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MAINTAINABILITY OF MANNED SPACECRAFT FOR LONG-DURATION FLIGHTS

Volume I - Summary Report

Prepared by
THE BOEING COMPANY
Seattle, Wash.
for Ames Research Center

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ABSTRACT

A study performed under Contract NAS2-3705 (NASA, OART-MAD, Ames Research Center), entitled "Study of Maintainability for Long-Duration Manned Space Flight," evaluates the influence of maintainability in sustaining a high level of reliability throughout long-term missions. A 99% probability of crew survival is a basic constraint in the analysis. Spacecraft of four representative but widely varying missions, one Earth-orbital and one interplanetary each in the mid-1970 and mid-1980 time periods, are examined to the replaceable component level. Detailed maintenance analyses of subsystems and components, vehicle configuration optimizations performed with a unique computer program, and statistical results of several hundred mission simulations are described and evaluated. The effects of hardware reliability and failure rates, skills, environmental factors, mission durations and resupply potential, and various resources are considered in many interrelationships. Optimum distributions of redundant and spare items to be included on board each spacecraft configuration for assuring mission success are identified, and their implications as to operational requirements and design philosophies are discussed. Tables, charts, and graphs summarizing analytical results and displaying parametric sensitivities are provided. Gross cost estimates are also included to indicate trends and place the respective missions in context relative to each other.

The study indicates that no attempt should be made to apply a single maintenance philosophy to all subsystems unilaterally. Rather, specific maintenance philosophies by subsystem, or by component where necessary should be used. This will require strong management control at all levels and very close design integration throughout program development. If an on-board workshop capability can be justified by maintenance requirements common to several subsystems, a substantial reduction in the weight of inflight support elements could be realized. Maximum commonality among components should be exercised for the same reason. Items requiring only a single spare to achieve a desired assurance level should be designed for standby redundancy where possible. Accurate, valid, and detailed design data on space hardware is lacking in many important areas; this should be developed and disseminated as soon as possible for future programs. Space mission planning can be enhanced by employing complementary optimization and mission simulation models to evaluate parameters affecting the maintainability and overall operation of manned vehicles.

Volume I summarizes results of the study and describes very briefly its approach and methods. Volume II discusses the study in detail, including source material and rationale, analytical effort, and explanations of procedures. Volume III is a compilation of the material developed during the course of the analysis.

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1.0 STUDY OBJECTIVES

Future long-duration manned space missions will require a drastic improvement in spacecraft capabilities to attain satisfactory probabilities of mission accomplishment. Increases in reliabilities of parts and assemblies, although mandatory, will not be sufficient in themselves to achieve the overall levels of assurance that are sought. The solution lies in the inclusion of appropriate on-board resources to augment or maintain, through the mission, the high reliability level that a spacecraft initially possesses. Three alternatives are available: (1) provide redundancies, (2) perform manual fault correction, or (3) incorporate a selective combination of the first two. Recognizing that certain redundancies will be necessary to accommodate operational or remedial requirements, it is evident that numerous opportunities also will exist for using crew capabilities effectively to perform maintenance. This study seeks to determine areas of such utilization, to develop an optimum approach to item (3), and to accomplish the following objectives:

a) Identify subsystems that are sensitive to maintenance philosophy; identify the effect of inflight maintenance requirements on their design, operation, and cost.

b) Specify, for subsystems and the overall spacecraft system, variations or additions that are needed to meet various levels of maintenance requirements.

c) Determine the effect that requirements for inflight maintenance will have on the development and performance of crew functions.

d) Develop maintainability design criteria for space vehicles, to be applied by designers of future systems.

e) Recommend maintenance philosophies for various types of space missions.

f) Identify areas warranting additional study and research on maintainability requirements and provisions.

When man embarks on a long-duration, unsupported space mission, design of the vehicle must include certain characteristics that would not necessarily be needed in an unmanned spacecraft. Chief among these is the life support/environmental control system. By its very nature, the life support function involves continuing, periodic manual servicing of several elements for which there are no known means of automation. Thus, some degree of scheduled maintenance becomes a mandatory requirement during a long-term manned mission, and must be planned for from the beginning. With on-board maintenance a foregone conclusion, the following objectives also become important: (1) to determine the extent of scheduled maintenance that could be expected, (2) to determine the kinds of activities and capabilities that would be involved, and (3) to determine the relationships of scheduled maintenance to any unscheduled restoration actions that might be performed. It should be noted that, throughout this report, the term "maintenance" generally refers to the unscheduled variety unless otherwise stated, or when the meaning is obvious from the context.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Many detailed conclusions can be derived from the data presented in Volume II and the worksheets reproduced in Volume III. This applies particularly to quantitative data associated with the specific missions and spacecraft selected for study, and reiteration would defeat the purpose of this summary. As a compromise, representative data of a single mission is reviewed briefly in Sections 4.0 and 5.0 to acquaint the reader with the kind of material available in the detailed report. The general conclusions given below are the most significant, and are capsulized from Volume II. In a few cases these would seem to be self-evident and conventional. It is pointed out, however, that study results have strongly supported them and they are now firm propositions rather than intuitive deductions. The only major factor lacking is actual flight experience of sufficient duration to prove them unequivocally.

For convenience, an abbreviated list of definitions is given below.

Crew Survival (Probability)	Assurance that no equipment-induced fatality occurs during a mission. In accordance with the work statement, this study used a factor of 99% probability of safe crew return as a mandatory requirement before any other mission assurances were considered.
Degree of Maintenance	An arbitrary division of the spectrum of possible concepts for performing unscheduled maintenance, increasing in order of complexity. Degree "0" is essentially fully automated, Degree "1" is limited to simple adjustments and manual switching, Degree "2" permits fault isolation and physical replacement with spares, Degree "3" expands Degree "2" to include on-board repair and more sophisticated support actions.
Maintainability	The quality of spacecraft hardware incorporated in its basic design to permit the performance of maintenance.
Maintenance	Actions necessary to ensure continued proper operation of a unit (scheduled), or to restore a faulty unit to its specified operating condition (unscheduled). Generally, the term "maintenance" as used in this report refers to the unscheduled variety, unless its meaning is obvious from the context.

MARCEP	Acronym for "Maintainability and Reliability Cost Effectiveness Program," a computerized optimization of redundant and spare components to support a total vehicle configuration, developed by The Boeing Company.
Mission Success (Probability)	Assurance that no equipment function is lost that would preclude completion of all mission objectives. In this study, no particular objective was specified; all mission success factors include 99% probability of crew survival as a prerequisite, and 99% probability of mission success was used as a data base for comparison.

This section has been organized into general and specific conclusions. Detailed study findings from which specific conclusions were drawn were referenced in parentheses, indicating the section of Volume II where the findings are discussed in detail. Recommendations given in Section 2.3 are based, to a great extent, on the areas requiring additional technical research as reported in Section 10.0 of Volume II.

2.1 GENERAL STUDY CONCLUSIONS

Implementation of many of the conclusions and recommendations will be a matter of management concern. For instance, it might have been inferred from some sources that subsystem maintenance concepts can be developed and implemented independently. This is not the case, as pointed out in Item 1) below. The principle of developing maintenance concepts for each subsystem, and implementing them to achieve an effective total spacecraft, will require closer control and coordination between subsystem design organizations than would be required if a single arbitrary concept were levied on all systems. A second example is that of component commonality, and this is where configuration management takes on an added dimension. There are a number of subsystems that could be designed with a larger number of common modules or components. Achievement of both the above goals will require very intensive intersubsystems discipline and will involve a high degree of management cognizance to provide the positive direction that will be necessary.

1) Development of Maintainability Concurrent with Hardware Design---Because the requirements for maintainability on a manned spacecraft form part of the hardware design criteria, it is necessary that maintainability characteristics be considered and their qualities included from the earliest phases of any design program for a manned mission. During the course of this study, it became apparent that no one maintenance philosophy could be applied unilaterally to all subsystems. Specific maintenance philosophies by subsystem, or by component if necessary, will be far more useful during design of the spacecraft. It will be necessary to modify the maintenance philosophies according to design progress, and to guide design with the planned baseline philosophy. In practice, this can be implemented only by a flexible and fully integrated team of maintenance and design engineers, with decision autonomy restricted to the highest level of engineering

management (problem areas should be resolved through mutual agreement at the working level wherever possible).

2) Detailed Subsystem Study Required---The MARCEP and maintenance task analysis sheets contained in Volume III indicate the depth of detail required at the component level to perform this study. Considerable research was done to obtain the data needed, but it was found that good detailed data (i.e., weight, volume, failure rate, etc.) unfortunately was not readily available. Therefore, it is recommended that this area be studied further so accurate valid data can be made available to designers and future research and study programs.

3) Effectiveness of Study Technique---The technique of using both a mathematical model (MARCEP in this study) and a general-purpose system simulation model to evaluate parameters that affect maintainability of long-duration manned space missions provides results that complement each other and should be very useful for planning future space missions.

2.2 SPECIFIC STUDY CONCLUSIONS

Some of the significant conclusions listed in Volume II are given here. For the missions studied:

1) The scheduled maintenance workload is significant, varying from 114 to 147 man-minutes per day on the average, for the four missions studied. The life support subsystem is a major contributor to the workload, but can be improved considerably by reducing the number and frequency of the filter, cartridge, and wick replacements, and designing for quick replacement of these items where it is necessary (Sections 5.2 and 6.2).

2) The crew workload imposed by unscheduled maintenance requirements is relatively low and does not significantly affect the operation of the spacecraft. No mission required unscheduled maintenance for more than 20% of the days involved; repair could be performed in less than 2 hours for well over half of the days requiring unscheduled maintenance, and the mean daily repair time during such days was under 1 hour. Also, one of each type of crew skill is sufficient to handle the unscheduled maintenance workload, and the amount of EVA required for unscheduled maintenance is negligible (Sections 5.3 and 6.3).

3) From the standpoint of the ratio of spares weight to total spacecraft weight, orbital missions should be planned for the longer resupply intervals whenever other factors permit a choice. Increased efficiency in the use of the spares provided, in terms of percentages of initial spares weight carried on board, will be realized at the longer mission durations. It was found that the weight which must be added to a basic system to achieve 99% assurance of mission success increases by about 27 to 30% when the mission duration is doubled (Sections 5.1, 5.3, and 6.3).

4) Increasing the mean-times-to-repair (MTTR), or the confidence level desired for repair, above the baseline system results in significant increases in the weight added for redundancies and spares required to achieve designated mission assurances. The study considered 99% confidence in the repair of safety-critical items to be a realistic level, and endeavored to keep

repair time estimates slightly pessimistic since reductions in repair times resulted in only minor weight improvement (Sections 5.1 and 6.1).

5) Commonality of components and equipment, both within and between spacecraft subsystems, and between elements of the spacecraft, on-board experiments, and reentry vehicle, is one of the most important of all design objectives. Spares requirements decrease significantly, program costs are reduced, and training can be consolidated when a high degree of commonality is achieved (Sections 7.1 and 7.2).

6) Modularization of components is an effective way to reduce the spares requirements and maintenance workload. The greater the commonality of modules the more effective is the spares usage, particularly for high failure rate components (Sections 5.1 and 6.1).

7) Subsystems should be designed for a Degree "2" maintenance concept (remove and replace) whenever practicable. This concept results in the most efficient use of spares, and the least weight and cost. As commonality of equipment increases, the concept becomes more advantageous. Particular exceptions to this concept include structural parts and large bulky items (Sections 7.1 and 7.2).

8) If only one spare of an item is required to achieve the desired probability of assurance, it probably could be used most effectively as a standby redundant item, whenever system design permits (Section 8.2).

9) One of the interesting results of this study was the validation of an original premise that maintenance will be necessary for long-duration manned space missions. Not only was it determined that maintenance will be necessary, but that it also will be desirable and practical. Maintenance is necessary because it is virtually impossible to eliminate all maintenance activities. Maintenance is desirable because significant weight and cost savings can be made through maintenance in comparison with conventional forms of redundancy for most subsystems. Maintenance is practical because no factors were identified which precluded the performance of the maintenance tasks considered. Sections 4.0 and 7.0, and the appendix, of Volume II contain details of the comparison between the redundancy and maintenance approaches to achieving desired levels of reliability.

2.3 RECOMMENDATIONS

2.3.1 APPLICATIONS

1) Further Development of Study Data---Further evaluation of the data developed by the analysis runs conducted in this study should be made to identify additional pertinent data and relationships not covered within the scope of this study. For example, it is known that increases in repair confidence levels or in MTTR's result in significant weight increases; the identification of the specific components causing these weight increases could lead to better definition of study areas for improving the reliability of specific items.

2) Documenting Subsystem Component Configurations---A document should be compiled that lists the subsystem components and equipment of each spacecraft configuration evaluated in this study, together with the basic component data such as failure rate, weight, etc., and additional component statistics derived from this study such as the quantity and type of redundancies allocated, the expected spares utilization, the expected repair task time, etc. The development of such a document with this information, organized by individual component and combining the results of both manual analysis and computer mechanization, was not attempted during this study. However, a document of this type, with all information readily accessible, would serve as a baseline or guideline to industry for future spacecraft studies.

