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SPACE BIOLOGY INITIATIVE
PROGRAM DEFINITION REVIEW

TRADE STUDY 1

AUTOMATION COSTS
vs.
CREW UTILIZATION

FINAL REPORT

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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

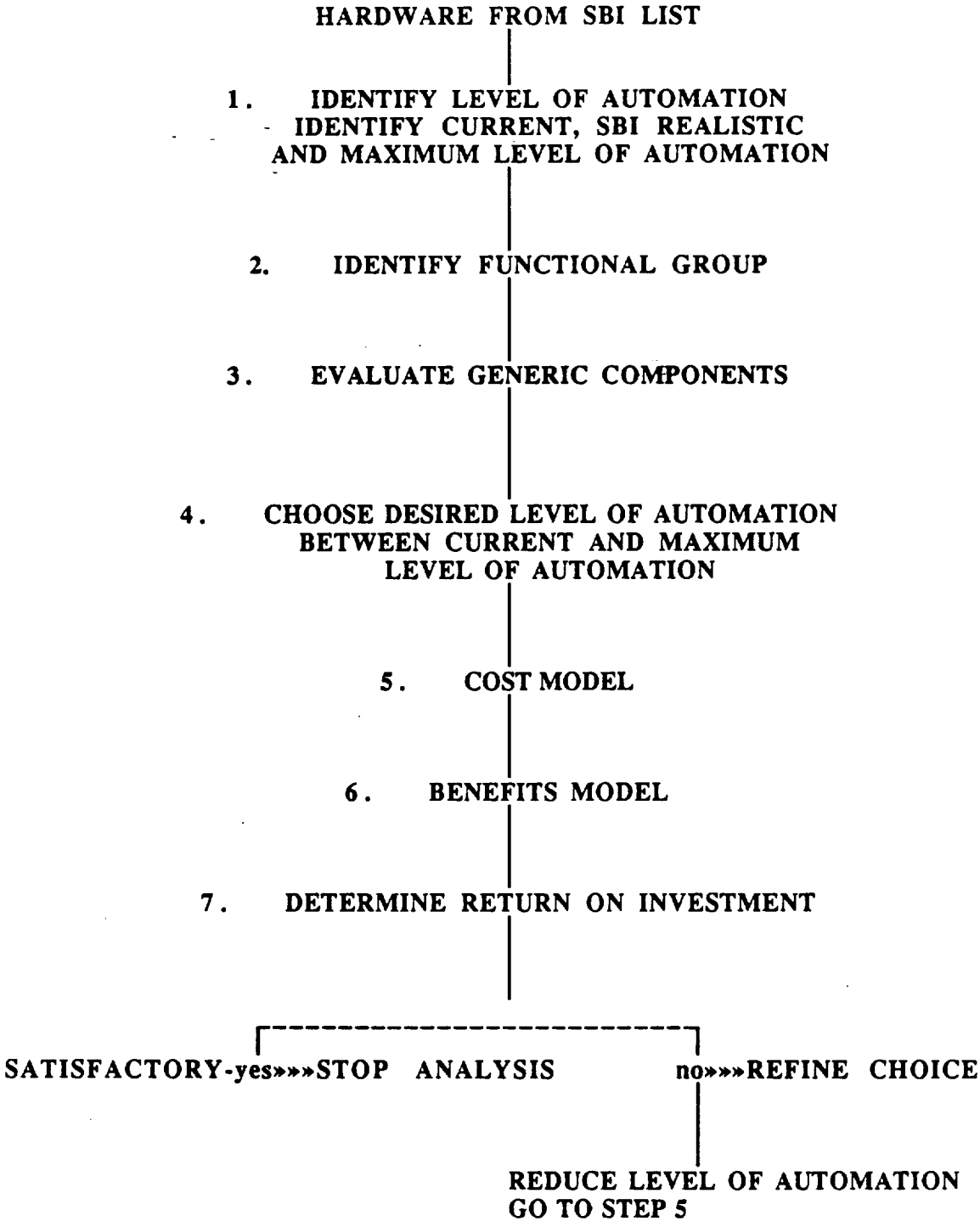

Figure 1 A Flow diagram to illustrate the methodology to determine the most cost effective automation level

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.

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

o The task network of the hardware item is small

o 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 :

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

o 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 :

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

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

o The task network of the hardware item is large.

o 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 :

o 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).

