1	S1	S1	S1	S1	A1	A1	A1
	TOTAL	0.67	130.7	669									

GROUP 5 - LARGE SCALE TEST FACILITIES

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT LVL-ByDomain DataPhysSyst			REALISTIC LVL-ByDomain DataPhysSyst			MAX AVAIL LVL-ByDomain DataPhysSyst		
168	Closed Ecological Life Support System (CELSS) Facility	1.920	1000.0	1300	I2	I1	I1	I2	I1	I1	I2	I2	I2
169	Gas Grain Simulator	1.920	800.0	1500	I1	A2	A3	I1	A2	A3	I2	I1	I1
	TOTAL	3.84	1800.0	2800									

GROUP 6 - SBI FACILITY SUPPORT EQUIPMENT

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT LVL-ByDomain Data	Phys	Syst	REALISTIC LVL-ByDomain Data	Phys	Syst	MAX AVAIL LVL-ByDomain Data	Phys	Syst
78	Mass Calibration Unit	0.01	2	0	M3	M3	M3	M3	M3	M3	M3	M3	M3
161	Inventory Control System	0.2	70	500	I2	I1	I1	I2	I1	I1	I3	I2	I2
162	Lab Materials Packaging and Handling Equipment	0.2	70	500	I2	I1	I1	I2	I1	I1	I3	I2	I2
163	Test/Checkout/Calibration Instrumentation	0.2	70	500	I1	A1	A2	I1	A1	A2	I2	A3	I1
165	Experiment Control Computer System	0.05	20	400	I1	S3	A2	I1	S3	A2	I3	A1	A3
167	Voice Recorder	0.003	0.26	0	A2	S3	A1	A2	S3	A1	A3	A3	A3
	TOTAL	0.663	232.26	1900									

3.7 Automation Range of SBI hardware

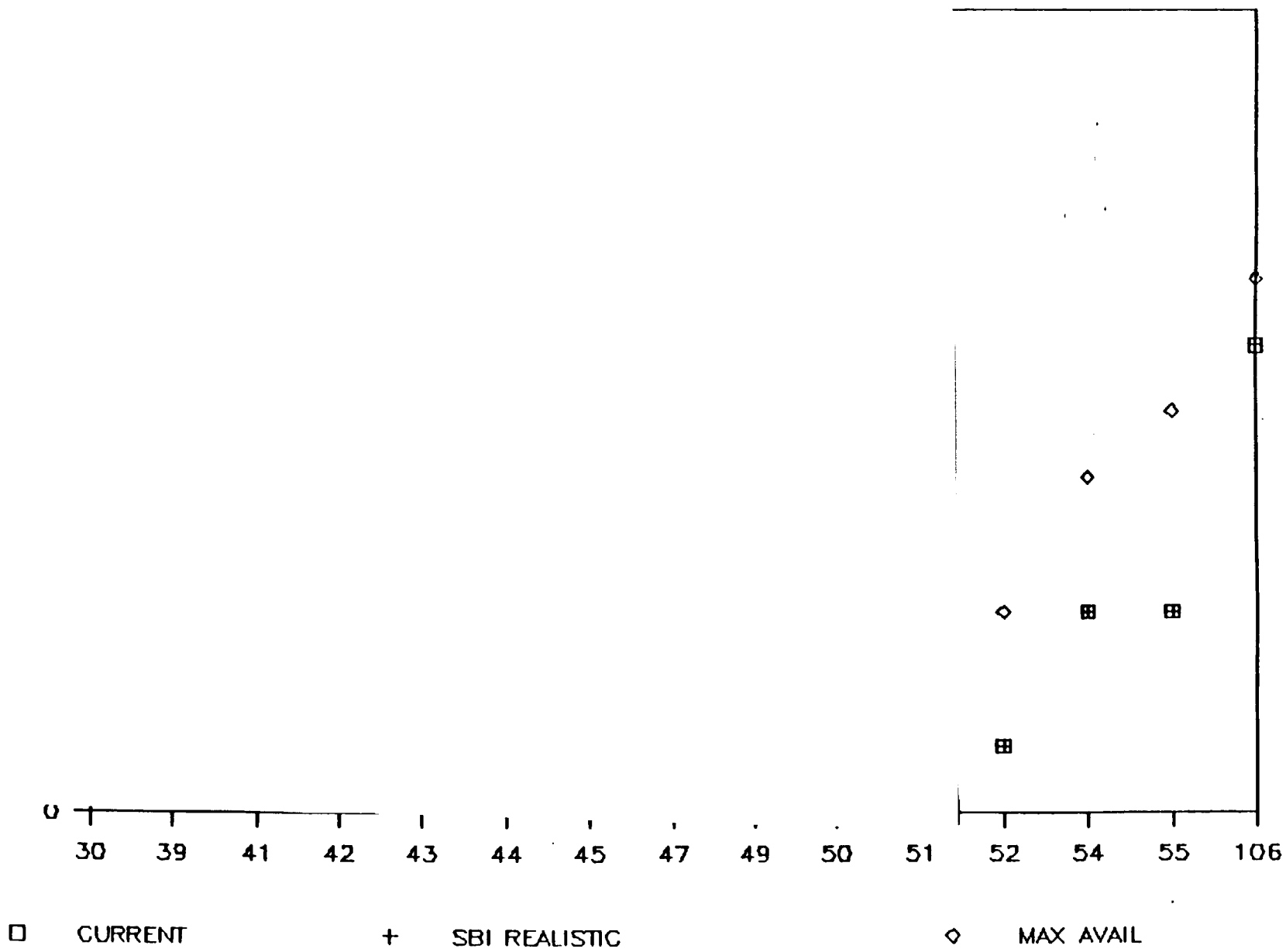
The following graphs show the range of possible automation level that an SBI hardware item can progress to. This is based on the information in sections 3.4 and 3.5. The range of possible automation level is defined as the range between the current level of automation and the maximum possible level of automation for the hardware item in question. The range of possible automation levels is graphically represented for the items of each functional group. The legend "**Current**" stands for current level of automation. The legend "**SBI Realistic**" stands for the level of automation that is technologically possible for the SBI program. The legend "**Max Avail**" stands for the maximum level of automation that is technologically possible in a terrestrial environment.

The following convention is used for the horizontal and vertical axis of the graphs presented in this section:

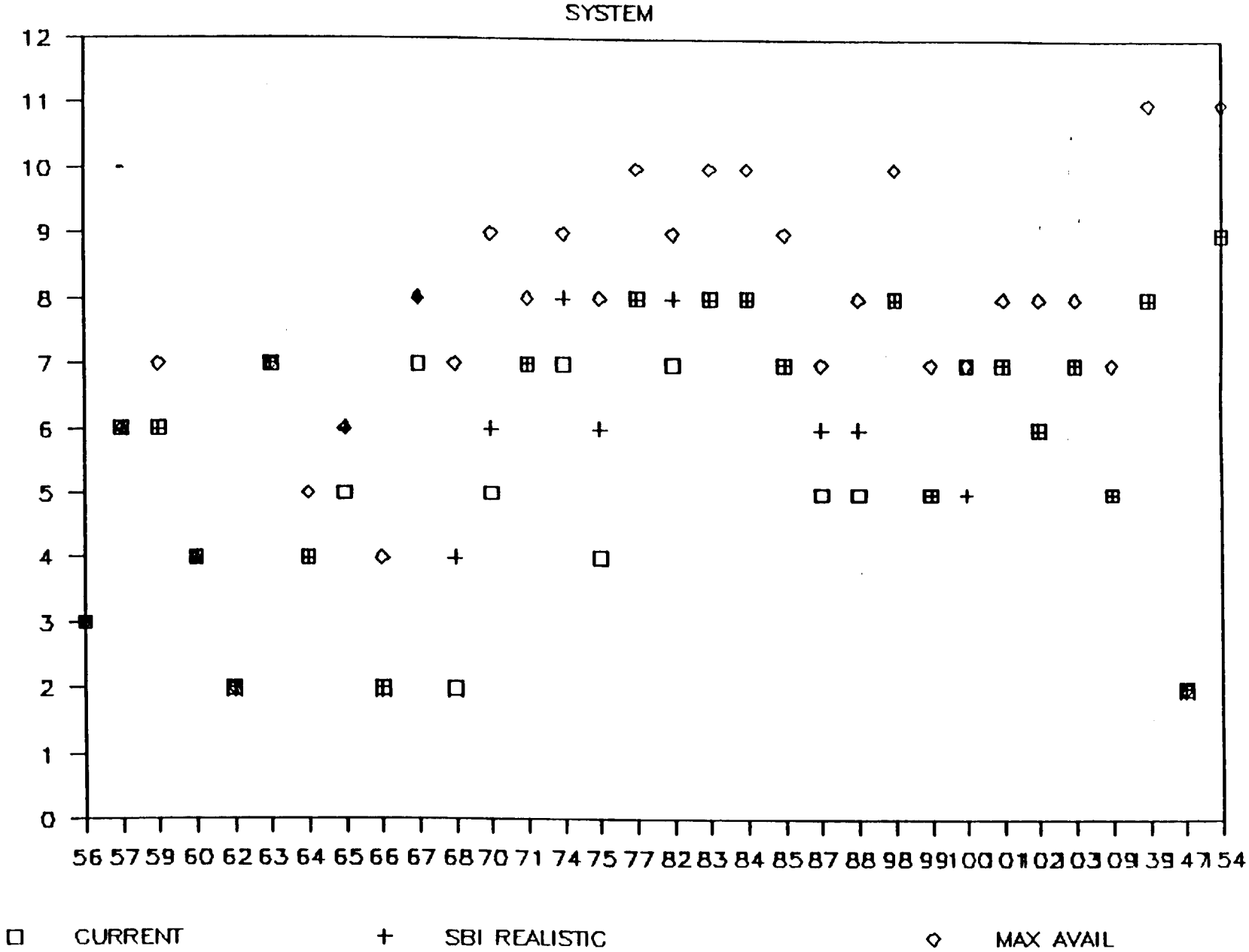
Horizontal Axis: The hardware unit number as assigned in reference 3.

Vertical Axis:
0 represents the automation level M1
1 represents the automation level M2
2 represents the automation level M3
3 represents the automation level S1
4 represents the automation level S2
5 represents the automation level S3
6 represents the automation level A1
7 represents the automation level A2
8 represents the automation level A3
9 represents the automation level I1
10 represents the automation level I2
11 represents the automation level I3

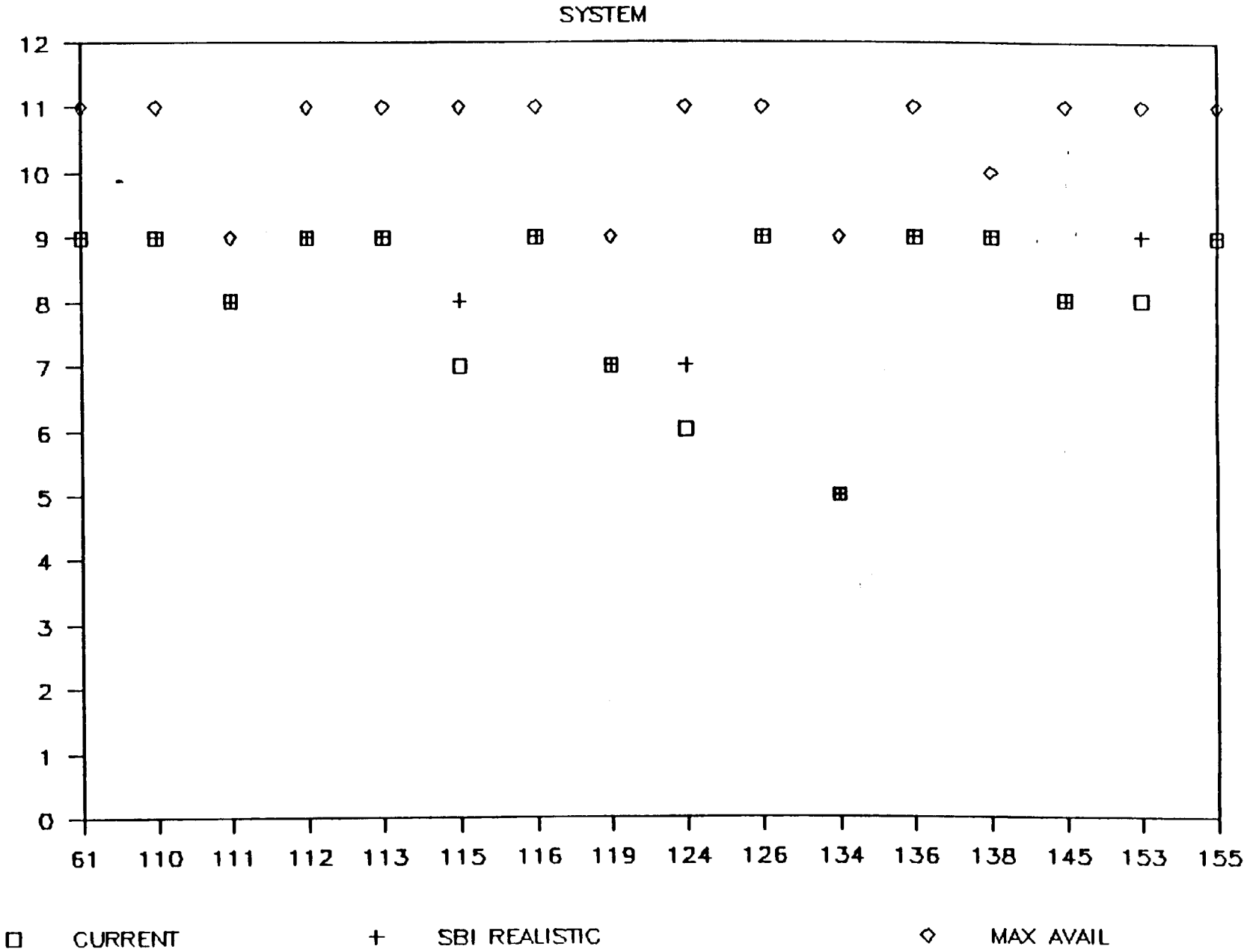
CLASS 1 — BIOLOGICAL SPECIMEN SUPPORT



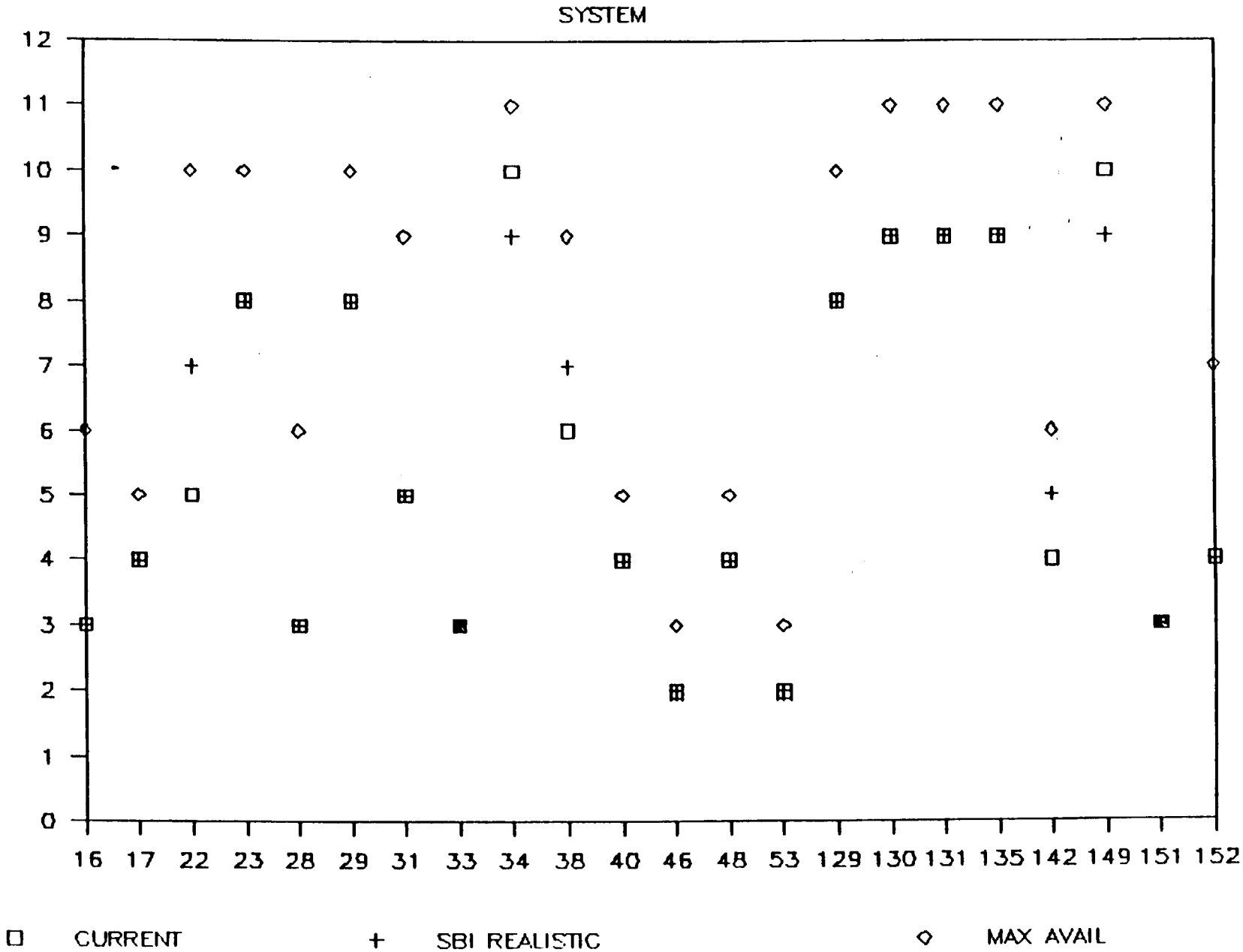
CLASS 2 – PHYSIOLOGICAL MEASURE/MONITOR



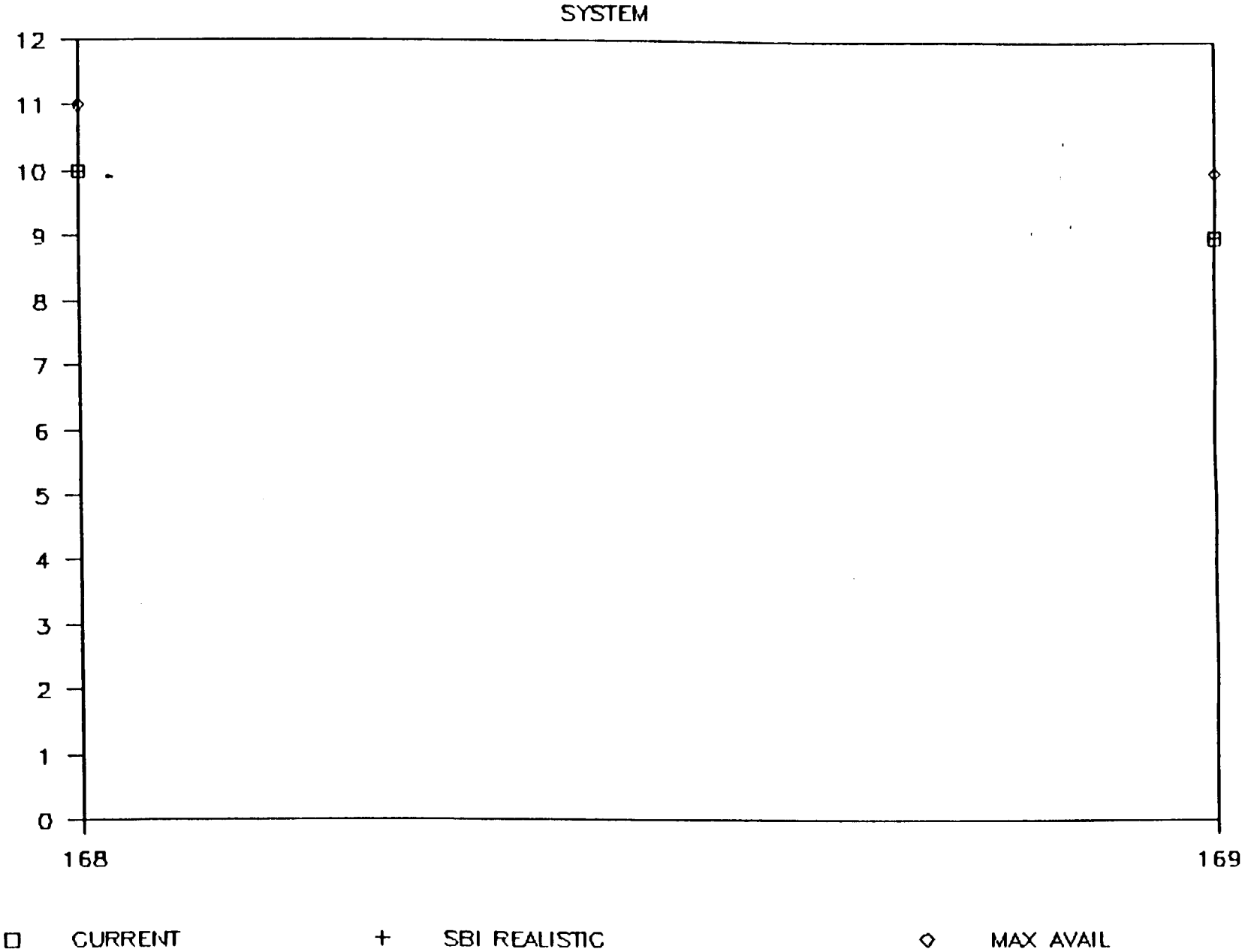
CLASS 3 – CHEMISTRY SYSTEMS



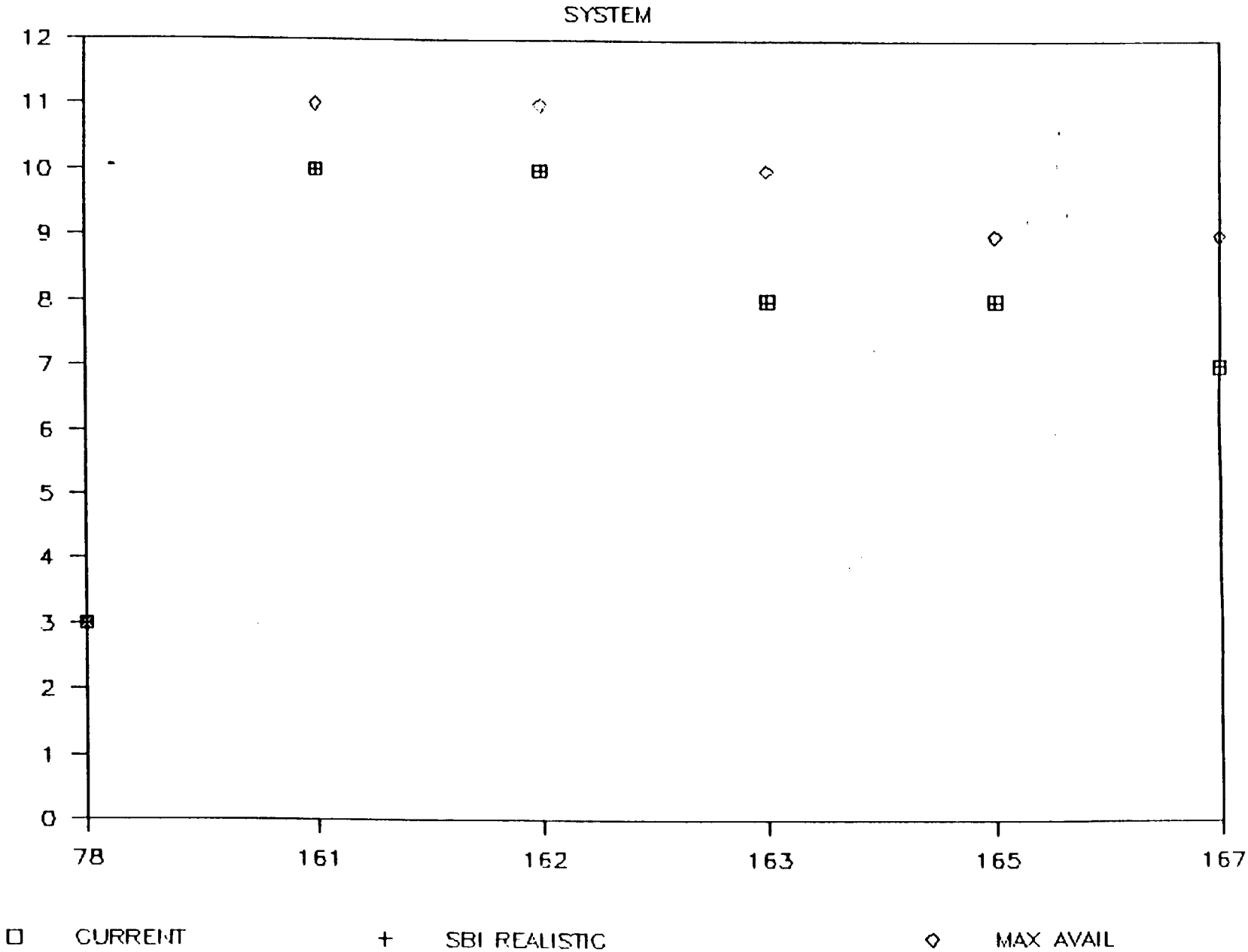
CLASS 4 – MAT'L PREP AND HANDLING



CLASS 5 – LARGE SCALE TEST FACILITIES



CLASS 6 – SBI FACILITY SUPPORT EQUIP



4.0 Summary of Results

The following section presents a summary of the main findings of our automation - crew utilization analysis. It was found that all the SBI hardware items can be grouped into six main functional groups. Each hardware item can be broken down into five main generic components, all of which directly influence the total cost of the equipment. Several trends in the increase/decrease of these generic component units as a function of the automation level was presented in matrix form for each of the functional groups. The cost matrices constitute the cost model. As a result of automation, five main mission benefits were also identified. A benefit model was developed in a similar way to the cost model. The proposed methodology can be used to determine the most cost effective automation level for a particular hardware item.

4.1 Identification of SBI Hardware Candidates for Automation

Section 2.2 identified various rules of thumb that can be used to determine SBI candidates suitable for automation. An SBI hardware item with the following characteristics should be considered for automation:

o High range of possible progressive levels of automation between the current and SBI realistic level of automation (section 2.2.7).

o High crew training time (section 2.2.4).

o High crew utilization index (section 2.2.5)

o Highly structured task process because a structured process is more suitable to automation than an unstructured one.

o A low automation level in the data domain, since it is easier to increase the automation level of the data domain as compared to the physical domain.

Although hardware items which belong to the M level of automation do possess many of the above characteristics, it is not necessarily cost effective to automate those items. The main reason being the total cost to automate will outweigh the benefits gained and/or the technology does not exist to increase the level of automation at this time. However, if cost-effective automation technology does become available at a future point, then they should be considered for automation.

The analysis shows that it is most beneficial to automate hardware items which belong to the S level and lower A level of automation because the appropriate technology is available, to maximize the gained benefits. Thus, the return on investment appears to be most optimal.

It is not cost effective to automate hardware items in the upper A and I levels of automation because of the saturation effect shown in section 2.3.3.

4.2 Cost Impact Analysis

4.2.1 Crew Utilization

In this study, we have defined a crew utilization index that relates to the crew utilization. In the benefit model of section 2.3.3, the cost impact of crew utilization was determined by the crew involvement time. Our assumption was based on the fact that a low crew involvement time would imply that the crew member can perform a wider selection of tasks, thus increasing the crew utilization factor. The cost impact of automation on crew utilization can not directly be related to $ savings. However, lowering crew involvement time will result in higher efficiency in mission accomplishments.

The hardware items in the biological specimen support group, with the exception of the surgery/dissection units, are fairly automated and thus have an average crew involvement time of 20% to 40%. As the level of automation is increased from a M level to a S level, the crew involvement time is reduced by a factor of 2. Increasing the level of automation from a S level to A level further reduces the cost of crew involvement by a factor of 2. Reducing the crew involvement time directly relates to a cost savings for the mission.

Hardware items in the physiological measurement/monitoring group as well as that of the chemistry group both show the same cost trend for crew utilization. Since these items have a medium - high automation index, the reduction in crew involvement time for increasing automation from a S level to an A level of automation is only 0.6 as compared to a factor of 2 for the hardware items of the biological specimen support group.

Hardware items in the preparation and handling group, the large scale test facilities and the SBI facility support equipment group on the average have a higher level of automation than hardware items in other groups. The reduction in crew involvement time for increasing the level of automation from a S level to an A level is 0.3.

To summarize the above observations, the higher the current level of automation, the lower the reduction in crew utilization time. The optimum ratio of level of automation to crew involvement reduction is in the biological specimen support group.

4.2.2 Crew Training

In section 2.2.4, rules of thumb were presented to quantify crew training by scoring hardware items from 1 to 5. The score 1 implies a requirement for a low level of training effort. The score 5 implies a requirement for a high level of training. Conceptually training consists of knowledge education and skill experience. Increasing automation enables the more complex tasks to be performed by the machine, resulting in lowering training demands on the crew, which in turn results in cost savings for the mission. Thus automation has a direct cost impact on crew training.

For the SBI hardware items, automation has either decreased the knowledge education or decreased the skill experience. It was found that 80% of the hardware items belonged to the class in which automation was cost beneficial in reducing the knowledge education while only 20% of the items belonged to the class in which automation reduced the skill experience. It is easier to reduce the knowledge education using menu driven software and expert systems then it is to reduce skill experience. The reason for this imbalance is mainly because the majority of the items have a medium/high percentage of electronics and software components. A reduction of skill experience requires material handling mechanisms such as transport networks and robotics. In addition, reduction of skill training will require design changes, which is more expensive than software enhancements. Therefore it is more cost effective to reduce the knowledge education requirements than it is to reduce the skill experience.

4.2.3 In-orbit Repair and Maintenance

In-orbit repair and maintenance capabilities are extremely important to reduce equipment downtime to a minimum. Downtime is defined as the time during which the equipment is not functional due to malfunctioning parts. The cost impact of automation on in-orbit repair and maintenance can not directly be measured in terms of $ savings for the mission. However, in-orbit repair will inevitably contribute to a higher dependability of the equipment.

Expert systems that will tutor a crew member in the event of a failure of a particular hardware item is the most obvious choice of automation to ensure minimum machine downtime. These expert systems may be stored on optical disks and archived on the space station or transferred via communication link between ground and mission. It is impossible for crew members to learn to diagnose all problems for each and every hardware item. Therefore, expert systems must definitely be considered for in-orbit diagnostics, maintenance and repair. The space station must also include a utility for retrieval of spare parts to repair a hardware item. An extensive storage of spare parts is improbable because of space constraints. However, those spare parts with low MTBF (mean time between failure) values should be stocked in the space station. Given a large number of common parts, a strictly controlled parts cannibalization program under the direction of a suitably designed expert system should be considered.

4.2.4 Equipment Accuracy

Equipment accuracy is the foundation for successful quality results of the experiments performed for the SBI. Since the experiments are carefully selected and each experiment is allocated a fixed duration of time and resources, experiment repetition due to equipment inaccuracy will result in a lower mission efficiency. The process of checking equipment accuracy is fairly structured as well as time consuming for most hardware items. Therefore, checking and enhancing equipment accuracy can be easily automated.

4.2.5 Productivity

All the mission benefits described in section 2.3.3 equate to increased mission productivity. For most of the hardware items in the SBI list, the crew productivity increases by a factor of 2 when the automation level is increased from a M level to a S level. When the automation level is increased from a S level to an A level, the average increase in factor of crew productivity is also 2. However, if the level of automation is increased from an A level to an I level, then crew productivity is only increased by a factor of 1.25. This is due to the saturation effect resulting from increased automation.

5.0 Problem areas

The main problems that we were faced with during this study are the following:

o . The level of detail to which the hardware items are identified in reference 4 is not consistent for every hardware item. Therefore it was difficult to determine a common base line

o The experiment protocol and procedures were not available for this study. We therefore had to rely on assumptions and educated guesses based on past experience with similar hardware.

o The unavailability of appropriate information on mission costs made it difficult to assign a cost value to each mission benefit described in section 2.2.3.

o The knowledge base of the experts who were consulted for evaluation of the SBI hardware items was sufficient in most areas and deficient in some. This was the main reason for the subjective quantitative analysis presented in this study.

o The study of analyzing automation for the SBI program must include not only SBI hardware items but also other items from the "C", "E" and "W" class. In our opinion, the level of automation of the SBI hardware items will also be dependent on items in the aforementioned class.

o In order to determine the impacts of automation on crew utilization, the combined cost impacts of automation, miniaturization, modularity and commonality must be analyzed rather than investigating separately. This will enable a cost analysis for the entire space station.

o The small number of references for automation in life science modules made a historical evaluation difficult.

6.0 Recommendations and Conclusions

It is possible to automate the methodology presented in this study by developing a computer model based on the scoring mechanism. This model will identify cost and benefit curves for an arbitrary SBI hardware item. This work has analyzed the cost and benefit model of only one representative hardware item in each functional group. In order to develop a more refined cost-benefit analysis, each hardware item in the SBI list must be analyzed as done in sections 2.3.2 and 2.3.3. A computer model would be useful in developing a more refined and accurate cost-benefit model for the SBI hardware items. The above described computer model will enable instant cost and benefit comparisons and display graphs of different hardware items when progressing from one level of automation to another. The data base of the model will consist of the most recent information available on the hardware items. The algorithms will use these to specify cost-effective automation levels for the individual SBI hardware items. We highly recommend developing such a computer model because this model will be applicable not only to the SBI hardware list but will also be a guideline for other automation analysis studies on the space station. We at SwRI are in a position to develop such a computer model based on expert knowledge of SBI hardware and the methodology proposed in this study.

In this work, several assumptions were made partly because of the lack of information available and partly because a detailed analysis of automation for SBI hardware items was beyond the scope of this work. For example, the assumption (f) of section 2.2.2 deserves careful investigation because generally a SBI hardware item will not possess equal weight on the data as well as physical domains. A follow on study is justified because it will enhance the quantitative scores assigned to the individual hardware items, resulting in a more robust cost-benefit model.

It is clear that only a SBI mission specialist with intimate knowledge of all the SBI hardware items will be successful in scoring the individual hardware items. A follow on study is recommended to identify the required qualifications of such a specialist.

In our opinion, the most effective and accurate cost-benefit model for the SBI program must include all of the following: automation, miniaturization, modularity and commonality. This study has investigated only the automation side. A follow on work should include a combined evaluation which will result in a more reliable cost-benefit model.

To conclude, we have in this study attempted to develop a handbook of rules of thumb that will aid the designer/engineer in analyzing the impacts of automation on the SBI hardware items. Although, the scoring is subjective, we feel confident that the proposed methodology and scoring mechanism is general enough to hold validity for a large spectrum of hardware items.

APPENDIX A

CURRENT STATUS OF AUTOMATION IN CLINICAL LABS

Current Status of Automation in Clinical Labs

The information contained in this Appendix is based on telephone interviews with lab technicians from two clinical labs. The two clinical labs chosen were:

a) The Severance Lab, which is a small-medium sized lab in San Antonio,

and

b) The Maryland Medical Labs, which is a large-sized lab situated in Baltimore.

The level of laboratory automation is generally proportional to the volume of samples being processed per unit time. Thus, small clinical labs are generally equipped with less automated sample analysis machines which require some manual work in the loading and unloading of samples, input of sample tests and archiving of test results. Current automation in small, medium or large labs all share a common trend, namely it is primarily dedicated towards analysis of pre-processed samples. There is little or no automation available in the preparation of samples prior to analysis.

The latest state of the art in automation technology is typically available in large medical analysis laboratories. The reason for such high levels of automation are primarily to accommodate the high volume of sample testing that has to be processed in the most efficient manner possible. For example the blood analysis automated machine, the Parallel and the Accel made by American Monitor, are capable of processing large workloads of 240 test tubes per hour, each test tube containing bar coded information of patient name, sex and up to 24 tests to be performed. The bar coding eliminates human input errors and enables some intelligent cross checking. This machine is connected to a mainframe computer, into which all test results are stored in special patient files. In another example, Kodak has developed a dry chemistry analysis system which is a fully automated stand-alone machine, that measures reactions and performs a spectrophotometry using layers of 35 mm film. The results are automatically stored and can be easily retrieved. The Technicon-H1, made by Technicon, is another example of a highly automated stand-alone analysis machine for use in hematology. The operator has to only collect the blood sample and feed it into the machine, the rest is totally automated. The Technicon-H1 will perform a red and white blood cell count, determine the percentage and size of the different types of white blood cells present in the sample and the data is automatically transferred and stored in a database. Another highly automated stand-alone analysis machine measures the drug content in a blood sample. The machine automatically performs a Gas Liquid Chromatograph Mass Spectrometry to determine the level and percentage of various drugs present in the bloodsample.