3) Use of Study Analysis Technique on Existing Systems---The concept of using an optimization model and a simulation model should be applied to an existing spacecraft/mission or to a spacecraft/mission in an advanced state of development. This would utilize a data base for existing equipment or for equipment in an advanced state of development, which should be broader and more accurate than that used in this study. The results of such an application would further validate the technique and yield results that could be used in refining existing mission planning.

4) Application of Computer Models to Experiment Programs---The study analysis technique mentioned in Item 3) above also should be applied to space experiment programs so that the maintenance requirements for experiments can be more accurately determined and be given appropriate consideration in the basic planning of an experiment program. Commonality between experiment and subsystem components can be maximized and the impact of experiments support on overall program requirements can be established with more precision and confidence.

2.3.2 RESEARCH

1) Degree "3" Maintenance Concept Evaluation---The concept of inflight bench-level maintenance (Degree "3" maintenance) should be studied in more detail to determine specific workshop equipment and weight requirements, and trades should be made to determine the effect of Degree "3" maintenance on crew maintenance workload and on possible weight savings.

2) Mission Analysis Optimization on Costs---Cost algorithms for the effects of adding parallel, standby, and spares redundancies should be developed. and a mission analysis based on optimization of dollar cost at the component level should be conducted and compared with the results of a weight optimization for the same mission.

3) Mockup of Life Support Subsystem---A representative life support subsystem for at least a six-man crew should be mocked up in detail and trial installations within a typical spacecraft cabin configuration should be made to determine the optimum placement of the subsystem for operation and maintenance. This is considered necessary because the study indicated that life support subsystem placement is a critical factor in spacecraft interior design.

4) Additional Study and Technology Research---A number of areas recommended for additional study or technology research are discussed in detail in Section 10.0 of Volume II. These recommendations generally include designing for modularization and commonality of equipment; investigation into the techniques required to repair large assemblies or structures in space, to minimize EVA or spacesuit use and to enhance malfunction detection; further development of analysis methodology; better definition of the space environment; and determination of human performance in that environment. Chapter 9.0 of this document summarizes some of the more significant items.

3.0 STUDY LIMITATIONS AND METHODOLOGY

Limitations on the study scope, the criteria developed and used in the study, and the method and techniques used in accomplishing the study are summarized in the following paragraphs. Study limitations are identified as ground rules, assumptions, and definitions. Ground rules were provided by NASA in the contract statement of work. The assumptions were made by the study team when required, and approved by the contract monitor. The definition of terms is a form of limitation in that it provides constraints upon the interpretation of certain words and phrases used frequently in the study. Only the key definitions have been included in this summary report. For a complete list see Volume II.

Criteria were developed for maintenance philosophy, reliability, and success and for determination of the maintenance requirement. Various criteria were used in making comparisons or as standards in developing detailed study data. These criteria are summarized in Section 3.4.

Detailed descriptions of the manner in which the study was conducted, and of the techniques used, are summarized in Section 3.5.

3.1 GROUND RULES

The following ground rules were established by the customer to provide limitations on the scope of the study:

1) Two levels of technology were to be studied: the mid-1970's level, and the mid-1980's level.

2) At least two classes of missions were to be studied: the Earth-orbital mission, and the interplanetary mission.

3) Crew survivability of 0.99 or better was to be assured for each mission considered. This was a mandatory requirement within the overall context of mission success.

4) Crew sizes to be considered were to fall within the range of a minimum of six men to a maximum of 30 men.

5) No provisions for artificial gravity were to be considered for any mission.

6) Provisions for extravehicular activity and remote experiments were to be included in the study.

7) Mission goals were to be retained irrespective of any system compromises that might be incurred for maintainability purposes.

8) During extravehicular activities, no metabolic losses were to be charged solely to pressure suit influence. The only disadvantages to be considered were a loss in reach capability and in tactile sensation, and the effects of the spacesuit mass.

9) Mission success was defined as the probability of all equipment functions of the spacecraft being available for the required time during the mission, provided crew survivability requirements were first satisfied.

3.2 ASSUMPTIONS

Proper performance of the maintenance analysis required that certain assumptions and guidelines be established to ensure uniformity of effort and reduce the number of variables to a manageable level. Some of the more important assumptions used in this study are summarized below:

1) Unscheduled maintenance has priority over scheduled maintenance. Therefore, if maintenance resources (including crew skills) being used for scheduled maintenance are required for unscheduled maintenance, the scheduled tasks will be delayed until completion of the unscheduled task.

2) The mean maintenance repair times include the time from receipt of a fault indication through completion of the repair or replacement including checkout, and return of equipment to storage. They also include the effects of other assumptions given here when applicable. Where EVA is required, the time reflects that necessary for checkout and donning the spacesuit, egress and ingress through the airlock, and doffing and servicing the spacesuit. Part of the time required for prebreathing pure oxygen is assumed to be simultaneous with donning the spacesuit.

3) Spares will be stored in a location readily accessible to the crew. An inventory will be kept of the spares on board and their storage location to facilitate finding the correct spare when needed; and where applicable, to aid in determining new spares needed at resupply.

4) The probability of death during the mission is not considered in the 99% probability of crew survival, which has been established as a mission requirement.

5) Where feasible, as an expediency for the study, it was assumed that the on board inflight test system, which includes the display panel indications, would isolate a failure to the replaceable component level, recognizing that certain design problems may be implicit in such an approach. This was assumed to be generally true for electronic equipment, in particular. Otherwise, it was assumed that test points would be available so a fault could be isolated to the replaceable component through the use of available maintenance and test equipment. It was also assumed that fault isolation could be performed without breaking electrical connections and that all components and test points would be accessible to a pressure-suited man where this was required.

6) Reliability factors used in mathematical mechanization of the missions did not include any values that might have been assigned to crew performance due to uncertainties in the validity of such a quantification. In effect, therefore, the study assumed that reliability of the crew equaled 1.0.

3.3 DEFINITIONS OF TERMS AND ABBREVIATIONS

Commonality	The provision for identical replaceable items within a subsystem or between subsystems. Such items would perform similar, but not necessarily identical, functions and be directly interchangeable.

Crew Survival (Probability)	The probability that no fatal crew incident, caused by equipment failure, occurs during the mission. See Section 3.4.
Criticality Code	An arbitrary means to specify the relative impact of a component failure. Ranges from requirement to operate continuously for safety, to indefinite deferral of repair.
Degree of Maintenance	An arbitrary indication of the complexity of unscheduled maintenance to be performed. Varies from Degree "0" with maximum built-in automatic redundancy to Degree "3" with maximum repair. See Section 3.4 for more detailed definition.
Maintainability	A quality of hardware design and installation that permits hardware to be retained in or restored to a specified operational condition, in accordance with predetermined requirements.
Maintenance Concept	A plan for accomplishing scheduled and unscheduled maintenance developed during equipment design. The degree of maintenance to be performed to be specified in the general plan at the system, subsystem, or component level.
MARCEP	Maintainability and Reliability Cost Effectiveness Program. A Boeing-developed optimization model used to augment basic spacecraft equipment component lists with spares and redundancies. See Section 3.5.2.
Mission Success (Probability)	The probability that no loss of hardware function occurs that precludes completion of all mission objectives, with a 99% probability of crew survival being prerequisite to any degree of mission success.
Modularization	The design of large assemblies for easy repair at the subassembly level through the use of plug-in or bolt-on packages, to reduce the overall weight of spares required. Commonality between replaceable packages is a desirable goal of modularization.
MTTR	Mean-time-to-repair. The average time required to restore an item to its original operating condition after a fault has been detected. Also termed "mean repair time" on data sheets in Volume III.

Parallel-Redundant Item	A duplicate unit not required for normal capability purposes, but provided in the system to enhance overall system integrity by operating concurrently with the basic unit.
Repair Confidence	The probability that an unscheduled maintenance task will be accomplished within a specified period of time.
Scheduled Maintenance	Maintenance activity that occurs on a regular cycle that can be anticipated and planned for prior to system operation.
Spare Item	A separately stored unit available for exchange and replacement of an identical basic unit.
Standby-Redundant Item	Same as parallel-redundant item, except operation occurs only when switched in (manually or automatically) at the time the basic unit fails.
Unscheduled Maintenance	All maintenance not classified as scheduled; including replacement of components due to random failures; repair of damage due to human error, spacecraft operations, or meteoroid impact; and adjustment required to meet established tolerances.

3.4 STUDY CRITERIA

To conduct the study in an organized and consistent manner for all of the missions studied, it was necessary to establish some criteria and procedural definitions to be used throughout the study. These are summarized in the following paragraphs.

3.4.1 MAINTENANCE CONCEPT

The primary objective of this study is to develop useful guidelines for evaluating the effects of different maintenance concepts on overall mission requirements. The factors considered in determining preferred maintenance concepts for each mission are grouped as follows:

1) Operational and performance factors including:
   - Performance constraints (such as minimum crew survival probability)
   - Mission duration
   - Resupply interval (for near-Earth missions)
   - Crew size and available discretionary time
   - Scheduled mission events
   - Fault isolation technique.

2) Resource or cost factors including:

- Dollar cost penalties
- Mission module weight penalties (and the resultant effect on number of launches and launch costs)
- Mission module volume penalties
- Crew skill variations.

3) Hardware and design factors including:

- Functional design constraints
- Component life and failure rate.

The selection criterion used to evaluate alternative maintenance concepts was primarily the weight required to achieve a desired level of mission success probability. This sterile criterion was tempered by the qualitative evaluation of the effect of a maintenance concept on other mission factors, including cost, crew skill and skill training requirements, equipment complexity, and expected design limitations, to mention only a few.

3.4.2 MAINTENANCE CONCEPT DEFINITIONS

The various maintenance concepts considered in this study for correcting unscheduled or random deficiencies may be defined in terms of the degrees of complexity of the maintenance action and the kinds and quantities of resources that would be required to restore the system after failure. These concepts cover a wide range of possibilities, varying from a Degree "0" maintenance, in which no unscheduled maintenance is contemplated so that the desired probability of success must be achieved by built-in automatic redundancy, to a Degree "3" maintenance in which maximum restoration of failed components can be accomplished. It must be remembered that the performance of <u>scheduled</u> maintenance has been established as an accepted requirement for the purposes of this study. These general concepts for unscheduled maintenance activities are defined as follows:

1) The Degree "0" concept incorporates only provisions for automatic restoration of the system after failure.

2) The Degree "1" concept limits maintenance to adjustment of out-of-tolerance equipment, and manual switching to activate standby-redundant elements. Some fault isolation instructions and simple hand tools are needed, but no special crew skills are required for this concept.

3) The Degree "2" concept incorporates provisions for physically removing failed components and replacing with a good spare. Fault isolation equipment, maintenance instructions, and tool kits are required. Also, the crew must have greater knowledge of the system and possess greater technical skills than for the Degree "1" concept.

4) The Degree "3" maintenance concept allows repairs within the functional component packages. Such repairs may be made with the package in place in the system, or by removing the failed component to a more convenient work location. Cutting and joining processes are included. Sophisticated fault

isolation equipment, maintenance instructions, and tools are required. The crew must have highly specialized maintenance skills in addition to their capabilities for performing primary mission objectives.

All of these concepts are further defined by identification of the resources (weight, volume, manhours, etc.) expended to incorporate maintenance provisions for specific subsystems and components.

3.4.3 SUCCESS CRITERIA

The basic success criteria used for this study were requirements for 99% probability of crew survival and 99% probability for mission success. The 99% probability of crew survival as a mandatory requirement within overall mission success was initially established as a study ground rule by NASA. The spacecraft components considered for calculating crew survival probability were those "reasoned" to be necessary for crew survival over the mission duration. The duration of the Earth-orbital missions was considered as the interval between resupplies. The duration of the planetary missions was considered as the interval between successful injection into transplanetary trajectory and the arrival of the ERV on the Earth's surface. Mission success was defined as the probability of all spacecraft equipment functions being available for the required time during the mission, provided crew survival requirements were first met. Examples of some equipment necessary for mission success, but not crew survival, are experiments, data management hardware, and recreation and exercise equipment.

As required, a 99% assurance of crew survival was met in all of the study optimizations and simulations. A 99% assurance of mission success was also met or exceeded in all of the analyses even though a specific requirement for this level of success was not levied.

3.4.4 RELIABILITY ASSESSMENT CRITERIA

Reliability criteria were of prime importance to the conduct of the study. Consequently, considerable care was exercised by the reliability experts assigned to the study in selecting component failure rates.

Selecting suitable failure rates for system components, in general, would require consideration of several influencing factors, including:

1) Operating environment (vibration, thermal, radiation, etc.);

2) Operating load (percent rates);

3) Specific component (by manufacturer's part or specification number) that might be selected, as influenced by dollar cost and development schedule limitations.

For this study, however, the engineering definition of components was not sufficiently detailed to allow precise assessment of the effects of these factors. For this reason most component failure rates were selected by the following method.

First, the following basic assumptions were made:

1) Procurement constraints based on cost or schedule considerations would be the same as currently encountered in NASA programs. Therefore, part and component failure rates would be as good as, or better than, military standard.

2) Hardware for the 1975 mission would be essentially the same as that now in existence or under development in 1967.

3) Reliability growth for most component types would continue at the same rate as has been experienced over the past 5 years.

Next, failure rates for each component type were found in several sources to establish a feasible range. The sources of these data were many and varied. The major portion of the data sources used were made available from The Boeing Company, Aerospace Reliability Data Center. This data center provides support to all Aerospace Group programs and also conducts data exchanges with other Boeing divisions, other companies, and governmental agencies.

