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**Payload Design Requirements Analysis  
(Study 2.2) Final Report  
Volume I  
Executive Summary**

**Prepared by ADVANCED VEHICLE SYSTEMS DIRECTORATE  
Systems Planning Division**

**5 October 1973**

**Prepared for OFFICE OF MANNED SPACE FLIGHT  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
Washington, D. C.**

**Contract No. NASW-2472**



**Systems Engineering Operations  
THE AEROSPACE CORPORATION**

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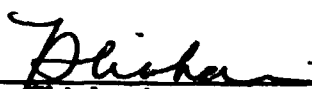


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**PAYLOAD DESIGN REQUIREMENTS ANALYSIS  
(STUDY 2.2) FINAL REPORT  
Volume I: Executive Summary**

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## FOREWORD

This report documents The Aerospace Corporation effort on Study 2.2, Payload Design Requirements Analysis, performed under NASA Contract No. NASW-2472 during Fiscal Year 1973. The Aerospace study was monitored by Dr. R. W. Johnson, NASA Headquarters; J. O. Ballance, Marshall Space Flight Center; and R. A. Berglund, Johnson Space Center, and their efforts as a team in providing technical direction throughout the duration of the study are greatly appreciated.

This volume is one of three volumes representing the final report of Study 2.2. The three volumes are:

Volume I	Executive Summary
Volume II	Payload Design Guidelines
Volume III	Guideline Analyses

Volume I summarizes the overall report in brief form and includes the relationship of this study to other NASA efforts, significant results, study limitations, suggested research, and recommended additional effort.

Volume II provides the design guidelines in concise format with sufficient information to permit tradeoff results. It also includes the application of the guidelines to an example satellite as a demonstration of their usefulness.

In Volume III, all of the analyses that were performed are documented to provide traceability. These analyses include analytical technique, design analyses of the Large Space Telescope and the Shuttle-Launched Defense Support Program (SLDSP) payloads, common hardware, and Sortie payload operations. (Figures showing conceptual design of the SLDSP were intentionally left out of Volume III for security reasons, but they are available from the Study Director upon establishment of need to know.) The subsystem analyses are presented in the appendixes of Volume III.

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## 1. INTRODUCTION

This study was conducted to provide data on ways to effectively realize the projected cost reductions for payloads to be developed and operated in the Shuttle era. Prior studies have indicated that the Shuttle concept of satellite operations will lead to a large reduction in overall payload cost. This study provides the data and insight into the methods of accomplishing these economic benefits.

The study examines only payloads that will be launched on the Shuttle/Tug/Sortie Lab combinations. These payloads are of four types:

- Expendable
- Ground Refurbishable
- On-Orbit Maintainable
- Sortie

The expendable payloads addressed in this study are intended specifically for the Shuttle/Tug and not for expendable launch vehicles. Economic comparisons were made only between these four types of Shuttle payloads and not between these payloads and current expendable launch vehicle payloads.

The FY 1972 study that preceded this study identified a series of design guidelines that were documented in Reference 1. This study attempted to quantify several of these guidelines that were identified as being cost effective. In addition to quantifying the selected guidelines from the 1972 study, additional system guidelines were developed in this study by analyzing parametrically two satellites and demonstrating the results on the Earth Observatory Satellite (EOS) as an example satellite. The study did not include any point designs. Besides analyzing the selected guidelines, the study emphasized economic tradeoff data and identified payload parameters influencing the low cost approaches. The economic analysis reported in these volumes should be viewed as providing trend data rather than absolute cost data.





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## **2. OBJECTIVE**

The objective of the study was to conduct analyses, tradeoff studies, and design efforts to provide detailed payload design guidelines for the four types of Shuttle payloads. These guidelines provide data to assist the user in developing the initial system specifications/design requirements document reflecting the lowest cost alternatives for carrying out the mission objectives.