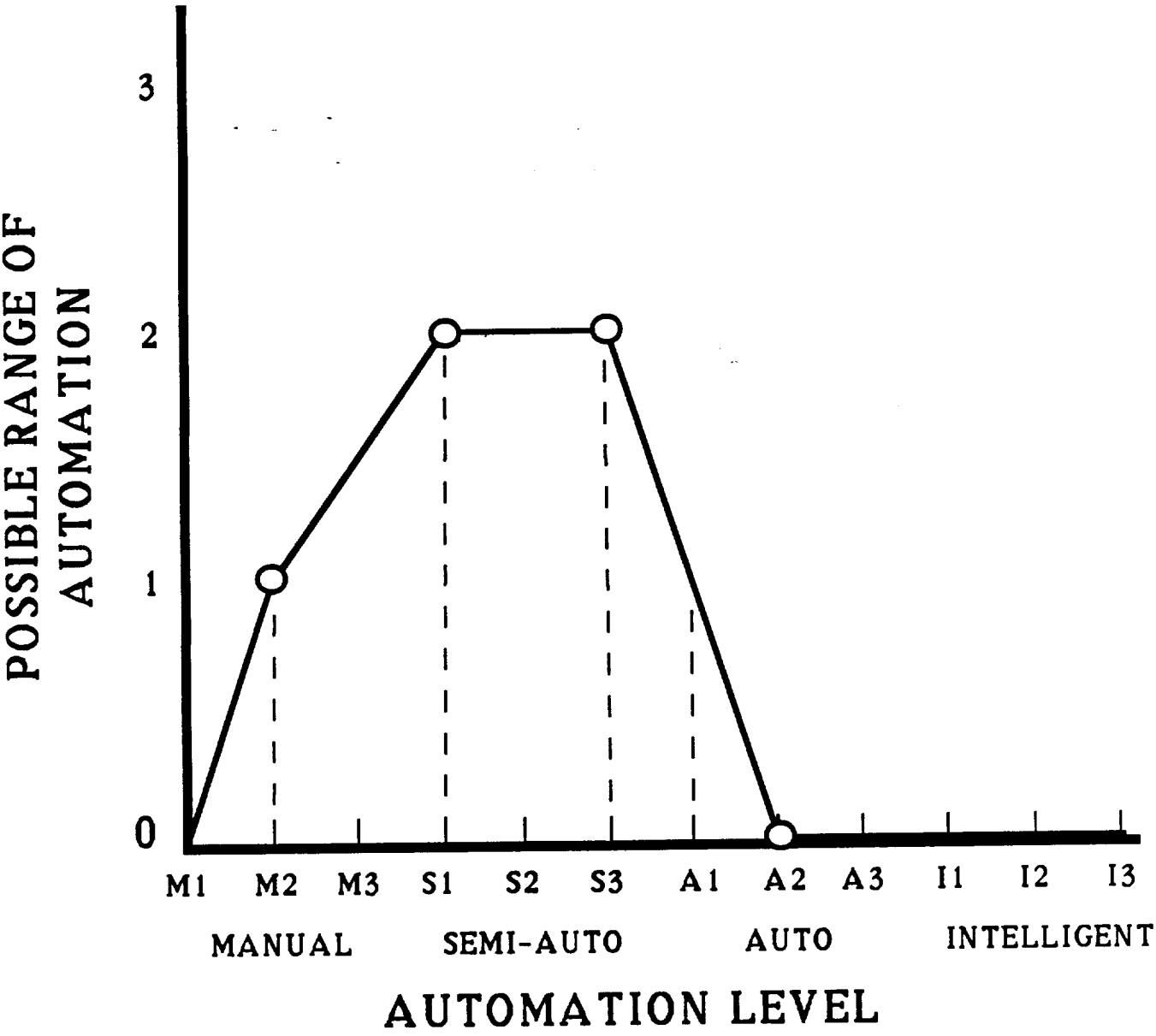

Figure 3
Range of
Possible Automation Levels
vs.
Automation Levels

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

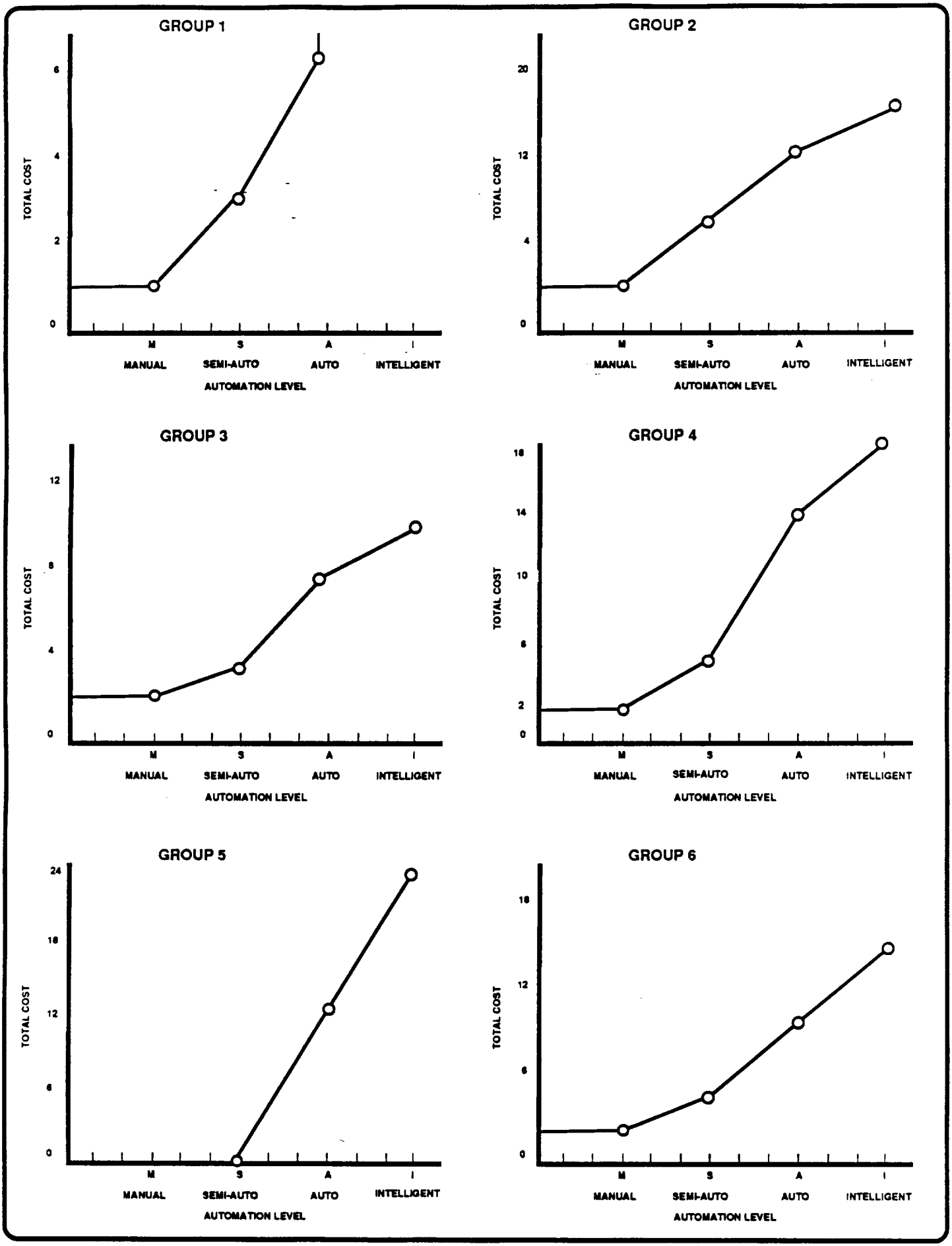

Figure 4 Total Cost vs. Automation Level for Each Functional Group

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 ($)/Total Cost to automate ($)

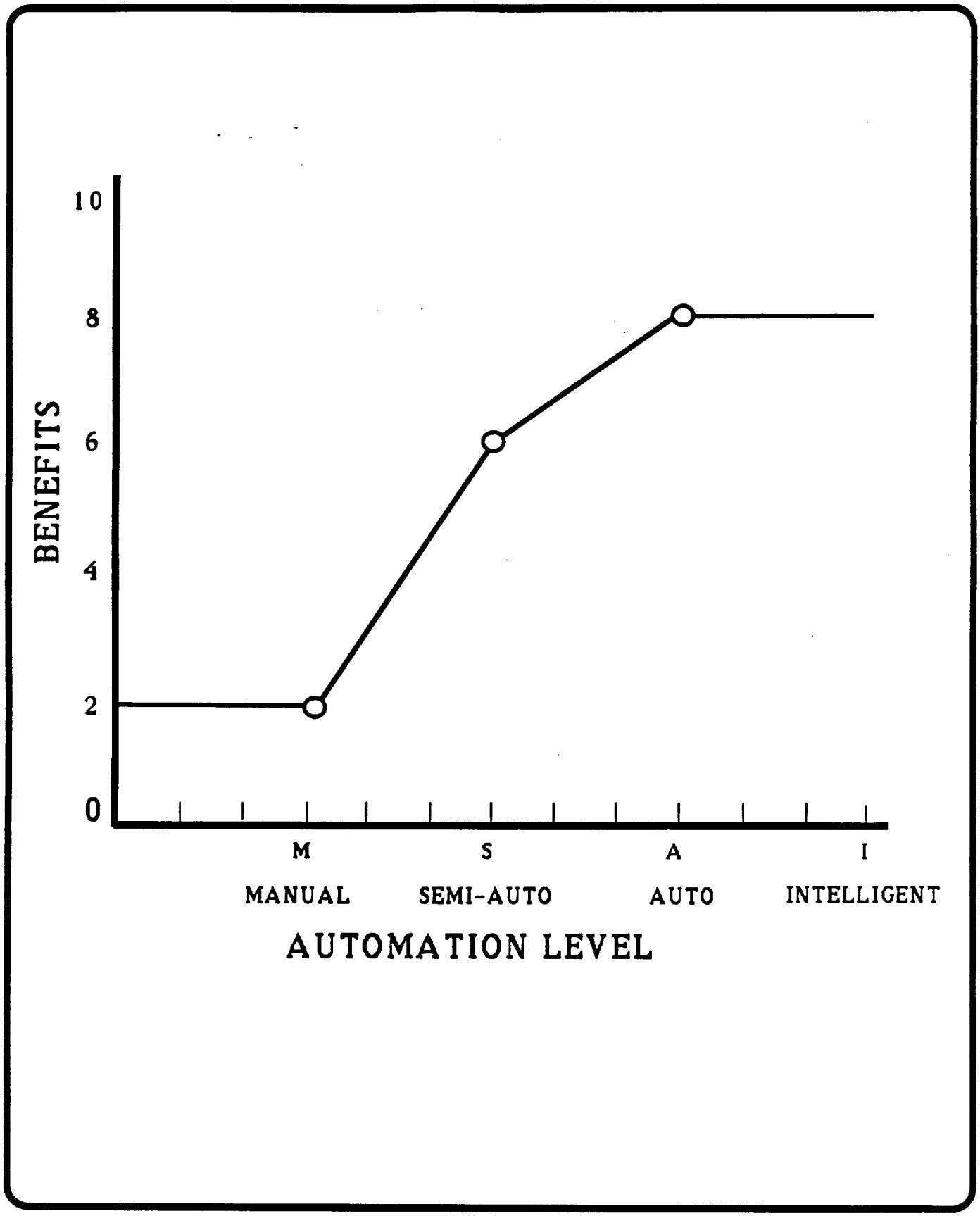

Figure 5
Benefits vs. Automation Level

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:

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.

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.