Since highly automated stand-alone analysis machines are currently available, present research is being focussed on the integration of all the stand-alone systems, in order to share data on a common data bus. Such a system has been developed in Europe, the Paruna, which is essentially a computer system into which other stand-alone machines interface and are thus able to share data between each other.

To summarize, the current level of automation in clinical labs is fairly advanced. The automation of data transfer or processing is impressive and continues to advance. These advances can be leveraged or exploited by NASA for use in the Space Station. However, the level of automation in material handling and transfer in clinical labs has not progressed as much as the data automation. The main reason for this is the fact that clinical labs do not have the same physical and power constraints as the Space Station. Therefore, NASA may be required to initiate a lead effort in the area of physical automation (interior vehicular robotics) to optimize the crew utilization in the SBI program.

Future Projections for Clinical Lab Automation

In the future, automated clinical analysis systems will become more portable and size reduced. Thus clinical testing and on-line analysis of the results will be performed by the side of the patient bed. This would greatly reduce the waiting time required for sample analysis and diagnosis.

Pre-processing of samples prior to the analysis stage is generally manually intensive. Automated pre-processing of samples will enhance quality and dependability of test results.

Future efforts will include integrating the stand-alone automated analysis machines into a central data base enabling inter-sharing of the test results on a common data bus. Integration of the stand-alone automated nodes into a central accounting system will keep track of information on patient billing and machine usage.

APPENDIX B

EXISTING AUTOMATION STUDIES RELATED TO THE SPACE BIOLOGY INITIATIVE

Existing Automation Studies Related to the Space Biology Initiative

A pilot program exists at Ames and at MIT's Laboratory under Dr. Larry Young entitled "Principle Investigator in a Box" (PI in a Box) that is a good example of the suggested SBI automation of information handling and decision making. The "PI in a Box" helps the astronaut conduct complete vestibular physiology experiments in zero-gravity. Normally an expert is required to validate the data obtained from the experiment and analyze the results. Decisions are then made regarding any retesting necessary.

The PI in a Box is an "expert system" artificial intelligence program, written in CLIPS, running on a MacIntosh II, that essentially replaces the vestibular physiology expert. This experiment has been flown on two Orbiter missions successfully. A primary computer is used to condition the vestibular physiology measurements, extract pertinent parameters and feed them into the MacIntosh II. Relating back to the SBI program, the PI in a Box concept would be applied to over a dozen relatively complex experiments involving expert decision making regarding validity of data, pertinent data and analysis of data. The resultant direct crew labor and crew training savings is expected to be significant. A more important benefit is the expected effect of reduced crew training requirements allowing more concentrated crew training on more strategic NSSP issues.

Another NASA pilot program entitled "Rack Mounted Robot" is in progress at Marshall Space Flight Center within the IVA (Interior Vehicular Activity) Robotics program under Mr. Ken House, Code EB. Concepts have been advanced for a small robot to achieve material transfers within the envelope of the U.S. standard rack frame. This robot is envisioned to make timely material or sample transfers from machine to machine on a precise schedule. The use of a robot would free the crew member from a time consuming waiting and observing sequence that usually precludes any alternative or parallel activities.

The two pilot programs described above can work quite well together in an integrated fashion to produce additional crew labor and crew training savings and improved data accuracy and volume. As an example: a solid or liquid sample can be extracted by the crew member from an experimental subject and placed in a sample processing station. The crew member denotes his actions on the main workstation which sets the automated experiment equipment in motion. The rack mounted robot retrieves the sample and positions it rapidly in view of a machine vision imaging station for archival recording. Then the robot positions the sample in an automated sample preparation apparatus. The sample may be split into two or more sub-samples each to be delivered by the robot to separate analytical processing equipment.

At the information processing level, data is being retrieved and the "principal investigator expert" is judging the validity of the experiments based upon data and is essentially directing the sequential motions of the robot. Note that the robot path trajectories are well known and preprogrammed, but the robot path sequences may very well be unstructured depending upon results of sample tests, frequency of parallel experiments, etc.

Upon completion of a sequence of experiments, the robot changes end effectors and performs housekeeping tasks such as equipment clean up operations and equipment element change out if needed. The robot then changes tools and positions a small camera at critical areas within the rack mounted equipment to perform an inspection of the "sample wetted" surfaces to confirm preparation for the next series of tests.

The experiment sequence described above is largely common to many biological experiments. The experimental work involved is meticulous and time consuming using conventional laboratory equipment. If the equipment is miniaturized for conservation of weight, space and power, then use of it by the crew becomes more difficult. With miniaturization however, robotics becomes much more cost effective since the robot handling of components, tools and samples becomes easier.

APPENDIX C

A PROPOSAL FOR AN INTERIOR VEHICULAR ACTIVITY ROBOT FOR THE SPACE BIOLOGY INITIATIVE

A Proposal for an Interior Vehicular Activity Robot for the Space Biology Initiative

This trade study has developed a cost and benefit model for bioinstrumentation designers to use to decide upon the degree of automation they could afford. Our findings indicate a very high potential for Interior Vehicular Activity (IVA) Robotics embedded within the SBI module racks. Figure 1 shows a conceptual illustration of an Interior Vehicular Robot that may be used to increase the crew utilization while performing life science experiments. An Interior Vehicular Robot would increase crew utilization by freeing the crew member from time consuming waiting and observing experiment sequences, thus enabling the crew member to perform other important mission activities. The robot would be a small dexterous arm capable of working within the standard U.S. rack frame. The robot would have a "home" position in one of the lower 19-in. rack enclosures. A machine vision imaging center would occupy another 19-in. rack enclosure for general purpose imaging tasks that have been identified on the SBI program.

Note in Figure 1 that the "robot home rack" has an end effector changer and its own machine vision camera for end effector inspection and check out tasks. We would like to build a full-scale mock-up of an automated rack frame containing the key bioprocessing modules that really need to be automated (sample handling, preparation and standard analytical procedures). The key thrust of this design effort would be to develop a "robot access corridor" at the rear of the U.S. standard rack frame so the robot could reach into strategic rack enclosure locations, retrieve samples, make measurements, place samples into automatic preparation devices or to place and retrieve samples from the imaging rack.

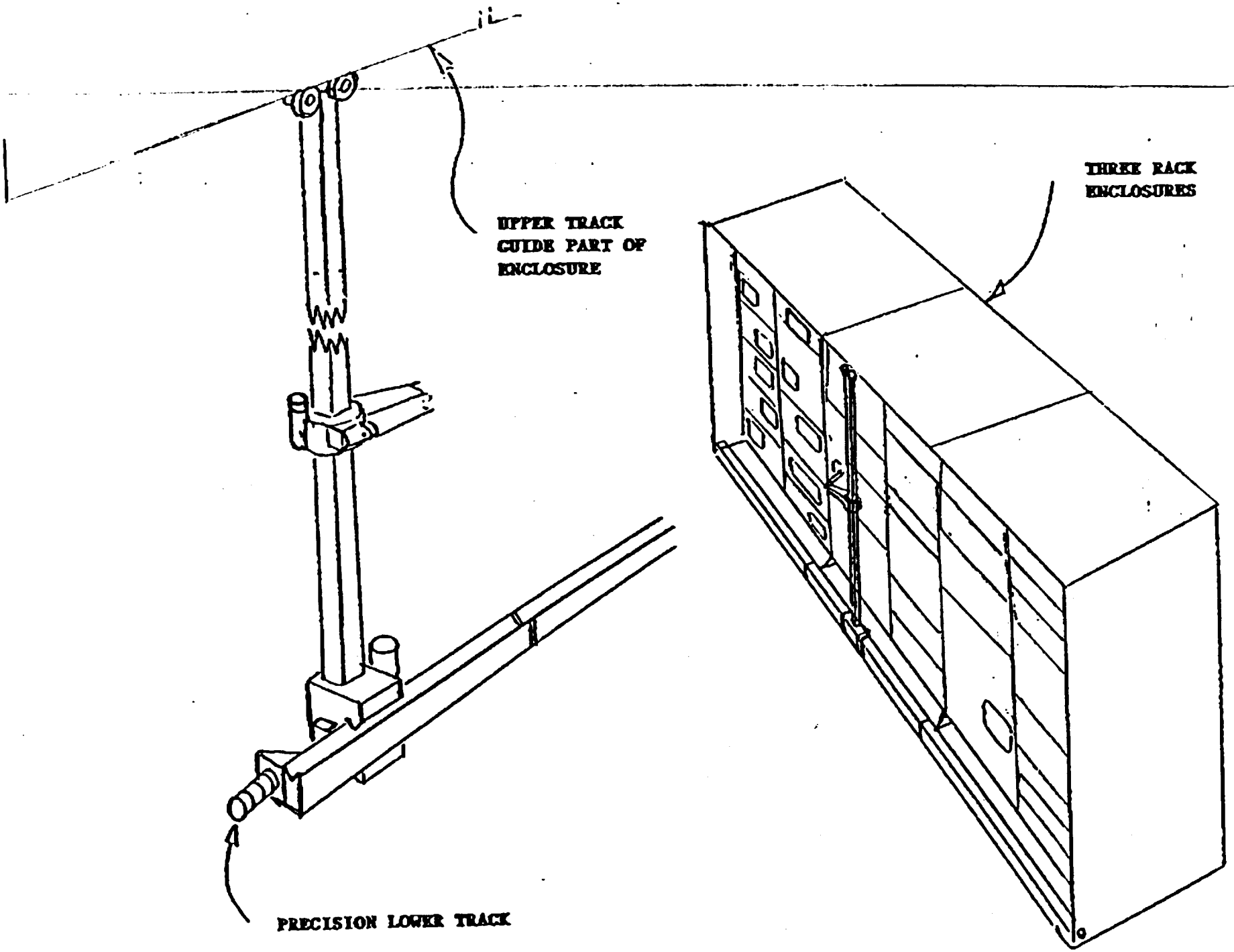
Rack enclosure design guidelines would be developed that would enable experiment package designers to strategically place various items in locations well within the robot gripper or end effector work envelope and at compatible orientations.

We believe that most of the important SBI operations such as sample handling, preparation, analysis, imaging, etc., might be located within a single rack frame containing two vertical columns of 19-in. enclosures. This rack enclosure contains about 1.5 cubic meters of equipment which would be equivalent to about 20 large 19-in. equipment racks. Our bioengineers have counted 96 SBI modules of which about 40 of these are machines, devices or instruments. They believe that the number of racks that should be accessed by the robot may exceed what can be placed in a single rack frame. Or, that many of the equipment racks of interest to us may necessarily have to be placed in different rack frames. It appears then that the robot should have access to the rear of several rack frames along one wall. A stochastic model and simulation of the work area and experiment flow should be done to optimize strategic placement of the SBI models for the most efficient operation by the crew and by the IVA robot.

Another problem that should be addressed in a prototype design effort is that of man-equivalent operations. Should the robot become inoperative or the sample be considered inappropriate for the robot to handle for some reason, then the crewmember will have to be able to take over the robot functions. One solution to this problem would involve having some of the

racks on drawer slides which would allow manual access from the top and robotic access from the side or rear of the rack.

On request, SwRI, in cooperation with Horizon Aerospace, will be pleased to submit a more detailed task list for the development of an Interior Vehicular Robot for the Space Biology Initiative.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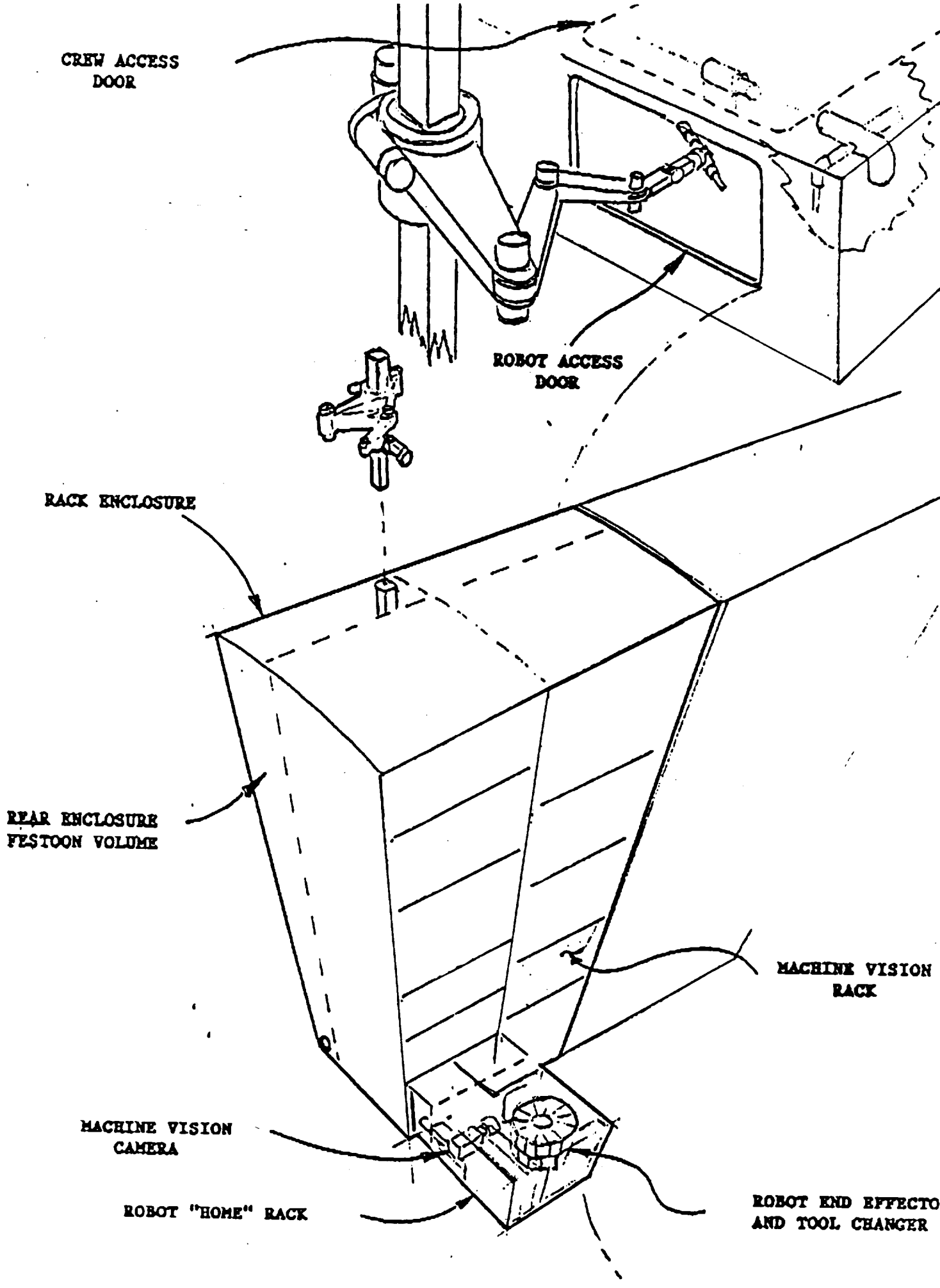
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MACHINE VISION RACK
MACHINE VISION CAMERA
ROBOT "HOME" RACK
ROBOT END EFFECTO
AND TOOL CHANGER

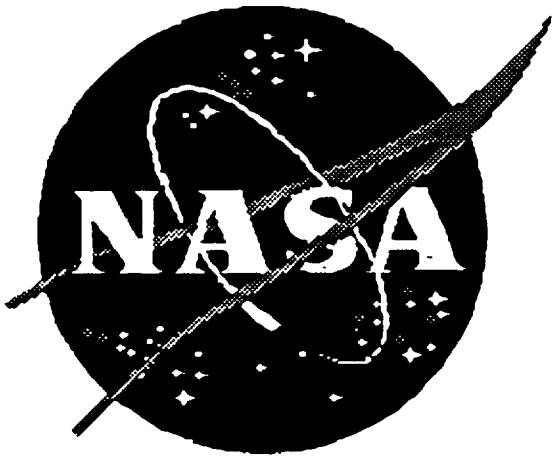
DESIGN MODULARITY AND COMMONALITY

TRADE STUDIES

JOHNSON SPACE CENTER
HOUSTON, TEXAS
77058

SPACE BIOLOGY

INITIATIVE

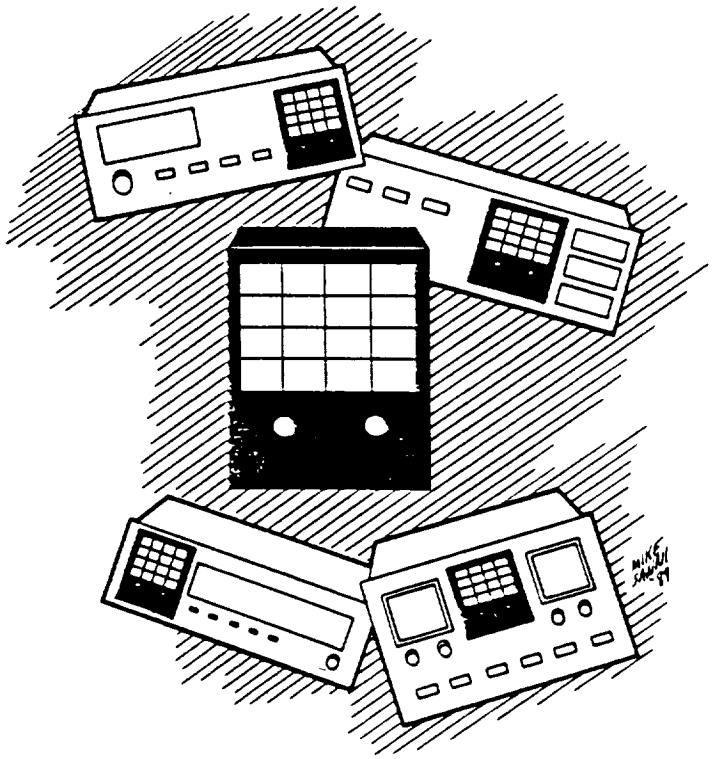


Space Biology Initiative
Program Definition Review

Lyndon B. Johnson Space Center
Houston, Texas 77058

HORIZON
AEROSPACE

Design Modularity and Commonality



FINAL REPORT

June 1, 1989

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SPACE BIOLOGY INITIATIVE
PROGRAM DEFINITION REVIEW

TRADE STUDY 4

DESIGN MODULARITY AND COMMONALITY

FINAL REPORT

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June 1, 1989

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List of Abbreviations and Acronyms

AI	Artificial Intelligence
ARC	Ames Research Center
BmRP	Biomedical Research Project (Human/Crew Members)
BRP	Biological Research Project (Non Human/Rodents, primates or plants)
BSHF	Biological Specimen Holding Facility
CAD	Computer Aided Design
CDR	Critical Design Review
CELSS	Closed Ecological Life Support System
CHeC	Crew Health Care
COTS	Commercial Off-The-Shelf
CR	Change Request
DDT&E	Design, Development, Test and Evaluation
DMS	Data Management System
ECF	Exercise Countermeasure Facility
ECLSS	Environmental Control and Life Support System
EDCO	Extended Duration Crew Operations
EHS	Environmental Health System
EPDS	Electrical Power Distribution System
FSU	Functional Support Unit
GGS	Gas Grain Simulator
HMF	Health Maintenance Facility
HPLC	High Performance Liquid Chromatograph
HQUL	Hardware Quantity and Usage List
HRF	Human Research Facility
JSC	Johnson Space Center
LAN	Local Area Network
LSE	Laboratory Support Equipment
LSLE	Life Sciences Laboratory Equipment
LSRF	Life Science Research Facility
MDE	Mission Dependent Equipment
MDU	Medical Development Unit
MLI	Multi-Layer Insulation
MRDB	Mission Requirements Data Base
MSK	Major Subcontractor
NASA	National Aeronautics and Space Administration
NSTS	NASA Space Transportation System
OTS	Off-The-Shelf
PI	Principal Investigator
PMC	Permanent Manned Capability
POCC	Payload Operations Control Center
RMOAD	Reference Mission Operational Analysis Document
SAIS	Science & Applications Information System
SBHB	Space Biology Hardware Baseline
SBI	Space Biology Initiative
SSF	Space Station Freedom

SLS	Space Laboratory Life Science
SSFP	Space Station Freedom Program
SSIS	Space Station Information Systems
STS	Space Transportation System
TDRSS	Tracking and Data Relay Satellite System
TFU	Theoretical First Unit
WAN	Wide Area Network

Glossary and Definitions

Assembly

An accumulation of subassemblies and/or components that perform specific functions within a system. Assemblies can consist of subassemblies, components, or both.

Certification

The process of assuring that experiment hardware can operate under adverse Space Station Freedom environmental conditions. Certification can be performed by analysis and/or test. The complete SSFP definition follows. Tests and analysis that demonstrate and formally document that all applicable standards and procedures were adhered to in the production of the product to be certified. Certification also includes demonstration of product acceptability for its operational use. Certification usually takes place in an environment similar to actual operating conditions.

Certification Test Plan

The organized approach to the certification test program which defines the testing required to demonstrate the capability of a flight item to meet established design and performance criteria. This plan is reviewed and approved by cognizant reliability engineering personnel. A quality engineering review is required and comments are furnished to Reliability.

Component

An assembly of parts, devices, and structures usually self-contained, which perform a distinctive function in the operation of the overall equipment.

Experiment

An investigation conducted on the Space Station Freedom using experiment unique equipment, common operational equipment of facility.

Experiment Developer

Government agency, company, university, or individual responsible for the development of an experiment/payload.

Experiment unique hardware

Hardware that is developed and utilized to support the unique requirements of an experiment/payload.

Facility

Hardware/software on Space Station Freedom used to conduct multiple experiments by various investigators.

Flight Increment

The interval of time between shuttle visits to the Space Station Freedom. Station operations are planned in units of flight increments.

Flight increment planning

The last step in the planning process. Includes development of detailed resource schedules, activity templates, procedures and operations supporting data in advance of the final processing, launch and integration of payloads and transfer of crew.

Ground operations

Includes all components of the Program which provide the planning, engineering, and operational management for the conduct of integrated logistics support, up to and including the interfaces with users. Logistics, sustaining engineering, pre/post-flight processing, and transportation services operations are included here.

Increment

The period of time between two nominal NSTS visits.

Interface simulator

Simulator developed to support a particular Space Station Freedom or NSTS system/subsystem interface to be used for interface verification and testing in the S&TC and/or SSPF.

Integrated logistics support

Includes an information system for user coordination, planning, reviews, and analysis. Provides fluid management, maintenance planning, supply support, equipment, training, facilities, technical data, packaging, handling, storage and transportation. Supports the ground and flight user requirements. The user is responsible for defining specific logistics requirements. This may include, but not be limited to resupply return in term of frequency, weight, volume, maintenance, servicing, storage, transportation, packaging, handling, crew requirements, and late and early access for launch site, on-orbit, and post-mission activities.

Integrated rack

A completely assembled rack which includes the individual rack unique subsystem components. Verification at this level ensures as installed component integrity, intra-rack mechanical and electrical hookup interface compatibility and mechanisms operability (drawer slides, rack latches, etc.).

Integration

All the necessary functions and activities required to combine, verify, and certify all elements of a payload to ensure that it can be launched, implemented, operated, and returned to earth successfully.

Orbit replaceable unit (ORU)

The lowest replaceable unit of the design that is fault detectable by automatic means, is accessible and removable (preferably without special tools and test equipment or highly skilled/trained personnel), and can have failures fault-isolated and repairs verified. The ORU is sized to permit movement through the Space Station Freedom Ports.

Payload integration activities

Space Station Freedom payload integration activities will include the following:

Pre-integration activities shall include receiving inspection, kitting, GSE preps and installation, servicing preps and servicing, post deliver verification, assembly and staging (off-line labs), rack and APAE assembly and staging, alignment and post assembly verification.

Experiment integration activities shall include experiment package installation into racks, deck carriers, platforms, etc., and payload to Space station interface verification testing. When the Freedom element is available on the ground, Space Station Freedom integration activities (final interface testing) shall include rack or attached payload installation into Freedom element (e.g., pressurized element, truss structure, platform) and shall include payload-to-element, interface verification, followed by module, truss, or platform off-loading of experiments, as required, for launch mass for follow-on increments, Space Station Freedom integration activities shall include rack or attached payload installation into the logistics element and verification of the payload-to-logistics element interface.

Integration activities (final interface testing) shall include: rack or attached payload installation into Space Station Freedom element (e.g., lab module, truss structure, platform) on the ground, when available, and shall include payload to element interface verification, configure and test for station to station interface verification, followed by module, truss or platform off-loading of experiments, as required, for launch mass.

Launch package configuration activities shall include configuring for launch and testing station to NSTS interfaces, (if required), stowage and closeout, hazardous servicing, (if required), and transport to the NSTS Orbiter.

NSTS Orbiter integrated operations activities shall include insertion of the launch package into the orbiter, interface verification (if required), pad operations, servicing, closeout, launch operations, and flight to Space Station Freedom.

On-orbit integration activities shall include payload installation and interface verification with Space Station Freedom.

Hardware removal that includes rack-from-module and experiment-from-rack removal activities.

Payload life cycle

The time which encompasses all payload activities from definition, to development through operation and disbursement.

Permanent manned capability (PMC)

The period of time where a minimum of capabilities are provided, including required margins, at the Space Station Freedom to allow crews of up to eight on various tour

durations to comfortably and safely work in pressurized volumes indefinitely. Also includes provisions for crew escape and EVA.

Physical integration

The process of hands-on assembly of the experiment complement; that is, building the integrated payload and installing it into a standard rack, and testing and checkout of the staged payload racks.

Principal Investigator

The individual scientist/engineer responsible for the definition, development and operation of an experiment/payload.

Rack staging

The process of preparing a rack for experiment/payload hardware physical integration: encompasses all pre-integration activities.

Space Station Freedom

The name for the first Unites States permanently manned space station. It should always be interpreted as global in nature, encompassing all of the component parts of the Program, manned and unmanned, both in space and on the ground.

Subassembly

Two or more components joined together as a unit package which is capable of disassembly and component replacement.

Subsystem

A group of hardware assemblies and/or software components combined to perform a single function and normally comprised of two or more components, including the supporting structure to which they are mounted and any interconnecting cables or tubing. A subsystem is composed of functionally related components that perform one or more prescribed functions.

Verification

The process of confirming the physical integration and interfaces of an experiment/payload with systems/subsystems and structures of the Space Station Freedom. The complete SSFP definition follows. A process that determines that products conform to the design specification and are free from manufacturing and workmanship defects. Design consideration includes performance, safety, reaction to design limits, fault tolerance, and error recovery. Verification includes analysis, testing, inspection, demonstration, or a combination thereof.

1.0 Introduction

1.1 Background

The JSC Life Sciences Project Division has been directly supporting NASA Headquarters, Life Sciences Division, in the preparation of data from JSC and ARC to assist in defining the Space Biology Initiative (SBI). GE Government Services and Horizon Aerospace have provided contract support for the development and integration of review data, reports, presentations, and detailed supporting data. SBI Definition (Non-Advocate) Review at NASA Headquarters, Code B, has been scheduled for the June-July 1989 time period. In a previous NASA Headquarters review, NASA determined that additional supporting data would be beneficial in clarifying the cost factors and impact in the SBI of modularizing appropriate SBI hardware items. In order to meet the demands of program implementation planning with the definition review in late spring of 1989, the definition trade study analysis must be adjusted in scope and schedule to be complete for the SBI Definition (Non-Advocate) Review.

1.2 Task Statement

The objective of this study is to define the relative cost impacts (up or down) of developing Space Biology hardware using design modularity and commonality. Recommendations for how the hardware development should be accomplished to meet optimum design modularity requirements for Life Science investigation hardware will be provided. In addition, this study will define the relative cost impacts of implementing commonality of hardware for all Space Biology hardware. Cost analysis and supporting recommendations for levels of modularity and commonality will be presented. The study will provide a mathematical or statistical cost analysis method with the capability to support development of production design modularity and commonality impacts to parametric cost analysis.

1.3 Application of Trade Study Results

The SBI cost definition is a critical element of the JSC submission to the SBI Definition (Non-Advocate) Review and the results of this trade study are intended to benefit the development of the SBI costs. It is anticipated that the GE PRICE cost estimating model will be used to assist in the formulation of the SBI cost definition. The trade study results are planned to be produced in the form of factors, guidelines, rules of thumb, and technical discussions which provide insight on the effect of modularity/commonality on the relative cost of the SBI hardware. The SBI cost estimators are required to define input parameters to the PRICE model which control the cost estimating algorithms. These trade study results can be used as a handbook of cost effects by the SBI cost estimators in developing and defining the required PRICE input parameters.

1.4 Scope

The space biology hardware to be investigated has been defined and baselined in Appendix A Space Biology Hardware Baseline (SBHB). By study contract direction, no other space biology hardware has been considered. The complexity and importance of the subject could warrant an extensive study if unlimited time and resources were available. However, due to the practical needs of the real program schedule and budget, the depth of study has been adjusted to satisfy

the available resources and time. In particular, cost analyses have emphasized the determination of influential factors and parametric relationships rather than developing detailed, numerical cost figures. While program objectives and mission definitions may be stable in the early program phases, hardware item specifications are often elusive and change many times before final design. For this reason, the trade study analyses have focused on the category and function of each hardware item (Table 1.4) rather than the particular, current definition of the item. In the process of acquiring trade study data, certain information could be considered a snapshot of the data at the time it was recorded for this study. The data have been analyzed as defined at the time of recording; no attempt has been made to maintain the currency of acquired trade study data.

1.5 Methodology

The methodology used in performing the Modularization/Commonality Trade Study, shown in Figure 1.5, consists of the initial, important phase of search and acquisition of related data; followed by a period of data integration and analysis; and, finally, the payoff phase where candidate items and implementation factors, including design modularity and commonality impacts to parametric cost analysis are identified.

1.5.1 Data And Documentation Survey

A literature review and database search were conducted immediately upon study initiation. Information pertaining to the modularization of commercial and space flight research hardware was considered for applicability to the study task.

1.5.2 Database Development

An analysis of the trade study data needs was performed to provide an understanding of the logical database design requirements. Based on the knowledge gained in the database analysis, the trade study data structures were developed and implemented on a computer system. The pertinent information collected from the data and documentation survey was input to the trade study database.

1.5.3 Costing Techniques Summary

Costing techniques used in previous projects were surveyed and historical cost factors were collected for review of applicability to this trade study. The applicable data were identified for use in cost analysis to demonstrate relative cost impacts of modularization/commonality for space biology technology hardware.

1.5.4 Survey Data Integration

The Space Biology Hardware Baseline was reviewed and the facilities, assemblies, subassemblies, components, and functions of this hardware that have the potential for design modularity and commonality were identified as candidates for design modularity and commonality. The technical data collected from the survey were integrated with the Space

Biology Hardware Baseline database and a matrix of candidate functions, specifications, cost Analysis, design modularity and commonality applications will be developed.

The initial survey data analysis was performed to select a sample of the SBHB items which could be potential candidates for modularization. With limited study time and a SBHB of 93 referenced hardware items, Appendix A, a method was needed to separate the items which could have the most cost impact and were worthy of study resource application. The "initial few and trivial many" method (SBI #96) was used. This method applies the principal that in any population which contributes to a common effort (cost). A relative few of the contributors account for the bulk of the effort (cost). All SBHB items were listed in descending order of probable acquisition cost. Weight was used as an indication of probable acquisition cost based on historical experience in previous space programs. It was found that 34 percent of the items (32 items) accounted for 93 percent of the mass or probable cost (Table 5.3). Therefore, consideration was immediately limited to these 32 items. The modularization candidate sample set was chosen from Table 5.4-1 based on amenability to modularization and commonality. This list of 32 items does not mean the remaining 61 (93-32) items are of lesser importance in obtaining space biology information.

The sample set was then subjected to a more detailed analysis to determine important factors relative to commonality and to select the most representative functions/assemblies for final analysis. By this process, a reasonable effort could be devoted to analyze the impact more thoroughly.

1.5.5 Cost Analysis

Analyses were performed to demonstrate the relative cost impact for modularity and commonality within the candidate hardware items. Additional study was dedicated to the final selected item. Based on this cost assessment and historical data, the relative relationship of modularization/commonality to space biology hardware cost was assessed.

1.6 Definitions

1.6.1 Modularity

Modularization is the packaging of the instrument equipment in units which correspond to system functional elements in such a way that the units can be easily removed, replaced, and reconfigured.

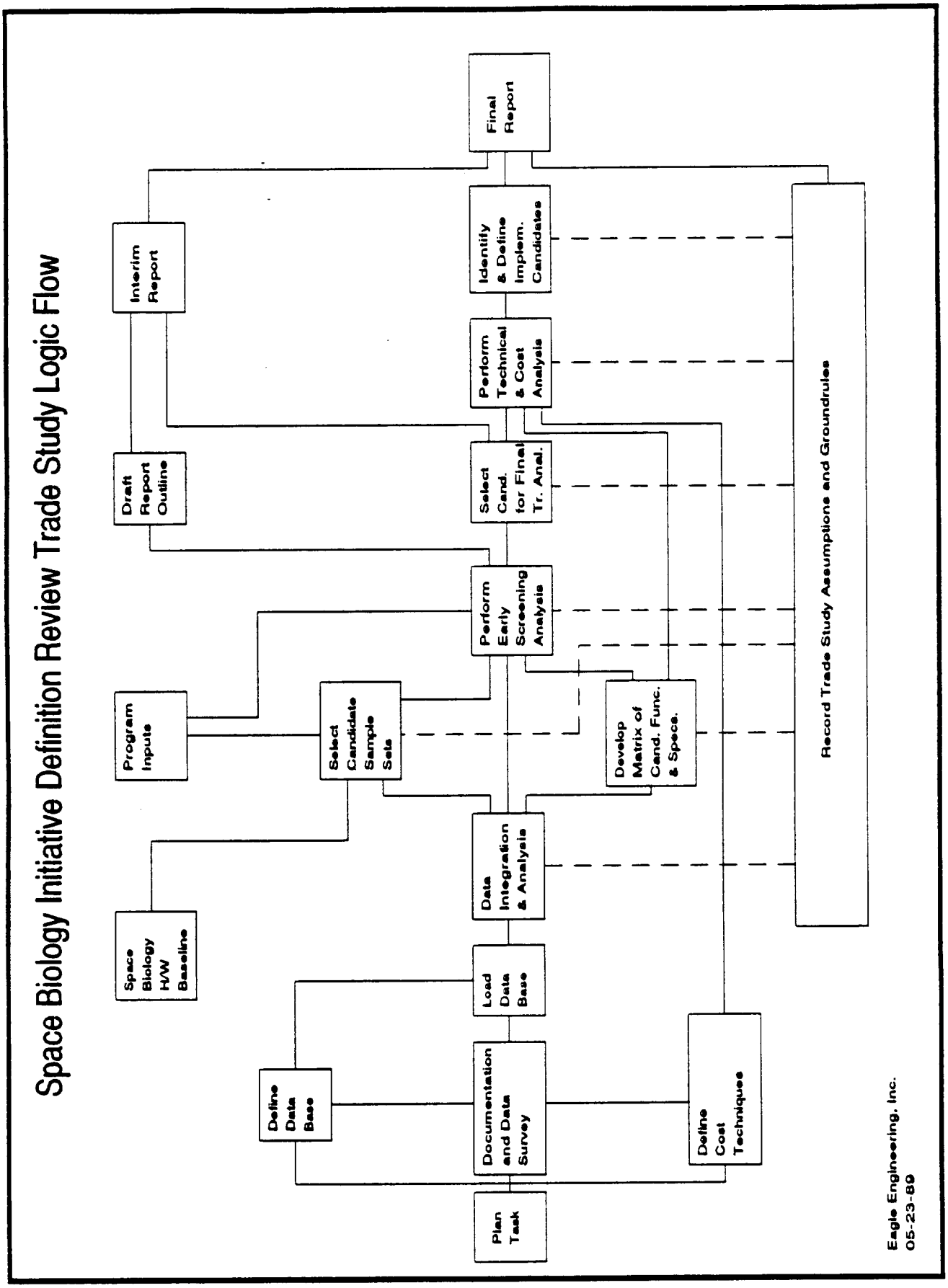
1.6.2 Commonality

Commonality refers to the commonness of an individual (item) "COMMON" from latin "communis" is defined as "belonging to or shared by two or more individuals or by all members of a group. It can broadly be defined as the use of identical, interchangeable, functionally compatible or similar items to satisfy different sets of functionally similar requirements.