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### 3. RELATIONSHIP TO OTHER NASA EFFORTS

This study coordinated its activities with other Aerospace/NASA studies wherever data and analysis could be shared. At the early phases of the study, it was planned to replace the SAMSO/Aerospace payload cost model with the cost equations to be developed in Study 2.3, "System Cost/Performance Analyses." This did not materialize because all of the subsystem cost equations were not available.

The development of the interim satellite subsystem weight estimating equations for the Spacecraft Synthesis Program was jointly shared with Study 2.4, "Space Shuttle/Payload Interface Analysis." The equations were developed by the process of correlation analysis utilizing NASA and DOD satellites for which weight data and design parameters were available. These equations provided the payload characteristics required for the SAMSO/Aerospace payload cost model.

The Earth Observatory Satellite (EOS) data for the example satellite task were obtained from Reference 2 and NASA Study 2.6, "Operations Analysis." The types of data obtained were reliability model and parts failure rate estimates of the baseline configuration and a conceptual design of a space-serviceable Earth Observatory Satellite.



#### 4. APPROACH

The study was divided into system and subsystem analyses with special emphasis on common hardware and Sortie payload operations. These analyses were performed to develop design guidelines which will result in low cost payloads. The results of the analyses were then applied to an example satellite (EOS) as a test to demonstrate the usefulness of the design guidelines.

To perform the system analyses, an analytical technique was developed to assess Shuttle payload types that operate in expendable, ground-refurbishable, on-orbit maintainable, and Sortie modes. The technique evaluated in terms of cost the effect of reliability, redundancy, program duration, repair cost, trip charge, and repair strategy on the Shuttle payload types. These parameters were quantified by analyzing a low-altitude and a high-altitude satellite, which were selected to be representative so that the results would provide realistic cost trend data.

The analytical technique consisted of a series of computer programs to systematically process the quantity of data necessary to compute the various cost estimates. These programs were: the reliability model which defined the redundancy level for various design lives based on the description of the mission equipment and spacecraft subsystem; the spacecraft synthesis program which computed the payload attributes that are necessary for payload cost estimates; the module simulation program which computed the expected number of launches; and the payload cost program which computed the total program cost.

The subsystem analyses were performed on those design guidelines that were selected from the FY 1972 study (Ref. 1). Those selected for analysis were considered to be effective payload cost reduction approaches and amenable to analysis. Because of funding constraints, it was not possible to analyze all of the potential cost reduction approaches that have

been identified. As an example, common hardware analysis was limited to the stabilization and control subsystem, and it was assumed that the results would be typical of other subsystems such as communication, data processing, instrumentation, electrical power, and reaction control.

The common hardware task analyzed the potential Shuttle payloads to group the missions having similar stabilization requirements and to define the common attitude control subsystem capable of meeting the needs of the missions within each group. The potential payloads were based on the 1972 NASA Mission Model and descriptions provided in the NASA Payload Data Book (Volume II of Reference 1). The components and assemblies for the common hardware listing were selected from off-the-shelf and flight-proven units that are currently available at the manufacturer.

In order to evaluate the Sortie operation, a "standard mission" definition was required. The Atmospheric and Solar Science disciplines were analyzed to determine if they could be flown as a joint Sortie to establish this "standard mission". However, a study indicated that they were not compatible and, as a result, the "standard mission" was defined for the operations analysis by expanding the Atmospheric Science mission capability.

## 5. BASIC DATA GENERATION AND SIGNIFICANT RESULTS

### A. GENERAL

Design guidelines were developed at the system and subsystem levels based on the analysis of a low-altitude Large Space Telescope (LS1) and a high-altitude Shuttle-Launched Defense Support Program (SLDSP) satellite. The system guidelines address the overall payload design. The subsystem guidelines that are presented have been analyzed independently and must be iterated at system level for applicability to a specific design. In general, the guidelines included in this report should stimulate future cost reduction approaches when applied to specific design and should be recognized as a start towards the Shuttle payload design guidelines.