Finally, point estimates of component failure rates were selected for the two mission time periods, 1975 and 1985. The variations in failure rates over the range found for each component type were due to differences in the following factors:

1) Complexity of functions provided and parts within the components;

2) Loading or stress level of the component parts;

3) Inherent reliability growth potential and the assumed date of procurement or use.

The selection of point estimates from this range was made on the basis of analogies to comparable equipment in known systems and judgment relative to the above factors.

3.5 STUDY METHODOLOGY

3.5.1 GENERAL APPROACH

Basically, the study used mission and design information previously developed elsewhere. Some design modifications were performed, but only when it appeared that available existing concepts would not be compatible with requirements of selected systems (e.g., electrical power subsystem, structural and shielding provisions). Launch vehicle and ground support aspects were considered for parametric cost trends, but their detailed analyses were not within the scope of the study. Two levels of technology were assumed for study application so that the effects of potential and anticipated technological improvements could be accommodated: the mid-1970's and the mid-1980's. Within each time period, two representative missions and associated spacecraft were postulated, one Earth-orbital and one interplanetary, thereby providing a broad base for comparative analysis of the hardware and procedures likely to be involved. Table 1 presents a summary of the missions selected for this study.

Table 1: RESUME OF SELECTED MISSIONS

Period	Mission	Duration	Orbital Altitude	Configuration Basis	Crew Size	Resupply Period
Mid-1970's	Near-Earth Orbit	5 years max.	200 n.mi.	Douglas-MORL	8	90-180 days
	Mars/Venus Flyby	550 days	---	NAA Concept	6	Preinjection orbit only
Mid-1980's	Earth-Moon Libration Center L_1	5 years max.	173,000 n.mi.	Douglas-MORL	12	180-360 days
	Mars Landing	460 days approx.	---	NAA Concept; IMISCD	8	Preinjection orbit only

Subsystems of the selected spacecraft configurations were broken down to their constituent modules and components to establish the maintenance levels necessary for identifying maintenance requirements. Each of the four missions involved about 550 types of components and 11,000 discrete units, and the study considered a total of approximately 66,000 data points. Subsystem variables that were evaluated included failure rates, operating times, weight, volume, cost, mean repair time, maximum allowable downtime, repairability factor, and criticality factor. Anticipated scheduled and unscheduled maintenance activities were determined for the selected systems and components. Design and operational requirements dictated by these maintenance activities also were defined. Computer mechanization was used for reiterations of variable maintainability parameters and simulations of mission events.

3.5.2 COMPUTER MECHANIZATION TECHNIQUES

A Boeing-developed computer-programmed model called MARCEP (Maintainability and Reliability Cost Effectiveness Program) was used to optimize postulated spacecraft configurations. With a complete, single-thread system provided, MARCEP first determines the reliability of each component and then the basic system reliability. Each item is then considered for addition to the system in one of three ways: parallel redundancy, standby redundancy, and spares redundancy. The method to be applied for any given component is determined by repairability and criticality codes used to describe the component when it is part of the basic system. Through many reiterations of this process, a complete spacecraft configuration is structured, with the least amount of added "cost" (generally in terms of weight), to achieve the desired level of overall reliability for the assigned mission duration or resupply interval. The useful result of this program is a printed readout of the components added to the system, shown with their sequence of addition, the new system reliability, method of addition (parallel, standby, or spare), and cumulative system "cost" parameters. This information is then grouped in numerous ways for analysis to determine

problem areas, necessary on-board resources, skill and training requirements, etc. The program uses Fortran IV language, which is operated on by a Univac 1108 digital computer.

The optimized complete spacecraft configuration was next used as an input to a mission simulation model to determine the effects of maintenance time, spares weight, mission duration or resupply interval, system reliability, and maintenance resources on the system. Random unscheduled failures are simulated through the duration of the mission. Consequences of the failures are tabulated, including component identification, resources to accomplish restoration tasks, queuing (if any), MTTR's and variations thereof about their mean values, number of crewmen involved, and EVA requirements. Statistics for a total simulation of 100 cycles of the selected mission duration or resupply interval were tabulated. The simulation method uses the IBM General Purpose System Simulation (GPSS) Model III language, which is operated on by an IBM 7094 digital computer.

3.5.3 RESOURCES

For this analytical "paper" study, three major sources of information were used: reference material available in published literature, some of which was not in general distribution; personal contact with NASA research centers and programs; and inhouse coordination. Section 11.0 of Volume II lists all published reference material used for conceptual and technical purposes in this study. A number of them are summarized briefly in Volume III. Some of the principal references are:

Ref. 1 Report on Optimization of the Manned Orbital Research Laboratory MORL System Concept, NASA-Langley, Contract NAS1-3612, September 1964.

Ref. 2 Manned Mars and/or Venus Flyby Vehicle Systems Study, NASA-MSC, Contract NAS9-3499, June 1965.

Ref. 48 Prototype Life Support System for Space Flights of Extended Time Periods, NASA-Langley, Contract NAS1-2934, 1963-1965.

Ref. 81 Summary Report of Reference 48, November 1966.

Ref. 86 Final Report---Integrated Manned Interplanetary Spacecraft Concept Definition (IMISCD), NASA-Langley, Contract NAS1-6774, January 1968.

Ref. 88 MARCEP---Maintainability and Reliability Cost Effectiveness Program, paper presented at Fourth Annual Reliability and Maintainability Conference, Los Angeles, July 1965; E. P. Trott, The Boeing Company.

The study in Reference 86 is currently in work at Boeing, and close coordination was maintained to apply information being developed there to the Mars landing mission of this study. Other inhouse coordination included consultation with technical staff experts on various subsystems; development of reliability, cost, and human factors data; and mathematical services in conducting the computer programs. Numerous contacts were made with NASA offices to acquire specialized subsystem and performance information, especially in the areas of life support, isotopic power generation, and cislunar environments.

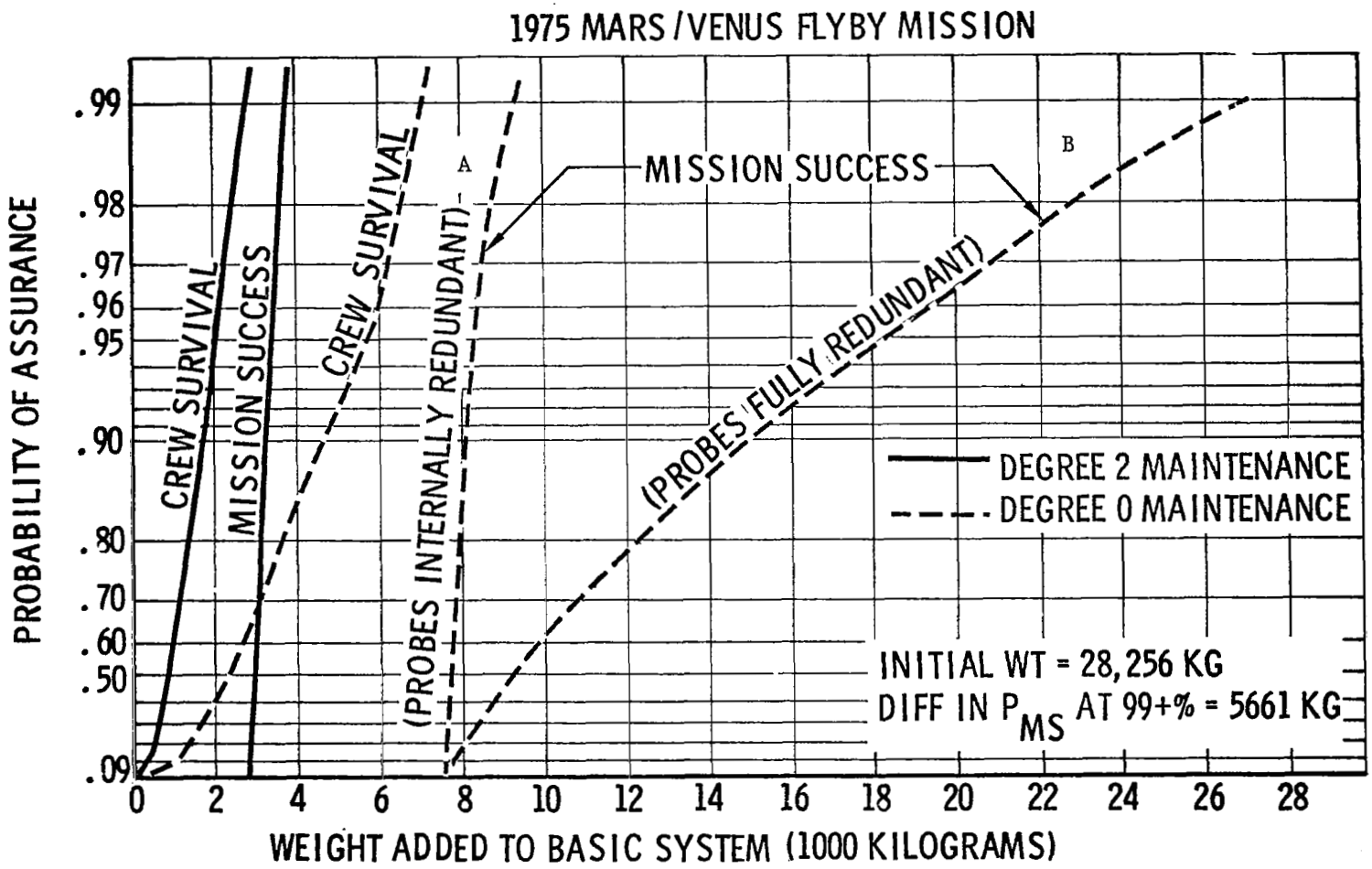


Figure 1: MAINTENANCE CONCEPT COMPARISON — Total Spacecraft Added Weight vs Probability of Assurance

4.0 MAINTENANCE CONCEPT COMPARISONS

The baseline maintenance concept used for the four missions studied was primarily Degree "2," with deviations to Degrees "0," "1," and "3" for specific items that did not lend themselves to Degree "2" maintenance. It was felt that this approach would yield a first approximation to the optimum maintenance concept. To substantiate this, a Degree "0" maintenance concept was generated for the 1975 Mars/Venus flyby mission and evaluated. The required probabilities of assurance for the Degree "0" maintenance concept are achieved in almost all cases by using built-in parallel (continuously operating) and standby (automatically switched) redundancies instead of spares. Therefore, essentially no unscheduled maintenance is required to correct component failures. It should be noted that the Degree "0" concept does not apply to scheduled maintenance activities, because it was found to be impractical to eliminate this maintenance. The concept of fixed redundancies for some components (such as structure, ducting, etc.) was found to be illogical within the constraints of the mathematical model used for optimization. Therefore, the Degree "0" concept does include some spares and maintenance kits for selected items, but for most components, fixed parallel or standby redundancies were allowed with relatively low penalties for automatic switching. Similarly, for the Degree "2" concept, due to various criticality factors it is illogical to spare every component that might fail, and, therefore, a small number of fixed redundancies together with automatic switching when required are included in the added weight for the Degree "2" concept when manual restoration appeared unfeasible.

The effects of Degrees "0" and "2" maintenance concepts were also evaluated at the subsystem level. Again, this comparison was made for the 1975 Mars/Venus flyby mission only; however, the trends found are considered representative of other missions as well. The detailed maintenance concept comparison by subsystem is found in the appendix to Volume II.

4.1 WEIGHT COMPARISON OF MAINTENANCE CONCEPTS

The first comparison of the Degrees "0" and "2" maintenance concepts was made at the total spacecraft level. Comparison at this level showed that less weight was added under a Degree "2" concept to achieve 99% assurance of mission success than was added for the Degree "0" concept. However, the weight added to achieve mission success for the Degree "0" concept appeared completely unreasonable. This resulted from including backup probes for the experiments subsystem. The number of probes carried to achieve 99% assurance of success was excessive even though the probability improvement was calculated by a spares formula. Results of the comparison are shown in Figure 1. The broken line curve labeled "B" shows the excessive weight of probes added to achieve 99% assurance of success. Because this approach was unfairly biased, the maintenance concept for the experiments subsystem was redefined. Increments of parallel redundancy were allowed to be added to the probe internal mechanisms and to the on-board experiment packages. The weight increments were very small in comparison to the basic weight of the probes and experiment packages; however, the probability increase gained by one increment addition to a probe was equivalent to that gained by launching two duplicate probes to accomplish one mission. This was considered

to be optimistic, but certainly fair for the comparison. The results of the redefined Degree "0" concept are shown as broken line curve "A" in Figure 1.

As expected, the Degree "2" maintenance concept showed significantly less weight added to achieve a 99% assurance of mission success. The numerical weight difference between the two concepts was over 5600 kg at the 99% mission success points.