Table 1.4 SBI Hardware Categories and Functions

SBI HARDWARE CATEGORIES	FUNCTIONS (Applicable to each Category)
Cardiovascular	Analysis
Cytology	Calibration
Environmental Monitoring	CELSS
Exobiology	Collection
Hematology	Health Maintenance
Histology	Measurement
Logistics	Preparation
Miscellaneous	Stowage
Neurophysiology	
Plant Sciences	
Pulmonary	
Surgical Science	
Urology	

Figure 1.5 Space Biology Initiative Definition Review Trade Study Logic Flow



2.0 Executive Summary

2.1 Assumptions And Groundrules

In the process of performing the subject trade study, certain data or study definition was not available or specified. Assumptions and groundrules have been established to document, for the purposes of this trade study, the definition of important information which is not definite fact or is not available in the study time period. Major assumptions and groundrules which affect the four EEI trade studies are provided in a list common to all of the studies (Table 2.1-1). The assumptions which primarily affect the design modularity and commonality study are documented in a separate list (Table 2.1-2).

2.2 SBI Functional Element Candidates for Modularization/Commonality

The baseline candidate list of 93 SBI hardware items is shown in Appendix A with an "S" by each item. Space flight history has established that project costs are mostly significantly affected by space equipment weight. To determine which SBI hardware warranted the most study resources, the SBI hardware list was prioritized by mass (Table 2.2-1 repeated from Table 5.2-1) showing the top 32 items which represent 93% by mass, 87% by volume and 87% by power (watts) of the total 93 items.

The 32 hardware items in Table 2.2-1 were reviewed and selective judgements were recorded on the potential for modularization (Table 2.2-2 repeated from Table 5.2-2). Each SBI hardware item was analyzed to determine if the entire item can be modularized or at least a portion of the components could be modularized. The confidence level is an indication of the knowledge and understanding of the individual items at the time of this study. There are five (5) items in this list where there was insufficient data to make an estimation for modularity/commonality (marked NO on Table 2.2-2). There are four (4) items on this list that are marked with a "P" for Pulmonary Group and four (4) marked "PL" for Plant Monitoring Group. The Pulmonary Group has a total of eleven (11) hardware items (#56 thru 66 listed in Appendix A) with interrelated use of hardware for the planned functions and experiments. The group will be treated as one item for this trade study. It is assumed that most of the Pulmonary Group can be packaged or modularized together. The heaviest items in the group is the mass spectrometer which can possibly be used for other SBI functions. The details and practicality of adapting the mass spectrometer to the different applications (Pulmonary functions, Plant Gas Chromatograph, etc.) is not known at this time. The CELSS hardware item is presently planned as a separate experiment, however the function of this hardware item is plant monitoring which is why it has been grouped into this category.

The modularity candidate sample set (Table 2.2-3 is a repeat of Table 5.2.1) was derived by removing those items that have insufficient data and little or no modularization potential. The item in the two groups Pulmonary (P) and Plant Monitoring (PL) were left in this sample set with a high confidence level that the group or a portion of the group could be packaged (modularized) together.

The candidate hardware items were analyzed for common functions/assemblies by sorting the vital database listing (Table 5.2-3 and summarized in Table 2.2-4). The level of commonality

was the lowest level possible with the available information. The Pulmonary Function Equipment Storage Assembly hardware items show an amplifier as being common. This particular hardware item would not use an amplifier; however, the Pulmonary Group would more than likely use this function/assembly. This type of analysis was used throughout the study for commonality. The number of common functions/assemblies will be subjective; however, the methodology does show a large potential cost savings through commonality. The level of commonality (i.e. assembly, sub assembly, component) has a direct effect on the implementation of the common solution which in turn has a direct effect on the overall cost of the program (SBI #89).

2.3 Modularity/Commonality Cost Impacts

The 15 candidates for modularity of the SBI hardware items are shown in Table 2.2-3. The cost impact of modularizing these items would require a redesign for the existing hardware, (i.e., Pulmonary and Plant Monitoring Group) and a new design for other items. Redesign costs would be much higher than new design of hardware in the conception phase. No cost analysis data is presented in this trade study for modularity.

The commonality list of functions/assemblies is shown in Tables 2.2-4 and summarized in Table 2.3. Table 2.2-4 shows some of the functions/assemblies for the 32 SBI hardware items. The number of potential SBI hardware items using each function/assembly is shown in Table 2.3 with the possible cost reduction for each function. To estimate the potential cost reduction for each SBI hardware item will require additional, more detailed information on the individual functions, assemblies, subassemblies and components, (lowest level possible). As seen from Table 2.3 the potential cost reduction is quite large for the first few units. After 10 items, however, the cost reduction is essentially a flat curve. The details of developing the cost impact analysis is in section 5.3.2.1.

2.4 Future Work

Future studies should include more details on all of the functions/assemblies (lowest level possible) of the individual SBI hardware items. This information would then allow for a cost impact analysis of the individual SBI hardware items versus just the functions/assemblies. There is a high degree of confidence that with further, more detailed, trade studies there can be a large cost savings of modules/common items within the SBI group as well as with in other Space Station Freedom related activities. There may also be further cost savings with an analysis between the different trade studies. Other SSF activities (i.e. CHeC, EDCO, and HMF will have common hardware items and many of these will be flown on SLS-1 which could greatly reduce development cost.

2.5 Conclusion Summary

The analysis of this modularity/commonality trade study indicates that there can be considerable cost saving within these groups by modularizing the various assemblies and components for long duration missions. The analysis of the functions/assemblies for commonality, regardless of the factors that influence cost, shows that very large potential savings are available. Size (weight), complexity, development cost, fabrication cost and learning factors can vary over any

foreseeable range of values, but common use of elements or assemblies will still produce large savings. The analysis in section 5.3.2.1, which relates development cost, first unit cost and learning factors, vividly demonstrates this important finding.

As can be seen from Table 7-1 in Appendix C, modularity has a favorable affect on life cycle costs in almost every step of a development, test, integration and operational life cycle. Therefore, a small cost in weight to make a design modular will yield large programmatic return over the whole Space Station life cycle. Modularity also can be implemented such that improved commonality results. Select the correct items for commonality development (Table 2.2-4) and major cost savings become achievable.

Table 2.1-1 Common SBI Trade Study Assumptions and Groundrules

1) Where project, hardware, and operations definition has been insufficient, detailed quantitative analysis has been supplemented with assessments based on experienced judgement of analysts with space flight experience from the Mercury Project through the current time.

2) Space flight hardware cost is primarily a function of weight based on historical evidence.

3) The effects of interrelationships with space biology and life science hardware and functions other than the SBI baseline hardware are not considered in the trade study analyses.

4) Trade study information, once defined during the analysis for the purpose of establishing a known and stable baseline, shall not be changed for the duration of the trade study.

5) Hardware life cycle costs cannot be studied with quantitative analyses due to the unavailability of definition data on hardware use cycles, maintenance plans, logistics concepts, and other factors of importance to the subject.

6) The SBI hardware as identified is assumed to be designed currently without any special emphasis or application of miniaturization, modularity, commonality, or modified commercial off-the-shelf adaptations.

7) It is assumed that the required hardware performance is defined in the original equipment specifications and must be satisfied without regard to implementation of miniaturization, modularization, commonality, or modified commercial off-the-shelf adaptations.

Table 2.1-2 Modularity and Commonality Trade Study Assumptions and Groundrules

1) Many of the SBI hardware items are interrelated, i.e., pulmonary group, plant monitoring, etc., and were not treated as separate entities.

2) Any current SBI equipment hardware concept is subject to being redesigned to meet the benefits of design modularity and commonality.

Item Priorities by Mass	Hardware Item #	Hardware Item Name	Mass		Power		Volume	
			Kg	Accumul.	(Watts)	Accumul.	M^3	Accumul.
1	168	CELSS	1000	1000	1300	1300	1.92	1.92
2	169	Gas Grain Simulator	800	1800	1500	2800	1.92	3.84
3	84	Soft Tissue Imaging System	300	2100	800	3600	.96	4.80
4	77	Hard Tissue Imaging System	136	2236	300	3900	.29	5.09
5	126	Scintillation Counter	90	2326	500	4400	.24	5.33
6	74	Force Resistance System	70	2396	100	4500	.40	5.73
7	145	Automated Microbic System	70	2466	110	4610	.20	5.93
8	155	Total Hydrocarbon Analyzer	70	2536	250	4860	.20	6.13
9	161	Inventory Control System	70	2606	500	5360	.20	6.33
10	162	Lab Materials Pack & Hand. Equip.	70	2676	500	5860	.20	6.53
11	163	Test/Ckout/Calibration Instrumentation	70	2746	200	5860	.20	6.73
12	106	Neck Baro-Cuff	45	2791	145	6205	.13	6.86
13	113	Blood Gas Analyzer	45	2836	250	6455	.13	6.99
14	61	Mass Spectrometer	41	2897	200	6655	.09	7.08
15	112	Plant HPLC Ion Chromatograph	40	2917	200	6855	.12	7.2
16	147	Head Torso Phantom	32	2949	0	6855	.12	7.32
17	63	Pulmonary Gas Cylinder Assem.	30	2979	0	6855	.09	7.41
18	110	Plant Gas Chromatograph/Mass Spectrometer	25	3004	100	6955	.20	7.61
19	115	Chemistry System	23	3027	100	7055	.08	7.69
20	138	Hematology	23	3050	200	7255	.07	7.76
21	34	Sample Preparation Device	22	3072	150	7405	.17	7.93
22	165	Experiment Control Computer System	20	3092	400	7805	.05	7.98
23	62	Pulmonary Function Equip Stor. Assem.	20	3112	0	7805	.05	8.03
24	82	Motion Analysis System	20	3132	100	7905	.05	8.08
25	99	Animal Biotelemetry System	20	3152	100	8005	.05	8.13
26	100	Blood Pressure & Flow Instrumentation	20	3172	200	8205	.06	8.19
27	109	Venous Pressure Transducer/Display	20	3192	100	8305	.05	8.24
28	129	Cell Handling Accessories	20	3212	50	8355	.05	8.29
29	57	Bag-in-Box	19	3231	0	8355	.15	8.44
30	111	Plant Gas Cylinder Assem.	19	3250	0	8355	.09	8.53
31	119	Gas Cylinder Assembly	19	3269	50	8405	.09	8.62
32	130	Cell Harvester	19	3288	50	8455	.06	8.68
93 SBI H/W Items 89 Items have 3535 kg mass 10.0M^3 of volume 10,359 watts of power 4 Items are TBD (all are small)								

Table 2.2-1 List of SBI Hardware Vital to Program Cost Impact Analysis

Item # Prioritized by Mass	Hardware Item #	Hardware Item Name	Sufficient Data Available	Modularity Potential	Assessment Confidence Level	
					Low	High
1	168	CELSS		X-PL		X
2	169	Gas Grain Simulator Facility		X		X
3	84	Soft Tissue Imaging System	NO			
4	77	Hard Tissue Imaging System	NO			
5	126	Scintillation Counter		X		X
6	74	Force Resistance System		NO	X	
7	145	Automated Microbic System		X		X
8	155	Total Hydrocarbon Analyzer	NO			
9	161	Inventory Control System		X		X
10	162	Lab Materials Pack & Hand. Equip.		X	X	
11	163	Test/Ckout/Calibration Instrumentation		X		X
12	106	Neck Baro-Cuff		X		X
13	113	Blood Gas Analyzer		X	X	
14	61	Mass Spectrometer		X-P	X	
15	112	Plant HPLC Ion Chromatograph		X-PL		X
16	147	Head Torso Phantom		NO		X
17	63	Pulmonary Gas Cylinder Assem.		X-P	X	
18	110	Plant Gas Chromatograph/Mass Spec		X-PL	X	
19	115	Chemistry System		X	X	
20	138	Hematology		X	X	
21	34	Sample Preparation Device		X	X	
22	165	Experiment Control Computer System		X		X
23	62	Pulmonary Function Equip Stor. Assem.		X-P	X	
24	82	Motion Analysis System		NO		
25	99	Animal Biotelemetry System		NO		
26	100	Blood Pressure & Flow Instrumentation	NO			
27	109	Venous Pressure Transducer/Display	NO			
28	129	Cell Handling Accessories		X	X	
29	57	Bag-in-Box		X-P	X	
30	111	Plant Gas Cylinder Assem.		X-PL	X	
31	119	Gas Cylinder Assembly		X	X	
32	130	Cell Harvester		X	X	

P - Pulmonary Group
PL - Plant Monitoring Group

Table 2.2-2 Modularity Assessment Review for Sample Selection

Item # Prioritized by Mass	Hardware Item #	Hardware Item Name	Modularity Potential	Assessment Confidence Level	
				Low	High
1	168	CELSS	X-PL		X
2	169	Gas Grain Simulator Facility	X		X
5	126	Scintillation Counter	X		X
7	145	Automated Microbic System	X		X
9	161	Inventory Control System	X		X
11	163	Test/Ckout/Calibration Instrumentation	X		X
12	106	Neck Baro-Cuff	X		X
14	61	Mass Spectrometer	X-P	X	
15	112	Plant HPLC Ion Chromatograph	X-PL		X
17	63	Pulmonary Gas Cylinder Assem.	X-P	X	
18	110	Plant Gas Chromatograph/Mass Spec	X-PL	X	
22	165	Experiment Control Computer System	X		X
23	62	Pulmonary Function Equip Stor. Assem.	X-P	X	
29	57	Bag-in-Box	X-P	X	
30	111	Plant Gas Cylinder Assem.	X-PL	X	

P - Pulmonary Group
PL - Plant Monitoring Group

Table 2.2-3 Modularity Candidate Sample Set

Item # Prioritized by Mass	Hardware Item #	Hardware Item Name	Representive List of Functions/Assemblies																										
			Aerosol Generator	Amplifiers	Automation/Robotics	Cameras/Video	Centrifuge	Computers&Accessories	Converters	Detectors	Displays-Transducer	Environmental Control	Fluid Handling	Freezers	Gas Handling	Mass Spectrometer	Microbial Monitoring	Motors	Power Supply	Pumps	Radiation Handling	Recorders	Sample Prep Animal	Sample Prep Human	Sample Prep Plant	Scintillation Counter	Storage Locker	Temp.Press.Hum.Monitor	Thermal/Shock Isolation
1	168	CELSS			X	X		X	X			X		X	X		X	X	X	X	X	X			X			X	X
2	169	Gas Grain Simulator Facility	X			X		X	X			X			X	X		X	X	X	X	X			X		X	X	X
3	84	Soft Tissue Imaging System																											
4	77	Hard Tissue Imaging System																											
5	126	Scintillation Counter																								X			
6	74	Force Resistance System				X		X				X										X							
7	145	Automated Microbic System						X				X	X				X					X		X					
8	155	Total Hydrocarbon Analyzer																											
9	161	Inventory Control System						X		X													X		X	X		X	X
10	162	Lab Materials Pack & Hand. Equip.			X										X						X		X		X				
11	163	Test/Ckout/Calibration Instrumentation		X	X			X	X		X	X				X			X		X	X				X		X	X
12	106	Neck Baro-Cuff		X					X									X	X	X		X						X	
13	113	Blood Gas Analyzer					X		X	X		X			X				X									X	
14	61	Mass Spectrometer														X													
15	112	Plant HPLC Ion Chromatograph			X		X	X	X	X	X		X		X			X	X	X					X			X	X
16	147	Head Torso Phantom		X	X					X	X	X									X	X						X	
17	63	Pulmonary Gas Cylinder Assem.													X														
18	110	Plant Gas Chromatograph/Mass Spec														X									X				
19	115	Chemistry System					X						X	X															
20	138	Hematology					X						X	X										X					
21	34	Sample Preparation Device			X								X										X	X	X				
22	165	Experiment Control Computer System		X				X																					
23	62	Pulmonary Function Equip Stor. Assem.		X																							X		
24	82	Motion Analysis System				X		X														X							
25	99	Animal Biotelemetry System		X		X		X	X	X	X	X							X			X	X					X	X
26	100	Blood Pressure & Flow Instrumentation																											
27	109	Venous Pressure Transducer/Display									X																		
28	129	Cell Handling Accessories											X											X					
29	57	Bag-In-Box													X							X						X	
30	111	Plant Gas Cylinder Assem.													X										X		X		
31	119	Gas Cylinder Assembly													X												X		
32	130	Cell Harvester																			X			X		X			
		Total Functions/Assemblies	1	6	6	5	4	10	7	5	5	8	6	3	9	4	2	4	7	4	6	10	4	5	8	4	4	10	6

Table 2.2-4 SBI Hardware Items for Commonality

Table 2.3 Commonality List of Functions/Assemblies

Function/Assembly H/W List from Table 5.4.2	Possible Number of SBI H/W Items with Common Functions/Assemblies	Percent Cost Decrease
1 Aerosol Generator	1	0
2 Amplifiers	6	51-59
3 Automation/Robotics	6	51-59
4 Cameras/Video	5	47-55
5 Centrifuge	4	43-51
6 Computers & Accessories	10	59-66
7 Converters	7	54-61
8 Detectors	5	47-55
9 Displays-Transducer	5	47-55
10 Environmental Control	8	55-63
11 Fluid Handling	6	51-59
12 Freezers	3	37-43
13 Gas Handling	9	57-65
14 Mass Spectrometer	4	43-51
15 Microbial Monitoring	2	25-31
16 Motors	4	43-51
17 Power Supply	7	54-61
18 Pumps	4	43-51
19 Radiation Handling	6	51-59
20 Recorders	10	59-66
21 Sample Prep Animal	4	43-51
22 Sample Prep Human	5	47-55
23 Sample Prep Plant	8	55-63
24 Scintillation Counter	4	43-51
25 Storage Locker	4	43-51
26 Temp.Press.Hum. Monitor	10	59-66
27 Thermal/Shock Isolation	6	51-59

3.0 Trade Study Database

The trade study database has been implemented on the dBase IV program by Ashton-Tate. The database definition including a database dictionary is provided in Appendix D.

3.1 Database Files

Four types of dBASE IV files were created for the Space Biology Initiative (SBI) Trade Studies database. These files are database files, index files, report files and view files. Database files have the file name extension dbf. A database file is composed of records and records comprise fields which contain the data. Index files have the file name extension ndx. Index files are used to maintain sort orders and to expedite searches for specific data. Report files have the file name extension frm. Report files contain information used to generate formatted reports. View files contain information used to relate different database (dbf) files. View files link different database files into a single view file.

3.2 Database Management

The development of the SBI Trade Studies database consist of two major steps, logical database development and physical database development. Defining attributes and relationships of data was the major emphasis of the logical database development. The attributes and relationships of the data were determined after analysis of available data and consultation with other SBI team members. Based on the knowledge from the logical database development, the physical structure of the database was developed and implemented on a computer. Setting up the database on a computer was the second major development process. The first step of this process was to determine how to store the data. dBASE IV allows data to be stored as character, numeric, date or logical data types. The second step was to create the database files. After the database files were created, the actual data was entered. For a complete listing of the database structures see Appendix D.

3.3 Database Use

To the maximum extent possible, data generated in performance of this trade study was stored in the database. This approach not only facilitated analysis and comparison of trade data, but also enabled the efficient publication and editing of tables and figures in the study report. In addition, the data are available in the database for future evaluation using different screening logic and report organization.

4.0 Documentation Survey

An extensive survey was made to collect all the latest information pertaining to Modularity & Commonality and associated cost experience. Library searches were made using titles, authors, key words, acronyms, phrases, synonyms, time periods and any possible related activities to modularization and commonality. Interviews with personnel in the various scientific disciplines were made throughout the initial portion of the study.

4.1 Documentation Sources

There were many personal & telephone interviews with knowledgeable personnel in the various scientific fields. These interviews are summarized in Appendix B.

The following documentation sources were checked during the initial portion of the study.

4.1.1 Common SBI Trade Study Bibliography

The complete list of all references used in the four Eagle Engineering, Inc. trade studies is provided in Appendix B. A unique SBI reference index number has been assigned to each information source.

4.1.2 Trade Study Bibliography for Modularity & Commonality

Particular reference information from Appendix B that is of special importance to modularity/commonality is repeated in Table 4.1.2.

4.2 Documentation Data

Cost effective reuse and checkout of hardware prior to launch will require an emphasis on standard tests, long design history of components, and modularity in components with a readily available set of spares. The program should emphasize maintainability, which must be made a priority at the beginning of the program during conceptual design. Although the belief is widespread that modularity and accessibility for maintenance and checkout will increase cost and weight, the experiences of Solar Max and the prelaunch history of the Hubble Space Telescope have refuted this thinking. The actual weight penalty for modularization of the Hubble was less than 400 lbs. on a 25,000 lb system. Had the modularization been initiated at conceptual design, Hubble Telescope engineers maintain there would not have been any weight penalty. Both Solar Max and Hubble system engineers have stated that modularity (ref the Space Assembly Maintenance and Servicing Study Report, USAF Space Division, 1988).

The Skylab program used a common amplifier for many of the Physiological Monitoring System (PMS) sensors. This amplifier was microminiaturized and became the standard amplifier throughout the program. The miniaturization was accomplished by reduction in size and weight of the electronic sensors which also reduced the cost of the various modules in the different hardware items. This same basic common microminiaturized amplifier is scheduled for use by the SBI Bioinstrumentation & Physiological Monitoring Group. (Appendix A lists this group 3)

Table 4.1-2 Bibliography for Modularity and Commonality

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI01	Kozarsky, D.	MUS Inputs		Lockheed Life Sciences Program Office	Lockheed Memo	Washington, DC	01/19/89
SBI02	Kozarsky, D.	Latest Space Station Rack Studies		NASA MSFC		Huntsville, AL.	02/02/89
SBI03	Holt, A.	PMWG-SS Freedom Assly. Seq. Trial Pyl. Manifest		Payload Manifest Working Group (PMWG)		Reston, VA.	12/09/88
SBI04	Shannon, J.	Business Practice Low Cost System Activity		NASA JSC		Houston, TX.	11/12/75
SBI11	NASA	Reference Mission Operational Analysis Document (RMOAD) For The Life Sciences Research Facilities.		NASA JSC	NASA TM 89604	Houston, TX.	02/01/87
SBI12	Breiling, R.	Cost Risk Analysis Using Price Models		RCA Price Systems		Mooreston, NJ.	09/01/87
SBI13	Fogleman, G.Schwart, D.Fonda, M.	Gas Grain Simulation Facility: Fundamental Studies of Particle Formation And Interactions	1	NASA Ames Research Center	NASA ARC/SSS 88-01	Moffet Field, CA.	08/31/87
SBI14	JPL	Flight Projects Office Payload Classification Product Assurance Provisions		JPL	JPL D-1489 Rev. A	Pasadena, CA.	04/30/87
SBI15	PRC Systems	Cost Estimate For The Search for Extraterrestrial Intelligence (SETI) Revised		PRC Systems Services		Huntsville, AL.	06/15/87
SBI16	NASA SSPO	Space Station Commonality Process Requirements Rev.B		NASA SSPO	SSP 30285 Rev. B	Reston, Virgina	09/15/88

Table 4.1-2 Bibliography for Modularity and Commonality

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI17	Webb, D.	Technology Forecasting Using Price - H		Rockwell International		Anaheim, CA.	04/17/86
SBI18	NASA	Classification Of NASA Office Of Space Science And Applications (OSSA) Space Station Payloads		NASA JSC		Houston, TX.	/ /
SBI19	NASA	Life Science Research Objectives And Representative Experiments For The Space Station (Green Book)		NASA Ames Life Science Division		Moffet. Field, CA.	01/01/86
SBI20	NASA	Medical Requirements Of An In-Flight Medical System For Space Station		NASA JSC	JSC 31013	Houston, TX.	11/30/87
SBI21	TRW	A Study Of Low Cost Approaches To Scientific Experiment Implementation For Shuttle Launched And Serviced Automated Spacecraft		TRW Systems Group	Contract NASW - 2717	Redondo Beach, CA.	03/19/89
SBI22	LMSC	Low-Cost Program Practices For Future NASA Space Programs		LMSC	LMSC-D387518	Sunnyvale, CA.	05/30/74
SBI23	Steward, GMiller, L	Biomedical Equipment Technology Assesment For The Science Laboratory Module		Management and Technical Services Company		Houston, TX.	08/01/86
SBI24	General Electric	WP-3 Commonality Plan		General Electric	NAS5-32000	Philadelphia, PA	04/22/88
SBI25	NASA	Microbiology Support Plan For Space Station		NASA JSC	JSC-32015	Houston, TX.	09/01/86

Table 4.1-2 Bibliography for Modularity and Commonality

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI26	NASA	Concepts And Requirements For Space Station Life Sciences Ground Support And Operations		NASA JSC	LS-70034	Houston, TX.	04/11/88
SBI27	NASA	Spacelab Mission 4 Integrated Payload Requirements Document		NASA JSC	SM-SE-03	Houston, TX.	06/01/83
SBI28	General Dynamics	Life Sciences Payload Definition And Integration Study	IV	General Dynamics	CASD-NAS-74-046	San Diego, CA.	08/01/74
SBI29	General Dynamics	Life Sciences Payload Definition and Integration Study - Executive Summary	1	General Dynamics	CASD-NAS-74-046	San Diego, CA.	08/01/74
SBI30	NASA	SL-3 Ames Research Center Life Sciences Payload Familiarization Manual		Ames Research Center	ADP-81-50-001	Moffet Field, CA.	02/01/81
SBI31	Rockwell Intl.	EMS Data Data Package 2.3A S4200.2 Methodology Definition - Commonality Analysis Trade Study		Rockwell Internation	SSS 85-0168	Downey, Ca.	10/04/85
SBI32	Rockwell Intl.	EMS Data Data Package 2.2B S4201.2, Module Commonality Analysis		Rockwell International	SSS 85-0137	Downey, CA	09/06/85
SBI33	General Electric	Space Station Work Package 3 Definition And Preliminary Design Commonality Candidates		General Electric Space Systems Division	DRD - 19	Philadelphia, PA	05/10/85
SBI34	Rockwell Intl.	EMS Data Data Package 2.3A S4203.2, Module Outfitting/System Commonality Analysis		Rockwell International	SSS 85-0158	Downey, CA	10/28/85

Table 4.1-2 Bibliography for Modularity and Commonality

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI35	NASA JSC	Space Station Freedom Human-Oriented Life Sciences Research Baseline Reference Experiment Scenario		JSC- Medical Sciences Space Station Office	Blue Book	Houston, TX.	10/01/88
SBI39	NASA JSC	July 1988 Pogress Report On Experiment Standard User Interfaces Study		JSC - Life Sciences Project Division		Houston, TX.	07/01/88
SBI40	Rockwell Intl.	EMS Data Data Package 2.3A S4207.2, GSE Commonality Analysis		Rockwell International	SSS 85-0099	Downey, CA	10/04/85
SBI41	NASA OSSA	Life Sciences Space Station Planning Document: A Reference Payload For The Life Sciences Research Facility		Office of Space Science and Applications	NASA TM 89188	Washington, D.C.	01/01/86
SBI44	Huffstetler, W.	Skylab Biomedical Hardware Development		AIAA 20th Annual Meeting		Los Angeles, CA	08/22/74
SBI46	Anderson, A.	Progressive Autonomy - For Space Station Systems Operation		AIAA		New York, NY	06/05/84
SBI47	NASA JSC	Life Sciences Research Laboratory (LSRL) Human Research Facility forSpace Station Initial Operating Configuration (IOC) Science Reqts.		NASA JSC	JSC 20799	Houston, TX	10/01/85
SBI48	MDAC	Crew Health Care System (CHec) Development Plan		Mcdonnell Douglas Space Station Co.		Houston, TX.	01/28/89
SBI49	Minsky, M.	Engines of Creation		Anchor Press		New York, NY	01/10/86
SBI50	MDAC	Crew Health Care	1	MDAC	MDC H3924	Houston, Texas	11/01/88

Table 4.1-2 Bibliography for Modularity and Commonality

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI54	NASA JSC	Mission Integration Plan		NASA JSC	SSP 30000 Appendix D	Houston, TX.	04/30/86
SBI55	Pacheo	Analyzing Commonality in a System		Boeing	NASA STI Facility	Baltimore, MD.	03/01/88
SBI56	NASA MSFC	Spacelab Configurations					/ /
SBI68	Hamaker, Joe	Telephone interview relating to MSFC history and techniques for cost estimating.		Cost Analysis Branch Chief MSFC		Huntsville, Al.	04/27/89
SBI69	Booker, Clef	Personal Interview		Man-Systems Division JSC		Houston, TX.	04/04/89
SBI70	Evans, Jim	Personal Interview		Life Science Project Division JSC		Houston, TX.	04/19/89
SBI76	Trowbridge, John	Personal interview relating CHeC experience to miniaturization, modularity and make-or-buy		McDonnell Douglas		Houston, TX.	03/29/89
SBI78	McFadyen, Gary	Personal Interview relating to life science hardware background at JSC		Southwest Research Institute		Houston, TX.	04/10/89
SBI80	McFadyen	Bioengineering on SBI hardware		Southwest Research Institute		San Antonio, TX.	04/06/89
SBI81	Allen, Joe	Personal interview - S.S. Life Science AIAA Meeting		Space Industries		Houston, TX.	04/07/89
SBI82	Averner, Maurice	Personal interview on CELSS		NASA HQ. CELSS Coordinator		Washington, DC.	04/07/89
SBI83	Fogleman, G. PhD	Personal interview relating to Gas Grain Simulation Facility		NASA AMES		Moffet Field, CA.	04/06/89

Table 4.1-2 Bibliography for Modularity and Commonality

ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI84	White. Bob	Personal Interview relating to modularity and commonality		NASA JPL		Pasadena, CA.	04/10/89
SBI85	Grumm, Richard	Personal interview relating to SBI hardware		NASA JPL		Pasadena, CA.	04/11/89
SBI86	Boeing	U.S. Lab Review Workshop					/ /
SBI87	McGillroy,B.	Personal Interview on CELSS		NASA AMES		Moffet Field, CA	05/05/89
SBI89	Boeing	Space Station Program Commonality Plan Draft 3		Boeing	D683-10112-1		10/31/88

5.0 Modularity/Commonality Trade Study

5.1 Guidelines for Modularity/Commonality Functional Elements

Modular functional elements are readily replaceable Modules should be plug-in with blind-mating connectors, guides, and hold-down hardware that facilitates installation and removal.

Modular functional elements are readily maintainable Individual elements should have well-defined functional characteristics to facilitate trouble shooting and allow the use of automatic test sets - module design should enhance accessibility for servicing.

Modular functional elements facilitate system modification and expansion Individual elements should have well-defined interface characteristics of individual functions should be reasonably general to allow application flexibility.

Modular functional elements may not be adaptable to incorporation of technological advances. The chosen functional level might not readily accommodate a new approach to component usage.

Common items should perform the same function as another item, which does not harm or degrate the system performance of that individual hardware item.

5.2 SBI Hardware Sample Selection

The Space Biology Hardware Baseline list is shown in Appendix A. This list has 169 hardware items, however, only 93 of these items are categorized for SBI functions. This list was based-lined December 1988 and then updated 23 March 1989. Many of these items are in the conceptional phase; however, some are existing hardware items that are in existence today. There will more than likely be future additions and deletions to this baseline list.

The initial survey data analysis was performed to select a sample of the SBHB items which could be potential candidates for implementation of modularity and commonality. With limited study time and a SBHB of 93 items, a method was needed to separate items which could have large cost impact and were worthy of study resource application. The following method was used. All SBHB items were listed in descending order of probable acquisition cost. Weight was used as an indication of probable acquisition cost based on historical experience in previous space programs. It was found that 34 percent of the items (32 items) accounted for 93 percent of the mass or probable cost (Table 5.2-1). The accumulated volume (8.68 M^3) of the 32 items represents 87% of the total volume. The accumulated power (8455 watts) represents 82% of total power requirements

The prioritized list of "vital" hardware items was considered for modularization and commonality. This list was further examined for those items that can be considered as a sample set of candidates for possible modularization (Table 5.2-2) and for commonality (Table 5.2-3). This list showing the possible level of modularity and commonality was developed using all available resources within the constraints of this trade study. This assessment of possible candidates is based upon the best knowledge of the SBI hardware items at the time of this study.

There will be additions and deletions from this list as new developments and techniques become known.

5.2.1 Modularity Candidate Sample Set

All of the items in Table 5.2-2 were analyzed to determine if the entire item could be modularized or at least a portion of the components within the item could be modularized. The items that did not meet this category are marked with a No in the "Modularity Potential Column" on Table 5.2-2. The confidence level is an indication of the knowledge and understanding of the individual item at the time of this study. There are 5 items out of the 32 that had insufficient data due to the fact that they are new developments still under the conception phase. There were two areas where the items which have modularization potential were grouped together due to the interrelationship of the individual items (function checks and experiments requires more than one item to complete) These two groups are labeled (P) for Pulmonary and (PL) for Plant Monitoring. There are other areas which may be grouped together but were not considered in the study. The Pulmonary Group has a total of (11) eleven hardware items (#56 thru 66 Appendix A Group 3A) Most of these items are interrelated which is why these items should be packaged (modularized) together. A portion of this group is already packaged together and will be flown on SLS-1 as Astronaut Lung Function Equipment (ALFE). The mass spectrometer is the heaviest item in this group and special handling will be required when dealing with gas analysis (molecular fragments according to their atomic mass). There can be a tremendous cost and weight savings if the mass spectrometer can be used for other SBI functions (Plant Monitoring etc.). Some of the components in the mass spectrometer may be common; however, the details and practicality of adapting the unit to different applications is not known at this time. The CELSS hardware item is presently being planned as a separate experiment for plant monitoring ("crop growth research facility for seed-to-seed crop studies"). This appears to be the same function as the other items for plant monitoring and was therefore placed in this group.

The modularity candidate sample set was derived by filtering the "vital" list in Table 5.2-2 to remove SBI hardware items which did not appear to warrant analysis at this time. The sample set (Table 5.2.1) resulted from removing hardware items from the "vital" list that have:

A. Insufficient data to preform assessments.

B. No modularization potential and assessment confidence level is high.

C. Modularity potential, but the assessment level is low (unless part of a group).

5.2.2 Commonality Candidate Sample Set

The candidate hardware items were defined for commonality by sorting the modularity/commonality data base on the basis of having a common function/assemblies. The "vital" hardware items were evaluated for the potential of containing functions/assemblies in a representative list that was considered for this SBI trade study. A subjective analysis was performed as to which hardware items might use each given function/assembly. The amplifier has six areas where it might be used. The Pulmonary Function Equipment Storage Assembly

hardware item would not use an amplifier; however, the Pulmonary Group will more than likely use this function. This type of analysis was used throughout the study for commonality. The numbers for common items will be subjective; however, this methodology was used to make a selection of those hardware items that may have possible potential cost savings through commonality. The level of commonality was analyzed to the lowest level possible with the available information. In most cases this was the assembly level or in a few cases subassembly. The level of commonality has a direct effect on the implementation of the common solution and the degree of commonality, which also has a direct affect on the overall cost of the program. (Ref. SBI #88)

All 28 (32-4 with insufficient data) of the vital hardware items had some areas of commonality (Table 5.2-3). The maximum number of common functions/assemblies shown on Table 5.2-3 is ten (10) and the smallest number is one (1).

5.3 Relative SBI Modularization and Commonality Cost Impact Analysis

Since modularity and commonality have multielements related design aspects (i.e. it is difficult to have successful modularity/commonality in a single equipment element), no example hardware item candidate was selected for individual cost analysis. The subjects were addressed in the multielement context or as related to the function that is modular or common.

5.3.1 Modularization Cost Impact Analysis

The redesign of the items listed for modularity will in most cases add additional cost. However, this redesign cost if incorporated into the initial conception phase may not add cost to the item. This initial increase in cost will in most cases be make up when life cycle analysis is incorporated into the overall cost. (Appendix C Table 7-1) The grouping of the hardware items may reduce an overlap in development cost if controlled by one organization.