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	CURRENT CONCEPT TRNG %Cw KnwSklTim	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	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 DataPhysSyst	CURRENT CONCEPT TRNG %Cw KnwSklTim	SBI REALISTIC TARGET LVL-ByDomain DataPhysSyst	SBI REALISTIC TARGET TRNG %Cw KnwSklTim	MAX AVAIL TECHNOLOGY LVL-ByDomain DataPhysSyst	MAX AVAIL TECHNOLOGY TRNG %Cw KnwSklTim
83	Plethysmograph Measuring System	NDSonly New	A3 A2 A2	3 2 4	A3 A2 A2	3 2 4	I2 I1 I1	2 1 3
84	Soft Tissue Imaging System	LSHWBL	I1 A1 A2	4 2 3	I1 A1 A2	4 2 3	I2 I1 I1	2 1 2
85	Tonometer		A2 A1 A1	2 1 5	A2 A1 A1	2 1 5	I1 A3 A3	2 1 3
87	EEG Cap	NDS890310 Mod	A2 M2 S2	3 2 1	A3 M3 S3	2 2 1	I1 S2 A1	1 2 1
88	EEG Signal Conditioner	NDS890310 Mod	A1 M3 S2	3 1 1	A2 S1 S3	2 1 1	I1 S3 A2	1 1 1
98	Visual Tracking System	LSHWBL	A3 A1 A2	2 2 4	A3 A1 A2	2 2 4	I2 I1 I1	1 1 1
99	Animal Biotelemetry System	LSHWBL	A2 M3 S2	2 2 1	A2 M3 S2	2 2 1	I1 S2 A1	1 2 1
100	Blood Pressure and Flow Instrum	NDSonly New	A2 M3 S2	2 2 5	A2 M3 S2	2 2 5	I1 S2 A1	1 2 4
101	Cardiodynamic Monitor	NDSonly New	A3 S2 A1	2 2 3	A3 S2 A1	2 2 3	I1 S3 A2	1 1 2
102	Electrocardiograph (ECG)	NDSonly "as i	A3 S1 S3	2 2 3	A3 S1 S3	2 2 3	I2 S3 A2	1 1 2
103	Holter Recorder	NDSonly "as i	A2 A1 A1	2 1 1	A2 A1 A1	2 1 1	A3 A1 A2	1 1 1
106	Neck Baro-Cuff	NDSnodate Mod	A2 A1 A1	2 2 1	A2 A1 A1	2 2 1	A3 A2 A2	1 2 1
109	Venous Pressure Transducer/Disp	NDSnodate SLS	A3 M2 S2	2 2 2	A3 M2 S2	2 2 2	I1 S1 A1	1 1 1
110	Plant Gas Chromatograph/Mass Sp	LSHWBL	I1 A3 A3	3 1 2	I1 A3 A3	3 1 2	I2 I2 I2	2 1 1
111	Plant Gas Cylinder Assembly	LSHWBL	A1 A3 A2	2 2 1	A1 A3 A2	2 2 1	A3 A3 A3	1 2 1
112	Plant HPLC Ion Chromatograph	LSHWBL	I1 A2 A3	3 1 2	I1 A2 A3	3 1 2	I2 I2 I2	2 1 1
113	Blood Gas Analyzer	NDSonly New	A3 A3 A3	3 1 2	A3 A3 A3	3 1 2	I2 I2 I2	2 1 1
115	Chemistry System	NDSnodate Mod	A3 S3 A1	4 2 2	I1 A1 A2	3 2 2	I2 I2 I2	2 1 1
116	Continuous Flow Electrophoresis	NDS890222 Mod	A3 I1 A3	3 2 2	I1 A3 A3	2 2 2	I2 I2 I2	2 1 1
119	Gas Cylinder Assembly	NDSonly "as i	A2 S3 A1	2 2 1	A2 S3 A1	2 2 1	A3 A3 A3	1 2 1
124	Qualitative Reagent Strip and R	NDS890302 COT	S3 S3 S3	3 1 2	I1 S3 A2	2 1 1	I2 I2 I2	2 1 1
126	Scintillation Counter	NDS890221 New	A3 A3 A3	3 2 2	I1 A3 A3	2 2 2	I2 I2 I2	2 1 1
129	Cell Handling Accessories	NDSonly New	A3 A2 A2	2 3 4	A3 A2 A2	2 3 4	I1 I2 I1	1 1 1
130	Cell Harvester	NDS890221 New	A3 A3 A3	2 1 2	I1 A3 A3	1 1 2	I2 I2 I2	1 1 1
131	Cell Perfusion Apparatus	NDS890221 New	A3 A3 A3	2 1 2	I1 A3 A3	1 1 2	I2 I2 I2	1 1 1
134	Centrifuge Hematocrit	NDSnodate LSL	S2 S2 S2	2 1 3	S3 S2 S2	2 1 3	A3 A3 A3	1 1 1
135	Chromosomal Slide Prep Device	NDS890221 New	A3 A3 A3	3 1 2	I1 A3 A3	2 1 2	I2 I2 I2	2 1 1
136	Fluoromeasure Probe		I1 A3 A3	3 2 4	I1 A3 A3	3 2 4	I2 I2 I2	2 1 1
138	Hematology System	NDSonly Mod	A3 A3 A3	3 2 2	A3 A3 A3	3 2 2	I1 I1 I1	2 1 1
139	Image Digitizing System	NDSnodate New	I1 A1 A2	4 2 2	I1 A1 A2	3 2 2	I2 I2 I2	2 1 1
142	Skin Window Device	NDSnodate New	M3 S3 S1	2 2 5	M3 A1 S2	2 1 5	S1 A2 S3	1 1 3
145	Automated Microbic System (AMS)	NDS890221 Mod	I1 S3 A2	2 1 1	I1 A3 A3	3 2 2	I2 I2 I2	1 1 1
147	Head/Torso Phantom	NDSnodate COT	M2 M2 M2	2 2 1	S1 M3 M3	1 2 1	A1 S1 S2	1 1 1
149	Microbial Preparation System	NDS890222 New	I2 I1 I1	2 1 1	I1 A3 A3	3 2 2	I2 I2 I2	1 1 1
151	Reuter Microbiology Air Sampler	NDS890221 Mod	M3 S1 M3	1 1 5	M3 S1 M3	1 1 5	S1 S1 S1	1 1 2
152	Solid Sorbent Air Sampler	LSHWBL	S1 S1 S1	1 1 5	S1 S1 S1	1 1 5	A1 A1 A1	1 1 2
153	Spectrometer (Proton/Heavy Ion)	NDSnodate New	A3 A2 A2	3 2 2	I1 A3 A3	3 1 2	I2 I2 I2	2 1 1
154	Tissue Equivalent Proportional		I1 A3 A3	2 2 2	I1 A3 A3	2 2 2	I2 I2 I2	1 1 1
155	Total Hydrocarbon Analyzer	LSHWBL	I1 A3 A3	2 1 2	I1 A3 A3	2 1 2	I2 I2 I2	2 1 1
161	Inventory Control System	NDSonly OTS	I2 I1 I1	2 1 1	I2 I1 I1	2 1 1	I3 I2 I2	1 1 1
162	Lab Materials Packaging and Han	NDSonly New	I2 I1 I1	2 1 1	I2 I1 I1	2 1 1	I3 I2 I2	1 1 1
163	Test/Checkout/Calibration Instr	LSHWBL	I1 A1 A2	3 2 3	I1 A1 A2	3 2 3	I2 A3 I1	2 2 2
165	Experiment Control Computer Sys	NDSonly New	I1 S3 A2	3 1 2	I2 S3 A2	2 1 1	I3 A1 A3	2 1 1
167	Voice Recorder	NDSnodate LSL	A2 S3 A1	2 1 2	A2 S3 A1	2 1 2	A3 A3 A3	2 1 2
168	Closed Ecological Life Support	LSHWBL	I2 I1 I1	2 1 1	I2 I1 I1	2 1 1	I2 I2 I2	1 1 1
169	Gas Grain Simulator	ARC/SSS New	I1 A2 A3	4 3 1	I1 A2 A3	4 2 1	I2 I1 I1	3 2 1