The major Shuttle characteristics that initiated most of the guidelines were the payload retrieval capability, reduced weight and volume constraints on the payload design, and low transportation cost. In the retrieval operation, the Orbiter and Tug were assumed to be the active part, and the payload was assumed to be passive but cooperative and stable during the retrieval and terminal docking operation. In the transportation cost area, the Orbiter trip charge was varied by sharing the trip. For the Orbiter/Tug combination, the charge was varied according to the performance capability for deployment, retrieval, and round-trip flights.

### B. SYSTEM GUIDELINES

The type of data that was generated in the system guidelines was the cost trend data for the various payload parameters. These parameters were the type of payload, reliability, modularity, repair strategy, trip charge, repair cost, and program duration. The payload types are the expendable, ground refurbishable, on-orbit maintainable, and Sortie. All of these parameters were systematically varied in the analysis to determine their sensitivity to producing low cost payload concepts.



The payload reliability was measured by the mean mission duration (MMD). The payload MMD is established by the components and assembly redundancy level, which is used to derive the payload characteristics to compute payload cost and the expected launch rate to compute the launch cost. The cost data for the LST and SLDSP are shown in Figures 5-1 and 5-2 for a one satellite on-orbit system and not a multi satellite system. The expendable payload shows a cost reduction with increasing MMD for both the low-altitude, high-weight LST and the high-altitude, low-weight SLDSP. The on-orbit maintainable payload shows a slight cost dip indicating that its optimum MMD occurs at a lower MMD than the expendable payload. The lowest total program cost payload is the on-orbit maintainable. The ground-refurbishable payload cost lies between the expendable and on-orbit maintainable costs.

For a short duration program, the expendable payload is more cost-effective because payloads on the average will not experience a failure during the short missions and the lowest unit cost payload should produce the lowest program cost. This characteristic is shown in Figure 5-3 where the crossover is at about three years program duration. The on-orbit maintainable payload shows cost advantages over the expendable as the duration is extended.

The trip charge was found to have small influence on program cost. The LST program cost is reduced by only 9 percent for a 10-year duration if the trip charge is reduced from \$10 million to \$2 million by sharing the flight. The repair cost factor also had similar characteristics in that the on-orbit maintainable payload showed the lowest cost when the repair cost was varied from 20 to 30 percent of space-replaceable module cost. When the ground-refurbishable payload cost was varied from 30 to 50 percent of unit payload cost, the cost fell between the expendable payload and the on-orbit maintainable payload costs. Over the range of repair costs used, the retrieval and repair operation is a highly cost-effective mode.

For the repair strategy, the number of modules to be replaced per visit and the method of selecting the modules were found to affect the total program cost. When the number of modules replaced per visit for the