5.3.2 Commonality Cost Impact Analysis

The candidate list of 32 hardware items was analyzed for commonality using the representative list of 27 functions/assemblies. The number of "Vital" SBI hardware items having potential application for each type of function/assembly has been compiled in Table 5.3.2. A lower level of commonality (i.e. subassembly/component) would increase the number of potential functions that would be common to the individual hardware items. This lower level of commonality may also allow for modularity of various subassemblies that would be common to more items. The number of common items would have a direct effect upon other areas such as the number of spares required, maintainability, transportation, packaging, storage, power requirements, crew training, crew time lines, and other potential cost drivers.

5.3.2.1 Empirical Cost Relationships

Analysis of the relative cost impact resulting the use of various numbers of common functions/assemblies in Table 5.3.2 must be based on empirical cost relationships since hardware definitions are not available. Appendix C contains a detailed definition of cost assessment techniques which can be applied to commonality. The techniques relate theoretical first unit

(TFU) cost to design and development (DD) cost and then applies learning factors to demonstrate the cost reduction potential for common application of hardware in SBI.

To further demonstrate how this assessment was applied to this trade study the formula used for calculations will be repeated from Appendix C Section 3.2.

$$CP_1 = D+Dcost\ (.35 \text{ or } .15\ D\&D \times L.F.)\ N$$

CP_1	= Cost of a single program or one (1) item
D&D	= Design and Development Cost
TFU	= Theoretical First Unit Cost
L.F.	= Learning Factor
N	= Number of Common Functions/Assemblies

For calculations used in this study

.15 and .35 D&D	= TFU
.80	= L.F.
Range of 0 to (10) Ten	= N

The Design and Development (D&D) cost factors of .15 and .35 were both used to give the range for the Theoretical First Unit (TFU) cost. The learning factor (L.F.) has a wide range based upon the type of hardware, type of fabrication, and type of manufacturing (automation). Table 3-5 in Appendix C displays the range of learning factors. This trade study used 80% (0.80) as an average learning factor (L.F.). The number (N) of common functions/assemblies for the SBI hardware items is from Table 5.2-3 (Data base print out). These numbers were generated from the information available at the time of this study. This same information on Table 5.2-3 is repeated in Table 2.2-3 Executive Summary.

The Figures 3-2 and 3-3 in appendix C were generated using (.35 D&D and .80 L.F. for Figure 3-2) and (.15 D&D and .80 L.F. for Figure 3-3) However, these figures only show (5) five items (N) and are shown primarily to dramatize the tremendous cost reduction for the first few units.

5.3.2.2 Lot Certification

The certification of various lots within the SBI Program is not feasible at this time.

5.3.2.3 Design Cost Reduction

The design cost reductions of the SBI items can be seen in Table 5.3.2-1 which shows the best possible candidates and the potential cost percentage reduction for these functions. This cost reduction is for applications within the SBI hardware list. There may be considerable more reduction if the trade study were to include other areas within Space Station Freedom. Many of the SBI commonality functions are common to the functions of Crew Health Care (CHeC) System, Extended Crew Operations (EDCO), and other Life Science activities. SBI #48 & 76.

Table 5.2-1 Database Listing of SBI Hardware Vital to Program Cost Impact Analysis

ITEM # PRIORITIZED BY MASS	HW ITEM #	HARDWARE ITEM NAME	ACCUM % OF ITEMS	MASS (kg)	ACCUM MASS	ACCUM MASS PERCENT	ACCUM POWER PERCENT	ACCUM VOLUME PERCENT
1	168	CELSS Test Facility	1	1000.0	1000	28	13	19
2	169	Gas Grain Simulator	2	800.0	1800	51	27	38
3	84	Soft Tissue Imaging System	3	300.0	2100	59	35	48
4	77	Hard Tissue Imaging System	4	136.0	2236	63	38	51
5	126	Scintillation Counter	5	90.0	2326	66	42	53
6	74	Force Resistance System	6	70.0	2396	68	45	57
7	145	Automated Microbal System	8	70.0	2466	70	46	59
8	155	Total Hyrdocarbon Analyzer	9	70.0	2536	72	48	61
9	161	Inventory Control System	10	70.0	2606	74	53	63
10	162	Lab Materials Packaging & Handling Equipment	11	70.0	2676	76	58	65
11	163	Test/Checkout/Calibration Instrumentation	12	70.0	2746	78	60	67
12	106	Neck Baro-Cuff	13	45.2	2791	79	61	69
13	113	Blood Gas Analyzer	14	45.0	2836	80	63	70
14	61	Mass Spectrometer	15	40.7	2877	81	65	71
15	112	Plant HLPC Ion Chromatograph	16	40.0	2917	83	67	72
16	147	Head/Torso Phantom	17	32.0	2949	83	67	73
17	63	Pulmonary Gas Cylinder Assembly	18	30.0	2979	84	67	74
18	110	Plant Gas Chromatograph/Mass Spectrometer	19	25.0	3004	85	68	76
19	115	Chemistry System	20	23.0	3027	86	69	77
20	138	Hematology System	22	23.0	3050	86	71	78
21	34	Sample Preparation Device	23	22.0	3072	87	73	79
22	165	Experiment Control Computer System	24	20.1	3092	87	77	80
23	62	Pulmonary Function Equipment Stowage Assembly	25	20.0	3112	88	77	80
24	82	Motion Analysis System	26	20.0	3132	89	77	81
25	99	Animal Biotelemetry System	27	20.0	3152	89	78	81
26	100	Blood Pressure and Flow Instrumentation	28	20.0	3172	90	80	82
27	109	Venous Pressure Transducer/Display	29	20.0	3192	90	81	82
28	129	Cell Handling Accessories	30	20.0	3212	91	82	83
29	57	Bag-in-Box	31	19.0	3231	91	82	84
30	111	Plant Gas Cylinder Assembly	32	19.0	3250	92	82	85
31	119	Gas Cylinder Assembly	33	19.0	3269	92	82	86
32	130	Cell Harvestor	34	19.0	3288	93	82	87

NOTES:

1. Total number of SBI hardware items = 93.
2. 89 items have 3535 kg mass, 10,359 Watts power, and 10 cubic meters volume.
3. 4 items are not currently defined, but all are small.

Table 5.2-2 Database Li. .ing for Modularity Sample Selection Assesment

Item # Prioritized by Mass	HW Item #	Hardware Item Name	Sufficient Data Available	Modularity	Modularity Confidence Level
1	168	CELSS Test Facility	Yes	PL	High
2	169	Gas Grain Simulator	Yes	Item	High
3	84	Soft Tissue Imaging System	No		
4	77	Hard Tissue Imaging System	No		
5	126	Scintillation Counter	Yes	Item	High
6	74	Force Resistance System	Yes	No	Low
7	145	Automated Microbal System	Yes	Item	High
8	155	Total Hyrdocarbon Analyzer	No		
9	161	Inventory Control System	Yes	Item	High
10	162	Lab Materials Packaging & Handling Equipment	Yes	Item	Low
11	163	Test/Checkout/Calibration Instrumentation	Yes	Item	High
12	106	Neck Baro-Cuff	Yes	Item	High
13	113	Blood Gas Analyzer	No	Item	Low
14	61	Mass Spectrometer	Yes	P	Low
15	112	Plant HLPC Ion Chromatograph	Yes	PL	High
16	147	Head/Torso Phantom	Yes	No	High
17	63	Pulmonary Gas Cylinder Assembly	Yes	P	Low
18	110	Plant Gas Chromatograph/Mass Spectrometer	Yes	PL	Low
19	115	Chemistry System	Yes	Item	Low
20	138	Hematology System	Yes	Item	Low
21	34	Sample Preparation Device	Yes	Item	Low
22	165	Experiment Control Computer System	Yes	Item	High
23	62	Pulmonary Function Equipment Stowage Assembly	Yes	P	Low
24	82	Motion Analysis System	Yes	No	Low
25	99	Animal Biotelemetry System	Yes	No	Low
26	100	Blood Pressure and Flow Instrumentation	No		
27	109	Venous Pressure Transducer/Display	No		
28	129	Cell Handling Accessories	Yes	Item	Low
29	57	Bag-in-Box	Yes	P	Low
30	111	Plant Gas Cylinder Assembly	Yes	PL	Low
31	119	Gas Cylinder Assembly	Yes	Item	Low
32	130	Cell Harvestor	Yes	Item	Low

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
** AERSOL GENERATOR				
AERSOL GENERATOR	2	169	Gas Grain Simulator	1
** Subtotal **				1
** AMPLIFIERS				
AMPLIFIERS	11	163	Test/Checkout/Calibration Instrumentation	1
AMPLIFIERS	12	106	Neck Baro-Cuff	1
AMPLIFIERS	16	147	Head/Torso Phantom	1
AMPLIFIERS	22	165	Experiment Control Computer System	1
AMPLIFIERS	23	62	Pulmonary Function Equipment Stowage Assembly	1
AMPLIFIERS	25	99	Animal Biotelemetry System	1
** Subtotal **				6
** AUTOMATION/ROBOTICS				
AUTOMATION/ROBOTICS	1	168	CELSS Test Facility	1
AUTOMATION/ROBOTICS	10	162	Lab Materials Packaging & Handling Equipment	1
AUTOMATION/ROBOTICS	11	163	Test/Checkout/Calibration Instrumentation	1
AUTOMATION/ROBOTICS	15	112	Plant HLPC Ion Chromatograph	1
AUTOMATION/ROBOTICS	16	147	Head/Torso Phantom	1
AUTOMATION/ROBOTICS	21	34	Sample Preparation Device	1
** Subtotal **				6
** CAMERAS/VIDEO				
CAMERAS/VIDEO	1	168	CELSS Test Facility	1
CAMERAS/VIDEO	2	169	Gas Grain Simulator	1
CAMERAS/VIDEO	6	74	Force Resistance System	1
CAMERAS/VIDEO	24	82	Motion Analysis System	1
CAMERAS/VIDEO	25	99	Animal Biotelemetry System	1
** Subtotal **				5

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
** CENTRIFUGE				
CENTRIFUGE	13	113	Blood Gas Analyzer	1
CENTRIFUGE	15	112	Plant HLPC Ion Chromatograph	1
CENTRIFUGE	19	115	Chemistry System	1
CENTRIFUGE	20	138	Hematology System	1
** Subtotal **				4
** COMPUTERS & ACCESSORIES				
COMPUTERS & ACCESSORIES	1	168	CELSS Test Facility	1
COMPUTERS & ACCESSORIES	2	169	Gas Grain Simulator	1
COMPUTERS & ACCESSORIES	6	74	Force Resistance System	1
COMPUTERS & ACCESSORIES	7	145	Automated Microbal System	1
COMPUTERS & ACCESSORIES	9	161	Inventory Control System	1
COMPUTERS & ACCESSORIES	11	163	Test/Checkout/Calibration Instrumentation	1
COMPUTERS & ACCESSORIES	15	112	Plant HLPC Ion Chromatograph	1
COMPUTERS & ACCESSORIES	22	165	Experiment Control Computer System	1
COMPUTERS & ACCESSORIES	24	82	Motion Analysis System	1
COMPUTERS & ACCESSORIES	25	99	Animal Biotelemetry System	1
** Subtotal **				10
** CONVERTERS				
CONVERTERS	1	168	CELSS Test Facility	1
CONVERTERS	2	169	Gas Grain Simulator	1
CONVERTERS	11	163	Test/Checkout/Calibration Instrumentation	1
CONVERTERS	12	106	Neck Baro-Cuff	1
CONVERTERS	13	113	Blood Gas Analyzer	1
CONVERTERS	15	112	Plant HLPC Ion Chromatograph	1
CONVERTERS	25	99	Animal Biotelemetry System	1
** Subtotal **				7
** DETECTORS				
DETECTORS	9	161	Inventory Control System	1
DETECTORS	13	113	Blood Gas Analyzer	1
DETECTORS	15	112	Plant HLPC Ion Chromatograph	1

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
DETECTORS	16	147	Head/Torso Phantom	1
DETECTORS	25	99	Animal Biotelemetry System	1
** Subtotal **				5
** DISPLAYS-TRANSDUCERS				
DISPLAYS-TRANSDUCERS	11	163	Test/Checkout/Calibration Instrumentation	1
DISPLAYS-TRANSDUCERS	15	112	Plant HLPC Ion Chromatograph	1
DISPLAYS-TRANSDUCERS	16	147	Head/Torso Phantom	1
DISPLAYS-TRANSDUCERS	25	99	Animal Biotelemetry System	1
DISPLAYS-TRANSDUCERS	27	109	Venous Pressure Transducer/Display	0
** Subtotal **				4
** ENVIRONMENTAL CONTROL				
ENVIRONMENTAL CONTROL	1	168	CELSS Test Facility	1
ENVIRONMENTAL CONTROL	2	169	Gas Grain Simulator	1
ENVIRONMENTAL CONTROL	6	74	Force Resistance System	1
ENVIRONMENTAL CONTROL	7	145	Automated Microbal System	1
ENVIRONMENTAL CONTROL	11	163	Test/Checkout/Calibration Instrumentation	1
ENVIRONMENTAL CONTROL	13	113	Blood Gas Analyzer	1
ENVIRONMENTAL CONTROL	16	147	Head/Torso Phantom	1
ENVIRONMENTAL CONTROL	25	99	Animal Biotelemetry System	1
** Subtotal **				8
** FLUID HANDLING				
FLUID HANDLING	7	145	Automated Microbal System	1
FLUID HANDLING	13	113	Blood Gas Analyzer	1
FLUID HANDLING	19	115	Chemistry System	1
FLUID HANDLING	20	138	Hematology System	1
FLUID HANDLING	21	34	Sample Preparation Device	1
FLUID HANDLING	28	129	Cell Handling Accessories	1
** Subtotal **				6

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
** FREEZERS				
FREEZERS	1	168	CELSS Test Facility	1
FREEZERS	19	115	Chemistry System	1
FREEZERS	20	138	Hematology System	1
** Subtotal **				3
** GAS HANDLING				
GAS HANDLING	1	168	CELSS Test Facility	1
GAS HANDLING	2	169	Gas Grain Simulator	1
GAS HANDLING	10	162	Lab Materials Packaging & Handling Equipment	1
GAS HANDLING	13	113	Blood Gas Analyzer	1
GAS HANDLING	15	112	Plant HLPC Ion Chromatograph	1
GAS HANDLING	17	63	Pulmonary Gas Cylinder Assembly	1
GAS HANDLING	29	57	Bag-in-Box	1
GAS HANDLING	30	111	Plant Gas Cylinder Assembly	1
GAS HANDLING	31	119	Gas Cylinder Assembly	1
** Subtotal **				9
** MASS SPECTROMETERS				
MASS SPECTROMETERS	2	169	Gas Grain Simulator	1
MASS SPECTROMETERS	11	163	Test/Checkout/Calibration Instrumentation	1
MASS SPECTROMETERS	14	61	Mass Spectrometer	1
MASS SPECTROMETERS	18	110	Plant Gas Chromatograph/Mass Spectrometer	1
** Subtotal **				4
** MICROBIAL MONITORING				
MICROBIAL MONITORING	1	168	CELSS Test Facility	1
MICROBIAL MONITORING	7	145	Automated Microbal System	1
** Subtotal **				2
** MOTORS				
MOTORS	1	168	CELSS Test Facility	1

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
MOTORS	2	169	Gas Grain Simulator	1
MOTORS	12	106	Neck Baro-Cuff	1
MOTORS	15	112	Plant HLPC Ion Chromatograph	1
** Subtotal **				4
** POWER SUPPLY				
POWER SUPPLY	1	168	CELSS Test Facility	1
POWER SUPPLY	2	169	Gas Grain Simulator	1
POWER SUPPLY	11	163	Test/Checkout/Calibration Instrumentation	1
POWER SUPPLY	12	106	Neck Baro-Cuff	1
POWER SUPPLY	13	113	Blood Gas Analyzer	1
POWER SUPPLY	15	112	Plant HLPC Ion Chromatograph	1
POWER SUPPLY	25	99	Animal Biotelemetry System	1
** Subtotal **				7
** PUMPS				
PUMPS	1	168	CELSS Test Facility	1
PUMPS	2	169	Gas Grain Simulator	1
PUMPS	12	106	Neck Baro-Cuff	1
PUMPS	15	112	Plant HLPC Ion Chromatograph	1
** Subtotal **				4
** RADIATION HANDLING				
RADIATION HANDLING	1	168	CELSS Test Facility	1
RADIATION HANDLING	2	169	Gas Grain Simulator	1
RADIATION HANDLING	10	162	Lab Materials Packaging & Handling Equipment	1
RADIATION HANDLING	11	163	Test/Checkout/Calibration Instrumentation	1
RADIATION HANDLING	16	147	Head/Torso Phantom	1
RADIATION HANDLING	32	130	Cell Harvestor	1
** Subtotal **				6
** RECORDERS				
RECORDERS	1	168	CELSS Test Facility	1

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
RECORDERS	2	169	Gas Grain Simulator	1
RECORDERS	6	74	Force Resistance System	1
RECORDERS	7	145	Automated Microbal System	1
RECORDERS	11	163	Test/Checkout/Calibration Instrumentation	1
RECORDERS	12	106	Neck Baro-Cuff	1
RECORDERS	16	147	Head/Torso Phantom	1
RECORDERS	24	82	Motion Analysis System	1
RECORDERS	25	99	Animal Biotelemetry System	1
RECORDERS	29	57	Bag-in-Box	1
** Subtotal **				10
** SAMPLE PREP. ANIMAL				
SAMPLE PREP. ANIMAL	9	161	Inventory Control System	1
SAMPLE PREP. ANIMAL	10	162	Lab Materials Packaging & Handling Equipment	1
SAMPLE PREP. ANIMAL	21	34	Sample Preparation Device	1
SAMPLE PREP. ANIMAL	25	99	Animal Biotelemetry System	1
** Subtotal **				4
** SAMPLE PREP. HUMAN				
SAMPLE PREP. HUMAN	7	145	Automated Microbal System	1
SAMPLE PREP. HUMAN	20	138	Hematology System	1
SAMPLE PREP. HUMAN	21	34	Sample Preparation Device	1
SAMPLE PREP. HUMAN	28	129	Cell Handling Accessories	1
SAMPLE PREP. HUMAN	32	130	Cell Harvestor	1
** Subtotal **				5
** SAMPLE PREP. PLANT				
SAMPLE PREP. PLANT	1	168	CELSS Test Facility	1
SAMPLE PREP. PLANT	2	169	Gas Grain Simulator	1
SAMPLE PREP. PLANT	9	161	Inventory Control System	1
SAMPLE PREP. PLANT	10	162	Lab Materials Packaging & Handling Equipment	1
SAMPLE PREP. PLANT	15	112	Plant HLPC Ion Chromatograph	1
SAMPLE PREP. PLANT	18	110	Plant Gas Chromatograph/Mass Spectrometer	1

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
RECORDERS	2	169	Gas Grain Simulator	1
RECORDERS	6	74	Force Resistance System	1
RECORDERS	7	145	Automated Microbal System	1
RECORDERS	11	163	Test/Checkout/Calibration Instrumentation	1
RECORDERS	12	106	Neck Baro-Cuff	1
RECORDERS	16	147	Head/Torso Phantom	1
RECORDERS	24	82	Motion Analysis System	1
RECORDERS	25	99	Animal Biotelemetry System	1
RECORDERS	29	57	Bag-in-Box	1
** Subtotal **				10
** SAMPLE PREP. ANIMAL				
SAMPLE PREP. ANIMAL	9	161	Inventory Control System	1
SAMPLE PREP. ANIMAL	10	162	Lab Materials Packaging & Handling Equipment	1
SAMPLE PREP. ANIMAL	21	34	Sample Preparation Device	1
SAMPLE PREP. ANIMAL	25	99	Animal Biotelemetry System	1
** Subtotal **				4
** SAMPLE PREP. HUMAN				
SAMPLE PREP. HUMAN	7	145	Automated Microbal System	1
SAMPLE PREP. HUMAN	20	138	Hematology System	1
SAMPLE PREP. HUMAN	21	34	Sample Preparation Device	1
SAMPLE PREP. HUMAN	28	129	Cell Handling Accessories	1
SAMPLE PREP. HUMAN	32	130	Cell Harvestor	1
** Subtotal **				5
** SAMPLE PREP. PLANT				
SAMPLE PREP. PLANT	1	168	CELSS Test Facility	1
SAMPLE PREP. PLANT	2	169	Gas Grain Simulator	1
SAMPLE PREP. PLANT	9	161	Inventory Control System	1
SAMPLE PREP. PLANT	10	162	Lab Materials Packaging & Handling Equipment	1
SAMPLE PREP. PLANT	15	112	Plant HLPC Ion Chromatograph	1
SAMPLE PREP. PLANT	18	110	Plant Gas Chromatograph/Mass Spectrometer	1

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
SAMPLE PREP. PLANT	21	34	Sample Preparation Device	1
SAMPLE PREP. PLANT	30	111	Plant Gas Cylinder Assembly	1
** Subtotal **				8
** SCINTILLATION COUNTER				
SCINTILLATION COUNTER	5	126	Scintillation Counter	1
SCINTILLATION COUNTER	9	161	Inventory Control System	1
SCINTILLATION COUNTER	11	163	Test/Checkout/Calibration Instrumentation	1
SCINTILLATION COUNTER	32	130	Cell Harvestor	1
** Subtotal **				4
** STORAGE LOCKER				
STORAGE LOCKER	2	169	Gas Grain Simulator	1
STORAGE LOCKER	23	62	Pulmonary Function Equipment Stowage Assembly	1
STORAGE LOCKER	30	111	Plant Gas Cylinder Assembly	1
STORAGE LOCKER	31	119	Gas Cylinder Assembly	1
** Subtotal **				4
** TEMP.PRESS.HUMIDITY MONITORING				
TEMP.PRESS.HUMIDITY MONITORING	1	168	CELSS Test Facility	1
TEMP.PRESS.HUMIDITY MONITORING	2	169	Gas Grain Simulator	1
TEMP.PRESS.HUMIDITY MONITORING	9	161	Inventory Control System	1
TEMP.PRESS.HUMIDITY MONITORING	11	163	Test/Checkout/Calibration Instrumentation	1
TEMP.PRESS.HUMIDITY MONITORING	12	106	Neck Baro-Cuff	1
TEMP.PRESS.HUMIDITY MONITORING	13	113	Blood Gas Analyzer	1
TEMP.PRESS.HUMIDITY MONITORING	15	112	Plant HLPC Ion Chromatograph	1
TEMP.PRESS.HUMIDITY MONITORING	16	147	Head/Torso Phantom	1
TEMP.PRESS.HUMIDITY MONITORING	25	99	Animal Biotelemetry System	1
TEMP.PRESS.HUMIDITY MONITORING	29	57	Bag-in-Box	1
** Subtotal **				10
** THERMAL/SHOCK ISOLATION				
THERMAL/SHOCK ISOLATION	9	161	Inventory Control System	1

Table 5.2-3 "Vital" Database Listing for Commonality Sample Selection Assesment

REPRESENTATIVE LIST OF FUNCTIONS AND ASSEMBLIES	PRIORITY # OF SBI HW. ITEM	HW ID #	SBI HARDWARE NAME	COUNT
THERMAL/SHOCK ISOLATION	15	112	Plant HLPC Ion Chromatograph	1
THERMAL/SHOCK ISOLATION	1	168	CELSS Test Facility	1
THERMAL/SHOCK ISOLATION	2	169	Gas Grain Simulator	1
THERMAL/SHOCK ISOLATION	11	163	Test/Checkout/Calibration Instrumentation	1
THERMAL/SHOCK ISOLATION	25	99	Animal Biotelemetry System	1
** Subtotal **				6
*** Total ***				151

Table 5.2.1 Database Listing of Modularity Candidate Sample Set

Item # Prioritized by Mass	HW Item #	Hardware Item Name	Sufficient Data Available	Modularity	Modularity Confidence Level
1	168	CELSS Test Facility	Yes	PL	High
2	169	Gas Grain Simulator	Yes	Item	High
5	126	Scintillation Counter	Yes	Item	High
7	145	Automated Microbal System	Yes	Item	High
9	161	Inventory Control System	Yes	Item	High
11	163	Test/Checkout/Calibration Instrumentation	Yes	Item	High
12	106	Neck Baro-Cuff	Yes	Item	High
14	61	Mass Spectrometer	Yes	P	Low
15	112	Plant HLPC Ion Chromatograph	Yes	PL	High
17	63	Pulmonary Gas Cylinder Assembly	Yes	P	Low
18	110	Plant Gas Chromatograph/Mass Spectrometer	Yes	PL	Low
22	165	Experiment Control Computer System	Yes	Item	High
23	62	Pulmonary Function Equipment Stowage Assembly	Yes	P	Low
29	57	Bag-in-Box	Yes	P	Low
30	111	Plant Gas Cylinder Assembly	Yes	PL	Low

Table 5.3.2 Commonality List of Functions/Assemblies

	Function/Assembly H/W List from Table 5.4.2	Possible Number of SBI H/W Items with Common Functions/Assemblies	Percent Cost Decrease
1	Aerosol Generator	1	0
2	Amplifiers	6	51-59
3	Automation/Robotics	6	51-59
4	Cameras/Video	5	47-55
5	Centrifuge	4	43-51
6	Computers & Accessories	10	59-66
7	Converters	7	54-61
8	Detectors	5	47-55
9	Displays-Transducer	5	47-55
10	Environmental Control	8	55-63
11	Fluid Handling	6	51-59
12	Freezers	3	37-43
13	Gas Handling	9	57-65
14	Mass Spectrometer	4	43-51
15	Microbial Monitoring	2	25-31
16	Motors	4	43-51
17	Power Supply	7	54-61
18	Pumps	4	43-51
19	Radiation Handling	6	51-59
20	Recorders	10	59-66
21	Sample Prep Animal	4	43-51
22	Sample Prep Human	5	47-55
23	Sample Prep Plant	8	55-63
24	Scintillation Counter	4	43-51
25	Storage Locker	4	43-51
26	Temp.Press.Hum. Monitor	10	59-66
27	Thermal/Shock Isolation	6	51-59

6.0 Conclusions

6.1 Discussion

There appears to be a potential cost savings for packaging (modularity) the various hardware items into groups of related activities and then have these supervised by one organization. The optimum case is where identical items can serve multiple purposes and be controlled and standardized by a single specification. The utilization of common components will enhance modularity and standardization across all systems and result in design and operational cost savings. Modularization/commonality should only be considered after assurance that all candidate hardware items will provide the performance, reliability, safety, energy efficiency, and can be worked within the program milestones as if they were developed as unique.

During the early phase of a conceptual design there may be little cost savings (may even add cost) resulting from commonality. However, in the later phases these costs would more than balance out by the elimination of duplicate design activity. These cost saving from commonality could possibly be increased substantially when other programs (i.e. CHeC etc) are considered.

6.2 Implementation Guidelines

- Use commonality as extensively as possible, but use it on only two applications if only two are available. The savings is substantial.
- To assess savings, use realistic learning factors. All SBI elements will be subject to some degree of learning factor.
- Consider minor weight penalties as acceptable for purposes of implementing common modules in design.
- Look outside SBI at CHeCs, etc., to broaden the opportunity to save cost.

6.3 Other Considerations

This trade study was limited to only SBI hardware for modularity and commonality. Future studies should consider Crew Health Care System (CHeC), Extended Crew Operations (EDCO) and other Life Science activities. The potential cost savings from having common modules/components throughout all of these systems is substantial. The cost reduction for spares, maintainability, transportation, packaging, storage, power requirements, crew training, and other potential cost drivers should be considered in all future studies.

Appendix A - Space Biology Hardware Baseline

LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

December 1988
UpDated 23 Mar 89

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
1.8 METER CENTRIFUGE FACILITY (1)					
	SPECIMEN SUPPORT GROUP (1A)				
1	1.8 M Centrifuge	C	2.40	1100	1500
2	Equipment Washer/Sanitizer	W	0.96	320	2500
3	Life Sciences Glove Box (Copy 1 of 2)	W	0.96	350	800
4	Modular Habitat Holding System	C	0.48	200	500
5	Plant Growth Module	C	0.10	50	550
6	Primate Module	C	0.10	50	220
7	Rodent Module	C	0.07	40	230
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2)					
	BIOWASTE COLLECTION & MONITORING GROUP (2A)				
8	Fecal Monitoring System (24 Hr)	E	0.12	25	50
9	Urine Monitoring System (24 Hr)	E	0.20	60	50
	BIOLOGICAL SAMPLE STORAGE GROUP (2B)				
10	Freeze Dryer	W	0.07	19	140
11	Freezer (-20 deg. C)	W	0.48	120	300
12	Freezer (-70 deg. C)	W	0.48	120	300
13	Freezer Cryogenic (-196 deg. C) w/ Snap Freezer	W	0.09	20	0
14	Radiation Shielded Locker (Copy 1 of 2)	W	0.20	80	0
15	Refrigerator (4 deg. C)	W	0.48	120	300

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2), (con't)					
	SAMPLE COLLECTION AND PROCESSING GROUP (2C)				
16	Animal Tissue Biopsy Equipment	S	0.03	8	0
17	Blood Collection System	S	0.02	1	0
18	Centrifuge Refrigerated	W	0.15	40	450
19	Centrifuge Standard Lab	E	0.09	26	200
20	Digital Thermometer	W	0.01	2	34
21	Drug Administration Equipment	E	0.01	1	0
22	Electrofusion Device	S	0.06	TBD	TBD
23	Fixation Unit	S	0.02	4	0
24	Fluid Handling Tools/System	W	0.48	80	100
25	Laboratory Sciences Workbench	W	0.96	300	700
26	Life Sciences Glove Box (Copy 2 of 2)	W	0.96	350	800
27	Microscope System (Stereo Macroscope Subset, Copy 2	W	0.25	80	200
28	Muscle Biopsy Equipment	S	0.01	1	0
29	Perfusion & Fixation Unit	S	0.01	2	0
30	Plant Care Unit	S	0.05	10	50
31	Plant Harvest/Dissection Unit	S	0.01	4	20
32	Radioimmunoassay Prep Device	E	0.01	2	0
33	Saliva Collection Unit	S	~~0.01~~ .001	~~1~~ .2	0
34	Sample Preparation Device	S	0.17	22	150
35	Shielded Isotope Container	E	0.02	22	0
36	Specimen Labeling Tools/Device	W	0.01	4	20
37	Surgery/Dissection Tools	W	0.06	20	0
38	Sweat Collection Device	S	~~0.01~~ .005	~~TBD~~ 5.05	~~0~~ .15

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOLOGICAL SAMPLE MANAGEMENT FACILITY (2), (con't)					
	RODENT SUPPORT GROUP (2D)				
39	CO2 Administration Device	S	0.01	3	0
40	Rodent Blood Collection System	S	0.03	10	50
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S	0.01	2	50
42	Rodent Guillotine	S	0.01	4	0
43	Rodent Restraint	S	0.01	3	0
44	Rodent Surgery Platform	S	0.01	3	0
45	Rodent Surgery/Dissection Unit	S	0.01	3	0
46	Rodent Urine Collection System	S	0.03	10	50
47	Rodent Veterinary Unit	S	0.03	10	0
	PRIMATE SUPPORT GROUP (2E)				
48	Primate Blood Collection System	S	0.05	2	140
49	Primate Handling Equipment	S	0.01	1	0
50	Primate LBNP Device	S	0.05	3	140
51	Primate Surgery Platform	S	0.04	5	0
52	Primate Surgery/Dissection Unit	S	0.02	5	0
53	Primate Urine Collection System	S	0.01	10	14
54	Primate Veterinary Unit	S	0.03	10	0
55	Small Primate Restraint	S	0.05	2	0

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (3)					
	PULMONARY ANALYSIS GROUP (3A)				
56	Bag Assembly	S	0.01	1	0
57	Bag-In-Box	S	0.15	19	0
58	Doppler Recorder	E	0.01	1	0
59	Electronics Control Assembly	S	0.08	13	100
60	Mask/Regulator System	S	0.01	3	30
61	Mass Spectrometer	S	~~0.02~~ .087	~~10~~ 40.7	~~100~~ 200
62	Pulmonary Function Equipment Stowage Assembly	S	~~0.39~~ .051	20	0
63	Pulmonary Gas Cylinder Assembly	S	0.09	30	0
64	Rebreathing Assembly	S	0.02	1	0
65	Spirometry Assembly	S	0.01	1	0
66	Syringe (3 Liter Calibration)	S	0.01	2	0
	PHYSICAL MONITORING GROUP (3B)				
67	Accelerometer And Recorder	S	0.04	16	35
68	Anthropometric Measurement System	S	0.02	~~TBD~~ 1	0
69	Cameras	W	0.15	50	150
70	Compliance Volumometer	S	~~0.06~~ .015	~~TBD~~ 16	~~TBD~~ 130
71	Electroencephalomagnetogram (EEMG)	S	0.06	~~TBD~~ 2	TBD
72	Electromyograph (EMG)	E	0.01	2	20
73	Force Measurement Device	E	0.01	1	10
74	Force Resistance System	S	0.40	70	~~100~~ 220
75	Fundus Camera	S	0.03 .003	~~TBD~~ 2	~~TBD~~ Bat. Of
76	Goniometer And Recorder	E	0.01	2	25

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (con't)					
	PHYSICAL MONITORING GROUP (3B) (con't)				
77	Hard Tissue Imaging System	S	0.29	136	300
78	Mass Calibration Unit	S	0.01	2	0
79	Mass Measurement Device-Body	E	0.65	35	15
80	Mass Measurement Device-Micro	W	0.08	17	15
81	Mass Measurement Device-Small	W	0.08	17	15
82	Motion Analysis System	S	0.05	20	100
83	Plethysmograph Measuring System	S	0.01	3	30
84	Soft Tissue Imaging System	S	0.96	300	800
85	Tonometer	S	~~0.01~~ .0002	~~TBD~~ .06	~~0~~ Bat OP
86	Video System	E	0.10	30	300
	NEUROPHYSIOLOGICAL ANALYSIS GROUP (3C)				
87	EEG Cap	S	0.01	2	0
88	EEG Signal Conditioner	S	0.01	2	20
89	Electrode Impedance Meter	E	0.01	1	0
90	Electro-oculograph (EOG)	E	0.01	2	20
91	Neurovestibular ECDI	E	0.09	11	120
92	Neurovestibular Helmet Interface Box	E	0.01	2	20
93	Neurovestibular Helmet Assembly	E	0.04	13	110
94	Neurovestibular Helmet Restraint	E	0.01	2	20
95	Neurovestibular Optokinetic Stimulus	E	0.01	2	20
96	Neurovestibular Rotating Chair	E	0.12	38	220
97	Subject Restraint System	E	0.05	18	0
98	Visual Tracking System	S	0.01	2	20