4.2 COST COMPARISON OF MAINTENANCE CONCEPTS

For mission planning purposes, one of the principal factors in selection of a maintenance concept will be dollar cost, assuming achievement of the same assurance level. To determine the cost impact of the Degrees "0" and "2" maintenance concepts, a relative cost comparison was made. The final configurations of the spacecraft under each of the maintenance concepts were inputs to the costing effort, along with assessments of requirements for additional design, crew training, technical data development, automated fault isolation, and numerous other factors affected by the maintenance concept. The summary of the costing is shown in Table 2. The equivalent dollar cost associated with the 1.000 relative cost shown for the Degree "2" concept is 3198 million dollars. Certain assumptions made in the costing, as well as elimination of some factors, were necessary for the study and are indicated in Sections 9.1 and 9.4 of Volume II. Other costing information for specific missions is provided in the subsystems descriptions given in Volume III. It is evident from examination of the costing table that the Degree "2" maintenance concept is desirable from a cost viewpoint as well as from a weight viewpoint. It should be noted that a relative cost factor of 0.001 is roughly equivalent to 3.2 million dollars, and the total difference of 0.149 between the two concepts represents approximately 477 million dollars. This figure does not include ancillary increases such as booster requirements to accommodate the additional weight incurred by the Degree "0" concept.

Table 2: COMPARISON OF RELATIVE COSTS FOR DEGREE "0" AND "2" MAINTENANCE---1975 MARS/VENUS FLYBY MISSION

	Degree "0" Maintenance Concept				Degree "2" Maintenance Concept			
	Dev.	Hdwe.	Op'n.	Total	Dev.	Hdwe.	Op'n.	Total
Subsystems								
Life Support	0.172	0.006		0.178	0.148	0.004		0.152
Communications	0.230	0.005		0.235	0.198	0.004		0.202
Crew System	0.019	0.002		0.021	0.017	0.001		0.018
Data Management	0.040	0.010		0.050	0.035	0.005		0.040
Electrical Power	0.050	0.007		0.057	0.043	0.004		0.047
Extravehicular Activity	0.043	0.005		0.048	0.037	0.002		0.039
Inflight Test	0.002	Negligible		0.002	0.001	Negligible		0.001
Maintenance Equipment	0.001	Negligible		0.001	0.001	Negligible		0.001
Propulsion	0.136	0.004		0.140	0.117	0.003		0.120
Navigation & Guidance	0.038	0.008		0.046	0.032	0.008		0.040
Stability & Control	0.022	0.007		0.029	0.019	0.006		0.025
Structure	0.087	0.008		0.095	0.075	0.008		0.083
AGE	0.101		0.005	0.106	0.087		0.004	0.091
Test and Demonstration	0.097			0.097	0.097			0.097
Software								
Computer Programming	Negligible		Negligible	Negligible	Negligible		Negligible	Negligible
Training Equipment	0.002		Negligible	0.002	0.002		Negligible	0.002
Simulation Equipment	0.003		Negligible	0.003	0.003		Negligible	0.003
Training	Negligible		Negligible	Negligible	Negligible		Negligible	Negligible
Technical Data	Negligible		Negligible	Negligible	Negligible		Negligible	Negligible
Launch Site Support	0.037		0.002	0.039	0.037		0.002	0.039
Total	1.080	0.062	0.007	1.149	0.949	0.045	0.006	1.000

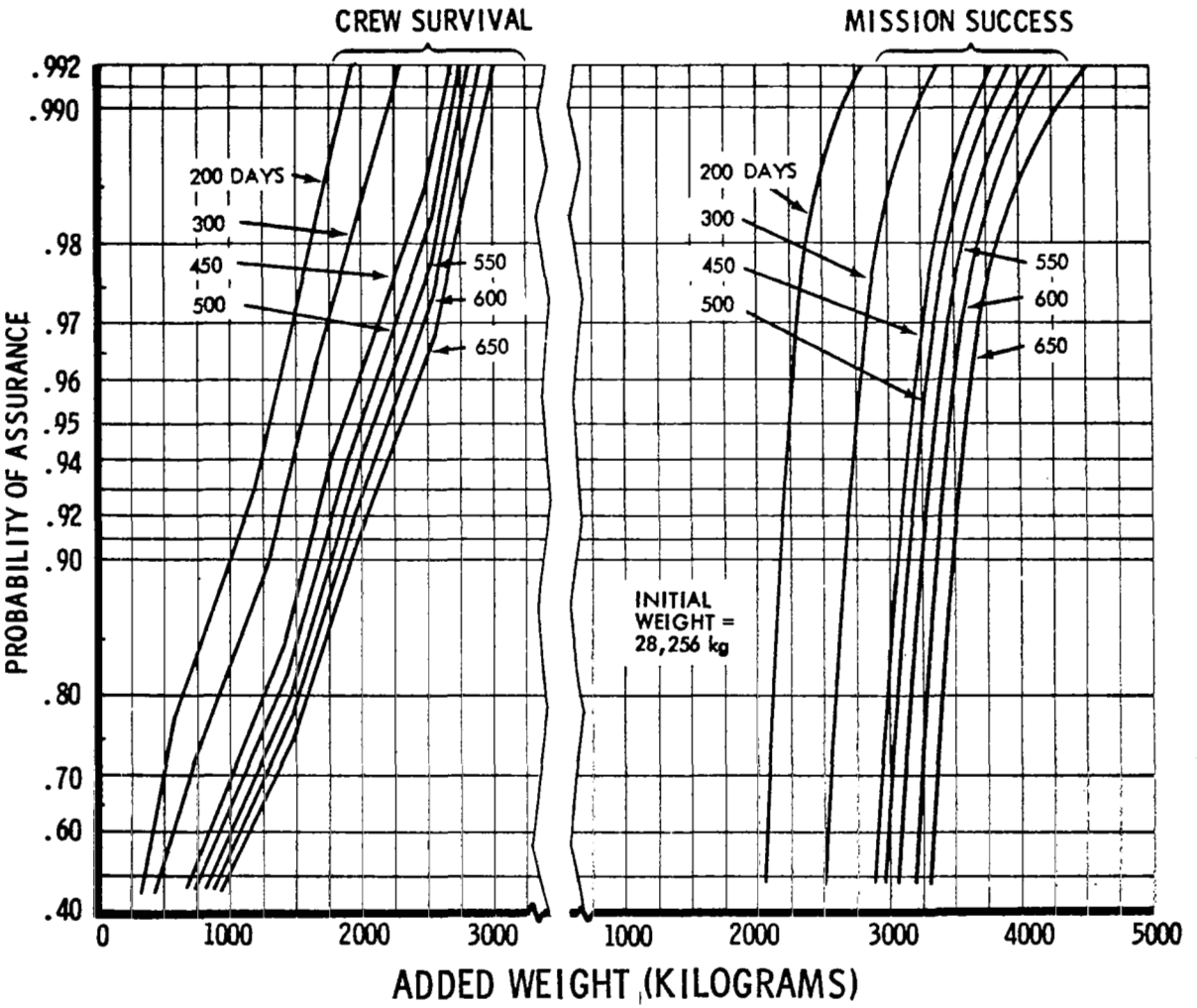


Figure 2: ADDITIONAL WEIGHT REQUIRED TO ACHIEVE PROBABILITY OF ASSURANCE — 1975 Mars/Venus Flyby Mission

5.0 EFFECTS OF MISSION PARAMETERS AND MAINTENANCE ON SPACE PROGRAMS

A number of different missions described in other studies were evaluated for mission concepts, goals, operational characteristics, personnel and hardware requirements, and depth of detailed information to establish representative and workable baseline missions that could be analyzed in this study. Volume III of this report presents a detailed discussion of the missions selected, spacecraft configuration analyses and selections, and the spacecraft subsystem analyses. It is necessary to review this information and examine the MARCEP data sheets and maintenance task analysis sheets (also contained in Volume III) to appreciate fully the depth of data that was used as a background for the study analyses.

At the system level, the effect of varying major mission/system parameters was investigated. These parameters included mission duration, weight, volume, mean repair time, and required level of repair confidence. In evaluating the effects of the mean repair time, gross errors in the estimation of repair times were assumed and applied as factors to the baseline repair times. The results of investigating the system-level effects of parametric variations are presented in Section 5.1 for a representative interplanetary mission.

Scheduled maintenance activity will have an effect on mission requirements. In particular, scheduled maintenance will affect crew workload and the weight of expendables required to conduct the mission. These aspects of scheduled maintenance are discussed in Section 5.2.

The effects of unscheduled maintenance on overall mission requirements were evaluated by conducting a series of simulations where the mission was examined under simulated real time conditions. In the simulations, failures were allowed to occur randomly and statistics on queuing, resource expenditures, and maintenance time (which was also determined randomly) were recorded. The results of these investigations are presented in Section 5.3.

Skill requirements to be provided within the flight crew to accomplish both scheduled and unscheduled maintenance were also evaluated for all the missions. The impact of spacecraft maintenance on crew skill distribution and use is discussed in Section 5.4.

The charts included here were prepared for the 1975 Mars/Venus flyby mission. These charts are typical of the kind of information available in Volume II for all of the missions considered during the study.

5.1 EFFECTS OF VARYING SELECTED MISSION/SYSTEM PARAMETERS

Figure 2 illustrates growth in total weight of components, added as parallel redundant, standby-redundant, or spare items to a complete, basic, nonredundant spacecraft in the most effective manner to achieve a desired probability of assurance. An inverted log scale has been used along the ordinate

to provide better visibility at the higher values of interest. Since 99% probability of crew survival is a mandatory requirement, components contributing to this are considered first in the optimization program. After 99% has been reached, the program is opened up to include all remaining items, causing a lower probability of mission success initially until proper components are again added to achieve the desired reliability level. At least 99% assurance of crew survival thus is always implicit in all portions of the mission success curves. The curve groups have been separated for clarity by repeating the weight scale along the abscissa. For an initial spacecraft nonredundant weight of*45,824 kilograms, it can be seen that approximately 3900 kilograms of additional redundant and spare items will be needed on board to ensure 99% probability of mission success for a 550-day mission.

Figure 3 shows the distribution by subsystem of the total weight added to achieve 99% probability of mission success. These weights, represented by the cross-hatched bars, are compared with initial weights of the respective subsystems as indicated by the solid bars. For a detailed discussion of some of the implications and reasons involved here, see Section 6.1 in Volume II. Other charts also were generated to evaluate sensitivity of weights and probabilities to various levels of repair confidence and to different MTTR's (mean-time-to-repair).

5.2 EFFECTS OF SCHEDULED MAINTENANCE ON OVERALL MISSION REQUIREMENTS

Table 3 summarizes the man-minutes required to perform planned maintenance tasks at 1-, 3-, 7-, 21-, 30- and 90-day intervals for each subsystem. The column of average man-minutes per day is the sum of all task-times performed on the respective subsystem, distributed throughout the mission duration as a statistical reference to gage relative impact of subsystem workloads. It can be seen that the crew system and life support subsystem far outweigh all others combined. A similar breakdown also has been charted against skill requirements. Total scheduled maintenance workload averages about 2.5 hours per day throughout the mission.

Expendables were hand-calculated for a six-man flyby mission. These are summarized by subsystem, as a function of mission duration, in Figure 4. Total expendables for a 550-day mission amount to about 7500 kilograms (16,500 lb).

5.3 EFFECTS OF UNSCHEDULED MAINTENANCE ON OVERALL MISSION REQUIREMENTS

Using the optimized configuration developed as indicated above, 100 Mars/Venus flyby missions involving random failures were simulated on a second computer program. This provided a broad statistical base on possible unscheduled maintenance activities, for determining the effects of maintenance time, spares weight, mission duration, system reliability, and maintenance resources on the mission. Unscheduled maintenance activities according to subsystem are shown in Table 4. It can be seen here that the data management subsystem incurred the largest proportion of failures (43%) and the highest frequency (a mean of 10.62 days between failures). However, average restoration time of 105 minutes per failure was well below most other subsystems. Averaged throughout a 550-day mission, the unscheduled maintenance load amounted to slightly more than