3.3 TABLE I - SBI HARDWARE INFORMATION SOURCE & COMPLETENESS

SBI#	HARDWARE IDENTIFICATION HW ITEM NAME	CURRENT SBI HW CONCEPT INFO SOURCE	W/T	H/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 H T	H O 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 T	H O W	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT CONCEPT LVL-ByDomain Data	Phys	Syst	TRNG %Cw KnwSkl	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 T	H O W	HW CHARACTERISTICS VOLUME (cu m)	MASS (kg)	POWER (watt)	CURRENT CONCEPT LVL-ByDomain Data	Phys	Syst	TRNG KnwSk	Tim	%Cw
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 KnwSklTim	SBI REALISTIC TARGET %Cw	MAX AVAIL TECHNOLOGY LVL-ByDomain DataPhysSyst	MAX AVAIL TECHNOLOGY TRNG KnwSklTim	MAX AVAIL TECHNOLOGY %Cw
16	Animal Tissue Biopsy Equipment	M3 M3 M3	3 4 5	2 2 4	S3 S3 S3	2 2 4	
17	Blood Collection System	M3 S2 S1	2 3 5	1 2 4	S3 S2 S2	1 2 4	
22	Electrofusion Device	A2 A1 A1	2 2 3	1 1 1	I1 I2 I1	1 1 1	
23	Fixation Unit	A3 A2 A2	3 2 2	2 1 1	I2 I1 I1	2 1 1	
28	Muscle Biopsy Equipment	M3 M3 M3	3 3 5	3 2 4	S3 A2 A1	3 2 4	
29	Perfusion and Fixation Unit	A3 A2 A2	3 2 2	2 1 1	I2 I1 I1	2 1 1	
30	Plant Care Unit	I1 A3 A3	2 1 1	1 1 1	I3 I2 I2	1 1 1	
31	Plant Harvest/Dissection Unit	S3 S1 S2	2 2 4	1 2 3	I1 A3 A3	1 2 3	
33	Saliva Collection Unit	M3 M3 M3	1 1 5	1 1 5	M3 M3 M3	1 1 5	
34	Sample Preparation Device	I1 A3 A3	3 2 2	1 1 1	I2 I2 I2	1 1 1	
38	Sweat Collection Device	A2 S3 A1	1 1 2	1 1 1	A3 A1 A2	1 1 1	
39	CO2 Administration Device	S1 S3 S2	2 2 1	1 1 1	A3 A3 A3	1 1 1	
40	Rodent Blood Collection System	M3 S2 S1	2 3 5	1 2 4	S3 S2 S2	1 2 4	
41	Rodent Caudal Vertebrae Thermal Device (CVTD)	S1 M3 M3	1 3 2	1 2 1	S2 S2 S2	1 2 1	
42	Rodent Guillotine	M3 S1 M3	2 2 5	2 1 3	S2 S3 S2	2 1 3	
43	Rodent Restraint	S1 S1 S1	2 3 3	2 2 2	A1 S3 S3	2 2 2	
44	Rodent Surgery Platform	S1 M3 M3	2 2 2	2 1 2	S3 A2 A1	2 1 2	
45	Rodent Surgery/Dissection Unit	M1 M2 M1	5 5 5	4 4 5	M2 S2 M3	4 4 5	
46	Rodent Urine Collection System	M3 M2 M2	2 3 5	2 2 5	S1 M3 M3	2 2 5	
47	Rodent Veterinary Unit	M2 S2 M3	4 3 4	3 3 4	S2 S3 S2	3 3 4	
48	Primate Blood Collection System	M3 S2 S1	2 3 5	1 2 4	S3 S2 S2	1 2 4	
49	Primate Handling Equipment	S1 M3 M3	2 2 3	2 2 2	S3 S3 S3	2 2 2	
50	Primate Lower Body Negative Pressure (LBNP) Device	S1 M3 M3	2 2 2	2 1 2	S1 S1 S1	2 1 2	
51	Primate Surgery Platform	S1 M3 M3	2 2 2	2 1 2	S2 A1 S3	2 1 2	
52	Primate Surgery/Dissection Unit	M1 M2 M1	5 5 5	4 4 5	M2 S2 M3	4 4 5	
53	Primate Urine Collection System	M3 M2 M2	2 3 5	2 2 5	S1 M3 M3	2 2 5	
54	Primate Veterinary Unit	M2 S1 M3	4 3 4	3 3 4	S2 S3 S2	3 3 4	
55	Small Primate Restraint	S1 M3 M3	2 3 3	2 2 2	S3 S3 S3	2 2 2	
56	Bag Assembly	M3 M3 M3	1 1 1	1 1 1	M3 M3 M3	1 1 1	
57	Bag-in-Box	S2 A1 S3	1 1 1	1 1 1	S2 A1 S3	1 1 1	
59	Electronics Control Assembly	S3 A1 S3	2 1 1	2 1 1	A1 A1 A1	2 1 1	
60	Mask/Regulator System	S1 S1 S1	1 1 1	1 1 1	S1 S1 S1	1 1 1	
61	Mass Spectrometer	I1 A3 A3	2 1 1	2 1 1	I2 I2 I2	2 1 1	
62	Pulmonary Function Equipment Stowage Assembly	M2 M3 M2	1 1 1	1 1 1	M2 M3 M2	1 1 1	
63	Pulmonary Gas Cylinder Assembly	A1 A1 A1	2 2 1	2 1 1	A1 A2 A1	2 1 1	
64	Rebreathing Assembly	M3 S3 S1	2 1 1	1 1 1	S1 S3 S2	1 1 1	
65	Spirometry Assembly	A1 S2 S3	2 1 1	1 1 1	A2 S2 S3	1 1 1	
66	Syringe (3 Liter Calibration)	M3 M2 M2	1 1 5	1 1 1	S1 S1 S1	1 1 1	
67	Accelerometer and Recorder	I1 S3 A2	2 1 1	1 1 1	I1 A1 A2	1 1 1	
68	Anthropometric Measurement System	S1 S1 S1	2 3 4	2 1 3	A3 S3 A1	2 1 3	
70	Compliance Volumometer	A2 S2 S3	1 3 5	1 2 4	A3 A3 A3	1 2 4	
71	Electroencephalomagnetogram (EEMG)	I1 S2 A1	3 3 1	2 2 1	I2 S3 A2	2 2 1	
74	Force Resistance System	I1 A1 A2	2 2 2	2 1 2	I1 A3 A3	2 1 2	
75	Fundus Camera	A2 S1 S3	2 2 4	1 1 4	I1 S3 A2	1 1 4	
77	Hard Tissue Imaging System	I1 A1 A2	4 2 3	2 1 2	I2 I1 I1	2 1 2	
78	Mass Calibration Unit	M3 M3 M3	1 1 5	1 1 5	M3 M3 M3	1 1 5	
82	Motion Analysis System	I1 A1 A2	2 1 3	1 1 1	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	%Cw	KnwSklTim	MAX AVAIL TECHNOLOGY LVL-ByDomain DataPhysSyst	TRNG	%Cw	KnwSklTim
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 DataPhysSyst			REALISTIC LVL-ByDomain DataPhysSyst			MAX AVAIL LVL-ByDomain DataPhysSyst		
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 DataPhysSyst			REALISTIC LVL-ByDomain DataPhysSyst			MAX AVAIL LVL-ByDomain DataPhysSyst		
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