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
BIOINSTRUMENTATION & PHYSIOLOGICAL MONITORING FACILITY (con't)					
	CARDIOVASCULAR GROUP (3D)				
99	Animal Biotelemetry System	S	0.05	20	100
100	Blood Pressure And Flow Instrumentation	S	0.06	20	200
101	Cardiodynamic Monitor	S	0.02	4	150
102	Electrocardiograph (ECG)	S	0.01	2	20
103	Holter Recorder	S	0.01	2	0
104	Human Biotelemetry System	E	0.05	17	140
105	LBNP Device — CAROTID SINUS BARORECEPTOR STIMULATOR	E	0.16	20	55
106	(Neck Baro-Cuff)	S	~~0.10~~ .132	~~TBD~~ 45.2	~~TBD~~ 145
107	Physiological Hemodynamic Assess Device	E	0.05	18	100
108	Ultrasonic Imaging System	W	0.20	70	600
109	Venous Pressure Transducer/Display	S	0.05	20	100
	PLANT MONITORING GROUP (3E)				
110	Plant Gas Chromatograph/Mass Spectrometer	S	0.20	25	100
111	Plant Gas Cylinder Assembly	S	0.09	19	0
112	Plant HPLC Ion Chromatograph	S	0.12	40	200

source codes: C=1.8 CFR S=SDL E=EDCO W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
ANALYTICAL INSTRUMENTS FACILITY (4)					
BIOLOGICAL SAMPLE ANALYSIS GROUP (4A)					
113	Blood Gas Analyzer	S	0.13	45	250
114	Chemistry Analysis System	E	0.10	30	200
115	Chemistry System	S	0.08	23	100
116	Continuous Flow Electrophoresis Device	S	0.06	TBD	TBD
117	ELISA Reader	E	0.02	6	100
118	Gas Chromatograph/Mass Spectrometer	W	0.20	25	100
119	Gas Cylinder Assembly	S	0.09	19	0
120	High Performance Liquid Chromatograph	W	0.12	40	100
121	Incubator (35-65 deg C Copy 1 of 2)	W	0.16	50	400
122	Osmometer	E	0.02	5	20
123	pH Meter/Ion Specific Analyzer	W	0.02	7	5
124	Qualitative Reagent Strip And Reader	S	0.03	10	100
125	Radioimmunoassay	E	0.05	20	0
126	Scintillation Counter	S	0.24	90	500
127	Spectrophotometer (UV/VIS/NIR)	W	0.11	40	300
128	Urine Analysis System	E	0.16	55	400
CELL ANALYSIS GROUP (4B)					
129	Cell Handling Accessories	S	0.05	20	50
130	Cell Harvestor	S	0.06	19	50
131	Cell Perfusion Apparatus	S	0.06	TBD	TBD
132	Centrifugal Incubator (5% CO2 @37 deg C Copy 1 of 2)	E	0.16	40	300
133	Centrifugal Incubator (5% CO2 @37 deg C Copy 2 of 2)	E	0.16	40	300

source codes: C=1.8 CFP S=SBI E=EDCO W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS		
			VOLUME (cu. m)	MASS (kg)	POWER (watts)
ANALYTICAL INSTRUMENTS FACILITY (4) (con't)					
CELL ANALYSIS GROUP (4B) (con't)					
134	Centrifuge Hematocrit	S	0.01	2	20
135	Chromosomal Slide Preparation Device	S	0.01	2	20
136	Fluoromeasure Probe	S	0.05	TBD	TBD
137	Flow Cytometer	E	0.24	36	500
138	Hematology System	S	0.07	23	200
139	Image Digitizing System	S	0.25.03	70-114	500
140	Microscope System (Optical & Stereo Macroscope Subsets)	W	0.40	100	400
141	Mitogen Culture Device	E	0.01	2	20
142	Skin Window Device	S	0.01	2	0
143	Slide Preparation Device	E	0.01	2	20

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
LAB SUPPORT EQUIPMENT FACILITY (5)					
	ENVIRONMENTAL MONITORING & CONTROL GROUP (5A)				
144	Accelerometer Subsystem	W	0.10	30	200
145	Automated Microbic System	S	0.20	70	~~500~~ 110
146	Dosimeter, Passive	W	0.09	35	0
147	Head/Torso Phantom	S	0.12	~~TBD~~ 32	0
148	Incubator (35-65 deg C Copy 2 of 2)	W	0.16	50	400
149	Microbial Preparation System	S	0.01	2	~~20~~ 10
150	Radiation Shielded Locker (Copy 2 of 2)	W	0.20	80	0
151	Reuter Microbiology Air Sampler	S	~~0.01~~ .005	~~1~~ 1.45	0
152	Solid Sorbent Air Sampler	S	0.01	5	0
153	Spectrometer (Proton/Heavy Ion)	S	0.03	10	20
154	Tissue Equivalent Proportional Counter	S	~~0.01~~ .001	~~TBD~~ 2	0
155	Total Hydrocarbon Analyzer	S	0.20	70	250
	HARDWARE MAINTENANCE GROUP (5B)				
156	Battery Charger	W	0.03	10	100
157	Camera Locker	W	0.30	100	0
158	Cleaning Equipment	W	0.20	70	500
159	Digital Multimeter	W	0.06	20	50
160	General Purpose Hand Tools	W	0.10	30	0
	LOGISTICS CONTROL GROUP (5C)				
161	Inventory Control System	S	0.20	70	500
162	Lab Materials Packaging & Handling Equipment	S	0.20	70	500
163	Test/Checkout/Calibration Instrumentation	S	0.20	70	200

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)
CENTRALIZED LIFE SCIENCES COMPUTER FACILITY (6)					
	LIFE SCIENCES DATA GROUP (6A)				
164	Digital Recording Oscilloscope	W	0.03	10	100
165	Experiment Control Computer System	S	0.05	20	400
166	Multichannel Data Recorder	E	0.09	30	150
167	Voice Recorder	S	~~0.01~~ .003	~~1~~ .26	~~0~~ Bat. OP
CLOSED ECOLOGICAL LIFE SUPPORT FACILITY (7)					
	FEAST GROUP (7A)				
168	CELSS Test Facility	S	1.92	1000	1300
EXOBIOLOGY FACILITY (8)					
	GAS/GRAIN GROUP (8A)				
169	Gas Grain Simulator	S	1.92	800	1500

source codes: C=1.8 CFP, S=SBI, E=EDCO, W=WP-01

From Neal Jackson 5.23

LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

Baselined: December 1988

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
16	Animal Tissue Biopsy Equipment	S	0.03	8	0				A
17	Blood Collection System	S	0.02	1	0				J
22	Electrofusion Device	S	0.06	TBD	TBD				J
23	Fixation Unit	S	0.02	4	0				A'J
28	Muscle Biopsy Equipment	S	0.01	1	0				A
29	Perfusion & Fixation Unit	S	0.01	2	0				A
30	Plant Care Unit	S	0.05	10	50				A
31	Plant Harvest/Dissection Unit	S	0.01	4	20				A
33	Saliva Collection Unit	S	0.01	1	0	0.001	0.2	0	J
34	Sample Preparation Device	S	0.17	22	150				J'A
38	Sweat Collection Device	S	0.01	TBD	0	0.005	5.05	15	J
39	CO2 Administration Device	S	0.01	3	0				A
40	Rodent Blood Collection System	S	0.03	10	50				A
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S	0.01	2	50				A
42	Rodent Guillotine	S	0.01	4	0				A
43	Rodent Restraint	S	0.01	3	0				A
44	Rodent Surgery Platform	S	0.01	3	0				A
45	Rodent Surgery/Dissection Unit	S	0.01	3	0				A
46	Rodent Urine Collection System	S	0.03	10	50				A
47	Rodent Veterinary Unit	S	0.03	10	0				A
48	Primate Blood Collection System	S	0.05	2	140				A
49	Primate Handling Equipment	S	0.01	1	0				A
50	Primate LBNP Device	S	0.05	3	140				A
51	Primate Surgery Platform	S	0.04	5	0				A
52	Primate Surgery/Dissection Unit	S	0.02	5	0				A
53	Primate Urine Collection System	S	0.01	10	14				A
54	Primate Veterinary Unit	S	0.03	10	0				A
55	Small Primate Restraint	S	0.05	2	0				A
56	Bag Assembly	S	0.01	1	0				J
57	Bag-In-Box	S	0.15	19	0				J
59	Electronics Control Assembly	S	0.08	13	100				J
60	Mask/Regulator System	S	0.01	3	30				J
61	Mass Spectrometer	S	0.02	10	100	0.087	40.7	200	J
62	Pulmonary Function Equipment Stowage Assembly	S	0.39	20	0	0.051	20	0	J
63	Pulmonary Gas Cylinder Assembly	S	0.09	30	0				J
64	Rebreathing Assembly	S	0.02	1	0				J
65	Spirometry Assembly	S	0.01	1	0				J
66	Syringe (3 Liter Calibration)	S	0.01	2	0				J
67	Accelerometer And Recorder	S	0.04	16	35		16.06		J

LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

Baselined: December 1988

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
68	Anthropometric Measurement System	S	0.02	TBD	0		1		J
70	Compliance Volumometer	S	0.06	TBD	TBD	0.0152	16	130	J
71	Electroencephalomagnetogram (EEMG)	S	0.06	TBD	TBD		2		J
74	Force Resistance System	S	0.40	70	100			220	J
75	Fundus Camera	S	0.03	TBD	TBD	0.003	2	Battery Op	J
77	Hard Tissue Imaging System	S	0.29	136	300				J
78	Mass Calibration Unit	S	0.01	2	0				J
82	Motion Analysis System	S	0.05	20	100				J
83	Plethysmograph Measuring System	S	0.01	3	30				J
84	Soft Tissue Imaging System	S	0.96	300	800				J
85	Tonometer	S	0.01	TBD	0	0.000226	0.06	Battery Op	J
87	EEG Cap	S	0.01	2	0				J
88	EEG Signal Conditioner	S	0.01	2	20				J
98	Visual Tracking System	S	0.01	2	20				J
99	Animal Biotelemetry System	S	0.05	20	100				A
100	Blood Pressure And Flow Instrumentation	S	0.06	20	200				A J
101	Cardiodynamic Monitor	S	0.02	4	150				J
102	Electrocardiograph (ECG)	S	0.01	2	20				J
103	Holter Recorder	S	0.01	2	0				J
106	Neck Baro-Cuff	S	0.10	TBD	TBD	0.132	45.2	145	J
109	Venous Pressure Transducer/Display	S	0.05	20	100				J
110	Plant Gas Chromatograph/Mass Spectrometer	S	0.20	25	100				A
111	Plant Gas Cylinder Assembly	S	0.09	19	0				A
112	Plant HPLC Ion Chromatograph	S	0.12	40	200				A
113	Blood Gas Analyzer	S	0.13	45	250				J
115	Chemistry System	S	0.08	23	100				J
116	Continuous Flow Electrophoresis Device	S	0.06	TBD	TBD				J
119	Gas Cylinder Assembly	S	0.09	19	0				J
124	Qualitative Reagent Strip And Reader	S	0.03	10	100				J
126	Scintillation Counter	S	0.24	90	500				J
129	Cell Handling Accessories	S	0.05	20	50				A J
130	Cell Harvestor	S	0.06	19	50				A J
131	Cell Perfusion Apparatus	S	0.06	TBD	TBD				A J
134	Centrifuge Hematocrit	S	0.01	2	20				A J
135	Chromosomal Slide Preparation Device	S	0.01	2	20				J
136	Fluoromeasure Probe	S	0.05	TBD	TBD				J
138	Hematology System	S	0.07	23	200				J
139	Image Digitizing System	S	0.25	70	500	0.03	11.4		J
142	Skin Window Device	S	0.01	2	0				J

A: ARC J: JSC

LIFE SCIENCES HARDWARE LIST FOR THE SPACE STATION FREEDOM ERA

Baselined: December 1988

H/W ITEM #	HARDWARE ITEM NAME	SOURCE CODE	UNIT HARDWARE PARAMETERS VOLUME (cu. m)	MASS (kg)	POWER (watts)	UNIT HARDWARE PARAMETERS UPDATED: 3-Mar BY:DRP VOLUME (cu. m)	MASS (kg)	POWER (watts)	RESP
145	Automated Microbic System	S	0.20	70	500	0.2	70	110	J
147	Head/Torso Phantom	S	0.12	TBD	0		32		J
149	Microbial Preparation System	S	0.01	2	20	0.01	2	110	J
151	Reuter Microbiology Air Sampler	S	0.01	1	0	0.005	1.45		A J'
152	Solid Sorbent Air Sampler	S	0.01	5	0				J
153	Spectrometer (Proton/Heavy Ion)	S	0.03	10	20				J
154	Tissue Equivalent Proportional Counter	S	0.01	TBD	0	0.001	2	0	J
155	Total Hydrocarbon Analyzer	S	0.20	70	250				J
161	Inventory Control System	S	0.20	70	500				A J'
162	Lab Materials Packaging & Handling Equipment	S	0.20	70	500				A'J
163	Test/Checkout/Calibration Instrumentation	S	0.20	70	200				A J'
165	Experiment Control Computer System	S	0.05	20	400				J'A
167	Voice Recorder	S	0.01	1	0	0.003	0.26	Battery Op	J
168	CELSS Test Facility	S	1.92	1000	1300				A
169	Gas Grain Simulator	S	1.92	800	1500				A

Appendix B - Complete SBI Trade Study Bibliography

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI01	Kozarsky, D.	MUS Inputs		Lockheed Life Sciences Program Office	Lockheed Memo	Washington, DC	01/19/89
SBI02	Kozarsky, D.	Latest Space Station Rack Studies		NASA MSFC		Huntsville, AL.	02/02/89
SBI03	Holt, A.	PMWG-SS Freedom Assly. Seq. Trial Pyl. Manifest		Payload Manifest Working Group (PMWG)		Reston, VA.	12/09/88
SBI04	Shannon, J.	Business Practice Low Cost System Activity		NASA JSC		Houston, TX.	11/12/75
SBI05	NASA	Off-the-Shelf Hardware Procurement		NASA JSC	NASA MEMO HB/73-M286	Houston, TX.	05/16/73
SBI06	NASA	OTS Technology Use For Space Shuttle Program		NASA JSC	NASA MEMO	Houston, TX.	11/20/73
SBI07	NASA	Proposed Space Shuttle Directive On OTS HW.		NASA JSC	NASA MEMO NB/74-L149	Houston, TX.	06/20/74
SBI08	NASA	Cancellation Of Space Shuttle Directive On OTS		NASA JSC		Houston, TX.	10/01/74
SBI09	NASA	Agency Balloon Pyl. Util. of Avail. Equip. & Exper		NASA JSC	NASA PLAN 323-50-XX-71	Houston, TX.	05/25/76
SBI10	NASA	Space Shuttle Program DTO/DSO Noncritical Requirements Document		Flight Support Equipment Office - JSC	NSTS 21096	Houston, TX.	08/01/88
SBI11	NASA	Reference Mission Operational Analysis Document (RMOAD) For The Life Sciences Research Facilities.		NASA JSC	NASA TM 89604	Houston, TX.	02/01/87
SBI12	Breiling, R.	Cost Risk Analysis Using Price Models		RCA Price Systems		Mooreston, NJ.	09/01/87
SBI13	Fogleman, G.Schwart, D.Fonda, M.	Gas Grain Simulation Facility: Fundamental Studies of Particle Formation And Interactions	1	NASA Ames Research Center	NASA ARC/SSS 88-01	Moffet Field, CA.	08/31/87

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI14	JPL	Flight Projects Office Payload Classification Product Assurance Provisions		JPL	JPL D-1489 Rev. A	Pasadena, CA.	04/30/87
SBI15	PRC Systems	Cost Estimate For The Search for Extraterrestrial Intelligence (SETI) Revised		PRC Systems Services		Huntsville, AL.	06/15/87
SBI16	NASA SSPO	Space Station Commonality Process Requirements Rev.B		NASA SSPO	SSP 30285 Rev. B	Reston, Virgina	09/15/88
SBI17	Webb, D.	Technology Forecasting Using Price - H		Rockwell International		Anaheim, CA.	04/17/86
SBI18	NASA	Classification Of NASA Office Of Space Science And Applications (OSSA) Space Station Payloads		NASA JSC		Houston, TX.	/ /
SBI19	NASA	Life Science Research Objectives And Representative Experiments For The Space Station (Green Book)		NASA Ames Life Science Division		Moffet Field, CA.	01/01/86
SBI20	NASA	Medical Requirements Of An In-Flight Medical System For Space Station		NASA JSC	JSC 31013	Houston, TX.	11/30/87
SBI21	TRW	A Study Of Low Cost Approaches To Scientific Experiment Implementation For Shuttle Launched And Serviced Automated Spacecraft		TRW Systems Group	Contract NASW - 2717	Redondo Beach, CA.	03/19/89

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI22	LMSC	Low-Cost Program Practices For Future NASA Space Programs		LMSC	LMSC-D387518	Sunnyvale, CA.	05/30/74
SBI23	Steward, GMiller, L	Biomedical Equipment Technology Assesment For The Science Laboratory Module		Management and Technical Services Company		Houston, TX.	08/01/86
SBI24	General Electric	WP-3 Commonality Plan		General Electric	NAS5-32000	Philadelphia, PA	04/22/88
SBI25	NASA	Microbiology Support Plan For Space Station		NASA JSC	JSC-32015	Houston, TX.	09/01/86
SBI26	NASA	Concepts And Requirements For Space Station Life Sciences Ground Support And Operations		NASA JSC	LS-70034	Houston, TX.	04/11/88
SBI27	NASA	Spacelab Mission 4 Integrated Payload Requirements Document		NASA JSC	SM-SE-03	Houston, TX.	06/01/83
SBI28	General Dynamics	Life Sciences Payload Definition And Integration Study	IV	General Dynamics	CASD-NAS-74-046	San Diego, CA.	08/01/74
SBI29	General Dynamics	Life Sciences Payload Definition and Integration Study - Executive Summary	1	General Dynamics	CASD-NAS-74-046	San Diego, CA.	08/01/74
SBI30	NASA	SL-3 Ames Research Center Life Sciences Payload Familiarization Manual		Ames Research Center	ADP-81-50-001	Moffet Field, CA.	02/01/81
SBI31	Rockwell Intl.	EMS Data Data Package 2.3A S4200.2 Methodology Definition - Commonality Analysis Trade Study		Rockwell Internation	SSS 85-0168	Downey, Ca.	10/04/85

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI32	Rockwell Intl.	EMS Data Data Package 2.2B S4201.2, Module Commonality Analysis		Rockwell International	SSS 85-0137	Downey, CA	09/06/85
SBI33	General Electric	Space Station Work Package 3 Definition And Preliminary Design Commonality Candidates		General Electric Space Systems Division	DRD - 19	Philadelphia, PA	05/10/85
SBI34	Rockwell Intl.	EMS Data Data Package 2.3A S4203.2, Module Outfitting/System Commonality Analysis		Rockwell International	SSS 85-0158	Downey, CA	10/28/85
SBI35	NASA JSC	Space Station Freedom Human-Oriented Life Sciences Research Baseline Reference Experiment Scenario		JSC- Medical Sciences Space Station Office	Blue Book	Houston, TX.	10/01/88
SBI36	NASA SSPO	Space Station Approved Electrical Electronic, And Electromechanical Parts List		Space Station Program Office	SSP 30423 Rev. A	Reston, Virgina	11/15/88
SBI37	NASA SSPO	Space Station Program Design Criteria and Practices		Space Station Program Office	SSP 30213 Rev. B	Reston, Virgina	07/30/88
SBI38	MDAC	Manufacturing Management Plan		McDonnel Douglas	DR MU-01	Houston, TX	/ /
SBI39	NASA JSC	July 1988 Pogress Report On Experiment Standard User Interfaces Study		JSC - Life Sciences Project Division		Houston, TX.	07/01/88
SBI40	Rockwell Intl.	EMS Data Data Package 2.3A S4207.2, GSE Commonality Analysis		Rockwell International	SSS 85-0099	Downey, CA	10/04/85
SBI41	NASA OSSA	Life Sciences Space Station Planning Document: A Reference Payload For The Life Sciences Research Facility		Office of Space Science and Applications	NASA TM 89188	Washington, D.C.	01/01/86

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI42	Buroni, A.Pascucci, B	The OBDH test equipment and its goals		ESA		Milan, Italy	10/01/78
SBI43	Shiokari, A.	Standarization and Program Effect Analysis - Final Report	111	Aerospace Corporation		El Segundo, CA	01/01/75
SBI44	Huffstetler, W.	Skylab Biomedical Hardware Development		AIAA 20th Annual Meeting		Los Angeles, CA	08/22/74
SBI45	Powell, A.	Commonality Analysis For The NASA Space Station Common Module - 36 IAF Meeting, October 7-12 1985		Pergamon Press		New York, NY	10/07/85
SBI46	Anderson, A.	Progressive Autonomy - For Space Station Systems Operation		AIAA		New York, NY	06/05/84
SBI47	NASA JSC	Life Sciences Research Laboratory (LSRL) Human Research Facility forSpace Station Initial Operating Configuration (IOC) Science Reqts.		NASA JSC	JSC 20799	Houston, TX	10/01/85
SBI48	MDAC	Crew Health Care System (CHec) Development Plan		Mcdonnell Douglas Space Station Co.		Houston, TX.	01/28/89
SBI49	Minsky, M.	Engines of Creation		Anchor Press		New York, NY	01/10/86
SBI50	MDAC	Crew Health Care	1	MDAC	MDC H3924	Houston, Texas	11/01/88
SBI51	NASA JSC	Columbus Reference Configuration Report		NASA JSC	RP 1213800000	Houston, TX.	05/31/88
SBI52	NASA HQ	Shuttle/Payload I/F Definition Document for Middeck Accomodations		NASA HQ	NSTS 21000	Washington, DC	03/01/88

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI53		Rack Accomodations Users Manual					/ /
SBI54	NASA JSC	Mission Integration Plan		NASA JSC	SSP 30000 Appendix D	Houston, TX.	04/30/86
SBI55	Pacheo	Analyzing Commonality in a System		Boeing	NASA STI Facility	Baltimore, MD.	03/01/88
SBI56	NASA MSFC	Spacelab Configurations					/ /
SBI57	Rockwell Intl.	Space Shuttle Management Proposal	II	Rockwell Intl.	SD 72-SH-50-2		05/12/72
SBI58	LMSC	Space Shuttle Management Proposal	II	LMSC	LMSC-D157364		05/12/72
SBI59	MDAC	Space Shuttle Program Management Proposal		MDAC	E0600		05/12/72
SBI60	MSFC	MSFC Space Station CER's Report		MSFC	PRC D-2185-H		12/01/82
SBI61	NASA JSC	CERV Target Costs for Benchmark and Reference Configurations		JSC CERV Office		Houston, TX.	06/15/88
SBI62	CBO	Cost Estimating For Air Missles		Congressional Budget Office		Washington, D.C.	01/01/83
SBI63	Evans, Jim	Meeting with Jim Evans Technical Assistant, NASA Space and Life Sciences		Eagle Engr.		Houston, TX.	04/19/89
SBI64	Whitlock, R.	JSC Cost Analysis Office		Eagle Engr.		Houston, TX.	04/11/89
SBI65	PRICE	PRICE Users Newsletter	12				10/01/88
SBI66	General Electric	PRICE H Reference Manual					01/01/88
SBI67	NASA JSC	Satellite Services Workshop	1&2	NASA JSC	JSC 20677	Houston, TX.	11/06/85

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI68	Hamaker, Joe	Telephone interview relating to MSFC history and techniques for cost estimating.		Cost Analysis Branch Chief MSFC		Huntsville, Al.	04/27/89
SBI69	Booker, Clef	Personal Interview		Man-Systems Division JSC		Houston, TX.	04/04/89
SBI70	Evans, Jim	Personal Interview		Life Science Project Division JSC		Houston, TX.	04/19/89
SBI71	Heberlig, Jack	Telephone interview relating to make-or-buy lessons learned from Apollo		International Business Machines (IBM)		Houston, TX.	03/10/89
SBI72	Loftus, Joe	Telephone interview relating to make-or-buy history		Assistant Director (Plans) JSC		Houston, TX.	03/14/89
SBI73	Christy, Neil	Telephone interview relating to hardware development student experiments, and make-or-buy				Houston, TX.	03/15/89
SBI74	McAllister, Fred	Telephone Interview		Man-System Division, JSC		Houston, TX	03/14/89
SBI75	Trowbridge, John	Interview relating to CHeC make-or-buy		McDonnell Douglas		Houston, TX.	03/17/89
SBI76	Trowbridge, John	Personal interview relating CHeC experience to miniaturization, modularity and make-or-buy		McDonnell Douglas		Houston, TX.	03/29/89
SBI77	Nagel, John	Personal Interview relating to LSLE make-or-buy experience		Eagle Technical Services		Houston, TX	03/27/89
SBI78	McFadyen, Gary	Personal Interview relating to life science hardware background at JSC		Southwest Research Institute		Houston, TX.	04/10/89

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI79	Booker, Clef	Personal Interview - Minaturization on amplifiers, computers and modularity		NASA JSC/SP 341 Man-System Division		Houston, TX.	04/04/89
SBI80	McFadyen	Bioengineering on SBI hardware		Southwest Research Institute		San Antonio, TX.	04/06/89
SBI81	Allen, Joe	Personal interview - S.S. Life Science AIAA Meeting		Space Industries		Houston, TX.	04/07/89
SBI82	Averner, Maurice	Personal interview on CELSS		NASA HQ. CELSS Coordinator		Washington, DC.	04/07/89
SBI83	Fogleman, G. PhD	Personal interview relating to Gas Grain Simulation Facility		NASA AMES		Moffet Field, CA.	04/06/89
SBI84	White. Bob	Personal Interview relating to modularity and commonality		NASA JPL		Pasadena, CA.	04/10/89
SBI85	Grumm, Richard	Personal interview relating to SBI hardware		NASA JPL		Pasadena, CA.	04/11/89
SBI86	Boeing	U.S. Lab Review Workshop					/ /
SBI87	McGillroy,B.	Personal Interview on CELSS		NASA AMES		Moffet Field, CA	05/05/89
SBI88	NASA JSC	Life Science Flight Experiments Program Life Sciences Laboratory Equipment (LSLE) Descriptions		NASA JSC	JSC-16254-I	Houston, TX.	09/01/86
SBI89	Boeing	Space Station Program Commonality Plan Draft 3		Boeing	D683-10112-1		10/31/88
SBI90	GE Govt.Services	Life Sciences Hardware List for the Space Station Freedom Era - Baselined December 1988 Updated 3/22/89		GE Government Services		Houston, TX.	03/22/89

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ID #	AUTHOR	TITLE	VOL. NO.	PUBLISHER	REPORT/DOCUMENT NUMBER	PUBLISHER LOCATION	DATE
SBI91		NASDA Standard Rack Envelope Study Status		NASDA			/ /
SBI92		Spacelab Payloads Accomodations Handbook		NASA MSFC	SLP/2104	Huntsvillle, Al.	08/16/85
SBI93		Station Interface Accomodations for Pressurized and Attached Payloads		NASA			02/01/89
SBI94		Life Sciences Study for the Space Station		Management and Technical Services Co.		Houston, TX.	08/01/84
SBI95	Crenshaw, John	Personal Interview with John Crenshaw - Discussion of standarized avoins (mounted on racks) in airlines.				Houston, TX.	05/16/89
SBI96	Juran, J.M.	The Non-Pareto Principle Mea Culpa					/ /
SBI97	Arabian, D.	Beware Off-the-Shelf Hardware		NASA JSC		Houston, TX.	10/17/73
SBI98	SBI98NASA JSC	Experimenting with Baroceptor Reflexes	12	NASA Tech Briefs	No. 11	New York, NY	12/01/88

Appendix C - Cost Assessment Techniques Summary

1.0 Introduction

1.1 Relative Cost Impact Analysis Task

JSC and GE Government Services are developing the SBI hardware cost estimate to be presented to NASA Headquarters. The cost related task in these trade studies is to develop and present factors which assist the cost estimators in using tools to develop the effect of the trade study specialty area (miniaturization, modularity and commonality, and Modified COTS) on SBI cost estimates. The life cycle costs are most important in judging the long term benefits of a new project. However, consideration of life cycle costs requires knowledge of the probable project life, operational use time lines, maintenance concepts, and logistics relationships. These data are not available at the time of these initial trade studies. Therefore, the trade studies address primarily the relative cost impact analysis of the design and development phase of the SBI. Life cycle costs are dealt with on a comparative, subjective basis in order to illustrate the influence of life cycle cost factors on the various trade study subjects.

1.2 Documentation Approach

The application of cost methods as applied to SBI trade studies involves some methods common to all of the studies and others that apply uniquely to a specific trade subject. Therefore, the selected approach to the problem is to deal with cost methods and cost trends in this appendix that is to be a part of each study report. In the cost appendix, subsequent sections of Section 1.0 deal with various methods examined for the trade studies, Section 2.0 defines the cost estimating relationship (CER's) and their factors and sensitivities, and Section 3.0 deals with specific variations and parameters of interest with respect to each trade study. Sections 4, 5 and 6 provide brief discussions of testing, SE&I and project management costs, Section 7.0 life cycle effects, and Section 8.0 summarizes the conclusions.

1.3 Cost Method Overview

Cost methods considered and evaluated in the course of this effort include the basic types listed below:

a. Detailed cost build-up method. The detailed cost estimate is compiled using estimates from specialists in the various design disciplines and is constructed from a spread of hours required in design, labor rates, overhead and other factors affecting the cost of DDT&E.

b. General Electric PRICE. The PRICE H model is a sophisticated cost modeling program requiring a variety of inputs including weight, manufacturing complexities, and design complexity plus secondary factors.

c. Cost estimating relationship (CER's). The simplest cost estimating tools are empirical relationships based primarily on system weight and derived to match past experience on previous programs.

d. Cost impact analysis methods. Parametric studies to establish and/or to quantify cost drivers and cost trend effects.

The choice between the foregoing alternatives was narrowed to options c and d which are used in combination as described in the balance of this report. Initial SBI cost estimates will be developed in a separate effort using PRICE H. Therefore, the task in the trade studies is to provide data and/or factors which will be helpful in assisting cost estimators in the use of the tools from which the actual estimates will be formulated. A secondary purpose is to develop parametric trend data that will help the reader understand the potential impact of the various trade study subjects on cost, i.e. miniaturization, commonality, and the use of commercial products (COTS) in lieu of new design.

Empirical cost relationships use system weight as the primary factor in deriving development and theoretical first unit (TFU) costs. A series of such relationships can be used to reflect the inherent complexity of different types of space-borne systems, i.e., one relationship for structural or mechanical systems, a second for packaged electronics, and a third for complex distributed hybrid systems. This approach has its roots in past program experience in that the end results are usually compared with past program actual costs and the relationships adjusted to match what has happened on similar system development during their life cycle. References SBI No. 60 and SBI No. 61 were used as a data source for CER's. Also, a discussion was held with the cost analysis specialist at JSC and MSFC (ref. SBI No. 64 and No. 68) as part of the effort to determine whether or not other cost work has been accomplished on the SBI trade study subjects.

As will be seen in the ensuing sections and in the trade studies proper, the results and trends also employ second order effects such as the amount of new design required, the impact of sophisticated technology and alternate materials.

Regardless of how one approaches the subject of cost development or cost trends there are three fundamental principles are involved in evaluating costs, cost drivers and cost trends (ref. SBI No. 65). These are as follows:

1. Estimates require reasoned judgments made by people and cannot be automated.

2. Estimates require a reasonably detailed definition of the project hardware that must be acquired or developed before estimates can be made.

3. All estimates are based upon comparisons. When we estimate, we evaluate how something is like or how it is unlike things we have seen before.

The SBI Program estimates are particularly challenging because the definition of the hardware items and the data that will permit comparisons is not detailed and complete. We are dealing with some items in their earliest conceptual phase of definition.

A couple of study principles should also be mentioned because they may help us understand the validity of the results we obtain. These are:

1. The sensitivity that study results show to variations in assumption provides an indication as to the fundamental nature of the assumption. If results are highly sensitive to variations in assumption then the assumption should be used with caution. Extrapolations are particularly hazardous in such instances. On the other

hand if results are not highly sensitive, then scaling over a wide range may be feasible, although extrapolations of cost values can yield misleading results in any event and should always be applied carefully.

2. Parametric approaches may be necessary in order to understand trends due to the absence of specific data for use in the study. Parametric in the sense used here means the arbitrary variation of a given parameter over a range of expected values, while holding other values constant.

The costing relationships used in SBI trade studies are applicable to space systems and are founded on past programs as described in references SBI No. 60 and No. 61. The only questions, therefore, are whether or not they can be used on SBI hardware (which does use subsystems similar in nature to other manned space systems) and how accurately they can be scaled to fit the range of SBI sizes. Insofar as practical, these questions have been circumvented by means of reporting cost trends in lieu of cost values.

2.0 General Development Cost Methods

2.1 Empirical Methods

As stated in Section 1.3 CER's are empirical cost estimating relationships that express expected costs on the basis of past program experience. Empirical cost estimating requires some sort of systems definition plus good judgement in the selection of the constants, and exponents. The nature of a system element or assembly, and the size/weight of the item are primary cost drivers. The most predominant variable is the exponent of the weight term in the following generalized equation:

$$\text{Cost} = df * (C_1 (Wt)^n) + C_2 (Wt)^n$$

Where
- wt = weight of the system, module or assembly
- n = an exponent selected on the basis of system complexity
- df = a factor reflecting the amount of new design required (design factor)
- C_1 = constant selected to establish the cost trend origin
- C_2 = a constant to reflect special requirements such as tooling - can be zero

Adjustments to the weight exponent and the constants yields values which show dramatic cost increases as a function of weight but decreasing cost per pound as the weight is increased. Cost relationships always show these trends when applied to launch vehicles, spacecraft, or payloads. Therefore, it is assumed that they apply to biology equipment (for space) as well. Economies of scale are present in all such systems. The larger the system, assembly, or component, the lower its cost per pound. There is, however, a limitation to the applicability of CER's to SBI hardware

due to size limitations. All CER's have a range of applicability and produce consistent results in terms of cost per pound over that range. The limitation comes into play when extrapolating outside the range of applicability, particularly where the size is small. Unfortunately, this limitation may be a factor in SBI hardware elements and assemblies due to their size being relatively small compared to manned spacecraft systems. Therefore, when a CER yields costs in a very high range, on the order of $100,000/lb. or $220,000/Kg, or higher, caution and judgement are necessary to avoid the use of misleading results.

2.2 System Complexity Exponents (n)

Past experience in estimating costs with empirical methods suggests that the exponent, n, increases with increasing system complexity and as a function of the degree to which a system is distributed. For example, relatively simple, structure or packaged power modules may be represented by n = 0.2. The cost of more complex mechanical systems and structures which are comprised of a variety of components and assemblies can be represented by an exponent, n = 0.4 and the most complex distributed electronics call for an exponent on the order of 0.5 to 0.6. Inasmuch as the SBI systems involve all the foregoing elements plus sophisticated sensors, it may be necessary to use exponents that are as high as 0.8 or 1.0 to represent cost trends of parts of the SBI systems. Reference No. 60 uses an exponent, n, equal to .5 for development when historical data are not available. This value has been used in SBI Reference No. 60 for displays and controls, instrumentation and communications, all of which are comprised of distributed electronics and is consistent with the range recommended here (.5 to .6).

The dramatic effect of the system complexity exponent is illustrated by Figure 2-1. Figure 2-1 is a plot of cost per pound vs. complexity exponent, n, for a range of values of n between 0.1 and 1.0. As can be seen from the figure, 1000 units of weight costs 0.2% per unit weight as much at n = 0.1 compared to the cost at n = 1.0. The point is that care must be exercised in making a proper selection of exponent in order to achieve reasonable accuracy in estimating actual costs.

The historical use of lower exponents for simple, packaged systems, and the use of higher values for complex distributed systems matches common sense expectations. To express it another way, one can safely assume that the cost of a system will be influenced dramatically by the number of different groups involved in the design, by the number of interfaces in the system, and by the complexity of the design integration effort required. Distributed power and data systems invariably cost more (per pound) to develop than do packaged elements. However, the degree to which this applies to SBI is not clear due to the fact that biological systems tend to be more packaged and less distributed than do other space systems.

2.3 Design Factors (df)

Figure 2-2 defines the design factors that represent the degree of new design required in a development. On the low side is the factor representing the use of existing designs that require very little modification, integration or testing. For all new current state-of-the-art designs which involve no new technology, the design factor is 0.9 to 1.0. The factor for new design requiring advancement in technology is expressed as greater than unity and can be as high as 2 or 3 for efforts that dictate a multiple design path approach to achieve the desired goals. Price H refers to this type of factor as the engineering complexity factor and uses design values similar to those

in Figure 2-2. However, Price H varies the experience of the design team as well as the complexity and the difficulty of the design.

2.4 Method Summary

The SBI trade studies will all require a definition of system element size, complexity and degree of new design. These factors may have to be varied over a range of probable values to evaluate trends, but they will all come into play in costing comparisons.