*includes 17 568 kilograms of experiments

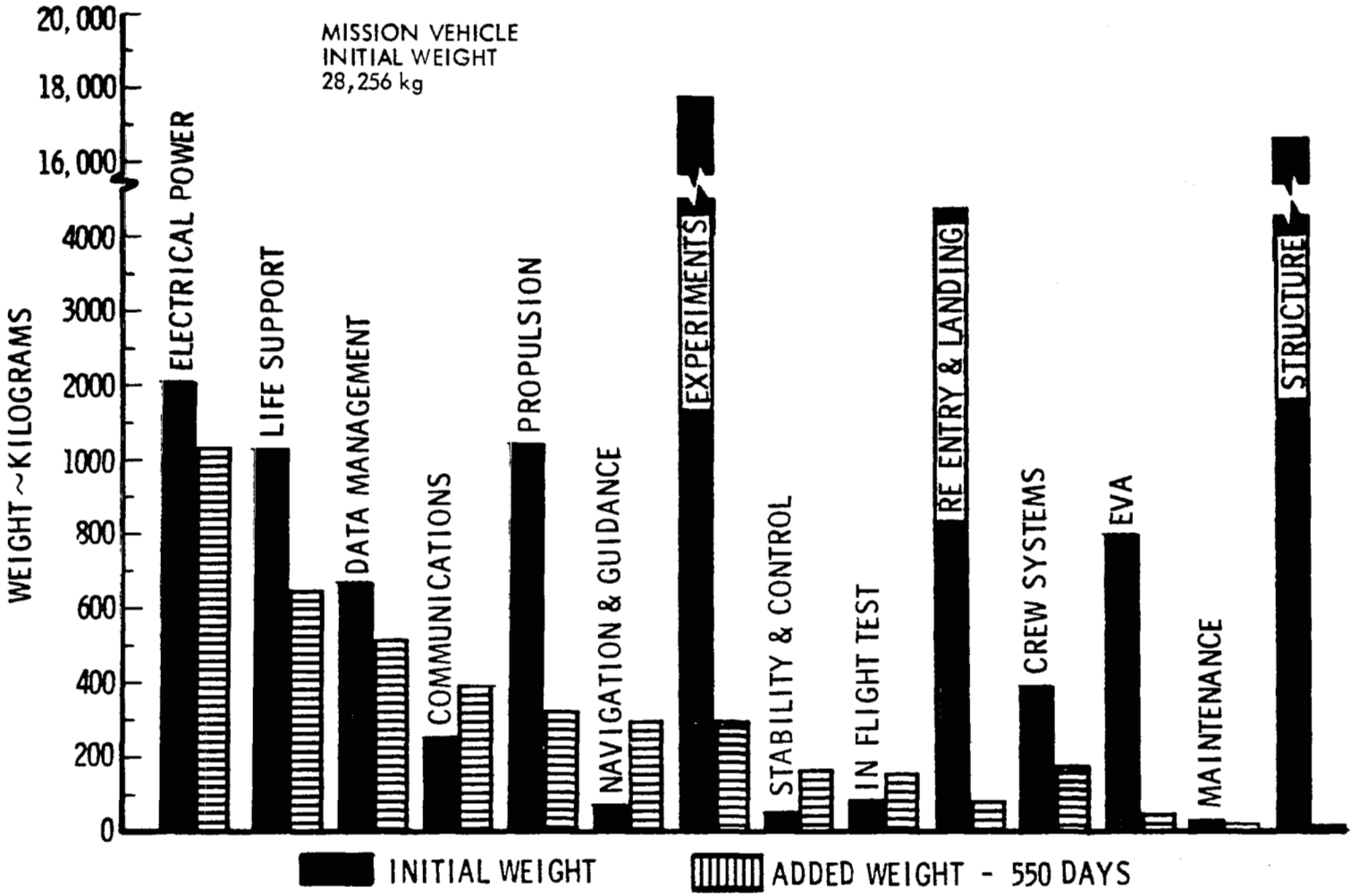


Figure 3: SUBSYSTEM INCREMENTAL WEIGHTS —
1975 Mars/Venus Flyby Mission

Table 3: SUBSYSTEM SCHEDULED MAINTENANCE REQUIREMENTS---
1975 MARS/VENUS FLYBY MISSION

Subsystem	Man-Minutes/Maintenance Interval (Days) 1	3	7	21	30	90	Average Man-Minutes/Day
Crew System			360		40	40	53.2
Data Management						110	1.2
Electrical Power					300		10.0
Extravehicular						30	0.3
Experiments						30	0.3
Inflight Test System	10				30		11.0
Life Support System	10	15	60	30	335	260	39.1
Propulsion					480		16.0
Reentry System						360	4.0
Structure							12.0
Total Man-minutes	20	15	420	30	1545	830	
Average Man-minutes/Day	20	5	60	1.4	51.5	9.2	147.1

NOTE: Scheduled maintenance required at intervals greater than 90 days and at the resupply periods are not shown in the above summary as these tasks must be done at about the time indicated and cannot realistically be apportioned over a number of days.

Table 4: SUBSYSTEM UNSCHEDULED MAINTENANCE REQUIREMENTS---
1975 MARS/VENUS FLYBY MISSION

Subsystem	Percent of Total System Failures	Percent of Total System Repair Time	Mean Days Between Failures	Average Min/Fail.	Average Min/Day
Life Support	12.88	11.73	36.52	143	3.92
Communications	3.76	6.92	122.12	282	2.31
Crew System	0.14	0.06	3437.50	69	0.02
Data Management	44.26	29.58	10.62	105	9.89
Electrical Power	4.15	5.20	113.64	198	1.74
Extravehicular Activity	0.27	0.33	1774.19	188	0.11
Experiments	0.69	2.48	679.01	562	0.83
Inflight Test	11.94	6.16	39.40	81	2.06
Maintenance Equipment	0.05	0.06	11,000.00	175	0.02
Propulsion	8.12	12.86	57.89	249	4.30
Earth Reentry System	0.26	0.72	1833.33	442	0.24
Stability and Control	6.05	6.61	77.79	172	2.21
Structure	0.27	0.72	1774.19	429	0.24
Navigation and Guidance	7.16	16.57	65.71	364	5.54
Totals	100.00	100.00	4.69 Average	161 Average	33.43

NOTE: The above data is based on one hundred 550-day simulation runs, which is the equivalent of 150 years of operation.

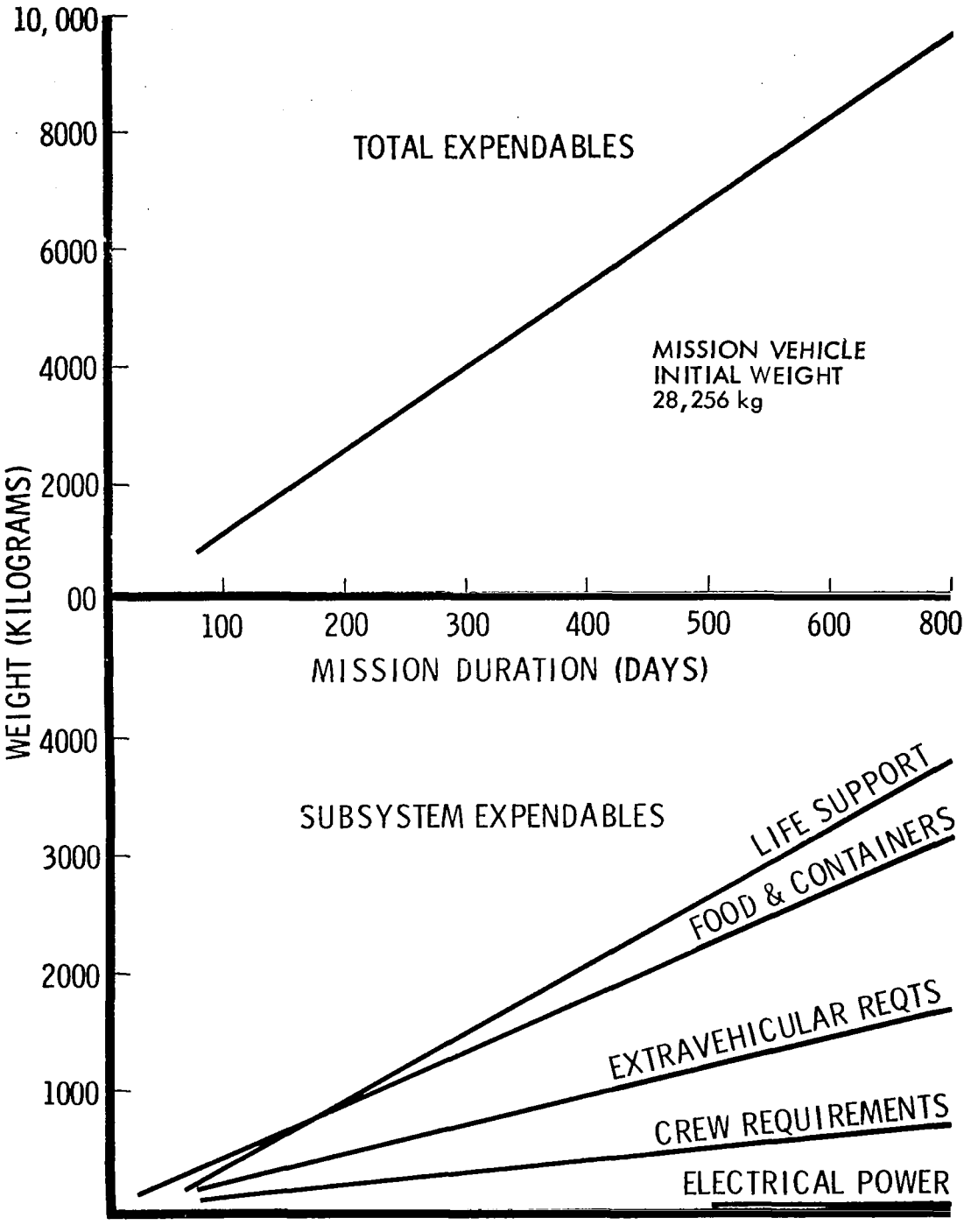


Figure 4: SUBSYSTEM EXPENDABLES REQUIREMENTS — 1975 Mars / Venus Flyby Mission

0.5 hour. Coupling this with the scheduled maintenance load noted previously results in a very moderate average total requirement (3 hours per day) for maintenance out of the 144 manhours per day available from a six-man crew. The other missions studied had approximately the same requirements.

Figure 5 shows the cumulative probability of spares usage by weight, over 100 mission simulations of the 550-day mission. The maximum usage was found to be 850 kilograms, or 21.8% of the total resources carried on board. The curve indicates that there is 100% probability that not more than 850 kilograms will be used during a mission. Similarly, there is a 95% probability that no more than 590 kilograms will be used, and approximately 67% probability that the mean of 312 kilograms, or 8% of initially allocated weight, will not be exceeded. Of course, all spares must be stocked for the trip since the necessity to use any given component cannot be predicted. Optimization of spares weight by eliminating duplication between those for crew survival and additional identical items for mission success, or by cannibalizing unused or removed components, was not attempted in this study. As a practical consideration, the latter practice may not be desirable anyway because of possible uncertainty in resulting reliabilities.

5.4 EFFECTS OF MAINTENANCE ON CREW SKILL REQUIREMENTS

Skill requirements to accomplish necessary scheduled maintenance during the 1975 Mars/Venus flyby mission were determined in the course of the maintenance analysis. Table 5 summarizes required scheduled maintenance by skill and maintenance interval, indicating the total man-minutes required. Scheduled maintenance requirements given in Tables 3 and 5 are not indicated beyond 90 days since it is felt that the maintenance actions occurring beyond 90 days are of an overhaul nature and cannot be averaged out over the entire mission. Special mission planning must be accomplished to accommodate such actions.

The mission simulation program mentioned in Section 5.2 also was used to identify expected skill usage for unscheduled maintenance during the 1975 Mars/Venus flyby mission. The results are given in Table 6, where it can be seen that the average daily demands on any one skill are minimal. The highest demands are required of the electrical/electronic and mechanical skills, with 20.2 and 10.9 minutes/day average workload, respectively. However, the average skill use time for any discrete task taken at random is 186 minutes; this figure considers both interior and exterior tasks. The average daily workload is calculated by dividing the average skill use time by the mean time between skill usages. When Tables 4 and 6 are compared, differences in the accumulated averages can be noted. These occur when two (or more) skills are applied to a task simultaneously, resulting in a total skill use time that exceeds the elapsed time for accomplishing the task.

In general, it can be stated that one of each primary skill should be sufficient to accommodate all scheduled and unscheduled maintenance tasks that can be expected during a 550-day interplanetary mission, and that no inordinate load will be placed on any particular skill.