3.7 Automation Range of SBI hardware

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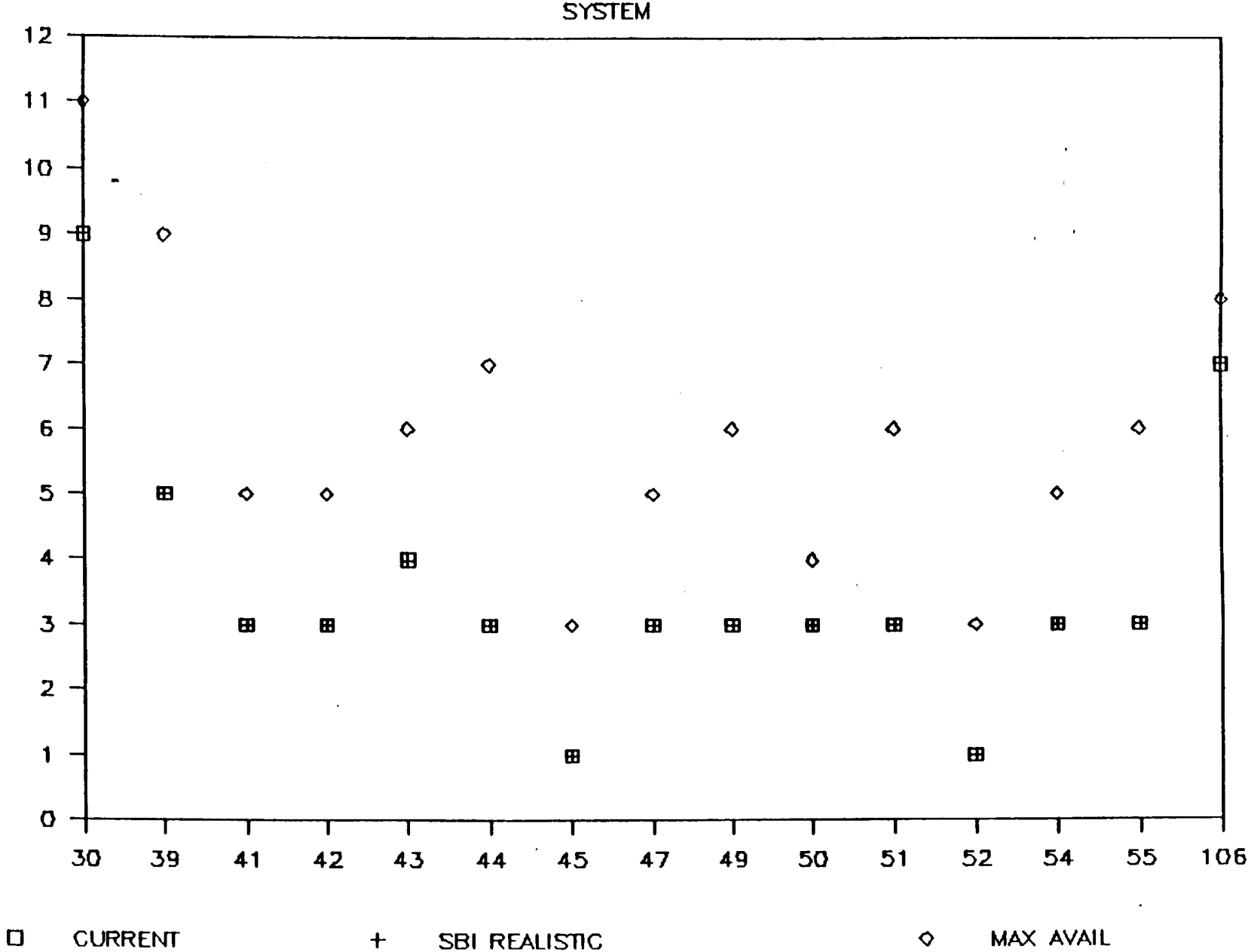
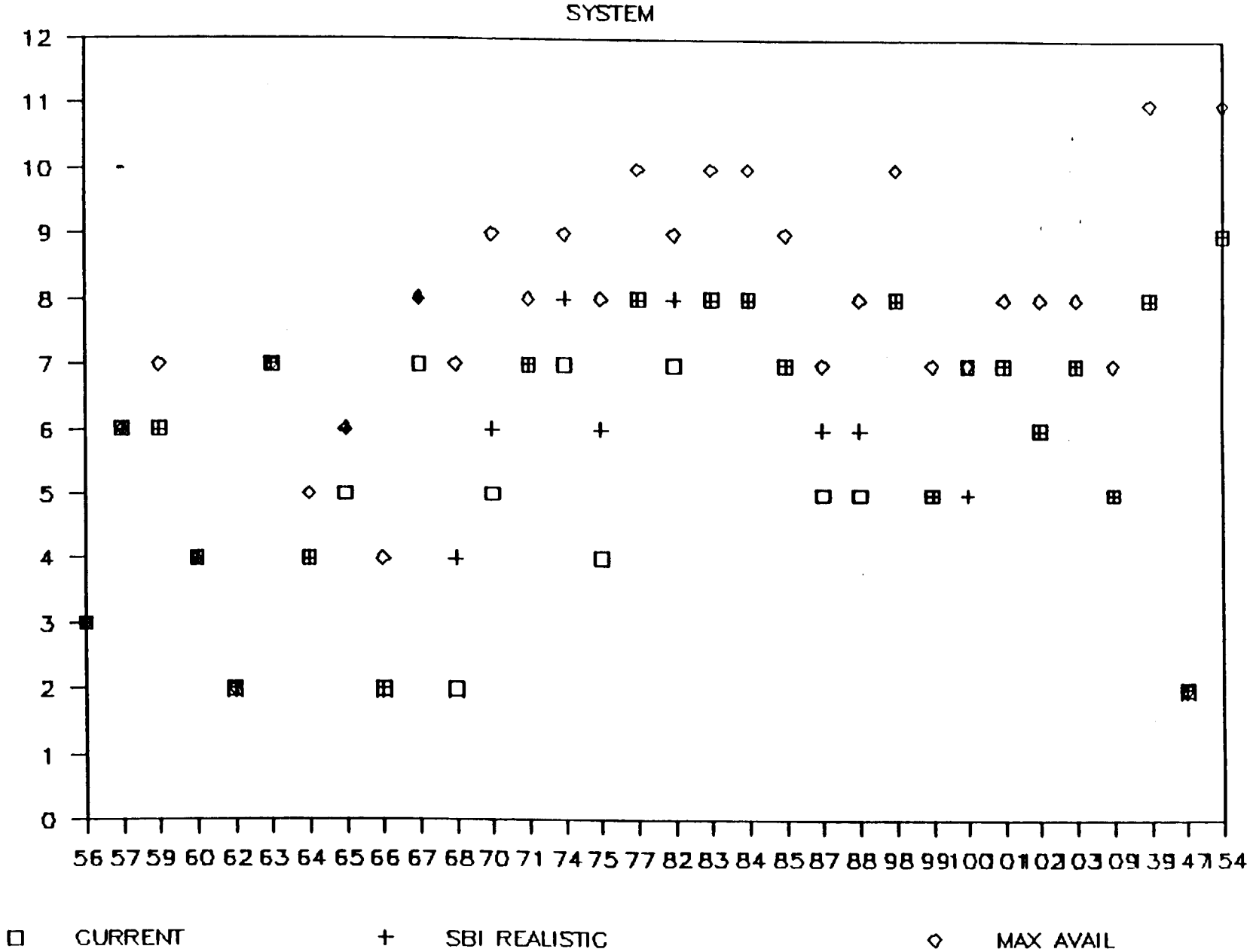
7 represents the automation level A2
8 represents the automation level A3
9 represents the automation level I1
10 represents the automation level I2
11 represents the automation level I3