FIGURE 2-1
Effect of Exponent "n" on Cost

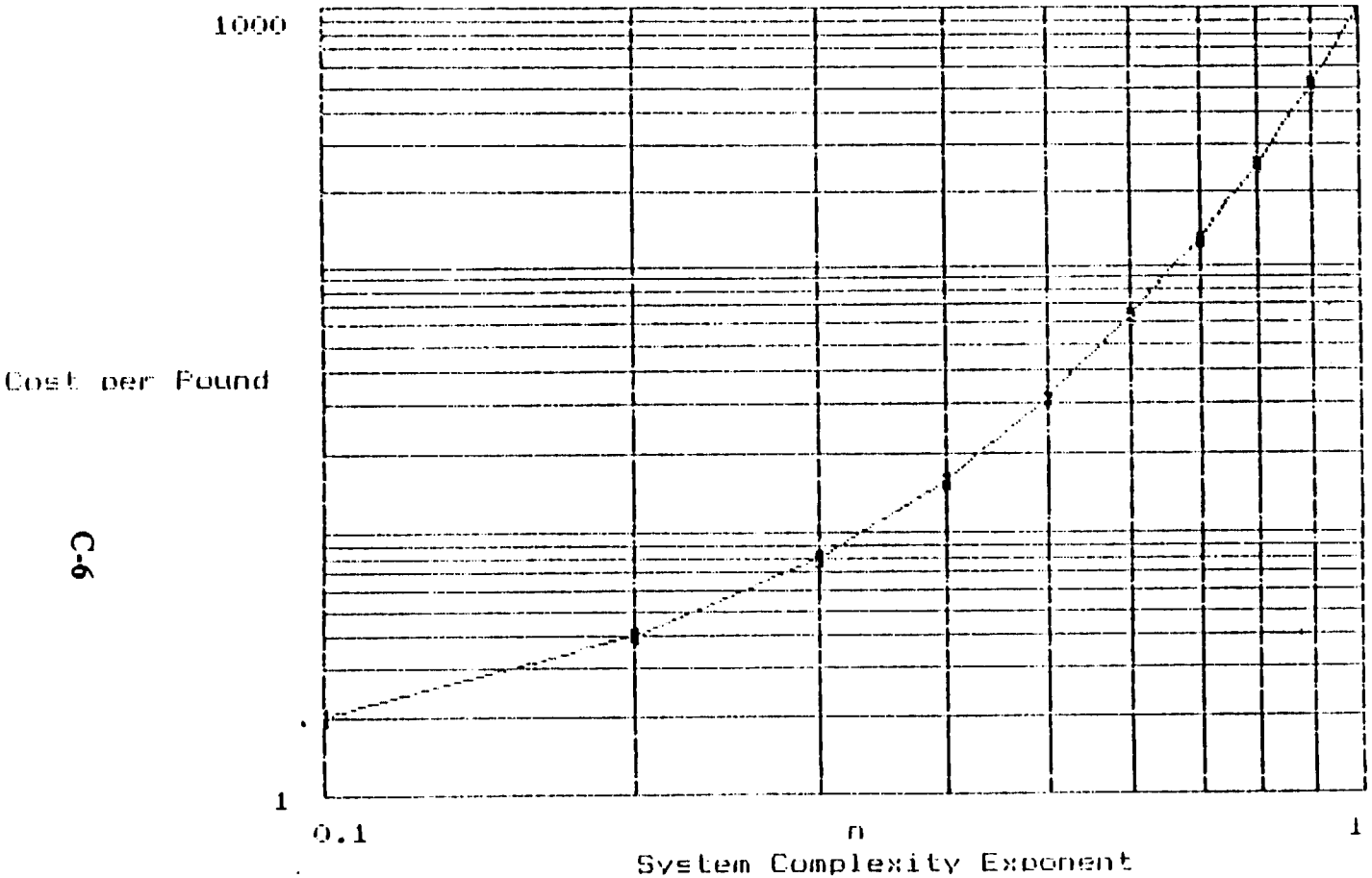


Figure 2-2 Design Factors

Design Factor	Description of the Design Task
.1 to .2	Off-The-Shelf. Minor design modifications and little or no qualification testing required
.3 to .4	Design Exists. Some new design drawings required Minimum integration costs involved
.5 to .6	Design exists but requires significant modification. On the order of 40% to 50% to existing drawings.
.7 to .8	Similar designs exist but mostly new drawings required No new technology involved in electronics, structure etc.
.9 to 1.0	New design with all new drawings. Little or no new technology required
1.0 to 3.0	All new design, new technology required. May require multiple attack on new technology problems

3.0 Cost Methods Applicable to Specific Trade Studies

Three of the four studies are discussed separately in this section although there are common elements associated with them that were not covered in Section 2.0. The intent is to examine the prime cost drivers that come into play with the subjects of miniaturization, modularity and commonality, use of COTS, and compatibility between spacecraft. Rack compatibility is covered in Section 7.4 under life cycle costs.

3.1 Hardware Miniaturization Cost Drivers

Fundamentally the variables of system (or component) weight, system complexity, and difficulty of design all influence miniaturization cost trends. For the purposes of this section weight and design difficulty will be varied, while system complexity will be treated as a series of constants, each being evaluated separately. Materials changes will not be dealt with even though it is valid to assume that the use of titanium, graphite, steel or composites will adversely affect cost. In fact, the dense materials (titanium and steel) will adversely affect cost due to weight and cost due to manufacturing complexity as well.

Given the foregoing exclusions, the miniaturization cost trends have been dealt with by parametric variation of the system size, and the degree of new design needed to achieve a given degree of miniaturization. The selected values of miniaturization vary between 10% and 90% in increments of 10%. In other words, if an unminiaturized system size is treated as 100%, Tables 3-1 through 3-4 show the effect on cost of weight reduction between zero and 90% on the first line. In order to include the effect of system complexity, Tables 3-1 through 3-4 are provided for values of n = 0.2, 0.4, 0.6, and 0.8.

The columns in the tables vary the design difficulty between a minimum change (.1 to .2 on Figure 2-2) and an all new design (0.9 to 1.0 on Figure 2-2). However, Tables 3-2 through 3-4 show the minimum design change as unity for reasons of simplifying the numbers. Thus the minimum design change number becomes 1.0 in lieu of 0.15 and the all new design becomes 6.0 which represents a relative value, compared to the minimum change value, i.e. 0.90 /0.15 = 6.0.

The use of Tables 3-1 through 3-4 is simple. Numbers less than 1.0 indicate a cost reduction and the degree of same, while numbers above 1.0 represent cost increases and the relative size of the increase. For example, using a 50% size reduction, and miniaturization requiring an all new design (df = 6) for n = 0.4, table 3-2 shows that the cost will be on the order of 4 1/2 times the cost for an unmodified item that is not miniaturized. In like manner, one can deduce that the cost of an all new design that achieves a 90% reduction in size (was 20 lbs., is 2.0 lbs.) will cost approximately 2 1/2 (2.4 from Table 3-2) the amount of an unmodified design.

Figure 3-1 is included to illustrate the cost trends for various systems complexity factors between n = .2 and n = .8. The curves all use a design factor df = 1.0 and all have been normalized so that the unminiaturized weight is unity. The purpose of Figure 3-1 is to show the effect of complexity factors on cost as weight is reduced. No design modification effects are included in Figure 3-1 so the curves indicate complexity trends only. To generate an estimate of the relative cost of miniaturization including redesign effects, one must multiply the cost factor (Figure 3-1) by a design factor as is done in Tables 3-1 through 3-4.

Table 3-1
Miniaturization Guide Chart
n=.2

% Miniat. / df	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.98	.96	.93	.90	.87	.83	.79	.73	.63
Significant Modification Req'd (30%)	2.00	1.96	1.92	1.86	1.80	1.74	1.66	1.58	1.46	1.26
Major Modification Req'd (50%)	3.00	2.94	2.88	2.79	2.70	2.61	2.49	2.37	2.19	1.89
All New Design	6.00	5.88	5.76	5.58	5.40	5.22	4.98	4.74	4.38	3.78

Table 3-2
Miniaturization Guide Chart
n=.4

% Miniat. / df	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.96	.92	.87	.82	.76	.69	.62	.53	.40
Significant Modification Req'd (30%)	2.00	1.92	1.84	1.74	1.64	1.52	1.38	1.24	1.06	.80
Major Modification Req'd (50%)	3.00	2.88	2.76	2.61	2.46	2.28	2.07	1.86	1.59	1.20
All New Design	6.00	5.76	5.52	5.22	4.92	4.56	4.14	3.72	3.18	2.40

Table 3-3
Miniaturization Guide Chart
n=.6

% Miniat. / df	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.94	.86	.81	.74	.66	.58	.49	.38	.25
Significant Modification Req'd (30%)	2.00	1.88	1.72	1.62	1.48	1.32	1.16	.98	.76	.50
Major Modification Req'd (50%)	3.00	2.82	2.58	2.43	2.22	1.98	1.74	1.47	1.14	.75
All New Design	6.00	5.64	5.16	4.86	4.44	3.96	3.48	2.94	2.28	1.50

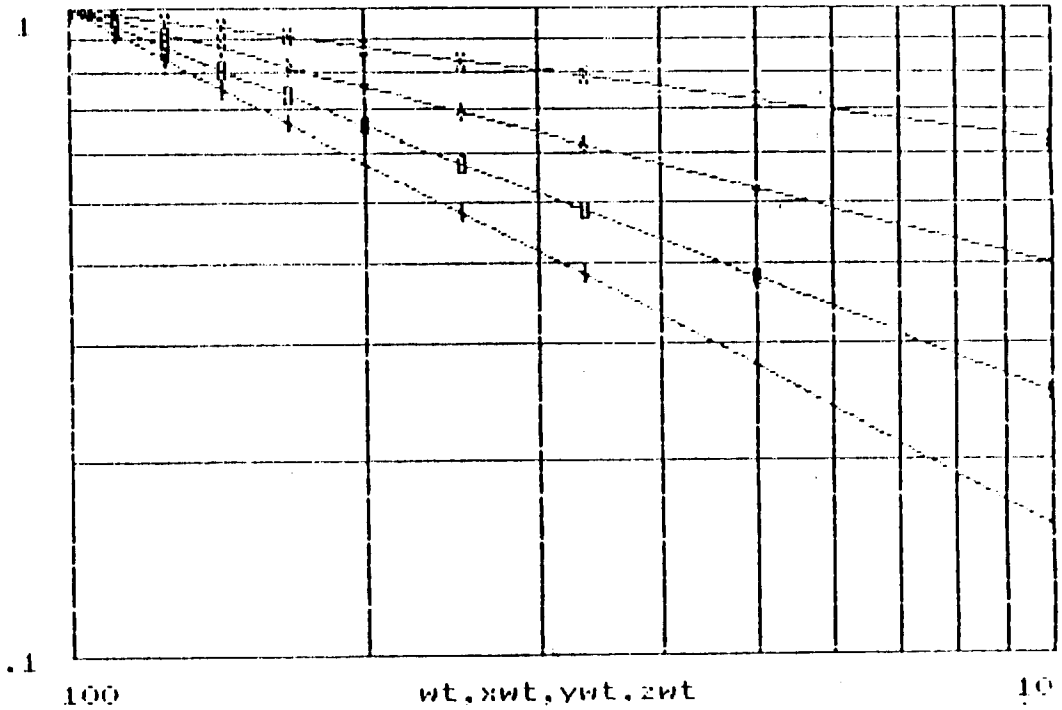
Table 3-4
Miniaturization Guide Chart
n=.8

% Miniat. / df	0	10	20	30	40	50	60	70	80	90
Design Integration Only	1.00	.92	.84	.75	.67	.57	.48	.38	.28	.16
Significant Modification Req'd (30%)	2.00	1.84	1.68	1.50	1.34	1.14	.96	.76	.56	.32
Major Modification Req'd (50%)	3.00	2.76	2.52	2.25	2.01	1.71	1.44	1.14	.84	.48
All New Design	6.00	5.52	5.04	4.50	4.02	3.42	2.88	2.28	1.68	.96

Cost Factor from Tables 3-1 thru 3-4
cost(wt,xwt,ywt,zwt)=df*(wt)^n/wt

Figure 3 -1

Variation of Cost as a Function of Weight



X = Normalized Cost for n =.2
V = Normalized Cost for n =.4
O = Normalized Cost for n =.6
+ = Normalized Cost for n =.8

The examples are not meant to suggest that certain combinations of miniaturization and design difficulty are more rational than others, but were selected simply to demonstrate table usage. It is conceivable that a modest degree of miniaturization is achievable with modest design (df = 2).

Caution is advised! for several reasons:

1. Some items cannot be reduced in size.

2. Some items should not be reduced in size.

3. Significant size reductions may require technology breakthroughs in materials, electronics, displays, etc. that could complicate the SBI development task.

4. Substitute materials will often negate weight reductions and raise costs even higher than estimated by the tables.

Notwithstanding all the adverse possibilities, one could conceivably reduce size and cost by miniaturizing an item or an assembly.

3.2 Modularity and Commonality

Common system modules, assemblies or components can have a profound impact upon development cost because of the potential savings associated with the use of a common module in more than one SBI hardware item. The following examples serve to illustrate this fact.

Table 3-5 shows the impact of using learning to reduce costs. For example, consider the case where sixteen units are to be constructed for a given SBI application of a system rack or drawer, but the item in question can be used in four applications rather than in only a single place. If the system is to be produced in small quantities, exotic tools and automation are not cost effective and the item is normally assembled using piece parts. Such systems usually have learning factors of 80%, i.e., each time the number of units is doubled (SBI Ref. No. 68), the cost of the nth unit is 80% of the previous cycle's end product cost. To be specific, the 2nd unit costs .8 times the first unit, the 4th unit .8 times the second, etc. See Table 3-5. In the case of a built-up drawer or rack which is used in four places, 16 units for prototypes, test, flight hardware, etc., becomes 64. As can be seen from Table 3-5, the cost of the 64th unit is 26.2% of the 1st unit and 64% of the 16th unit. The average cost for 64 items is reduced to 37.4% of the first unit cost compared to 55.8% of the first unit cost for 16 items. The lower the learning, the less dramatic the unit cost reduction, but for any item that is fabricated by other than completely automated processes, there is a cost reduction to be realized by common use in more than one application.

If one considers the programmatic input of multiple applications, there also exists the opportunity to avoid duplicate design and development efforts. For the sake of simplicity, we will confine this discussion to D&D plus fabrication and assume that four separate developments each require a test program. This being the case, we can treat a single, dual, triple and quadruple application in terms of the D&D effort and include the effect of reduced costs due to learning as well.

D&D = Design and Development Cost
TFU = Theoretical First Unit Cost
L.F. = .80
Number of articles required per application = 16

Then:

Let CP_1 = Cost of a single program,
Let 35% D&D = TFU Cost

$$C.P_1 = 1.0\ D\&D_{cost} + [.35\ D\&D * L.F.]\ 16$$

$$= 1.0\ D\&D + [.35\ D\&D * .558]\ 16$$

$$C.P_1 = 1.0\ D\&D + 3.1248\ D\&D = 4.1248\ D\&D$$

Normalized cost = C.P./4.1248 D&D

In a similar manner, the cost of 2, 3 and 4 applications can be calculated which yields the data in Table 3-6.

TABLE 3-5
Learning Factor Table
All First Articles are 100%

Quantity		2	4	8	16	24	32	64
Learning Factor								
0.95	N^{th}	95.0%	90.3%	85.7%	81.5%	79.0%	77.4%	73.5%
	Aver.	97.5%	94.4%	90.8%	87.0%	84.65	83.0%	79.1%
0.90	N^{th}	90.0%	81.0%	72.9%	65.6%	61.7%	59.0%	53.1%
	Aver.	95.0%	88.9%	82.2%	75.2%	71.3%	68.5%	62.0%
0.85	N^{th}	85.0%	72.3%	61.4%	52.2%	47.5%	44.4%	37.7%
	Aver.	92.5%	83.6%	74.2%	64.9%	59.7%	56.2%	48.3%
0.80	N^{th}	80.0%	64.0%	51.2%	41.0%	35.9%	32.8%	26.2%
	Aver.	90.0%	78.6%	69.3%	55.8%	49.8%	45.9%	37.4%

Notes:

1. N^{th} refers to the 2^{nd}, 4^{th} etc article in the fabrication of identical articles by the same process

2."Aver.", refers to the average cost of the 1^{st} through the N^{th} article under the same conditions

3. The External Tank learning factor has been estimated at 80% (0.80) due to the relatively large amount of manual labor that goes into the fabrication process. In general the more manual the process, the greater the learning and the smaller is the number from the table that applies.

4. As the learning factors approach unity the reduction in cost for each succeeding cycle is reduced and 1.0 represents a fully automated process wherein the first article and the N^{th} article cost is the same.

5. For the purposes of the SBI trade studies we can use the guidelines that the manual fabrication and assembly processes of sheet metal have learning factors of 80% to 90% while the more automated and repetitive processes range between 90% and 95% or even as high as 97%. There probably won't be any automated processes where the costs of a number of articles remains the same as the first article cost.

Table 3-6
Cost of Multiple Applications

Applications	D&D Cost	Production Cost	Normalized Total Cost Per Application
1	1.0 (D&D)	3.1248 (D&D)	1.00
2	.50 (D&D)	5.1408 (D&D)	.744
3	.33 (D&D)	6.7704 (D&D)	.628
4	.25 (D&D)	8.3776 (D&D)	.568
5	.20 (D&D)	9.785 (D&D)	.523

Figure 3-2 is a linear plot of the foregoing information based upon a theoretical first unit (TFU) cost of 35% * (DD), Figure 3-3 is based on a TFU of 15% * (DD). Figures 3-2 and 3-3 illustrate two facts. The first is that a significant cost reduction result from the use of hardware in more than a single application. The second is that the point of diminishing cost return occurs rapidly beyond the third application.

Modularity, although similar to commonality in some respects, offers other advantages as well. However, one must acknowledge that modular designs may cost more initially than non-modular designs due to the tendency for them to require added weight for packaging and more design integration due to an increase in the number of interfaces present in the system. Nevertheless, such systems have lower life cycle costs because of simplicity in assembly, repair, replacement, problem diagnosis and upkeep in general. Also there are the advantages of being able to upgrade individual modules with new technology and/or design improvements without impacting the rest of the system and without complicated disassembly and assembly to affect a module changeout.

Thus, if modules can be made common, the system possesses the attributes of modularization and offers potential cost savings from the multiple use of various system modules. The long and short of it is that the system cost can be reduced and the system flexibility and life cycle attributes improved. Common elements in modular designs should be a major, high priority goal in all SBI systems.

3.3 Modification of Existing Hardware (COTS) vs. New Hardware Build

Commercial off-the-shelf (COTS) hardware has been used for space applications sporadically since the early days of manned space flight and it poses the same cost-related challenges today as it did 25 years ago. The variables involved are the cost of the item, the cost of modification to meet space flight requirements, and the cost of demonstrating the hardware's reliability in qualification testing.

Past experience indicates that the cost of hardware modification is normally the primary cost factor of the cost elements listed. In an effort to assign an order of magnitude to modification costs, the weight of the COTS, the degree of modification (design factor, df), and the nature of the system (weight and system complexity, n) are used as prime cost drivers. Table 3-6 and 3-7 show the cost of modification against size (wt), and for systems with complexity factors (n) of .2 and .4. The higher order complexity factors are assumed to be not applicable on the basis that COTS is usually procured as modules or assemblies and then integrated into a larger system as necessary.

The costs shown in Tables 3-7 and 3-8 are based upon the assumption that COTS modifications are approximately the same cost as are redesigns to existing systems. The degree of modification (or redesign) is reflected in the design factor, df. The degree of system complexity is reflected by the system complexity factor, n. The range of weights over which these parameters are varied was selected on the basis that few items to be modified would be heavier than 50 Kg and that the small items less tnan 5 Kg would be procured as components or small assemblies which would be used in the design of a new system. The assumed size limit can be modified if necessary but were made to keep the number of weight variables in a reasonable size range with modest increments between each one. Here, again, caution is needed when applying CER type relationships to small items and to items where the portion of a hardware element being modified is small. See paragraph 2.1 for a discussion of scaling limitations.

Specific modifications to COTS may be simple enough to invalidate the assumption that modifications and redesign costs are similar. If so, alternate COTS modification cost methods will be required and will reflect greater savings. Thus, the foregoing assumption degrades gracefully because it is conservative from a cost point of view.

A popular viewpoint today is that modified COTS is always less costly than is a new design. This belief is reflected in the emphasis on "make or buy" in recent NASA RFP's and also in recent cost seminars held by major aerospace companies. Nonetheless, some cost specialists express the opinion that modifications to COTS greater than 30-35% probably makes a new design preferable. The COTS vs. new design trade study deals with these subjects so this part of the report will be confined to cost trends only. From the viewpoint of modification costs alone it appears straightforward that COTS has great cost reduction potential and should be seriously considered whenever a commercially available system element exists that can be utilized in SBI.

In order to illustrate the cost trends for modification costs and modification cost per pound, Figure 3-4 and 3-5 are included. Figure 3.4 represents minor modifications (df = .15) and n = .2, and, therefore, shows the lowest cost per pound of any of the cases in Tables 3-7 and 3-8. Figure 3-5 is for the case of substantial modifications and n = .4, df = .55 and thus represents a high side cost case. The figures both show the trends that are typical for the values presented in the tables.

Figure 3-2
Effect on Cost of Multiple
Applications of Hardware

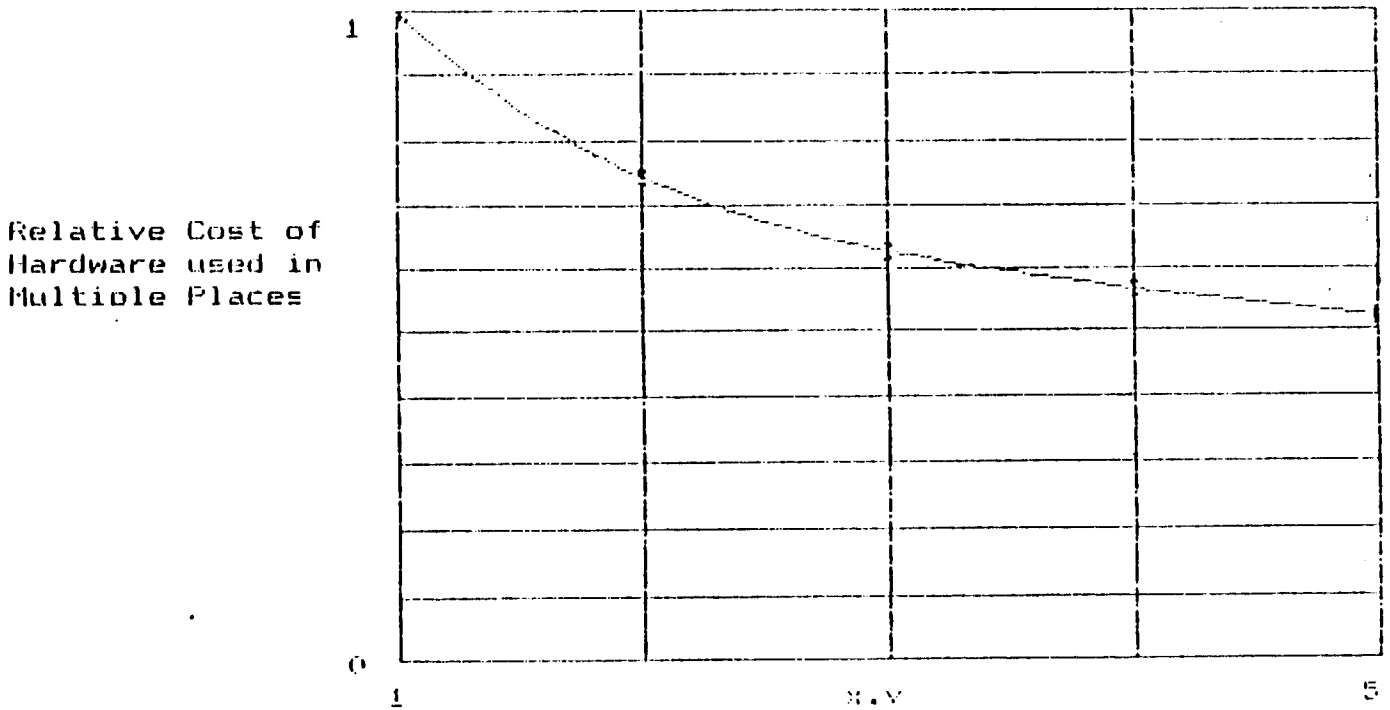
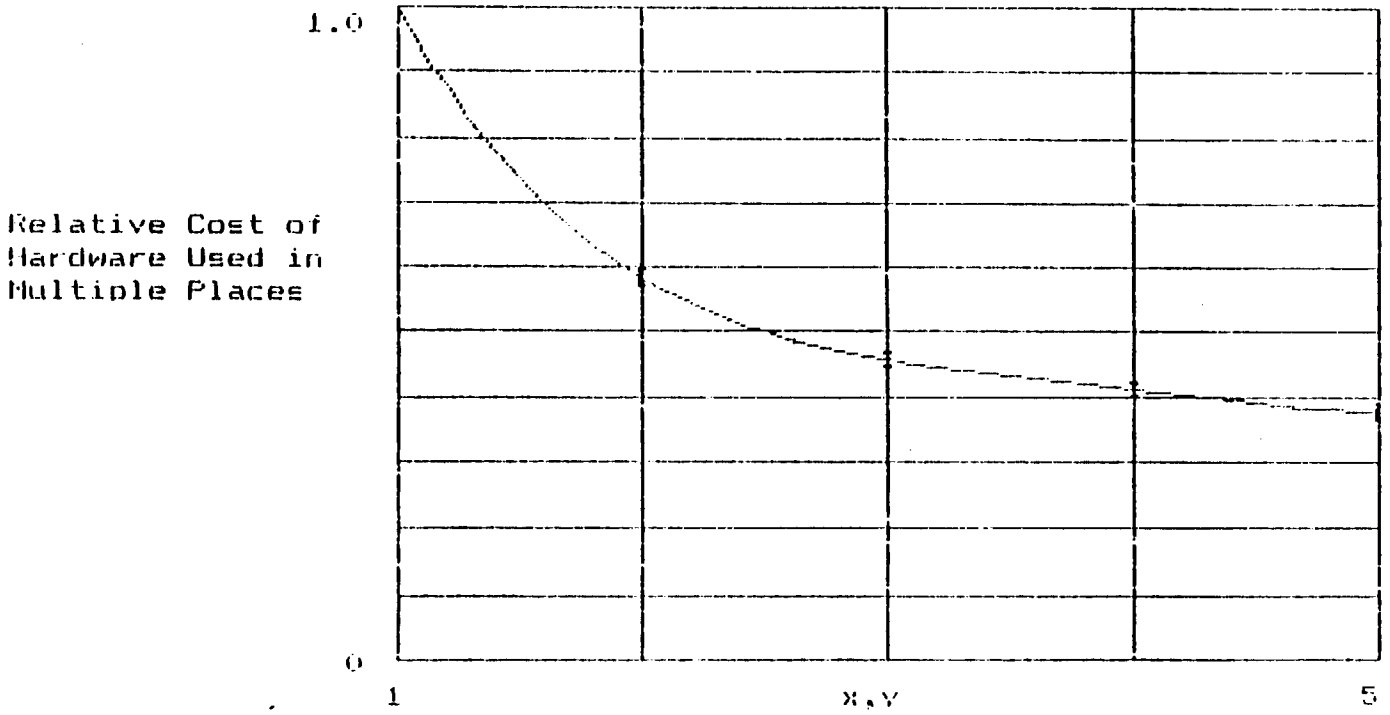


Figure 3-3
Effect on Cost of Multiple
Applications of Hardware



First Unit Cost (TFU) = .15%(Dev.Cost)

Learning Factor = 80%

Table 3-7 Cost of Modifying Commercial Off-the Shelf Hardware

System Complexity Factor (n) =.2

Weight of Part Modified \ Design Factor	Minor Mods df=.15		Modest Mods df=.35		Substantial Mods df=.55		Major Mods df=.75	
	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg
Weight =5 kgs	242.3	48.46	565.4	113.1	888.5	177.7	1212	242.3
Weight = 10 kgs.	278.3	27.83	649.5	64.95	1021	102.1	1392	139.2
Weight = 20 kgs.	319.7	15.99	746.0	37.3	1172	58.62	1599	79.93
Weight = 30kgs.	346.7	11.56	809.1	26.97	1271	42.38	1734	57.79
Weight = 40 kgs.	376.0	9.182	857.0	21.42	1347	33.67	1836	45.91
Weight = 50 kgs.	384.0	7.681	896.1	17.92	1408	28.16	1920	38.40

Notes: 1) All costs are in thousands of dollars

Table 3-8 Cost of Modifying Commercial Off-the Shelf Hardware

System Complexity Factor (n) =.4

Weight of Part Modified / Design Factor	Minor Mods df=.15		Modest Mods df=.35		Substantial Mods df=.55		Major Mods df=.75	
	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg	Mod. Cost	Cost/kg
Weight =5 kgs.	391.4	78.28	913.3	182.7	1435	287.0	1957	391.4
Weight = 10 kgs.	516.5	51.65	1205	120.5	1894	189.4	2582	258.2
Weight = 20 kgs.	681.5	34.08	1590	79.51	2499	148.5	3408	170.4
Weight = 30 kgs.	801.5	26.72	1870	62.34	2939	97.96	4008	133.6
Weight = 40 kgs.	899.3	22.48	2098	52.46	3297	82.43	4496	112.4
Weight = 50 kgs.	983.2	19.66	2294	45.88	3605	72.10	4916	98.32

Notes: 1) All costs are in thousands of dollars

Figure 3 - 4
Variation of Cost & Cost/kg for COTS Mods
df=.15 n=.2

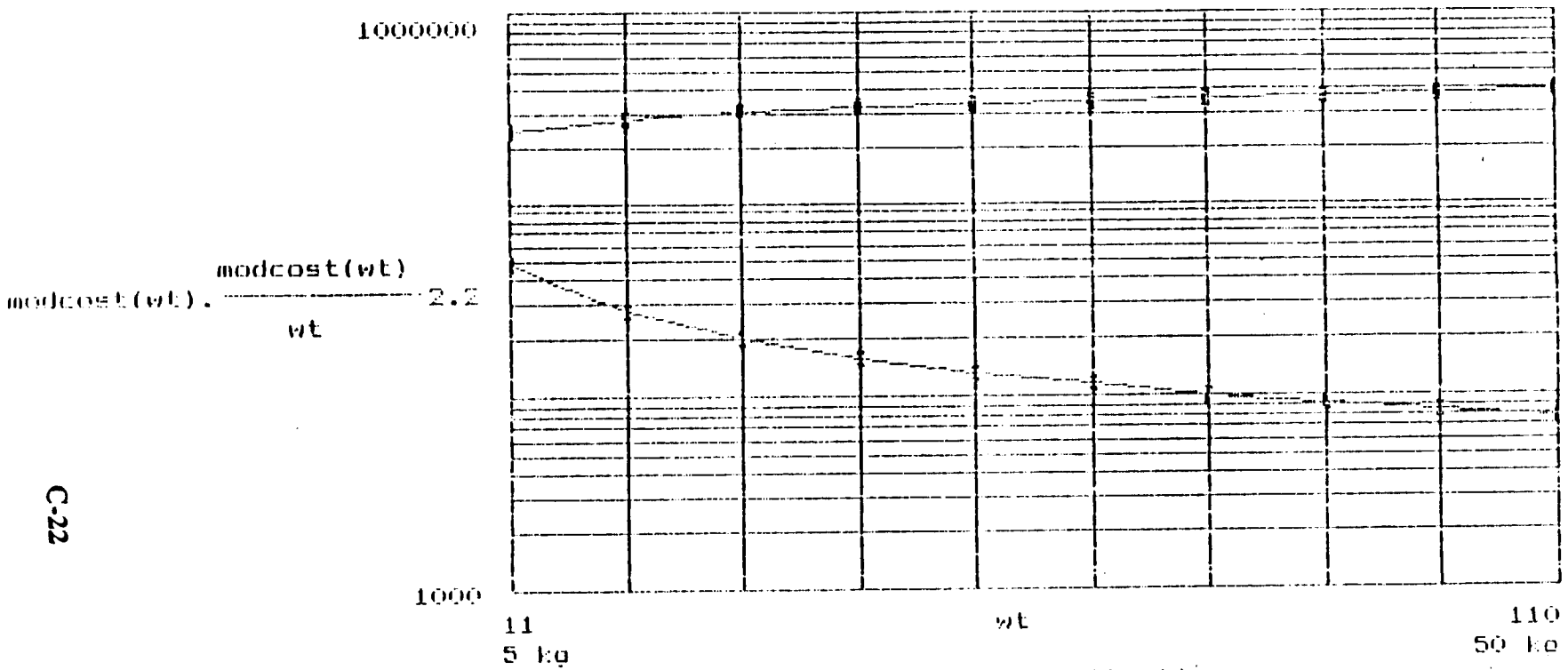
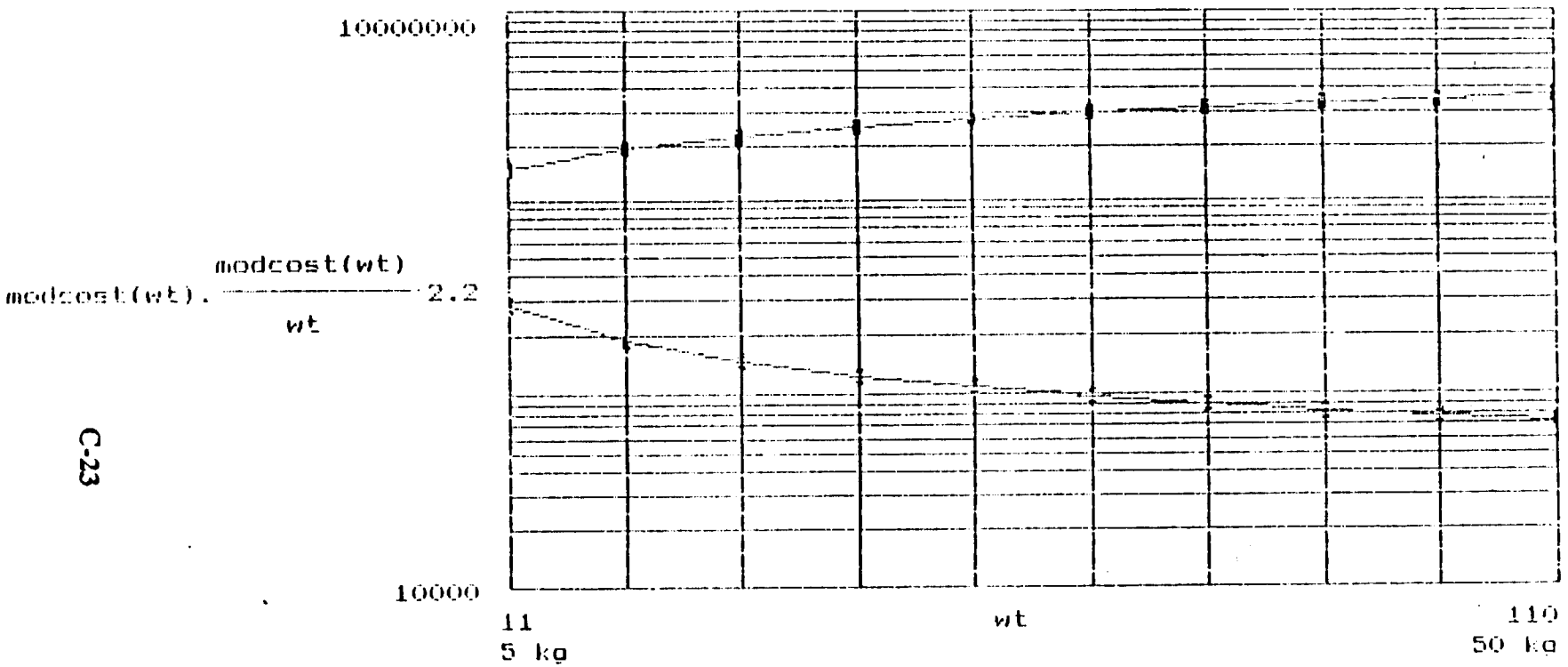


Figure 3 - 5
Variation of Cost & Cost/kg for COTS Mods
df=.55 n=.4



4.0 Testing Costs

A cursory treatment of testing costs is presented so as to make the cost picture as complete as possible. However, the applicability of test costs to SBI has not been validated and the guidelines presented should be applied with care only where a similarity exists between SBI elements and/or subsystems, and other manned spacecraft systems.

4.1 Test Hardware

Test hardware costs in past manned programs have included the cost of labor and materials for major test articles used to verify design concepts. However, test hardware cost relationships exclude element tests, component tests, qualification and certification tests. The cost of labor and material for the design, procurement, installation, checkout and operation of the instrumentation system on major test articles is included and as one might expect, these factors drive the cost of test hardware up to a value greater than the first unit cost.

The CER's examined put the cost of test hardware at 30% more than the theoretical first unit (TFU) cost, i.e. 1.3 * TFU. It should be noted that this cost is to demonstrate and to verify the operation of the designed hardware and should not be construed to include experimentation and testing to acquire biological information of an experimental or research character.