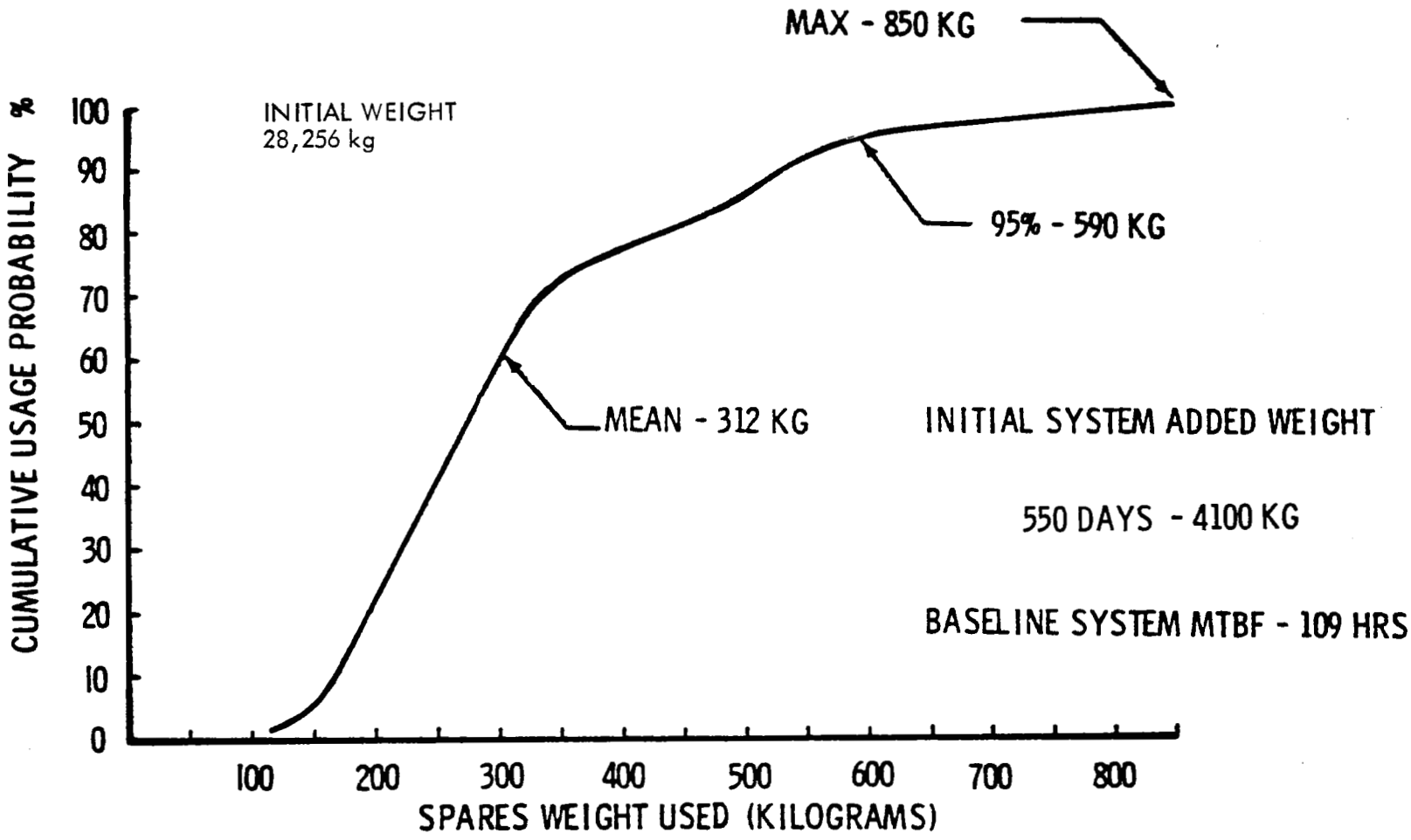


Figure 5: SPARES WEIGHT USAGE PROBABILITY — 1975 Mars/ Venus Flyby Mission

Table 5: SCHEDULED MAINTENANCE CREW SKILL REQUIREMENTS - 1975 MARS/VENUS FLYBY MISSION

Skill	Man-Minutes/Maintenance Interval (Days) 1	3	7	21	30	90	Total Man-Minutes/Day
Communications						80	0.9
Electrical/Electronic	10				300	390	24.3
Guidance & Navigation						60	0.7
Life Support	10	15	240	30	215	240	60.6
Mechanical			180		610	60	46.7
Structures					420		14.0
Total Man-Minutes	20	15	420	30	1545	830	
Average Man-Minutes/Day	20	5.0	60.0	1.4	51.5	9.2	147.1

NOTE: Scheduled maintenance required at intervals greater than 90 days is not shown in the above summary as these tasks must be done at about the time indicated and cannot realistically be apportioned over a number of days.

Table 6: UNSCHEDULED MAINTENANCE CREW SKILL REQUIREMENTS---
1975 MARS/VENUS FLYBY MISSION

Crew Skill	% of Total Repair Time	Mean Days Between Skill Use	Average Min./Skill Use	Average Min./Day
Life Support Systems	8.7	36.8	142	3.9
Electrical/Electronic	45.4	7.5	152	20.2
Mechanical	24.4	31.1	338	10.9
Structures	7.9	74.9	260	2.9
Communications	6.5	57.0	164	5.0
Guidance and Control	5.4	76.1	180	2.4
Medical	0.6	27,500.0	770	0.03
Scientist-Experiments	1.1	524.0	480	0.92
Totals	100.0	4.26 Average	186 Average	44.8

NOTE: The above data is based on one hundred 550-day simulation runs, which is the equivalent of 150 years of operation.

6.0 GUIDELINES FOR SELECTING SUBSYSTEM MAINTENANCE CONCEPTS

Early in the study it became evident that the only meaningful generalized maintenance concept for a long-duration manned space mission can be expressed in a single statement: it is inevitable that on-board maintenance, both scheduled and unscheduled, will be performed by the crew and must be planned for from the inception of the program. All further discussion should be directed at the scope of maintenance that will be required by various elements of a spacecraft. Thus, two subsidiary philosophies on the degree of maintenance that should be performed were examined during the study analysis:

1) Maintenance actions by the crew were permitted whenever overall reliability of the spacecraft and level of mission assurance could be enhanced thereby.

2) Maintenance actions by the crew were restricted to the barest essentials, and system redundancy was incorporated to the maximum extent possible, consistent with logical design concepts.

Most of the study effort centered around Item 1, where it was found that various maintenance concepts emerged depending upon the selection criteria. These included operational and performance factors, resource or cost factors, and hardware and design factors. The concepts were defined in terms of maintenance action complexity and kinds and quantities of restoration resources. The four degrees of maintenance thus identified were applied as appropriate to the several subsystems analyzed. Also, it was decided that the most meaningful selection criterion should be one in which a fixed probability of success (e.g., 99% probability of crew survival) would be achieved at a minimum cost penalty. The general study approach allowed the cost penalty to be measured in the form of dollar cost, weight, or crew manhours, or combinations of these. For the most part, the parameter of weight was used since this bore directly on operational feasibility and logistic characteristics. Section 7.0 in Volume II discusses in detail the maintenance concepts derived for each of the subsystems of each postulated configuration. No meaningful overall statement of principles can be made since the concepts vary from zero scheduled maintenance (e.g., elements of the communications subsystem) to significant requirements for the life support subsystem, and characteristics of the subsystems vary radically.

Figures 6 through 9 summarize the maintenance concepts suggested for each subsystem in each of the missions studied. The recommended concept is noted by heavy lines and the letter "R." Where there are exceptions to the recommended concept, these are shown under the appropriate degree of maintenance by a brief notation. If further study needs to be done, the notation "FS" is shown. As shown in Figure 6, the communications and structure subsystems are the only exceptions to the recommendation or Degree "2" maintenance for the 1975 near-Earth orbit mission. Degree "1" is recommended for the former because of the low number of spares required to achieve the desired reliability. If only one or two spares are required, it is usually practical to wire them into the system. Since redundant or replaceable structure is not a logical maintenance approach, Degree "3" (repair) has been selected for the latter subsystem. Evaluation of

the 1985 L_1 Libration Center mission subsystems (Figure 7) resulted in the same recommendations for essentially the same reasons, although there were some individual differences in subsystem characteristics. For example, the allowable downtime for the receiver/decoder used in 1975 was assumed to be greater for the 1985 system, and that, together with improved reliability, permitted this item to be spared instead of parallel-redundant.

In general, Degree "2" maintenance is recommended for subsystems of the interplanetary configurations, given in Figures 8 and 9. The communications and structure subsystems again are exceptions for the same reasons given above; however, in the 1985 mission, the laser assembly is the principal maintenance-significant component and requires periodic replacement due to its limited lifetime. Because the nuclear power supply has a variety of component types, maintenance concept recommendations cover the full range from parallel redundancy (Degree "0") for the fuel block, to repair (Degree "3") for radiators and tubing. The type of component thus becomes determinant on the concept to be followed. Since elements of EVA equipment in general can be maintained by repair action, this concept was recommended for both missions. The stable platform in the navigation and guidance subsystem constitutes the major maintenance problem due to platform alignment requirements. Tentatively, it is recommended that one level of standby redundancy be provided, with the basic unit designed for replacement and backed up by the necessary spares.

MAINTENANCE CONCEPT / SUBSYSTEM	DEGREES OF MAINTENANCE			
	0 PARALLEL REDUN	1 STANDBY REDUN	2 REMOVE & REPLACE	3 REPAIR
COMMUNICATIONS	RECEIVER/DECODER	R – FOR 90 DAY RESUPPLY IN PARTICULAR FS◄	►FS INTERCOM TV EQUIP	
CREW SUBSYSTEM			R	TAPES, BUNKS, BEDDING, EXERCISE EQUIPMENT
DATA MANAGEMENT			R – WITH MODULARIZATION	
ELECTRICAL POWER	SOLAR PANELS MAIN CONTACTORS	INVERTERS VOLTAGE REGULATOR	R	WIRING AND CONNECTORS
EXPERIMENTS			R – MAXIMUM COMMONALITY WITH SPACECRAFT EQUIP. FS◄	►FS
EXTRAVEHICULAR ACTIVITY			R FS◄	AIRLOCKS, SPACE SUITS, RESTRAINT AIDS ►FS
MAINTENANCE EQUIPMENT			R FS◄	►FS
INFLIGHT TEST			R	
LIFE SUPPORT			R	RADIATORS, STORAGE TANKS, PLUMBING, AND DUCTS (FS)
NAVIGATION AND GUIDANCE	NOT IDENTIFIED FOR THIS MISSION			
PROPULSION	RCS ENGINES, SOME PRESSURIZATION EQUIPMENT (FS)		R – SPARES BACKUP FOR REDUNDANT ITEMS (FS)	(FS)
REENTRY			R (FS)	STRUCTURE (FS)
RENDEZVOUS AND DOCKING			R FS◄	►FS
STABILITY CONTROL	CRITICAL ATTITUDE CONTROL ITEMS, REGULATED POWER SUPPLY FS◄	►FS◄	R – SPARES BACKUP FOR REDUNDANT ITEMS ►(FS)	
STRUCTURE			PORTS AND WINDOWS FS◄	R ►FS

R – RECOMMENDED, EXCEPT FOR ITEMS NOTED IN OTHER COLUMNS

FS – FURTHER STUDY OR TRADE INDICATED

Figure 6: SUBSYSTEM MAINTENANCE CONCEPT MATRIX — 1975 Near Earth Orbit Mission

MAINTENANCE CONCEPT / SUBSYSTEM	DEGREES OF MAINTENANCE			
	0 PARALLEL REDUN	1 STANDBY REDUN	2 REMOVE & REPLACE	3 REPAIR
COMMUNICATIONS		R - FOR 180-DAY RESUPPLY, IN PARTICULAR FS	INTERCOM TV EQUIPMT FS	PARABOLIC ANTENNA FS
CREW SUBSYSTEM			R	TAPES, BUNKS BEDDING, EXERCISE EQUIP, ETC.
DATA MANAGEMENT			R - WITH MODULARIZATION	
ELECTRICAL POWER	SOLAR PANELS, MAIN CONTACTORS	INVERTER, VOLTAGE REGULATOR, BATTERY	R	WIRING AND CONTACTORS
EXPERIMENTS			R - MAXIMUM COMMONALITY WITH SPACECRAFT EQUIPMT FS	FS
EXTRAVEHICULAR ACTIVITY			R FS	AIRLOCKS, SPACE SUITS, RESTRAINT AIDS FS
MAINTENANCE EQUIPMENT			R FS	FS
INFLIGHT TEST			R - MODULARIZE SOME TEST AND MONITOR EQUIPMT	
LIFE SUPPORT		BOSCH REACTOR	R - SPARES BACKUP FOR BOSCH REACTOR	RADIATORS, STORAGE TANKS, PLUMBING, AND DUCTS (FS)
NAVIGATION AND GUIDANCE	INERTIAL PLATFORM (DEGREE 2 MAINT IF MODULARIZED)		R	
PROPULSION	RCS ENGINES, TANKS SOME PRESSURIZATION EQUIPMT		R - SPARES BACKUP FOR REDUNDANT ITEMS (FS)	(FS)
REENTRY			R (FS)	STRUCTURE (FS)
RENDEZVOUS AND DOCKING			R - MODULARIZE TRANSPONDER	
STABILITY CONTROL	SUN-SEEKER, HORIZON SCANNER, REGULATED POWER SUPPLY FS	CONSIDER FOR SOME OF ELECTRONICS EQUIPMT	R-SPARES BACKUP FOR REDUNDANT ITEMS FS	
STRUCTURE			PORTS, WINDOWS FS	R FS

R - RECOMMENDED, EXCEPT FOR ITEMS NOTED IN OTHER COLUMNS FS - FURTHER STUDY OR TRADE INDICATED

Figure 7: SUBSYSTEM MAINTENANCE CONCEPT MATRIX — 1985 L_1 Libration Center Mission

MAINTENANCE CONCEPT / SUBSYSTEM	DEGREES OF MAINTENANCE			
	0 PARALLEL REDUN	1 STANDBY REDUN	2 REMOVE & REPLACE	3 REPAIR
COMMUNICATIONS		R (FS) ←	500 W TRANSMITTER INTERCOM → (FS)	ANTENNAS, WIRING (FS)
CREW SUBSYSTEM			R	BUNKS, BEDDING, TV TAPES, ETC.
DATA MANAGEMENT	INACCESSIBLE SENSORS		R MODULARIZED COMPUTER, DATA ADAPTER	FILM PROCESSING AND TV UNIT
ELECTRICAL POWER	DETERMINE DEGREE OF MAINTENANCE BY COMPONENT FS	FS	R (FOR MOST ITEMS)	RADIATORS (FS)
EXPERIMENTS	(FS - PROBE INTERNAL REDUNDANCY)		R (PROBES) FS ←	ONBOARD EXPERIMENTS → FS
EXTRAVEHICULAR ACTIVITY			MMU, AMU, AEV FS ←	R → FS
MAINTENANCE EQUIPMENT			R FS ←	→ FS
INFLIGHT TEST			R	
LIFE SUPPORT			R	TANKS, PLUMBING, DUCTS
NAVIGATION AND GUIDANCE		R FS ←	ELECTRONIC PACKAGES → FS	(FS - POSSIBLE REPAIR OF INERTIAL UNIT)
PROPULSION	TANKS, FLUID EXPULSION DEVICES FS		R FS ←	→ FS
REENTRY			R (FS - COMMONALITY WITH MM ITEMS)	STRUCTURE, HEAT SHIELD FS
RENDEZVOUS AND DOCKING	INCLUDED IN STRUCTURE SUBSYSTEM			
STABILITY CONTROL			R	
STRUCTURE			PORTS, WINDOWS, ETC. FS	R FS

R - RECOMMENDED, EXCEPT FOR ITEMS NOTED IN OTHER COLUMNS.