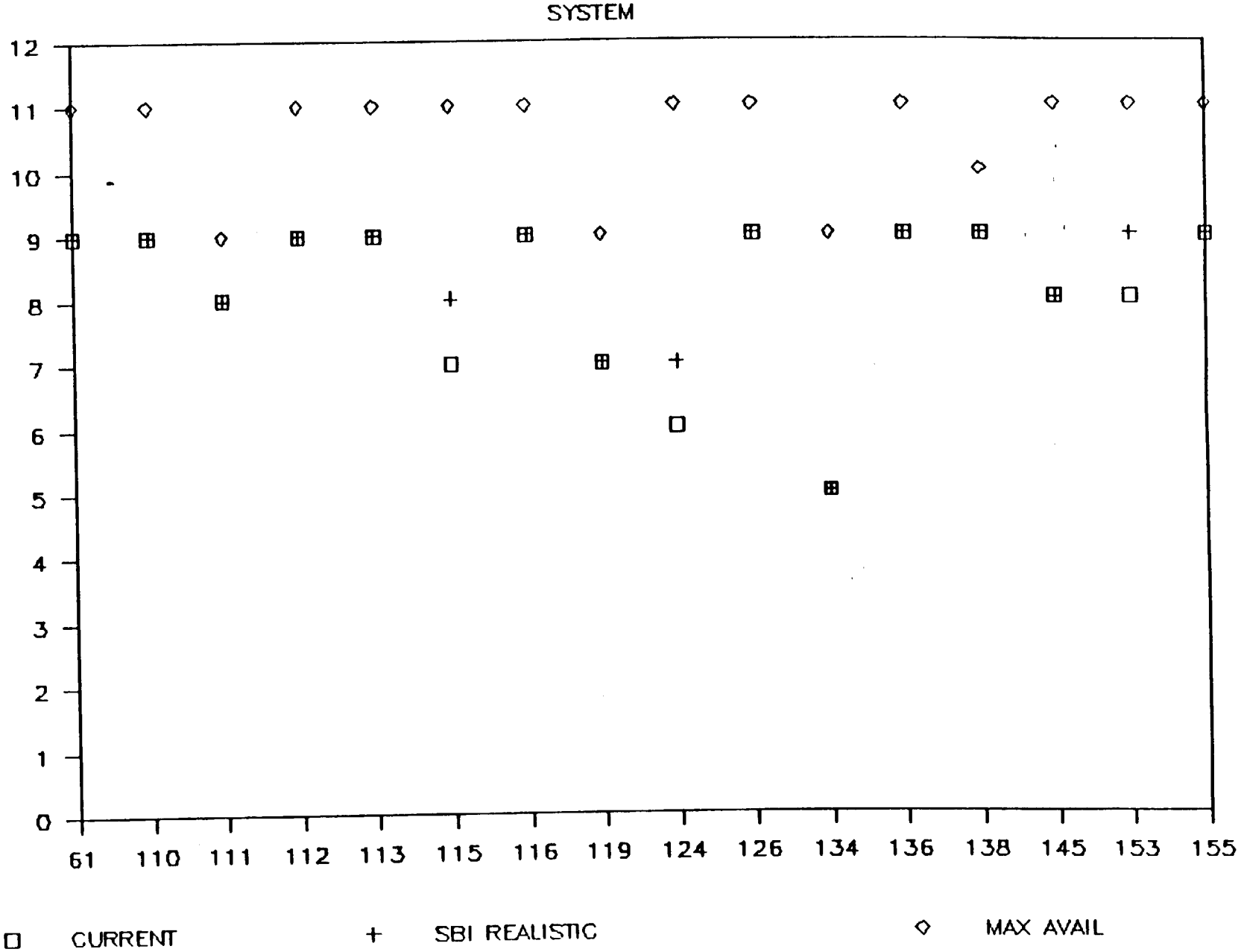
CLASS 1 – BIOLOGICAL SPECIMEN SUPPORT



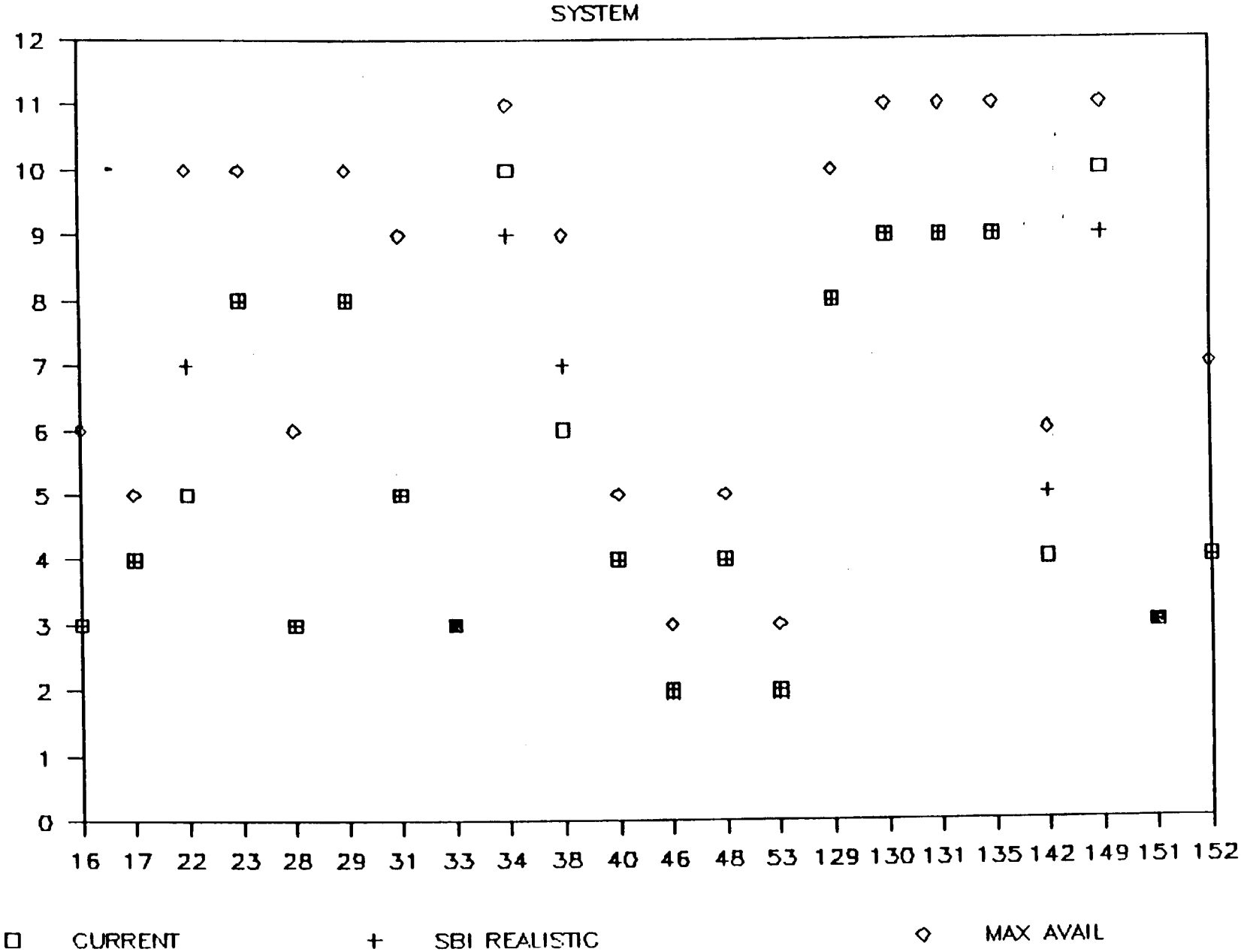
CLASS 2 – PHYSIOLOGICAL MEASURE/MONITOR



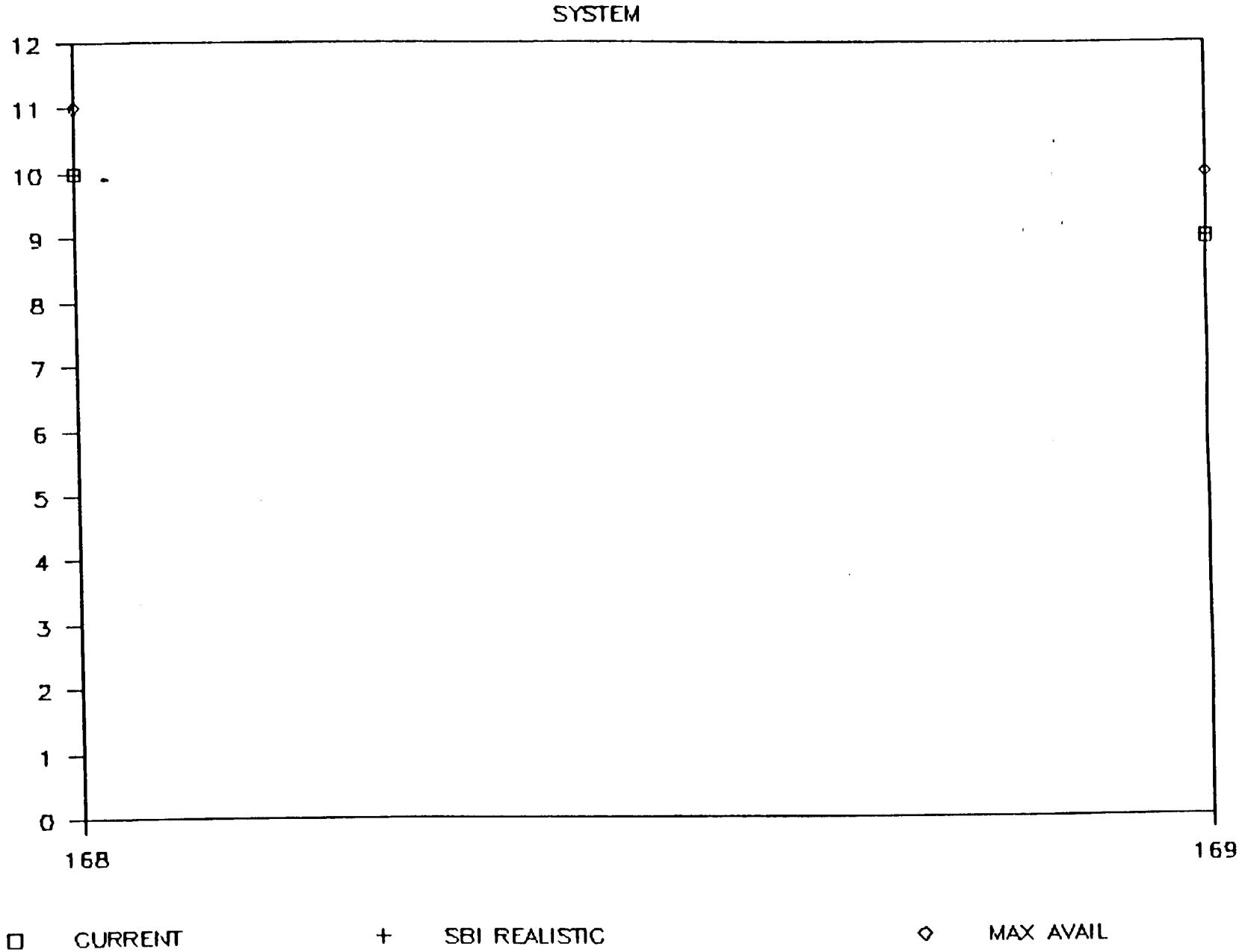
CLASS 3 – CHEMISTRY SYSTEMS



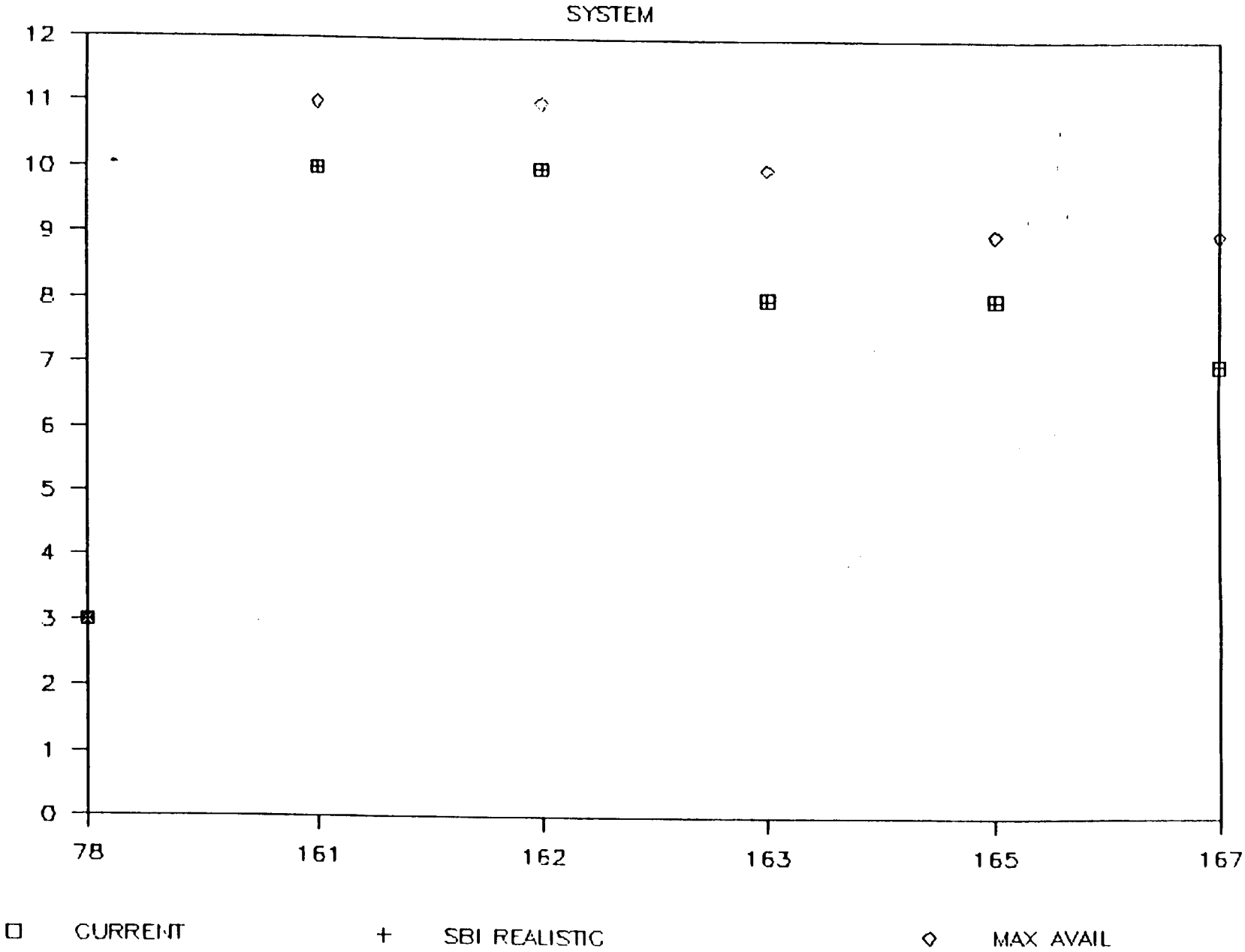
CLASS 4 – MAT'L PREP AND HANDLING