4.2 Integration Assembly and Checkout (IACO)

This factor is most commonly estimated as a function of TFU costs or test hardware costs. It will generally run on the order of 10 - 20% of test hardware costs for manned systems, but care must be exercised in applying such a rough rule of thumb to SBI. Therefore, a simple CER is suggested in cases where PRICE H estimates have not yet been formulated. The CER is as listed below:

$$IACO = .3\ (1.3\ TFU)^{0.7}$$

The resulting estimate can only be generated when all other hardware costs are available.

4.3 Test Operations

Test operations CER's indicate that costs generally run on the order of 20% to 30% of the cost of test hardware plus integration, assembly and checkout costs. However, as is the case with other test related items of cost, the applicability to SBI hardware has not been validated. Nonetheless, the order of magnitude could be used for SBI estimates pending specific definition of test requirements for the various experiments.

Examination of the SBI hardware list (Ref.SBI No. 87) and the Life Science Laboratory Equipment description (Ref. SBI No.88) suggests that test operations could vary from little or nothing all the way up to the level indicated in CER's and approximated above.

5.0 SE&I Costs

SE&I cost for the design and development phase are generally expressed as a function of the DDT&E + Systems Test Hardware + IACO + Test Operations + GSE costs. However, the lower end of the validity range is almost $1.0 billion of DDT&E costs and the applicability to SBI is extremely doubtful. For that reason, it is recommended that the preliminary SBI SE&I cost be taken as 10% to 15% of the SBI total system development cost until a detailed estimate or a PRICE H value is generated.

6.0 Program Management Costs

Program management costs usually run 5% of the total of all other costs, i.e., 5% of the sum of DDT&E + IACO + Test Hardware + Test Operations + GSE + SE&I (for DDT&E) costs. Inasmuch as there is no basis to assume that SBI program management cost is any more or any less than other types of programs, it seems reasonable to use a very preliminary value of this order of magnitude for budgetary estimating purposes.

7.0 Life Cycle Costs

As noted previously in this appendix, life cycle cost information is not available and therefore only a subjective treatment of the subject is possible. Nonetheless, Table 7-1 provides some worthwhile insights concerning all the SBI trade study subjects being addressed by Eagle. Taken singly, these subjects reveal the following probable life cycle impacts.

7.1 Study No. 3 - Miniaturization

The possible reduction of cost due to the impact of weight reduction is more theoretical than achievable. Indications are fairly clear that most attempts to miniaturize will cost rather than save money. Therefore, one must conclude that the reason for attempting size reductions is other than cost savings. It is beyond the scope of this write-up to postulate or to speculate further.

7.2 Study No. 4 - Modularity and Commonality

If the SBI program-wide support can be mobilized to support modular design and the development of hardware for common application to a number of SBI experiments and/or facilities, the cost benefit should be very significant. All the factors noted in Table 7-1 tend to substantiate this conclusion and only the programmatic direction and support has any identifiable cost or problem related to it.

Modular designs and common equipment should be a top priority requirement, goal and objective of SBI effort.

7.3 Study No. 5 - COTS vs. New Hardware

COTS should be regarded as a slightly trickier subject than commonality due to the potential pitfalls and cost penalties that can be incurred in its application to spaceflight. Nonetheless, the potential cost savings are large enough so that judicious use of COTS where it fits with the SBI program appears to be a cost-wise approach which could yield tremendous cost benefits for only nominal technical risk. Technical risk which can be offset by care in selecting, testing, and screening the procured items.

The use of modified COTS in lieu of a new design appears to pay off until the modification cost approaches the cost of an optimized new piece of hardware. The cut-off point has not been defined but would make an interesting and worthwhile follow-on study. Intuitively one would expect to find a series of cut-off points that are a function of the hardware complexity, and therefore, the cost and complexity of the modification program.

7.4 Study No. 6 - Rack Compatibility

To a greater degree than the other SBI trade studies, this subject seems to defy analysis that could give cost trend indications or life cycle cost indicators. Nevertheless, if one assumes that the inter-program coordination of rack compatibility can be accomplished with a reasonable effort, there exists the possibility to lower cost, to reduce the cost of data normalizing and

comparison, and improved scientific data return might possibly be a companion benefit to lower experimentation costs.

The entire spectrum of life cycle costs beyond the design and program management phase that would accrue due to compatibility all appear to be very positive and beneficial. Logistics, ground processing, pre-flight checkout, operations, repair and replacement all would be impacted in a beneficial way by this approach. A comparable achievement that comes to mind is the establishment of standard equipment racks by the International Air Transport Association (IATA). The benefits apply to a large number of items (commercial transports) and of course the impact is greater, but the concept has been a true bonanza to all the world's commercial airlines. Rack compatibility is potentially a smaller sized cousin to IATA's achievement.

Table 7 -1 Life Cycle Cost

Phase \ Study	Study No. 3 Hardware Miniaturization	Study No. 4 Modularity and Commonality	Study No. 5 COTS vs. New Hardware	Study No. 6 Rack Compatibility
Design	Design change always required. Cost of redesign may be partially offset by size & weight reduction.	Requires programmatic support and some allowance for increased weight and cost in design phase.	Dependent upon availability and suitability of commercial modules and/or elements for SBI system application.	Requires inter-program coordination/communication and direction which is very difficult to achieve.
Development	Fabrication may be complicated due to size reduction.	Development, manufacture or procurement is facilitated by modularity. Commonality cost impacts all positive.	Modified COTS appears to have significant potential advantage. Requires sound make or buy anlysis & eval.	Common source would be highly desireable but will be hard to do due to specification differences & organiz. barriers
Test and Evaluation	Test costs may increase due to difficulty in set-up and trouble shooting.	Module testing, integrated testing and test trouble shooting are simplified and cost savings result.	Testing impact appears to be negative due to need for extra qualification tests and periodic retest (screening).	Should have only minor impact which stems from differences in test requirements.
Sustaining Engineering	No significant impact pro or con is apparent.	Individual engineering groups can operate with less sytems integration effort.	Should be automatically supported by vendor's program. Generally positive. Mods could pose problems.	Responsibility may be difficult to establish and to identify. Problem potential is small due to type of hardware.
Technology Upgrade	May be less likely due to absence of alternate hardware availability.	Facilitated and made easier by modular design.	Not predictable. Experience indicates that it can vary from easy and to very painful and awkward.	Should be possible within a rack or module. Compatibility will reduce the overall cost of inserting new tech. upgrades.
Maintenance and Operations	Possible adverse impact on maintenance due to small size. Operation should not be affected.	Common module impacts on maintenance, logistics and operations are all positive & highly significant.	Maintenance of unmodified portion could pose problem. Operation not affected if reliability is adequate.	Design for long life should mean small scale preventive maintenance is all that is required.
Replacement	May be less costly due to size and favorable impact on logistics.	Can be accomplished in planned phases and/or steps with minimum disruption to system operation.	COTS use suggests that low cost replacements are available. Advantage can erode with age.	Standard interfaces can only work to reduce the cost of replacement. Fewer spares, standard procedures etc.
Overall Life Cycle Cost Impact	Tends to look negative. The need to miniaturize must be based upon reasons other than cost.	Life cycle cost impacts are all highly favorable except for design phase coordination & possible weight penalties.	Very significant life cycle cost advantage inherent in COTS. However, initial selection and mod program must be prudent.	Whatever the cost of inter-program coordination, ICD's etc., the impact on overall NASA cost is very beneficial

8.0 Recommendations

1. Perform a follow-on effort to generate a designer's "John Commonsense" manual for cost avoidance and/or reduction. The manual should be a series of simple groundrules and guidelines to help reduce Space Biology Initiative Program costs. Where possible, a series of tables or curves to help assess the potential cost gain should be included.

2. Mount an effort to accumulate an SBI historical cost data base. The objective should be at least two-fold. First, identify the breakpoint for various cost trade-offs. Examples are presented in Figures 3-2 and 3-3 which show that commonality soon reaches a point of diminishing return insofar as it pertains to development and manufacturing. Given such breakpoints, explore the possibility of additional life cycle cost benefits which result from reduced sparing, simplified logistics, reduced maintenance, etc. Second, obtain enough historical cost information to permit the development of CER's that are properly scaled for the range of sizes in question. Existing CER's have limitations that may invalidate their use on SBI. Therefore, actual cost data from ongoing SBI efforts would provide a valuable asset to future work of a similar nature.

3. Consider a follow-on program to develop a rule-based or expert system that could be used for quick cost estimates and cost comparisons. Such an effort can only proceed in parallel with item 2, above, but the development time is such that it should begin as soon as practical.

4. Generate a comprehensive compendium of cost estimating relationships and apply them to SBI. Subsequently, make comparisons with other cost estimating methods in an attempt to remove the existing programmatic skepticism about the voodoo and black magic of cost predictions.

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Appendix D - Database Definition

Appendix D - Database Definition

The database files for the SBI trade Studies were developed using dBASE IV. The database files consist of dbf, ndx, and frm files. The dbf files are dBASE IV database files. NDX files are the index files for the dbf (database) files. The frm files are report files for the trade study candidate and bibliography reports. The SBI trade study database consist of 4 database files with 78 fields of information. A complete listing of the database structure and dictionary is included in this database definition.

Database Structure For SBI Trade Studies

Structure for database: W:hardware.dbf
Number of data records: 93
Date of last update : 05/30/89

Field	Field Name	Type	Width	Dec
1	HW_ID	Character	3	
2	HW_NAME	Character	50	
3	HW_DESCRTN	Character	254	
4	HW_FACILIT	Character	55	
5	INFO_SOURC	Character	250	
6	HW_MASS	Numeric	6	3
7	HW_VOLUME	Numeric	8	6
8	HW_POWER	Numeric	4	
9	HW_VOLTAGE	Numeric	6	
10	HW_HEIGHT	Numeric	6	
11	HW_WIDTH	Numeric	6	
12	HW_DEPTH	Numeric	8	
13	REMARKS	Character	50	
14	RECORD_DAT	Date	8	
15	GROUP	Character	50	
16	CATEGORY	Character	50	
17	FUNCTION	Character	60	
18	FAC_ID	Character	4	
19	GROUP_ID	Character	4	
20	MIN_LEVEL	Character	5	
21	CONFIDENCE	Character	5	
22	SUFFIC_DAT	Character	4	
23	PRIORITY	Character	2	
24	MIN_LV_POT	Character	6	
25	MIN_EST_CF	Character	6	
26	MOD_LV_POT	Character	6	
27	MOD_EST_CF	Character	6	
28	COM_LV_POT	Character	6	
29	COM_EST_CF	Character	6	
30	SYS_COMPLX	Character	6	
31	DSN_COMPLX	Character	6	
32	BUY_LV_POT	Numeric	4	
33	BUY_MOD_LV	Numeric	4	
34	BUY_EST_CF	Character	4	
35	BUY_OTS_PT	Numeric	4	
36	BUY_DAT_AV	Character	4	
37	MOD_CAN	Logical	1	
** Total **			968	

```
Structure for database: W:biblo.dbf
Number of data records:      98
Date of last update    : 05/26/89
Field  Field Name  Type        Width    Dec
    1  BB_ID       Character       5
    2  AUTHOR_NO1  Character      16
    3  AUTHOR_NO2  Character      12
    4  AUTHOR_NO3  Character      12
    5  ART_TITLE   Character     135
    6  BOOK_TITLE  Character     100
    7  VOLUME_NO   Character       3
    8  PUBLISHER   Character      42
    9  PUBL_LOC    Character      32
   10  DATE        Date            8
   11  PAGE_NOS    Character       4
   12  ABSTRACT    Character     100
   13  ACQUIRED    Character      20
   14  COST        Numeric         6
   15  LOANED      Character       4
   16  REP_DOC_NO  Character      22
   17  MOD         Logical         1
   18  MIN         Logical         1
   19  COTS        Logical         1
   20  RACK        Logical         1
** Total **                     526

Structure for database: W:rack_com.dbf
Number of data records:     166
Date of last update    : 05/26/89
Field  Field Name  Type        Width    Dec
    1  IF_ITEM     Character      38
    2  UNITS       Character       8
    3  UNIT_SYS    Character       1
    4  ITEM_TYPE   Character      12
    5  VALUE       Character      50
    6  MODULE      Character      25
** Total **                     135


Structure for database: W:comm_mod.dbf
Number of data records:     153
Date of last update    : 05/30/89
Field  Field Name  Type        Width    Dec
    1  HW_ID       Character       3
    2  COMM_MOD    Character      30
    3  COUNT       Numeric         1
    4  COST_DECSC  Numeric         4      2
    5  MASS        Numeric         4      2
** Total **                      43
```

Appendix D - Database Dictionary for Space Biology Initiative Trade Studies

Hardware.dbf **This is the database file for SBI hardware.**

Field 1	HW_ID	Unique identification number for each hardware item
Field 2	HW_NAME	Hardware name
Field 3	HW_DESCRTN	Hardware description
Field 4	HW_FACILIT	Facility where SBI hardware is used
Field 5	INFO_SOURC	Information source for SBI hardware data
Field 6	HW_MASS	Hardware mass
Field 7	HW_VOLUME	Hardware volume
Field 8	HW_POWER	Hardware power requirement
Field 9	HW_VOLTAGE	Hardware voltage requirements
Field 10	HW_HEIGHT	Hardware height
Field 11	HW_WIDTH	Hardware width
Field 12	HW_DEPTH	Hardware depth
Field 13	REMARKS	Remarks concerning SBI hardware equipment
Field 14	RECORD_DAT	Update of last record
Field 15	GROUP	Hardware group
Field 16	CATEGORY	Hardware category
Field 17	FUNCTION	Hardware function
Field 18	FAC_ID	Hardware facility ID number
Field 19	GROUP_ID	Hardware group ID number
Field 20	MIN_LEVEL	Miniaturization level for hardware
Field 21	CONFIDENCE	Confidence level for miniaturization
Field 22	SUFFIC_DAT	Is there sufficient data to make a decision of hardware miniaturization?
Field 23	PRIORITY	Priority level for hardware item based on mass
Field 24	MIN_LV_POT	Miniaturization level potential for the hardware item
Field 25	MIN_EST_CF	Confidence level for miniaturization
Field 26	MOD_LV_POT	Modularity potential for hardware item
Field 27	MOD_EST_CF	Confidence level for modularity estimate
Field 28	COM_LV_POT	Commonality potential for hardware item
Field 29	COM_EST_CF	Confidence level for commonality estimate
Field 30	SYS_COMPLX	System complexity for hardware item
Field 31	DSN_COMPLX	Design complexity for hardware item
Field 32	BUY_LV_POT	Percent Buy for Hardware Item
Field 33	BUY_MOD_LV	Percent modification to Buy Hardware Item
Field 34	BUY_EST_CF	Confidence Level for Make-or-Buy Estimate
Field 35	BUY_OTS_PT	Percentage of COTS hardware that does not require modification
Field 36	BUY_DAT_AV	Is sufficient data available for make-or-buy estimate
Field 37	MOD_CAN	Logical field can the hardware item be modularized Y or N

biblo.dbf **This is the database for bibliography information.**

Field 1	BB_ID	Identification number for the reference
Field 2	AUTHOR_NO1	First author
Field 3	AUTHOR_NO2	Second author
Field 4	AUTHOR_NO3	Third author
Field 5	ART_TITLE	Title of article
Field 6	BOOK_TITLE	Title of book
Field 7	VOLUME_NO	Volume number
Field 8	PUBLISHER	Publisher
Field 9	PUBL_LOC	Publisher's address
Field 10	DATE	Date of publication
Field 11	PAGE_NOS	Page number of reference
Field 12	ABSTRACT	Abstract
Field 13	ACQUIRED	Where the reference was acquired
Field 14	COST	Cost of reference
Field 15	LOANED	Where the reference was loaned from
Field 16	REP_DOC_NO	Report or document number
Field 17	MOD	Was this reference used on the modularity trade study? y or n
Field 18	MIN	Was this reference used on the miniaturization trade study? y or n
Field 19	CUTS	Was this reference used on the make-or-buy trade study? y or n
Field 20	RACK	Was this reference used on the rack compatibility trade study? y or n

rack_com.dbf **This is the database file for the rack comparison study.**

Field 1	IF_ITEM	I/F item being compared, i.e. power converters
Field 2	UNITS	Units of comparison, i.e. inches
Field 3	UNIT_SYS_	Unit system, i.e. metric
Field 4	ITEM_TYPE	Functional Grouping of IF Item i.e. Data Mgmt.
Field 4	VALUE	Value of the comparison
Field 5	MODULE	Module, i.e. U.S. Lab

comm_mod.dbf **This is the design modularity and commonality database**

Field 1	HW_ID	Unique identification number for each hardware item
Field 2	COMM_MOD	Modularity function/assembly
Field 3	COUNT	Used to total hardware items in COMM_MOD Field
Field 4	COST_DECSC	Cost description
Field 5	MASS	Mass of hardware item

Appendix E - Detailed Hardware Descriptions

CELSS

Controlled Ecological Life Support System

Title Germination Experiment Kit

Element No 1 **Revision** A

Project FEAST

Hardware Status Mod existing

Revision Date Apr 4, 1989

Objective

1.) Provide a means for initial screening of plant cultivars in terms of their ability to germinate in μ-g.
2.) Determine root-shoot orientation under μ-g conditions.

Hardware Description

Modified Plant Growth Unit.

Desired Features/Functions

1. Lighting : LED @ >180 μmol/sq.m/s
2. Basic nutrient delivery
3. Video recording and/or downlink capability

Hardware Specifications

Weight (Kg) 27.3 **Height (m)** .253 **Width (m)** .440

Depth (m) .516 **Temp Range** Ambient

Peak Power (Kw) .300 **Cont Power (Kw)** .150

Power Source

STS Mid-deck.

Item Specific Support Equipt

Plant Growth Module

Data Downlink Reqs

1.5 MBPS Video; 1.6 KBPS Voice

Rack Mounted/Stowed STS Middeck

Hardware Specifications

Design Status

Modification to PGU required.

Development Cost ($K)	5,700
Development Time (months)	12
Anticipated Launch Date	1992 & 1996
Risk Category	1

CELSS/FEAST Hardware Data Sheet

Report Date 4/5/89

Germination Experiment Kit

Science Justification

Identified Experiments

CELSS Germination Studies.

History

Utilizes existing PGU design with modification for germination studies.

Problem/Issues&Concerns

none

Vendor Source List

Interface Requirements

STS Mid-deck.

Special Considerations

none

Safety Issues

none

Flight Opportunity USML-1 (3/92) & USML-4 (5/96)

Notes

1.) Two flights needed : Possible flights are USML-1 and USML-4.

REV A : Revised cost 4/4/89 from $5250K to $2700K to reflect changes in Cost Estimates.

CELSS/FEAST Hardware Data Sheet
Report Date 4/5/89

Controlled Ecological Life Support System

Hardware Status Planned

Revision Date Apr 4, 1989

Title Gas/Liquid Handling Experiment H/W

Element No 2 **Revision** A

Project FEAST

Objective

1.) To evaluate and demonstrate fundamental physical principles of gas and liquid handling, mixing and separation under μ-g environment as applied to CELSS technology development.
2.) To demonstrate concept design for gas/liquid handling systems in μ-g.

Hardware Description

An experiment package for KC-135, STS (GAS or Mid-deck) or Spacelab for evaluating physical principles pertaining to gas and liquid handling, mixing and separation under μ-g conditions.

Desired Features/Functions

1. Video recording and/or downlink capability
2. Capable of mixing and separation tests of a variety of gas/liquid combinations common to CELSS (water/air, nutrient solution/air, etc)
3. Thermal and shock isolation
4. Liquid and gas containment
5. Various gas and liquid reservoirs
6. Mixing and separation chamber
7. Simple PLC control with control valves.

Hardware Specifications

Weight (Kg) 27.3 **Height (m)** .253 **Width (m)** .440

Depth (m) .516 **Temp Range** Ambient

Peak Power (Kw) .3 **Cont Power (Kw)** .15

Power Source

Standard KC-135, Spacelab or NSTS source.

Item Specific Support Equipt

none

Data Downlink Reqs

.05 KBPS Command; 1.5 KBPS Digital; 1.5 MBPS Video; 1.6 KBPS Voice

Rack Mounted/Stowed NSTS:Mid-deck Stowage
SL : Rack Mounted

Hardware Specifications

1. Mid-deck locker size, may be partial SL rack size.

Design Status

New Design

Development Cost ($K)	1,500
Development Time (months)	24
Anticipated Launch Date	1993
Risk Category	3

Gas/Liquid Handling Experiment H/W

Science Justification

Evaluation of physical principles for FEAST.

Identified Experiments

History

Existing liquid/gas transfer, mixing and separation technologies for μ-g from previous space flight vehicles and payloads.

Problem/Issues&Concerns

none at present

Vendor Source List

none at present

Interface Requirements

Standard KC-135, NSTS or SL

Special Considerations

Containment of liquids and gases.

Safety Issues

none

Flight Opportunity USML-2 (8/93)

Notes

REV A : Revised cost 4/4/89 from $3000K to $1500K. Changed Unit No. from 3 to 2 to reflect Cost Estimate categorization; added misc data to various categories.

CELSS/FEAST Hardware Data Sheet
Report Date 4/5/89

Controlled Ecological Life Support System

Hardware Status Planned

Revision Date Apr 4, 1989

Title Water Condensation & Re-cycling Exp H/W

Element No 3 **Revision** A

Project FEAST

Objective

1.) To determine problems associated with water condensation technologies under μ-g.
2.) Demonstrate and prove-out conceptual designs.

Hardware Description

Spacelab, NSTS middeck or KC-135 size experiment package for water condensation studies.

Desired Features/Functions

1. Video recording and/or downlink capability
2. Water vapor source and water reservoir
3. Condensation chamber with cooling
4. Stream processing capability at various rates
5. Monitoring capability of : relative humidty, liquid volume, process rates

Hardware Specifications

Weight (Kg) 27.3 **Height (m)** .253 **Width (m)** .440

Depth (m) .516 **Temp Range** Ambient

Peak Power (Kw) .300 **Cont Power (Kw)** .150

Power Source

Standard platform source.

Item Specific Support Equipt

none

Data Downlink Reqs

Rack Mounted/Stowed Rack Mounted or Stowed.

Hardware Specifications

Design Status

New Design

Development Cost ($K) 2,900

Development Time (months)

Anticipated Launch Date 1995

Risk Category 4

CELSS/FEAST Hardware Data Sheet

Report Date 4/5/89

Water Condensation & Re-cycling Exp H/W

Science Justification

Identified Experiments

History

Problem/Issues&Concerns

Vendor Source List

Interface Requirements

Special Considerations

Safety Issues

Flight Opportunity USML-3 (1/95)

Notes

1.) Two flights may be required.
2.) May only require KC-135 flight to validate.
3.)

REV A : Revised cost 4/4/89 from $5800K to $2900K. Changed Unit No. from 2 to 3 to reflect Cost Estimate categorization.

Controlled Ecological Life Support System

Hardware Status Planned

Revision Date Apr 4, 1989

Title Nutrient Delivery Test H/W

Element No 4 **Revision** A

Project FEAST

Hardware Description

Size of two middeck lockers on STS to study basic μ-g nutrient delivery systems.

Objective

1. To evaluate plant nutrient delivery concepts under μ-g conditions for CELSS technology development.

Desired Features/Functions

1. Video recording and/or downlink capability.
2. Capability for testing a number of nutrient delivery concepts
3. Liquid and gas containment

Hardware Specifications

Weight (Kg) 27.3 **Height (m)** .253 **Width (m)** .440

Depth (m) .516 **Temp Range** Ambient

Peak Power (Kw) .300 **Cont Power (Kw)** .150

Power Source

Standard mid-deck power source or equivalent

Item Specific Support Equipt

none

Data Downlink Reqs

.05 KBPS Command; 1.5 KBPS Digital; 1.5 MBPS Video; 1.6 KBPS Voice

Rack Mounted/Stowed Stowed

Hardware Specifications

Design Status

New Design

Development Cost ($K)	3,475
Development Time (months)	24
Anticipated Launch Date	1992 & 1996
Risk Category	4

Nutrient Delivery Test H/W

Science Justification

Provides test and demonstration of nutrient delivery systems for CELSS technologies.

Identified Experiments

History

None

Problem/Issues&Concerns

Vendor Source List

None

Interface Requirements

Special Considerations

Safety Issues

Flight Opportunity SLS-2 (7/92) & IML-4 (3/96)

Notes

REV A : Revised cost 4/4/89 from $6850K to $3475K.

CELSS/FEAST Hardware Data Sheet

Report Date 4/5/89

Controlled Ecological Life Support System

Hardware Status Planned

Revision Date Apr 4, 1989

Title CELSS Test Facility

Element No 5 **Revision** A

Project FEAST

Hardware Description

Crop growth research facility for seed-to-seed crop studies under μ-gravity. IOC Station Freedom implementation.

Objective

1.) To provide a facility for conducting plant productivity studies from seed to maturity (in some instances seed to seed) with mixed crops and in mixed maturities under μ-gravity conditions.

2.) Assess system reliability and maintainability for CELSS technologies.

Desired Features/Functions

1. Modular subsystem elements to allow for design evolution.
2. LED lighting system
3. Standard double rack size.
4. Complete control of inputs and outputs to Station ambient atm.
5. Implements automation and expert systems.
6. Full complement DAS.
7. Maximized degree of closure

Hardware Specifications

Weight (Kg) 634.7 **Height (m)** 1.89 **Width (m)** 1.05

Depth (m) 0.91 **Temp Range** S.S. Ambient

Peak Power (Kw) 2.0 **Cont Power (Kw)** 1.5

Power Source

Standard Rack power

Item Specific Support Equipt

CTF Germination and Storage Chamber.

Data Downlink Reqs

.05 KBPS Command, 1.5 KBPS Digital, 1.5 MBPS Video, 1.6 KBPS Voice

Rack Mounted/Stowed Rack Mounted

Hardware Specifications

1. Lighting : 0 - 3000 μmol/sq.m/s
2. Modular nutrient delivery system
3. Sealed enclosure w/ access and windows
4. Fully controllable HVAC
5. Pressure compensation system
6. Water condensation & re-cycling capability
7. Control of internal gaseous environment (O2, CO2, N2)
8. Microbial monitoring capability
9. Monitoring, control and data acquisition systems
10. Automated specimen handling
11. Growing Area: 0.71 sq.m, max growing height : 0.85 m
12. Self-contained with modular subsystems
13. Fuill control of parameters withing specified ranges

Design Status

New Design

Development Cost (SK)	42,050
Development Time (months)	72
Anticipated Launch Date	1998
Risk Category	3

CELSS/FEAST Hardware Data Sheet

Report Date 4/5/89

CELSS Test Facility

Science Justification

Hardware is mandatory for developement of future CELSS technologies and advanced life support systems.

Identified Experiments

Hardware to be used in meeting CELSS Project FEAST objectives.

History

Major design elements derived from non-flight Crop Growth Research Chamber (CGRC) requirements.

Problem/Issues&Concerns

Nutrient dlivery system, lighting, & power.

Vendor Source List

None at present.

Interface Requirements

Standard Space Station Freedom rack interfaces.

Special Considerations

None

Safety Issues

None

Flight Opportunity PMC S.S. Freedom

Notes

1. Establish reliability baseline for CELSS hardware
2. Needs maintenance scenario and possibly S/E for same.
3. Current crop candidates are : Potatoes, soybeans, wheat, tomato, lettuce, radish, rice, onion, legume & spinach.

REV A : Revised cost 4/4/89 from $15,000K to $42,050K to reflect incorporation of CROP elements into CTF. Revised growing area from 1.5 - 2.0 sq.m to 0.71 sq.m, power from 1.8kW to 2.0 Kw peak and 1.2 - 1.3 kW cont to 1.5kW, mass changed from 1000 kg to 634.7 kg.

Controlled Ecological Life Support System

Hardware Status Planned

Revision Date

Title CTF Germination Chamber

Element No 6 **Revision** NR

Project FEAST

Hardware Description

Provides germination environment for seed germination proir to planting in the CELSS Test Facility, Approx. the size of STS Middeck Locker

Objective

1. To provide environment for germinating seeds prior to planting in the CTF.
2. To provide seed storage.

Desired Features/Functions

1. Air-tight chamber
2. Humidity controlled
3. Heat, shock and vibration isolated

Hardware Specifications

Weight (Kg) 6.8 **Height (m)** .253 **Width (m)** .440

Depth (m) .516 **Temp Range** S.S. Ambient

Peak Power (Kw) .300 **Cont Power (Kw)** .150

Power Source

none required

Item Specific Support Equipt

none

Data Downlink Reqs

none

Rack Mounted/Stowed Stowed

Hardware Specifications

Approximately the size of a NSTS Middeck Locker.

Design Status

New Design

Development Cost ($K)	800
Development Time (months)	12
Anticipated Launch Date	1998
Risk Category	1

CELSS/FEAST Hardware Data Sheet

Report Date 4/5/89

CTF Germination Chamber

Science Justification

Provides germination of seeds prior to planting in the CTF. Reduces operational power demand on CTF. Provides seed storage.

Identified Experiments

none

History

Plant Growth Unit.

Problem/Issues&Concerns

none

Vendor Source List

none

Interface Requirements

Special Considerations

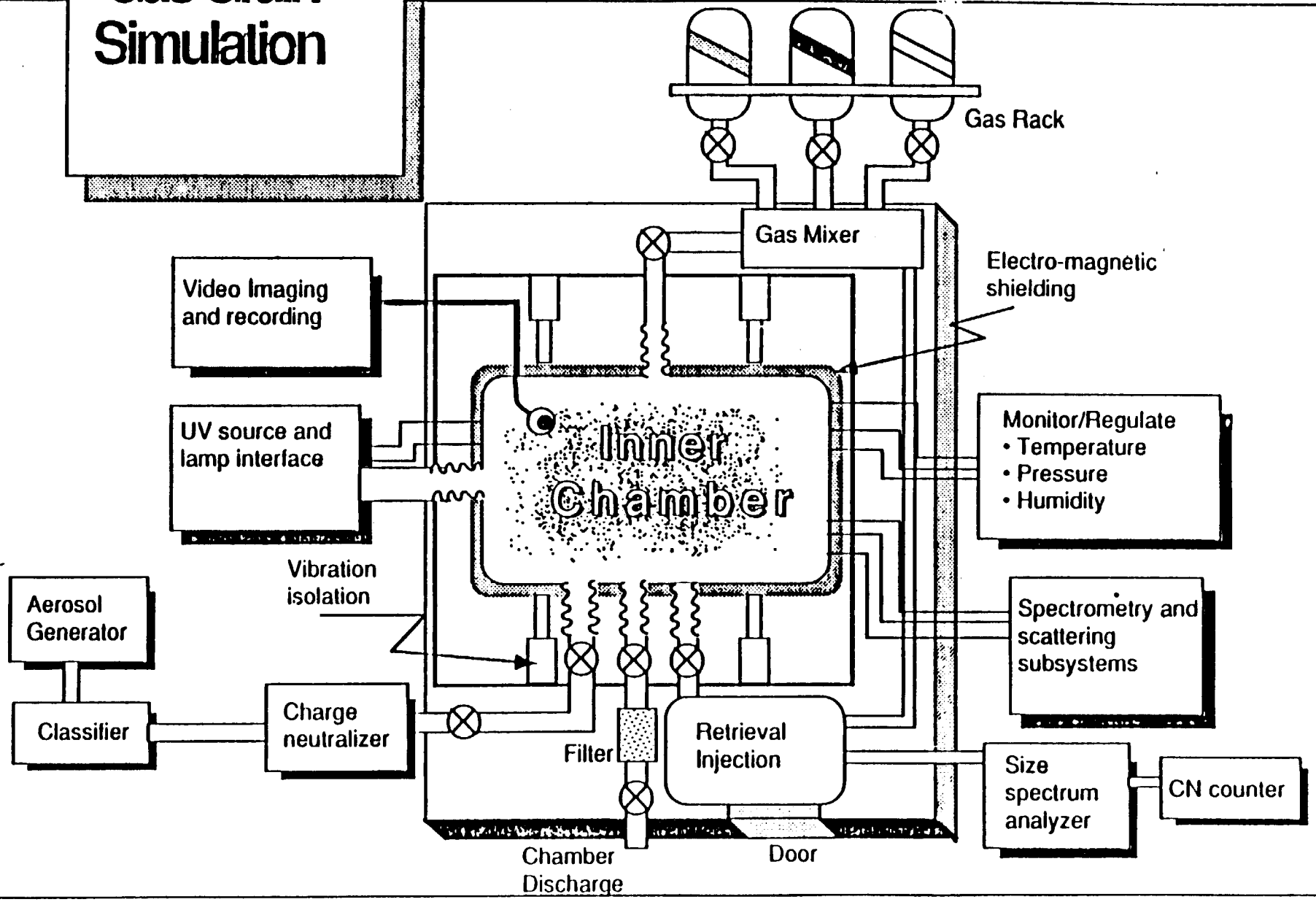
Safety Issues

Flight Opportunity PMC Space Station Freedom

Notes

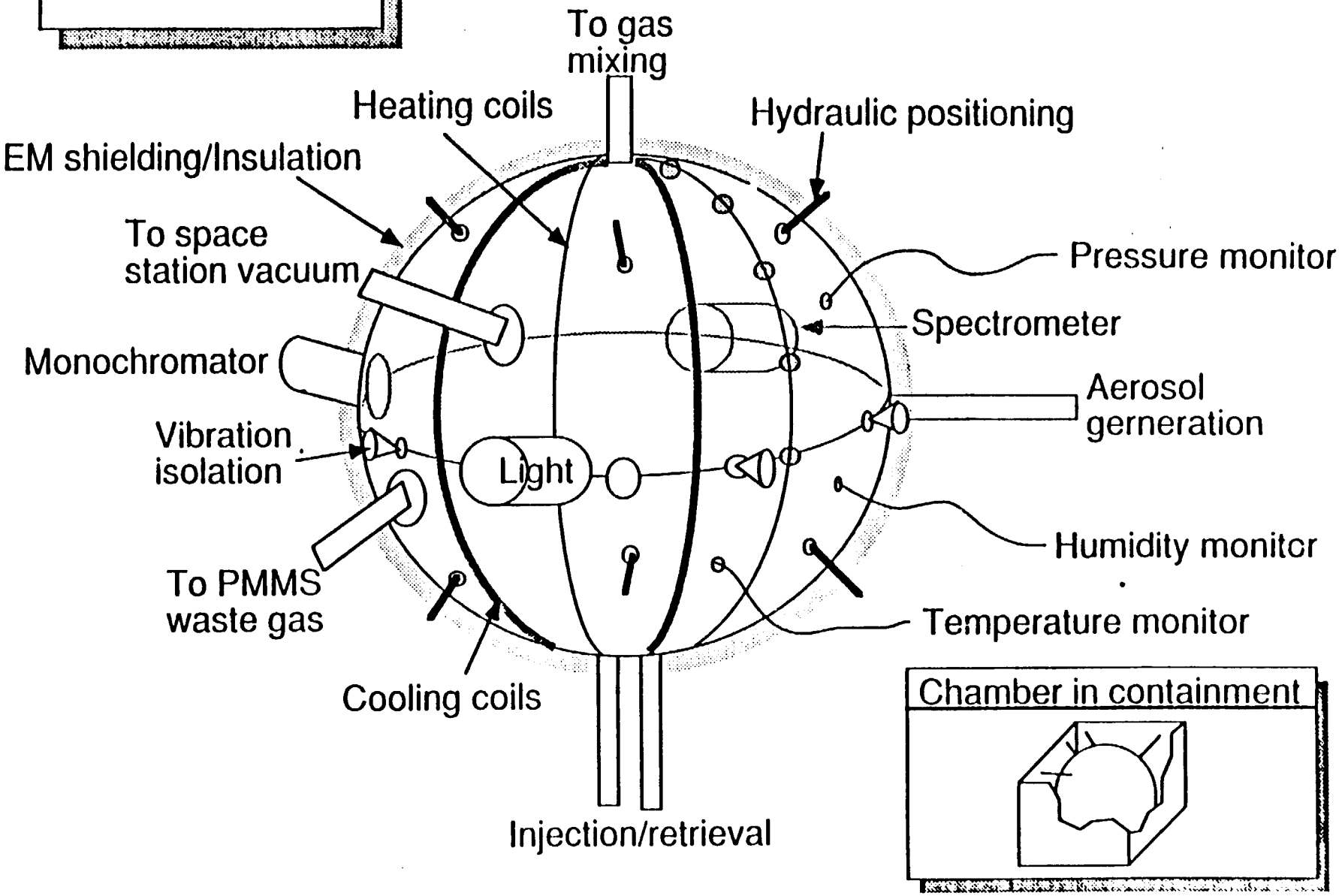
1. Provides for two separate and independent compartments: a.) Seed storage compartment and b.) Germination compartment.
2. Seed compartment could also be used for misc. equipment stowage