FS - FURTHER STUDY OR TRADE INDICATED

Figure 8: SUBSYSTEM MAINTENANCE CONCEPT MATRIX — 1975 Mars/ Venus Flyby Mission

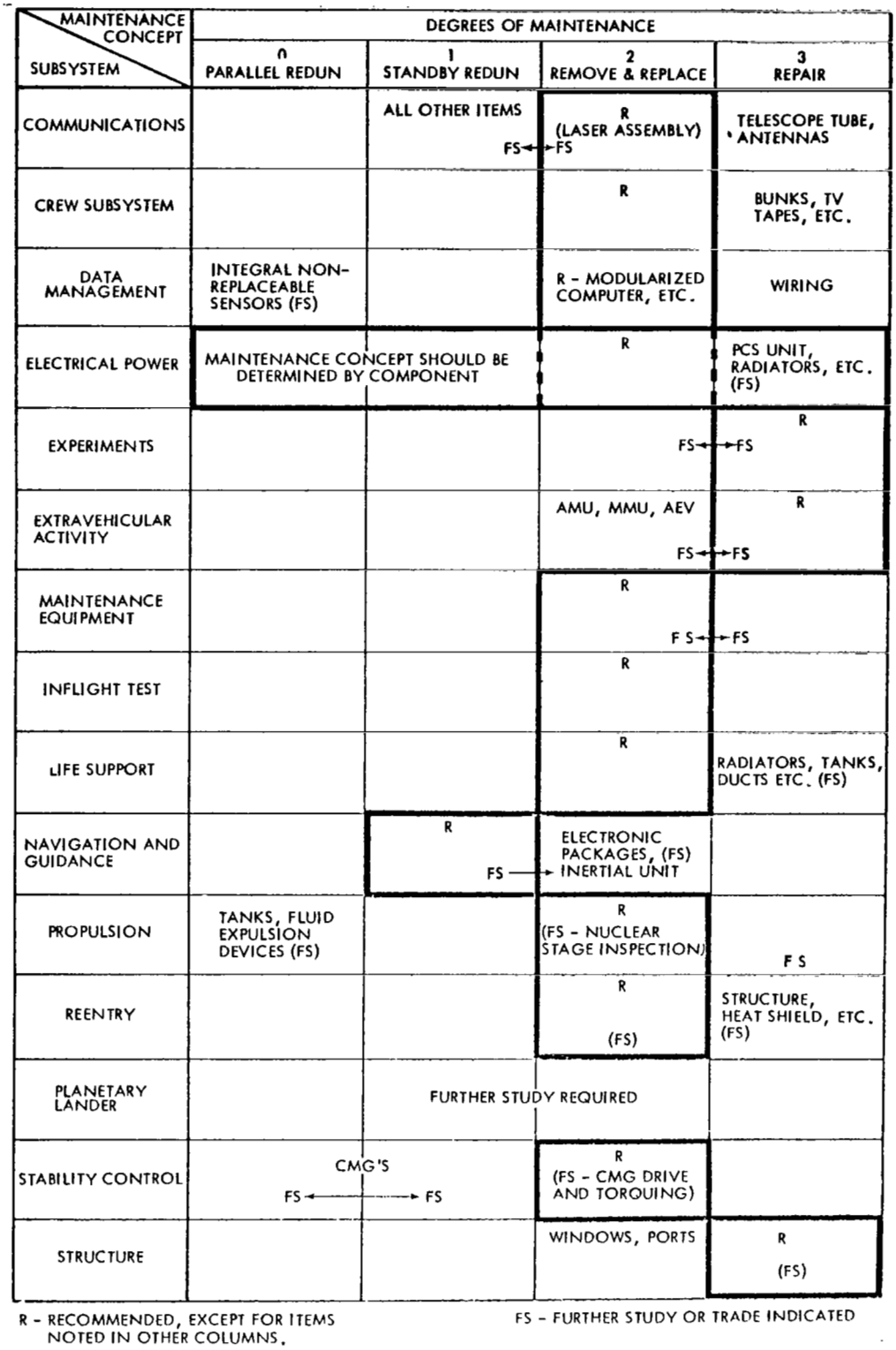


Figure 9: SUBSYSTEM MAINTENANCE CONCEPT MATRIX — 1985 Mars Landing Mission

7.0 MAINTENANCE PHILOSOPHY AND DESIGN PRECEPTS COMMON TO ALL MISSIONS

7.1 GENERAL DISCUSSION

The maintenance philosophy selected for a mission significantly affects the approach taken in the basic design of the spacecraft. If a concept of no maintenance is assumed, then the spacecraft must include parallel or standby - redundant components, with automatic or remotely controlled switchover capability for all spacecraft functions that must operate for the duration of the mission. For long-duration missions this can result in an excessively complex and heavy configuration.

In general, selecting a maintenance philosophy requires consideration of several factors. These include:

- Knowledge of mission objectives.
- Mission effects on system/subsystem design.
- Mission demands on crew time.
- Technical capabilities of the crew to provide maintenance.
- Feasible level of maintenance action and associated demands on packaging concepts.
- An estimate of the inherent reliability of the subsystem hardware (failure rates and useful life) and configuration.
- Safety implications associated with alternate maintenance philosophies that are considered.
- An estimate of equipment allowable downtimes and repair/restoration times (repair time distributions and mathematical models used to evaluate probability of no system failure due to exceeding the allowable downtime).

The optimum maintenance philosophy for a stated mission will be based on the most effective blend of the parameters that measure the influence of these factors. Section 6.0 indicates the maintenance philosophies or concepts that were thought to be most effective for the subsystems of the missions selected for this study. Section 7.2, which follows, summarizes those maintenance philosophies that were found to be common to all the missions studied.

7.2 MAINTENANCE PHILOSOPHY COMMON TO ALL MISSIONS

1) Plan maintenance on a remove-and -replace (Degree "2") basis whenever practicable. Component packaging must be at a level that will facilitate this concept. Use special maintenance kits only for repairs of large, bulky items for which a remove-and-replace concept may not be desirable; e.g., structural parts, plumbing, ducts, large tanks, etc.

2) With relatively few exceptions, an on-board bench repair (Degree "3") maintenance capability is not justified. Exceptions must be evaluated

individually. because most unscheduled maintenance requirements are insufficient to warrant such a capability. Component replacement requiring EVA, in which the removed assemblies are returned to the bench where Degree "3" maintenance can be performed in a shirtsleeve environment; or situations where the experiments subsystem requires an on-board workshop and other subsystems can be designed to take advantage of its availability, may be considered for Degree "3" maintenance.

3) Use scheduled maintenance only when other means of attaining desired assurance levels are too costly in terms of weight (spares, expendables), crew time, cost, and reliability of affected systems.

4) When only one spare of an item is required to achieve the desired level of assurance, consider making the spare standby-redundant so it can be switched into the system when the main item fails. This will eliminate a remove-and-replace maintenance action.

5) Give unscheduled maintenance precedence over scheduled maintenance; i.e., unscheduled maintenance has first priority over maintenance resources including crew skills, except where unscheduled maintenance of nonsafety critical items logically is preempted by scheduled maintenance of safety critical items.

6) Make available fully detailed procedures for all scheduled and expected unscheduled maintenance functions.

7) Provide adequate spares to ensure the required probability of crew survival and mission success.

7.3 DESIGN PRECEPTS COMMON TO ALL MISSIONS

These principles augment the assumptions given in Section 7.2.

1) Place Emphasis on Design of Life Support Subsystem---The life support subsystem, which included life support and environmental control in this study, is the major source of scheduled and unscheduled maintenance workload. In addition, it requires an extended period of training to develop the necessary operation and maintenance skill. Spacecraft interior design should be planned about a life support subsystem configuration and location that optimizes operation and maintenance.

2) Modularize High Failure Items---Equipment should be modularized whenever it can be broken down in a number of identical modules. The greater the number of identical modules, the more effective is the use of spares, and initial spares weight provided for a mission is reduced considerably.

3) Design for Commonality of Spacecraft Components---Achieve commonality of components, within and between subsystems, whenever possible. Spares requirements decrease significantly when a high degree of commonality can be attained. For example, electronic subsystems could standardize on a small variety of amplifier modules that would be replaceable and common between the subsystems.

4) Design for Commonality of Experiment and Spacecraft Equipment---In planning experiment programs and identifying the equipment required, use items that

are common with spacecraft system equipment wherever possible. Better use of equipment, less cost, and fewer spares to support the spacecraft and experiments will result.

5) Spare Heavy Noncritical Items Only at Resupply---For some large items of equipment, where the probability of failure is quite remote, only one spare is necessary to achieve the desired assurance of mission success. If resupply is available and failure of the item can be tolerated for a number of days by using an alternate mode of operation, the practicability of not providing a spare initially should be considered. If the item fails, a spare can be brought up at the next resupply.

6) Minimize EVA---In the interest of reducing EVA, place high-failure-rate and long-maintenance-time items within the pressure hull whenever practical.

7) Reduce Hazards to Personnel during EVA---Design equipment mounted on exterior surfaces to withstand an inadvertent impact, and minimize hazards to a pressure-suited man, by such means as eliminating unprotected sharp surfaces and making surfaces easily visible under all lighting conditions.

8) Design Airlock for at least Two Men---It is assumed that EVA will require two workers for maximum safety (the "buddy" system). Accordingly, design airlocks for a minimum of two spacesuited men and arrange for the doors to interlock (permitting only one to open at a time) unless the cabin pressure is dumped.

9) Incorporate Safety Measures---Provide protection for all switches and controls against inadvertent activation. Plan all maintenance tasks that could possibly cause loss of cabin pressure, and design the equipment, so that functions can be performed by spacesuited personnel; for example, airlock interior seal replacement. Also, consider compartmented design to reduce the possibility of catastrophic failure throughout the spacecraft.

10) Develop Alternate Design of Panel Display Indicators---When designing fault indication and status displays, consider electromechanical flags and solid-state lights as well as a fault matrix display, as alternatives to a conventional display with indicator lamps. The replacement of bulbs takes only a short time, but failures must first be detected, and frequent replacement can be a major nuisance.

11) Identify Fasteners Selectively---Limit fasteners for all items that can be maintained to a few common types and sizes, to minimize tool requirements. Fasteners for items requiring removal by a spacesuited man should be as large as practical and few in number.

12) Limit Electrical Connections---No EVA repair of connectors or plugs should be planned. For interior electrical connections wire-wrap or crimp (one or the other) connections should be used to permit inflight repair without soldering.

8.0 COST ANALYSIS

8.1 BACKGROUND DATA AND ESTIMATING TECHNIQUES

A decision was made early in the study to conduct the analysis initially with weight as the major influence on configuration optimization. However, dollar cost as a potential trade parameter was borne in mind at all times in the event a decision required this as a basis. Also, cost elements became important when dealing with multiple launches for a given single mission. As it turned out, the study team could find no case where cost as an independent parameter was influential in selecting a maintenance concept or revising a configuration approach; design requirements and associated reliability factors were the overriding considerations.

Cost factors are of interest, however, in the analysis of contending maintenance philosophies, and in gross comparisons of differing missions. For this study, because of the uncertainty of costs for systems 20 years hence, a method was used where the relative cost number for a baseline spacecraft flight configuration totaled to 1.000. This permitted comparison of systems and concepts on an absolute basis, within the context of current economics, on the assumption that hardware and program cost relationships do not vary significantly with time regardless of the external financial environment.

8.1.1 COST ANALYSIS APPROACH

In estimating costs for the various missions, two baselines were set up: one for the mission vehicle and the other for the total program. These baselines were initiated using Douglas MORL and Boeing MOL cost information data as guides, realizing that the basic values would change as the study effort progressed. As the system configurations were developed and more cost information became available, these cost figures were updated using detailed information from several data resources. By ground rule, and because primary interest centered in the mission vehicle hardware, emphasis of the costing effort was placed on the mission vehicle. However, software, launch site support, boosters, and other costing elements were estimated to obtain total program costs. The basic aspect of the costing effort was to develop relative cost numbers for each subsystem so that their total for the mission vehicle would equal 1.000. In addition to deriving relative cost numbers on the specific configurations, total system program cost tables were developed for each program to show predicted costing trends between programs and for major program elements.

8.1.2 DERIVATION OF RELATIVE COSTS

Relative costs are merely decimal proportions of an overall cost unit. In this case, the mission vehicle was selected as the most meaningful unit article in the study to be evaluated, and relative costs were broken down into various elements in such a manner that their summation would be 1.000 for the total mission vehicle. Relative cost numbers were derived from a combination of parameters and detail estimating techniques, using direct application of experience, extrapolation of historical data, detailed estimates of comparable systems, and

other sources of similar information. These values are expressed as a relationship to dollars or manhours against weight, size, time, etc., to form a coordinate system within which the relationship is expressed as a median line, or a set of limits. This approach was used in estimating the total systems cost as well as a check point for verifying the total mission vehicle cost.