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.

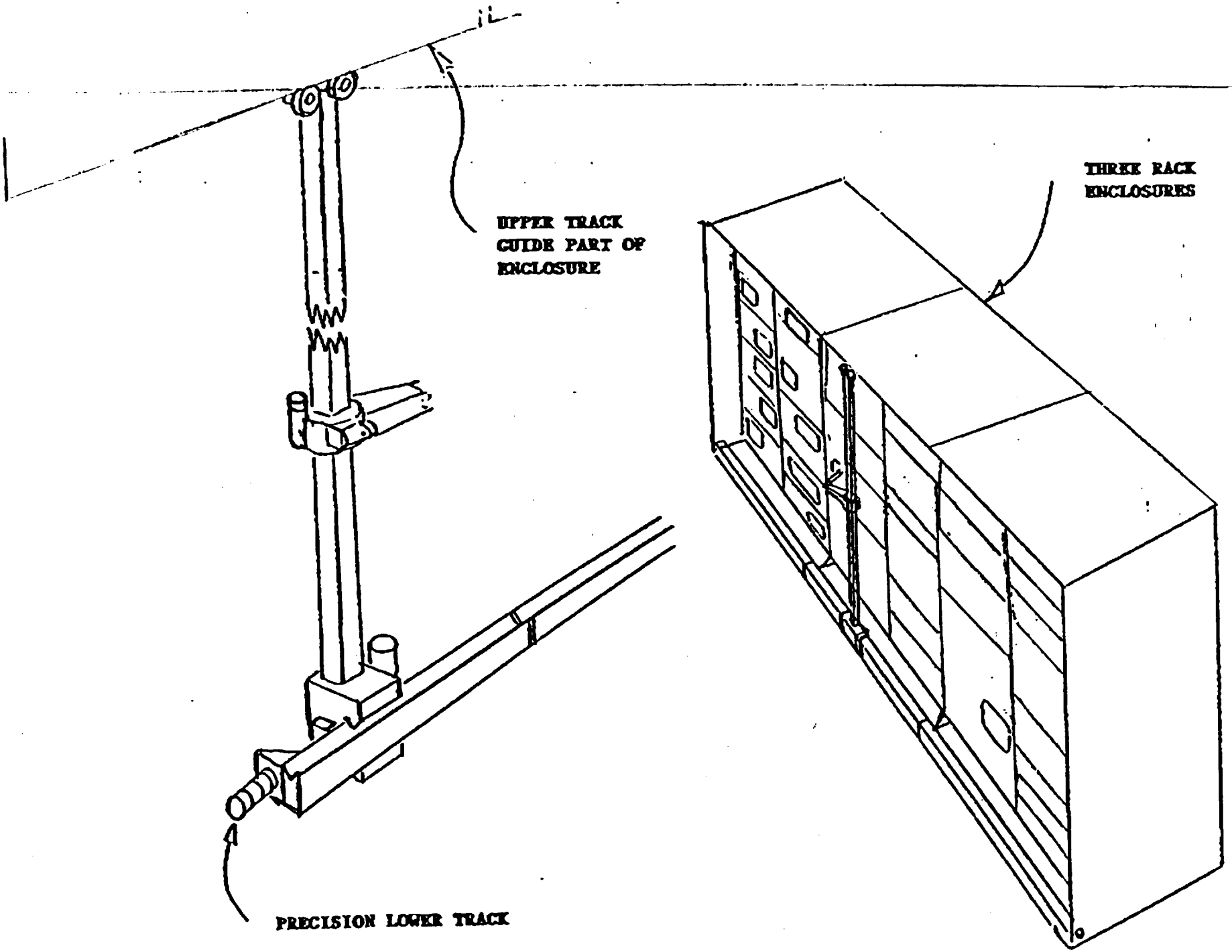
Rack enclosure design guidelines would be developed that would enable experiment package designers to strategically place various items in locations well within the robot gripper or end effector work envelope and at compatible orientations.