Gas Grain Simulation

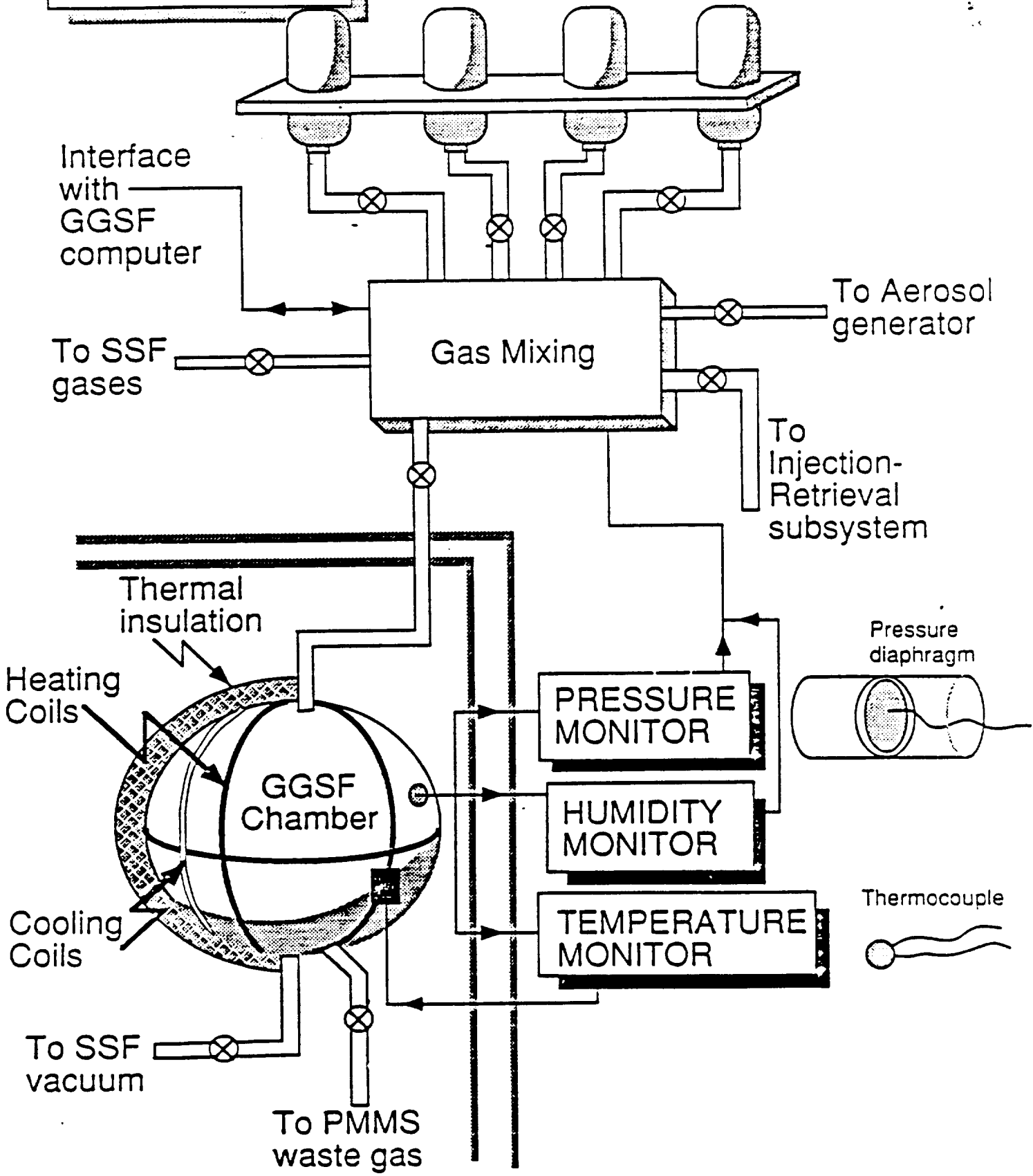


GGSF Chamber

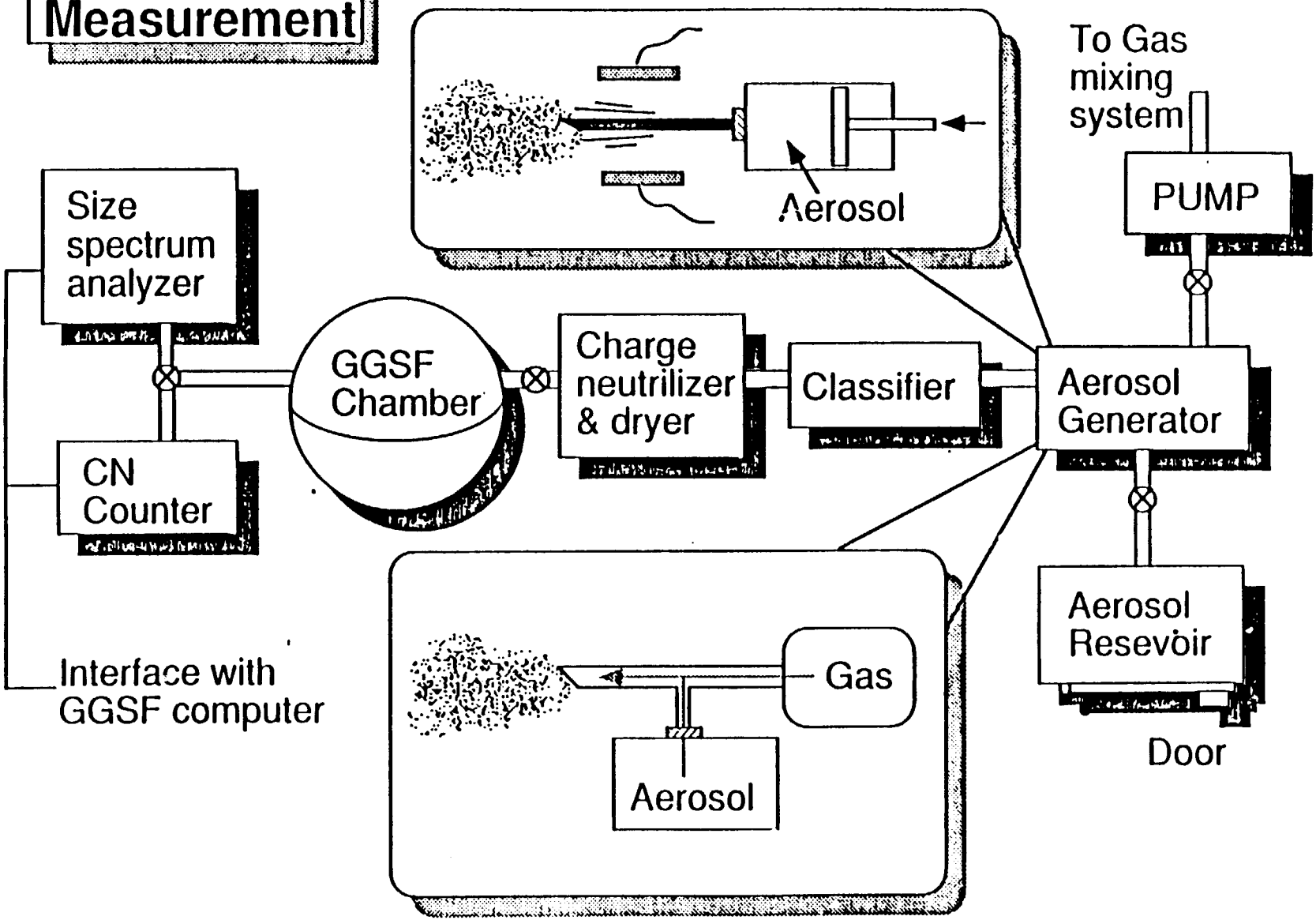
Ports and component connections indicated



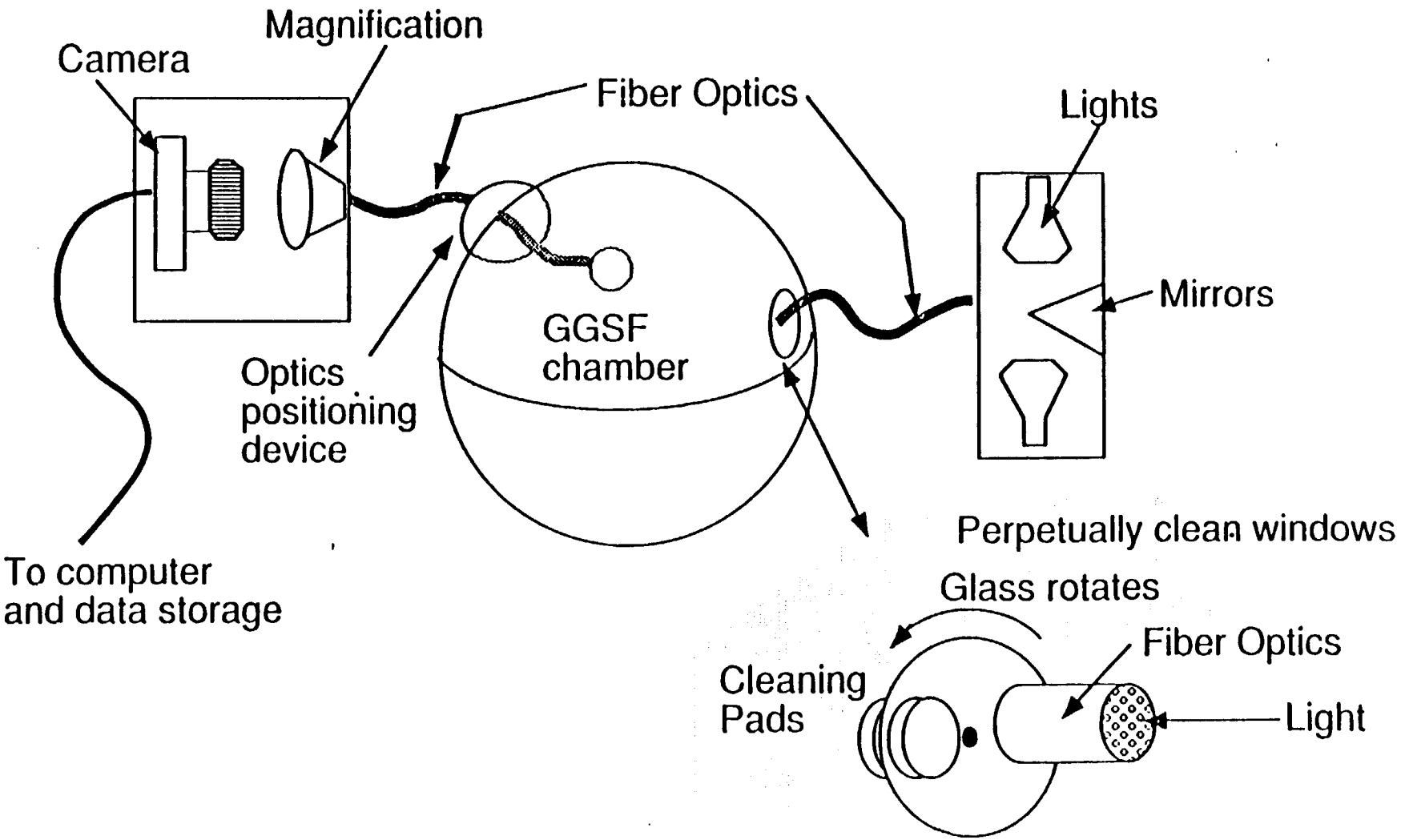
Environment Control



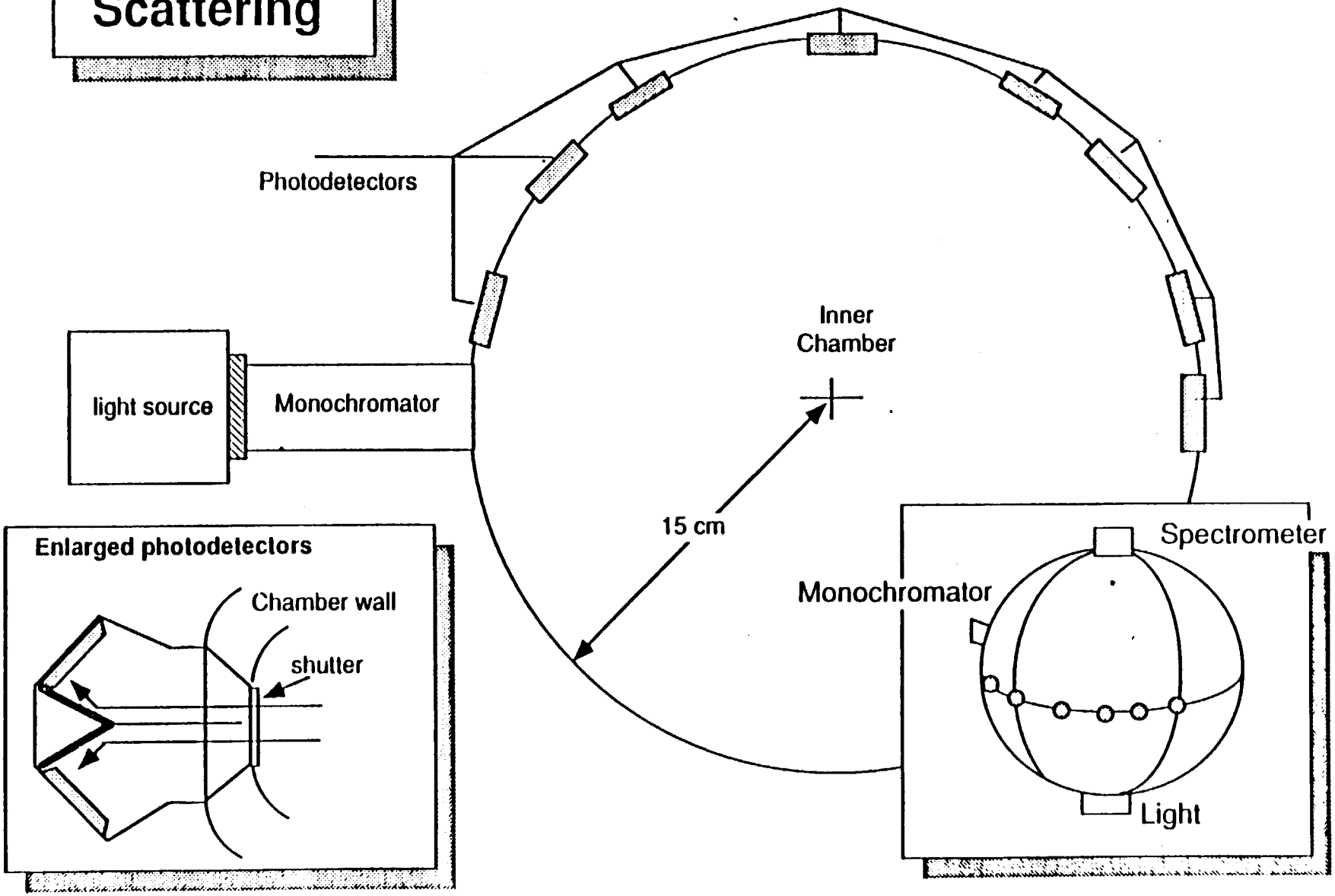
Aerosol Generation-Measurement



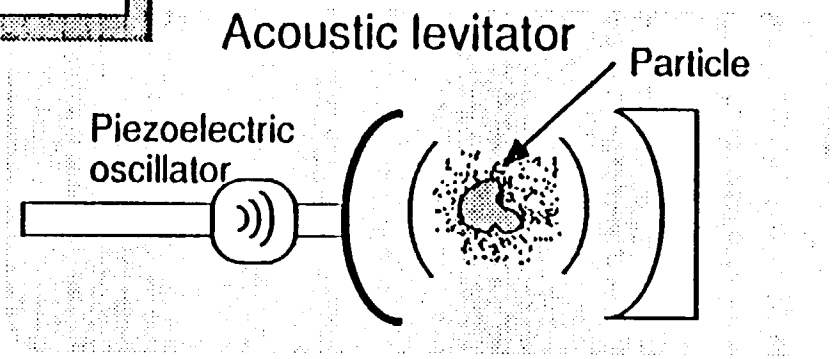
Imaging Systems

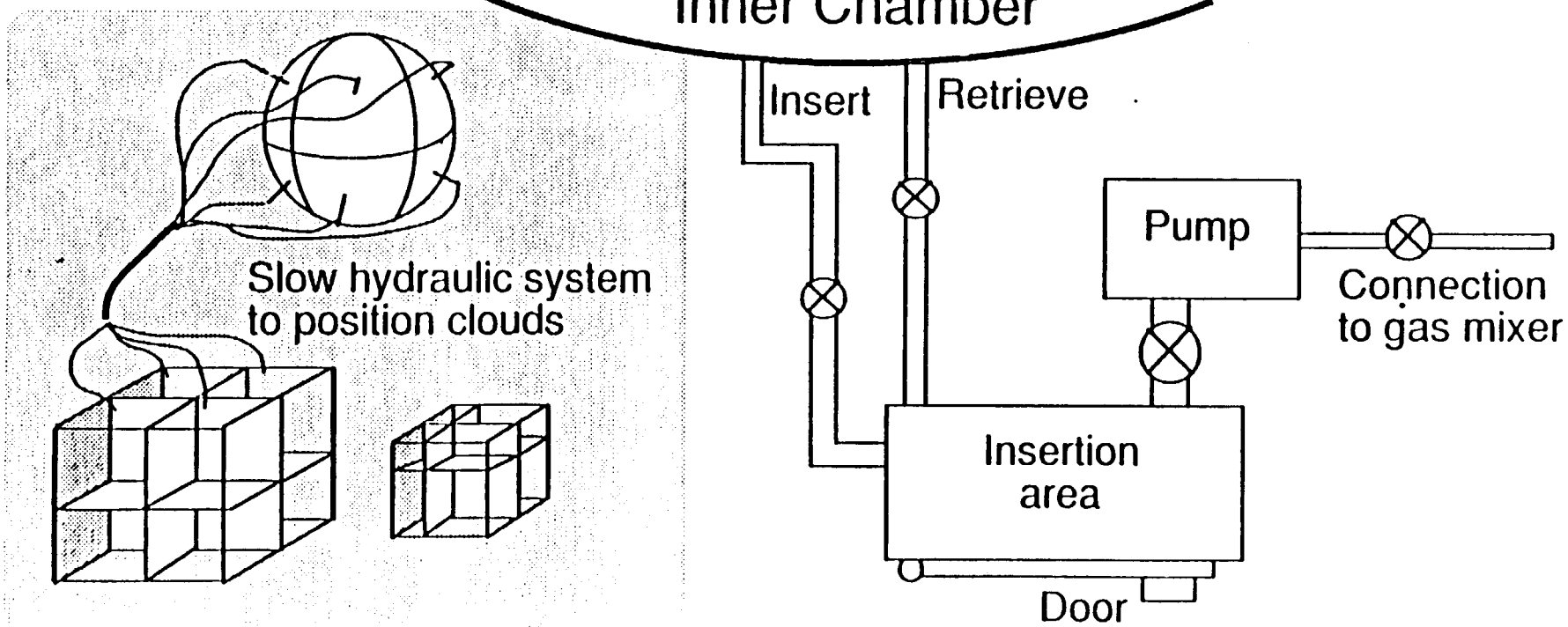


Spectrometry and Scattering

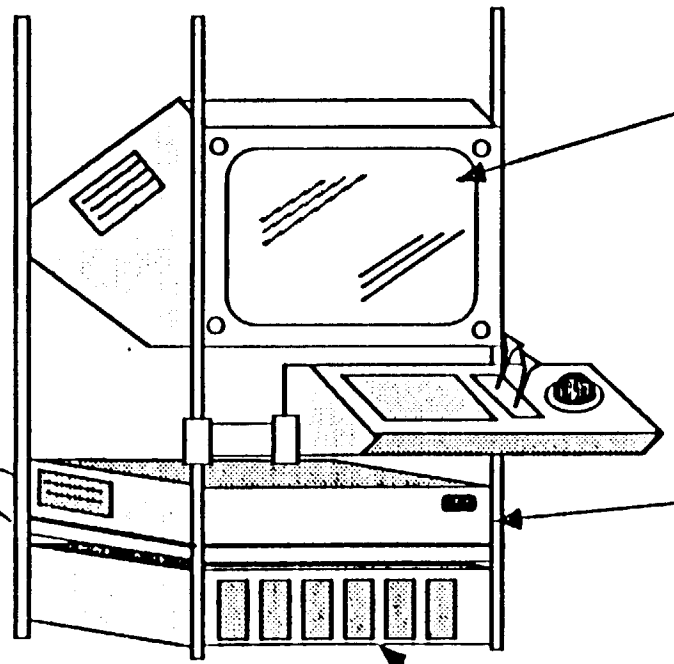


Retrieval Injection Manipulation





Computer Control



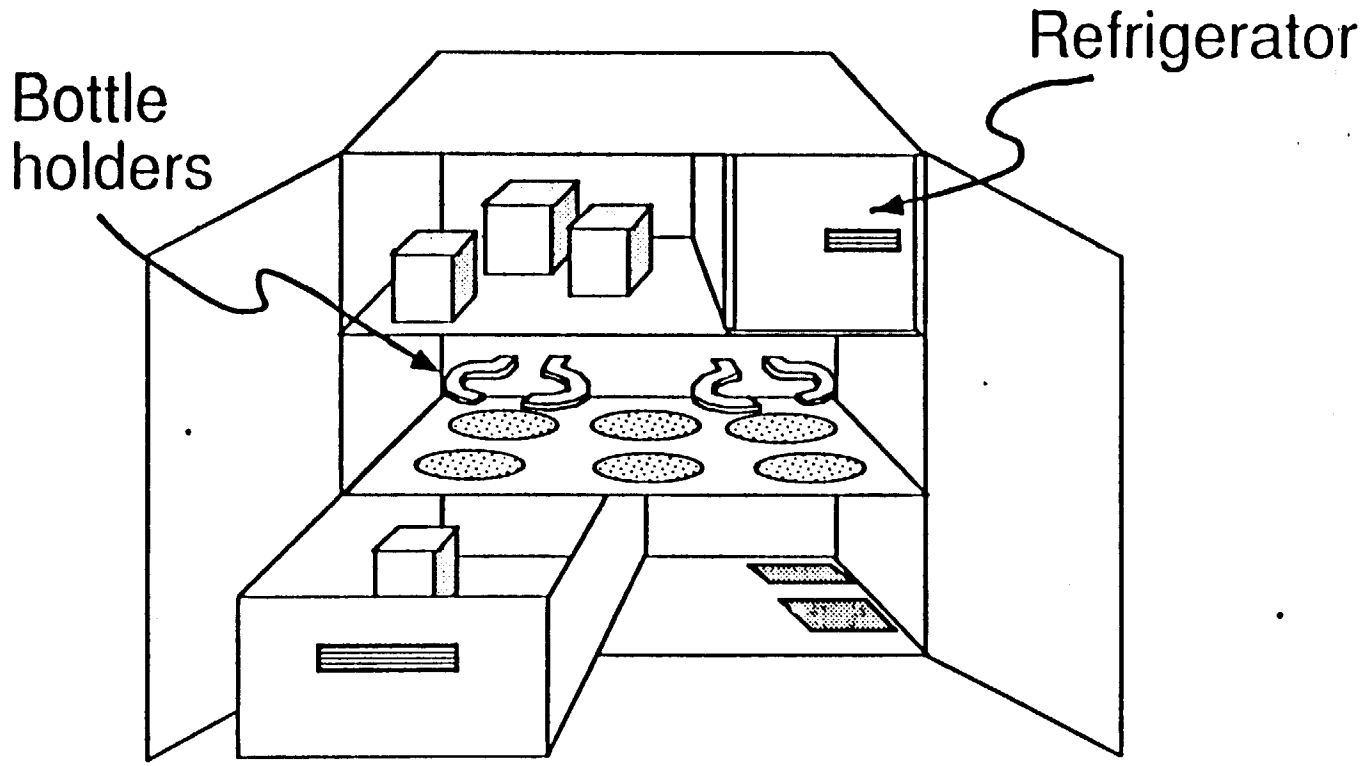
Full color screen for
- Data Display
- Imaging

Data bus to GGSF systems

CPU and mass storage

Slots for P.I. provided electronics

Storage Locker



Gas-Grain Simulation Facility: Description

The Gas-Grain Simulation Facility (GGSF), currently under development by the Exobiology Flight Experiments Program at Ames Research Center, is a facility-class payload proposed for the Space Station. The GGSF will be used to simulate and investigate fundamental chemical and physical processes such as the formation, collision and interaction of droplets, grains and other particles.

The Gas-Grain Simulation Facility will occupy a Space Station double rack. It will consist of several subsystems supporting an adaptable 10 liter experiment chamber. Subsystems will provide environmental control (e.g., temperature, pressure, gas mixture and humidity), measurement equipment (e.g., video cameras, optical particle counters, spectrometers, and photometers), and energy sources. Subsystems will also furnish: command and control capability; mechanisms for producing, injecting, and removing particles and clouds of particles; and levitation devices for positioning particles and keeping them in fixed positions away from the chamber walls. GGSF mass and power requirements are estimated to be 700 to 800 Kg and 1500 W peak (750 W average) respectively.

The GGSF will be modular in design; that is, it will have an adaptable configuration allowing subsystem components to be connected in a number of ways. Modularity will also allow the GGSF to evolve. At an early stage, the GGSF would be capable of supporting those experiments which promise high scientific yield and require only a few subsystems. Further, modularity will allow outdated subsystems to be replaced. New experiment chambers will be brought to the Space Station once a year so the GGSF will have a very long, useful lifetime (i.e., 10 years).

The facility's computer will control all operations of the facility during an experiment and have an autonomous decision making capability. Data exchange requirements, estimated at 20 to 40 kilobytes per day, are modest. Data/command uplinks will occur about twice per week. Aside from time needed for the initial set-up and calibration of experiments, crew time requirements will be minimal.

One possible GGSF operational sequence is as follows: A chamber designed for a series of experiments is "plugged in" to the GGSF and subsystems are attached in the configuration necessary for the first experiment. A command is then given to begin the execution of preprogrammed instructions for performing the experiment. After the first experiment is completed, the system may be reconfigured for the second experiment. When the sequence of experiments associated with the first chamber is completed, the chamber is removed and stored for return to Earth and a second chamber is attached for the next sequence of experiments.

Since many of the suggested GGSF experiments require gravitational accelerations of 10^{-4} to 10^{-5} g, it will be necessary to consider the background gravitational gradient when deciding where in the Space Station to place the GGSF. The GGSF will take advantage of some of the user support systems supplied by the Space Station such as the 10^{-3} torr "house" vacuum and data from the accelerometer system. Also, given the delicate physical and chemical properties of some particles generated in the GGSF, some preliminary sample analysis on the Space Station may be desirable. Such analysis will require special sample handling equipment and analytical tools. For example, some GGSF experiments will use a Scanning Electron Microscope, a Gas Chromatograph, a Mass Spectrometer, a (micro) mass measurement system, and/or a High Pressure Liquid Chromatograph if they are available.

Gas-Grain Simulation Facility: Science Rationale/Objectives

In many astrophysical and geological systems (atmospheric clouds, interstellar clouds, planetary rings, Titan's organic aerosols, Martian dust storms, etc.), processes involving small particles significantly contribute to the overall behavior of the system. Grain nucleation and aggregation, low velocity particle collisions, and charge accumulation are a few of the processes that influence such systems. Particles undergoing these processes include interstellar grains, protoplanetary particles, atmospheric aerosols, combustion products, and pre-biotic organic polymers.

The ability to simulate and investigate these types of systems and processes would present an exciting opportunity to answer long-standing scientific questions concerning the life and death of stars, the formation of the Solar System, and the connection between the Solar System's evolution and the appearance of life. These investigations would also increase our understanding of processes of immediate concern such as acid rain formation, ozone depletion, and climatic change on Earth. Furthermore, investigation of particle systems is essential to the achievement of NASA's scientific goal to attain a deep understanding of the Solar System, Earth, and the origin of life.

Many particle systems are not well understood because parameters relevant to these systems are poorly determined or unknown. Examples of such parameters are the coagulation rate of aerosol particles, the size distribution of particles nucleated from a gas, and the dependence of aggregation efficiency on material properties. Due to rapid particle settling in a 1g environment, these parameters are difficult and in many cases impossible to measure in experimental simulations on Earth.

In the study of small particle processes relevant to scientific issues mentioned above, the demands on experiment design are severe. Two common requirements are low relative velocities between particles and long time periods during which the particles must be suspended. Generally, the suspension times required are substantially longer than can be attained in 1g. Furthermore, for many studies, Earth's gravity can interfere directly with the phenomenon under study (e.g., weak inter-particle forces) or preclude the establishment of proper experimental conditions (e.g., a convection-free environment). Consequently, many processes are not amenable to experimentation in 1g.

However, in the Earth-orbital environment, the effects of gravity are reduced by a factor of as much as one million. In this environment, previously impractical or impossible experiments become feasible. Small-particle processes which cannot be studied on Earth can be investigated in Earth-orbit with a general-purpose microgravity particle research facility such as the Gas-Grain Simulation Facility (GGSF).

The GGSF, a facility-class payload proposed for the Space Station, will be used to simulate and investigate fundamental chemical and physical processes such as the formation, collision and interaction of droplets, grains and other particles. Scientific issues that can be addressed with the Gas-Grain Simulation Facility are relevant to the disciplines of exobiology, planetary science, astrophysics, atmospheric science, biology, and physics and chemistry. To date, twenty candidate GGSF experiments have been identified and described in detail. The candidate experiments are as follows:

1. Low-Velocity Collisions Between Fragile Aggregates

2. Low-Energy Grain Interaction/Solid Surface Tension

3. Cloud Forming Experiment

4. Planetary Ring Particle Dynamics
5. Aggregation of Fine Geological Particulates in Planetary Atmospheres
6. Condensation of Water on Carbonaceous Particles
7. Optical Properties of Low-Temperature Cloud Crystals
8. Ice Scavenging and Aggregation
9. Synthesis of Tholin in Microgravity and Measurement of its Optical Properties
10. Metallic Behavior of Aggregates
11. Investigations of Organic Compound Synthesis on Surfaces of Growing Particles
12. Crystallization of Protein Crystal-Growth Inhibitors
13. Dipolar Grain Coagulation and Orientation
14. Titan Atmospheric Aerosol Simulation
15. Surface Condensation and Annealing of Chondritic Dust
16. Studies of Fractal Particles
17. Emission Properties of Particles and Clusters
18. Effect of Convection on Particle Deposition and Coagulation
19. Growth and Reproduction of Microorganisms in a Nutrient Aerosol
20. Long Term Survival of Human Microbiota in and on Aerosols

The GGSF will be sufficiantly flexible to accommodate the above as well as many other scientifically important investigations without compromising the requirements of any particular investigation. By extending the range of conditions in which experiments can be performed, the GGSF will be a powerful tool for studying the physics of small particles and grains. Important advances in our understanding of the many small-particle phenomena should follow from the new ability to study subtle small-particle effects and interactions.

Gas-Grain Simulation Facility: Hardware

The Gas-Grain Simulation Facility (GGSF) consists of eight subsystems which are complimentary and interdependent. All of the subsystems are necessary for meeting the facility science requirements. The GGSF subsystems and hardware are as follows:

1. General Purpose Experiment Chamber/Containment Subsystem
   (Includes ports, feed-throughs, subsystem interfaces, double- or triple-containment, vibration isolation, EM shielding, etc.)

2. Chamber Environment Regulation/Monitoring Subsystem
   (For regulation and monitoring of temperature, pressure, and humidity. Includes gas-handling system, filters, etc.)

3. Aerosol Generation/Measurement Subsystem
   (Includes aerosol generators, size spectrum analyzers, CN counter, electrostatic classifier, dryer, charge neutralizer, etc.)

4. Chamber Illumination, Optics, and Imaging Subsystem
   (Includes UV sources, camera with optics, various lamps, photometer, etc.)

5. Spectrometry/Optical Scattering Subsystem
   (Includes spectrometers, lasers, photodetectors and other support equipment for light scattering measurements, etc.)

6. Particle Manipulation and Positioning Subsystem
   (Includes acoustic levitator, particle injection mechanisms, particle retrieval mechanisms, etc.)

7. Computer Control and Data Acquisition Subsystem
   (Includes microcomputer and console, data bus, data storage, control electronics, etc.)

8. Storage Locker
   (For storing special gas mixtures, fluids for aerosol generators, interfaces and adaptors, PI-provided hardware, samples produced in experiment runs, film, etc.)

LIFE SCIENCES FLIGHT PROGRAMS CHANGE REQUEST

Reference Documentation:

Life Sciences Hardware List for the Space Station Freedom Era. R-0006

Description of Change:

Change the **Exobiology Facility** section to reflect the following:

EXOBIOLOGY FACILITY (8)

		Volume (cu. m)	Weight (kg)	Power (watts)
Gas-Grain Simulation Facility Hardware Group (8A)		**2.40**	**800**	**1500**
1.	General Purpose Experiment Chamber/Containment Subsystem	0.48	200	0
2.	Chamber Environment Regulation/Monitoring Subsystem	0.23	80	200
3.	Aerosol Generation/Measurement Subsystem	0.45	150	300
4.	Chamber Illumination, Optics, and Imaging Subsystem	0.20	80	200
5.	Spectrometry/Optical Scattering Subsystem	0.20	150	300
6.	Particle Manipulation and Positioning Subsystem	0.16	50	200
7.	Computer Control and Data Acquisition Subsystem	0.20	50	300
8.	Storage Locker	0.48	40	0

Justification/Rationale:

This Change Request identifies the component subsystems of the Gas-Grain Simulation Facility (8A) and includes the volume, weight and power estimates for each subsystem. The additional 0.48 cubic meters of volume indicated in this Change Request is required for storage of items such as special gas mixtures, fluids for aerosol generators, experiment-produced samples to be returned to Earth, and film. These changes reflect further refinement of the Gas-Grain Simulation Facility requirements.

Gas-Grain Simulation Facility: Hardware Definitions

General Purpose Experiment Chamber/Containment Subsystem: The Gas-Grain Simulation Facility (GGSF) experiment chamber for studying small-particle processes and interactions in microgravity.

Chamber Environment Regulation/Monitoring Subsystem: A Gas-Grain Simulation Facility (GGSF) subsystem that establishes, regulates, and removes the gas-mixture in the GGSF chamber as well as monitors and regulates the chamber/gas temperature, pressure, and humidity.

Aerosol Generation/Measurement Subsystem: A Gas-Grain Simulation Facility (GGSF) subsystem that generates and introduces into the GGSF chamber aerosol clouds of various concentration, particle-size, and dispersion and monitors the cloud size-distribution and total concentration.

Chamber Illumination, Optics, and Imaging Subsystem: A Gas-Grain Simulation Facility (GGSF) subsystem that provides optical imaging of processes occurring in the GGSF chamber and provides various light/energy sources.

Spectrometry/Optical Scattering Subsystem: A Gas-Grain Simulation Facility (GGSF) subsystem that measures light-scattering and extinction properties of aerosol/dust clouds and single grains.

Particle Manipulation and Positioning Subsystem: A Gas-Grain Simulation Facility (GGSF) subsystem that mechanically and/or aerodynamically injects particles into the chamber, manipulates them by acoustic and/or aerodynamic levitation, and retrieves samples from the chamber.

Gas-Grain Simulation Facility Computer Control and Data Acquisition Subsystem: A Gas-Grain Simulation Facility (GGSF) subsystem which provides computer and electronic control of experiments, data acquisition and storage.

Gas-Grain Simulation Facility Storage Locker: A locker to store Gas-Grain Simulation Facility (GGSF) support materials such as PI-provided equipment and special dust or aerosol mixtures for a planned suite of experiments and to store samples for return to Earth.