Parametric information was developed by cross-plotting subsystem characteristics. These cross-plots included cost versus weight and cost versus mandays in orbit, among others. In this manner, trends could be detected that would provide a range of values applicable to the studies. Estimates then were made for what could be called a "basic" mission vehicle, using charts of the parametric historical data so far evolved. The "basic" mission vehicle is that which is single-thread without redundancies or spares, but otherwise is operationally complete. Using the optimized data developed by MARCEP for the Degree "2" maintenance concept, the complete mission vehicle was estimated, and relative cost numbers were developed for each subsystem such that they totaled to 1.000. Having established relative cost numbers for the subsystems, each subsystem then was further broken down to determine relative cost values at the component level. Since relative costs were carried out to the third decimal place, items that contributed substantially less than 1/1000 of the total mission vehicle costs were listed as negligible in the cost tabulations, although their dollar costs in some cases were included in the overall dollar figures.

By equating the factor of 1.000 for the mission vehicle to the cost shown for that vehicle in the program cost table, current dollar estimates of subsidiary elements expressed in terms of relative cost numbers can be determined.

8.1.3 COST COMPOSITION

Elements of cost for a total manned space program as defined for this study include the mission vehicle, the reentry vehicle, a logistics module(s) for the orbital missions, tankers for the planetary missions, launch vehicles as required to initiate the operational mission, and initial operations costs. For the orbital missions, a 5-year resupply capability was postulated, with costs being apportioned against the reentry vehicle, the logistics module, launch vehicles at the stated normal intervals, and operations. Resupply for a normal 1975 near-Earth orbital mission was considered to be on a 90-day basis, while resupply for the 1985 L_1 Libration Center mission was considered to be on a 180-day basis. Since the study was not intended to develop a complete mission analysis, no attempt was made to include certain cost categories. These were capital investments such as new tracking stations; development costs of launch vehicles, propulsion modules, and tankers; all costs associated with the experiments, that were not defined in detail for this study; assembly and docking units used for mating purposes, that were not a part of the basic mission vehicle; fuels, including nuclear sources, and gases; the planetary lander (MEM); the initial recovery task force; and personnel and staffing costs, including the flight crew, except for instructor training time allocated to the mission vehicle.

Mission vehicle costs include the total costs to develop the hardware, one operational set of hardware, and all launch site support operations, before integration with the launch vehicle. These in turn are broken down in terms of

a flight configuration mission module. Also included are aerospace ground equipment for direct support of the flight configuration; a small amount of test demonstration activities; software, such as computer programming and training; and launch site support for prelaunch activities.

Table 7 summarizes total systems costs in millions of dollars for all four missions considered during the study. Because the Degree "2" maintenance concept was the clear choice in the majority of cases during analysis of subsystem requirements, cost estimate emphasis was placed on configuration hardware and functions incorporating that concept in the missions. The costs shown in the table reflect this approach. Each of the orbital missions is further subdivided into totals for initial implementation of the mission, plus totals for 5 years of orbital operation at given basic resupply intervals. It should be noted that the relationship between the missions is shown here in terms of dollars, but relative cost factors of 1.000 apply only to the mission vehicle for each specific mission.

8.2 1975 MARS/VENUS FLYBY MISSION

In analyzing the configuration for this mission, a relative cost number of 1.000 was established for the total flight configuration (mission vehicle) in the Degree "2" maintenance concept mode. This relates to the mission vehicle dollar cost estimated to be approximately 3.2 billion dollars, within a total program cost estimate of 8.5 billion dollars. The total program cost includes major entries of mission vehicle, reentry vehicle, tankers and launch vehicles. For the Degree "0" concept, the total relative cost number was determined to be 1.149 for the flight configuration, or an increase of 14.9%. Table 2 in Section 4.2 shows the relative cost factors for both degrees of maintenance, broken down by subsystem, support hardware, support software, test demonstration and launch site support; these are further segregated across the table by categories of development, hardware, and operation. Each 0.1 of a percentage point is equivalent to 3.2 million dollars, since the entire tabulation is related to the mission vehicle of the Degree "2" maintenance concept.

Table 7: TOTAL SYSTEMS COSTS (MILLIONS)

	Earth Orbital Missions				Planetary Missions	
	1975-90D Resupply		1985-180D Resupply			
	Initial	Resupply	Initial	Resupply	1975 Mars Flyby	1985 Mars Landing
Mission Vehicle	2,752	20	2,759	16	3,198	3,438
Reentry Vehicle	1,762	905	1,762	472	2,145	2,047
Logistics Module	304	153	319	86	----	----
Launch Vehicles	454	620	454	310	1,374	1,796
Operations	827	1,191	829	1,125	1,578	2,013
Tankers	----	----	----	----	218	145
Propulsion Modules	----	----	----	----	----	142
Totals	6,099	2,889	6,123	2,009	8,513	9,581

9.0 AREAS REQUIRING ADDITIONAL STUDY OR TECHNICAL RESEARCH

As a part of the analysis conducted in this study it was necessary to channel the effort into certain areas to stay within budgetary time and cost constraints. Consequently, several areas of interest were uncovered that could not be adequately covered in this study. Those areas requiring additional study or technical research have been summarized from Volume II and are categorized into four major headings: hardware design, methodology development, space data and environment, and maintenance procedures and techniques.

9.1 HARDWARE DESIGN

9.1.1 LIFE SUPPORT SYSTEM PACKAGING CONFIGURATIONS

The life support system imposes the greatest unscheduled and scheduled maintenance workload on the spacecraft crew. Optimum design, packaging, and layout of this system within the spacecraft are necessary to reduce this workload. A major effort is required in additional study and research to achieve this reduction.

9.1.2 COMMONALITY OF SPACECRAFT COMPONENTS

Maximum commonality of spacecraft components, within and between subsystems, was an effective means of reducing on-board spares requirements and maintenance workload. Additional study is required to make a detailed investigation of the components used in a space mission and to determine what components can be designed realistically for common use.

9.1.3 COMMONALITY OF EXPERIMENT COMPONENTS

Equipment used for experiments should be considered not only for intra-experiment commonality, but also for commonality with components in other subsystems of the mission vehicle. This would provide an additional source of spares, allow more effective use of the spares provisioned on board, permit a reduction in total spares requirements, and, under certain circumstances, strengthen justification for an onboard workshop to support the performance of Degree "3" (repair) maintenance.

9.1.4 MODULARIZATION

Modularization of relatively high failure rate equipment was an effective way to reduce spares weight requirements. Additional research is required to identify the most effective technique of modularizing different types of equipment to obtain the maximum benefits to the spares concept.

9.1.5 EXTERNAL LSS PLUG-IN RECEPTACLES

The feasibility of providing external plug-in receptacles that could be used to operate spacesuits from the spacecraft life support system instead of

the backpack should be investigated. This could extend the length of time an astronaut could be extravehicular, and save weight of expendables that are otherwise lost during backpack operation.

9.1.6 STRUCTURE LEAK DETECTION AND REPAIR

Structural repair was assumed for both mission time periods, but it is not clear what methods, techniques, and tools will be required to accomplish it. It is recommended that the general field of structural repair be reviewed and the most promising methods of repair be investigated in detail.

9.1.7 FILAMENT WOUND TANKS

The use of filament wound storage tanks for fluid was assumed for the 1985 mission at a considerable saving in weight. This technology should be researched further so the benefits can be used as soon as possible.

9.1.8 TANK REPAIR

The failure modes of various types and sizes of tanks should be identified and the possibility of repair assessed considering the failure mode, type of material, pressure, and tank contents.

9.1.9 EMERGENCY ELECTRICAL POWER SOURCE

The use of an isotope fuel may make possible the generation of emergency electrical power by incorporating thermocouples in the fuel block or in the block shield. The power generated would be low level, but adequate to provide minimum lighting and control power until the main power system is restored to operation.

9.1.10 RADIATION SHIELDING FROM EXPENDABLES

Considerable radiation shielding weight could be saved by judicious placement of spares, food, other expendables, and waste products. A study should be made to determine practical methods of storing these items to obtain maximum shielding benefits while permitting access for eacy removal and/or storage.

9.1.11 REFURBISHMENT OF REENTRY VEHICLES

A long-duration mission with periodic resupply requires the use of several reentry vehicles. The total cost of the mission could be reduced substantially if the command module were designed for refurbishment and subsequent reuse.

9.2 METHODOLOGY DEVELOPMENT

The area of space mission analysis and optimization has many deficient areas that could be improved with additional research and study. Refined mission planning requires determination of definitive and valid optimization criteria, development of a better data base to enable accurate total mission planning, construction of more versatile mission risk and probability models, and

availability of better optimization techniques. The MARCEP technique used in this study is one of the most advanced optimization models available, but it has several soft areas where improvements would extend the model's usefulness.

9.3 SPACE DATA AND ENVIRONMENT

9.3.1 EFFECTS OF SPACE ENVIRONMENT ON EQUIPMENT

The long-term effects of space environment factors on the life and operation of spacecraft equipment need to be defined. Self life of spares stored in this environment should also be investigated; the need for rotation or recycling during resupply due to radiation dosage may be a factor.

9.3.2 HUMAN PERFORMANCE IN SPACE ENVIRONMENT

There is a need for further quantification of human performance in the space environment. Until this is done, all design criteria and mission planning will be based on limited data that is insufficient to safely perform the mission goals.

9.3.3 SPACECRAFT LEAKAGE RATES

The spacecraft leakage rate assumed in this study was 2.0 pounds per day. Boeing studies indicate this is overly optimistic and 5.0 pounds per day would be more realistic. Additional research is required in this area to establish and validate a realistic leakage rate for various spacecraft structure configurations.

9.4 MAINTENANCE PROCEDURES AND TECHNIQUES

9.4.1 ANTICIPATORY MALFUNCTION DETECTION

The use of anticipatory malfunction detection, such as electrical noise, thermal, and sonic, monitoring should be evaluated as a means of delaying scheduled maintenance until a wearout failure is imminent, and to anticipate random failures so that repair tasks may be scheduled into the daily workload.

9.4.2 BUILT-IN TEST EQUIPMENT

Built-in test equipment (BITE) provides a means of sensing faults and indicating the condition of the equipment being monitored. Trade studies should be conducted to evaluate the use of the BITE concept as opposed to the use of external test equipment, which implies the need for crew skills and training in operation of the latter.

9.4.3 MAINTENANCE TECHNIQUES AND SPARES CONCEPTS FOR LARGE ASSEMBLIES

Large assemblies such as radiators, tanks, powered locomotion devices, etc., were assumed to be repaired by special maintenance or repair kits, using average weights and volumes for lack of more definitive information. Additional study is required to determine the best techniques for handling these maintenance requirements.

9.4.4 HANDLING LARGE EQUIPMENT

Handling large items of equipment that require two men and coordination of their actions could present problems in a zero-g environment and should be researched.

9.4.5 REPAIR OF LARGE EQUIPMENT

Investigation is needed in repair of space radiators, large tanks, antennas, solar cells, and similar large items where use of a total remove-and-replace concept is not practical. The use of equipment such as electron-beam welders, fusion joining processes, and other possible techniques should be evaluated.

9.4.6 SPACECRAFT HAZARDS TO EXTRAVEHICULAR MOVEMENT

Solar arrays, antennas, external experiments, and experiment booms may present a hazard to EVA and rendezvous and docking maneuvers. The magnitude of these hazards should be assessed and procedures and equipment should be developed to minimize the hazards.

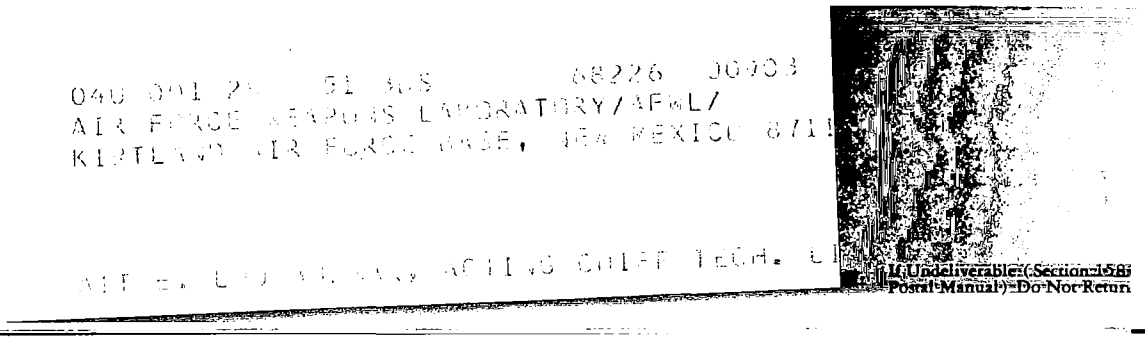
9.4.7 HANDLING FLUIDS IN ZERO-G ENVIRONMENT

Procedures and techniques need to be established and evaluated under actual space flight conditions for handling fluids in a zero-g environment during servicing and maintenance activities.

9.4.8 DEGREE "3" (REMOVE AND REPAIR) MAINTENANCE

This concept should be studied in more detail to determine specifically when it may be economical and what workshop facilities and crew skills are required. For some of the subsystems it might be possible to justify a limited bench-level repair capability, but this needs to be studied more thoroughly.

NASA-Langley, 1968 —— 31 CR-1108



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