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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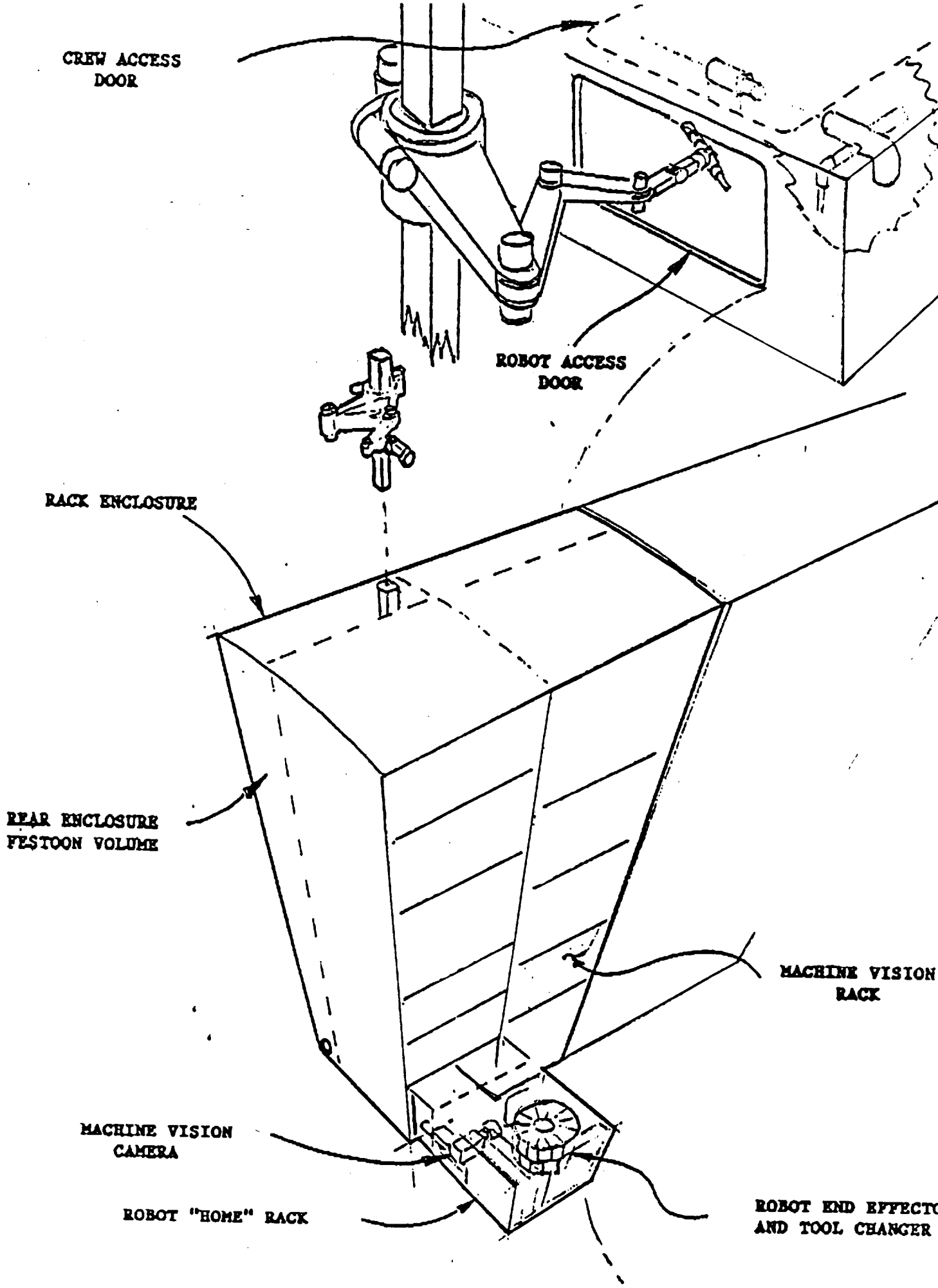
ENCLOSURE
THREE RACK
ENCLOSURES
PRECISION LOWER TRACK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ROBOT ACCESS DOOR
RACK ENCLOSURE
REAR ENCLOSURE FESTOON VOLUME
MACHINE VISION RACK
MACHINE VISION CAMERA
ROBOT "HOME" RACK
ROBOT END EFFECT
AND TOOL CHANGER

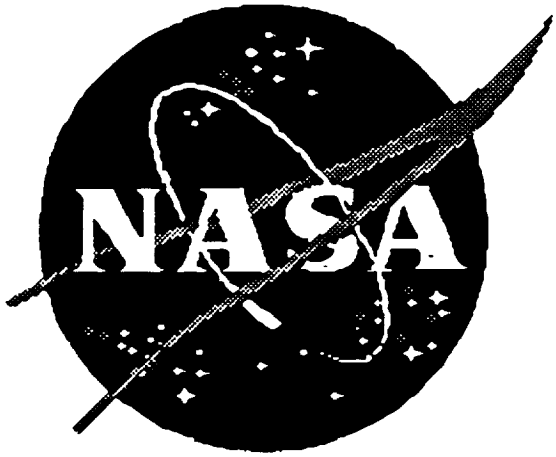
DESIGN MODULARITY AND COMMONALITY

TRADE STUDIES

JOHNSON SPACE CENTER
HOUSTON, TEXAS
77058

SPACE BIOLOGY

INITIATIVE

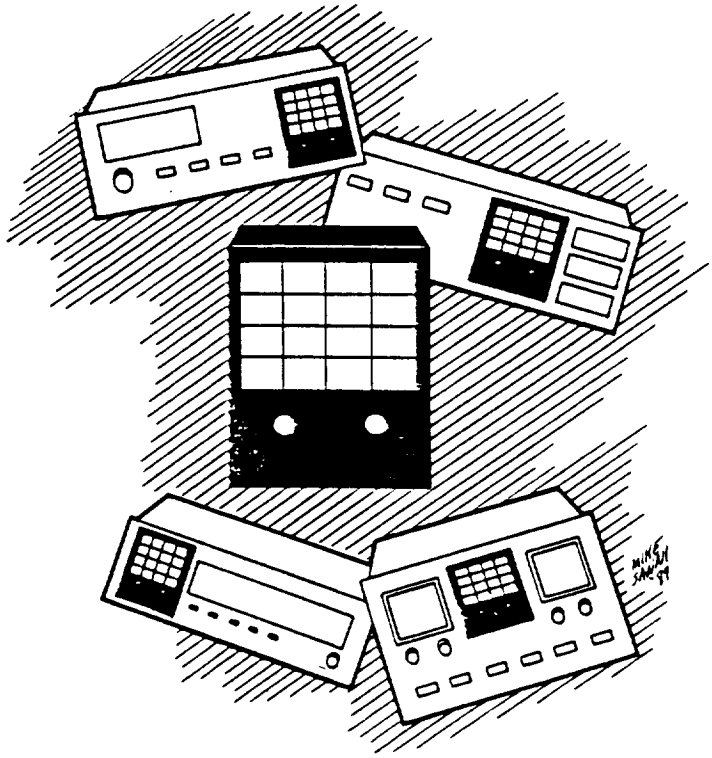


Space Biology Initiative
Program Definition Review

Lyndon B. Johnson Space Center
Houston, Texas 77058

HORIZON
AEROSPACE

Design Modularity and Commonality



FINAL REPORT

June 1, 1989