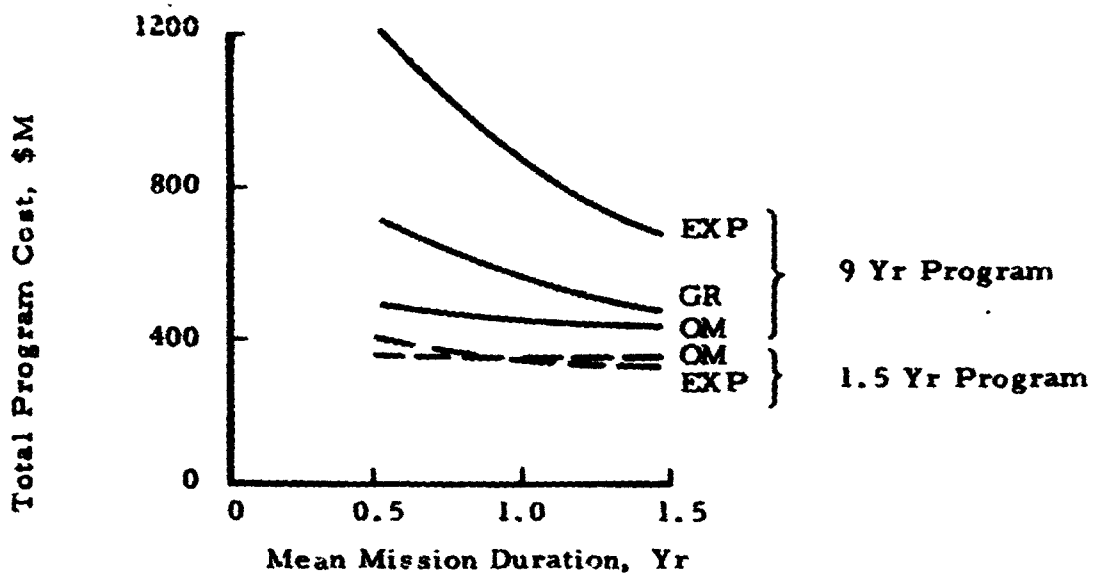


Figure 5-1. Effect of Mean Mission Duration on LST Program Cost

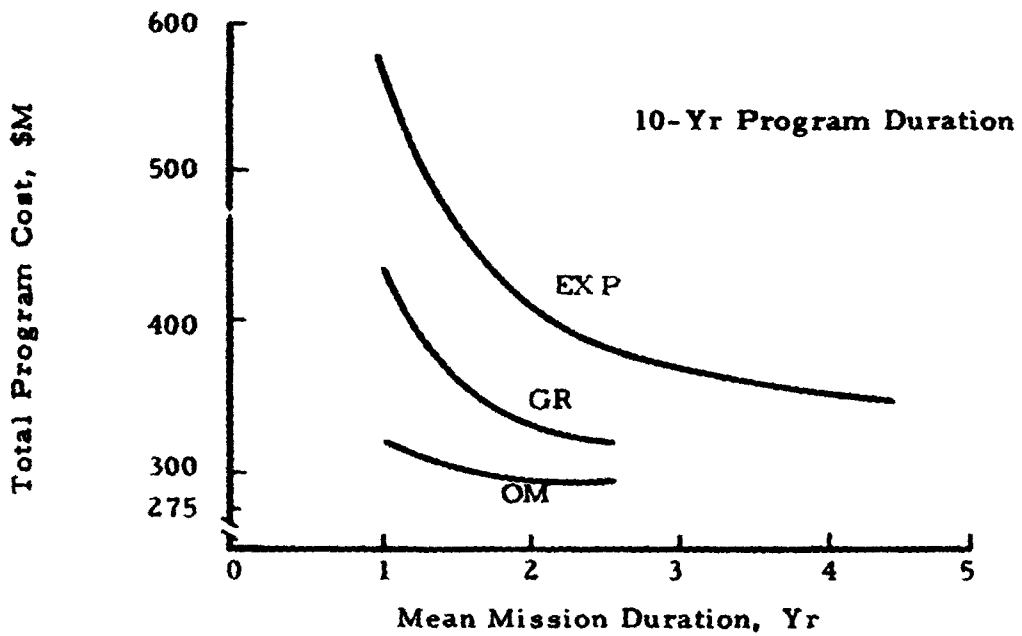


Figure 5-2. Effect of Mean Mission Duration on SLDSP Program Cost

MMD = 1.5 Yr  
Nominal Repair Cost  
Trip Charge = \$3.5M

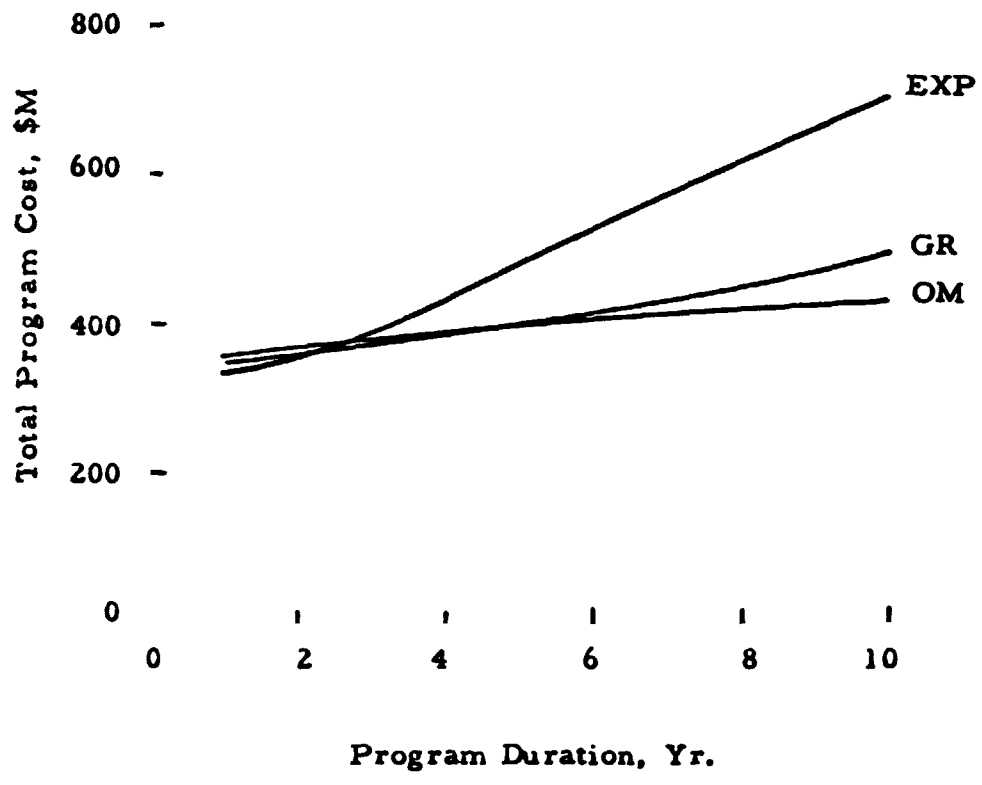


Figure 5-3. Effect of Program Duration on Total Program Cost for LST

LST and SLDSP was varied from one to all of the space-replaceable modules, the program cost was reduced substantially by replacing more than just the failed modules and reached an optimum when about 30 percent of the total space-replaceable modules were replaced per visit. This characteristic is shown in Figures 5-4 and 5-5. The effect of module replacement per visit for LST was a smooth transition. The plot of the SLDSP module replacement rate was not a continuous function because of the Tug performance limitation. The Tug performance must include a service unit to house the modules and to remotely service payloads. For the SLDSP servicing operation, the trip charge was shared between two payloads until the Tug performance limit was reached at which time the trip charge was not shared. This transition can be observed at six and more module replacements for the SLDSP.

The number of space-replaceable modules in the payload does not appear to influence the payload cost significantly if there are sufficient modules to benefit from the optimum replacement rate of 30 percent per visit. This was observed by estimating the cost of the SLDSP with 2, 8, and 13 modules with each configuration designed for a 1-, 2-, and 4.5-year MMD. These costs are shown in Figure 5-6. The 4.5-year design does not show any trend because expected maintenance can be serviced by the spare payload in the inventory. The one- and two-year MMDs show a high program cost for the two-module configuration because a maintenance flight will service either 50 percent or 100 percent of the payload. The two-module configuration does not benefit from the 30 percent optimum replacement rate.

Along with the analytical derivation of cost trends, conceptual designs were conducted to determine ways of performing on-orbit service with the Orbiter and Tug by remote teleoperators. For the Orbiter, the payload was docked to the docking module in the cargo bay and the remote manipulator system was used to replace the space-replaceable module. For the Tug, a service unit is adapted to the Tug to dock with the payload. This unit remotely indexes to accept a failed module and reindexes to replace the module. These conceptual designs provided data to synthesize on-orbit maintainable and ground-refurbishable payloads for the analytical technique.

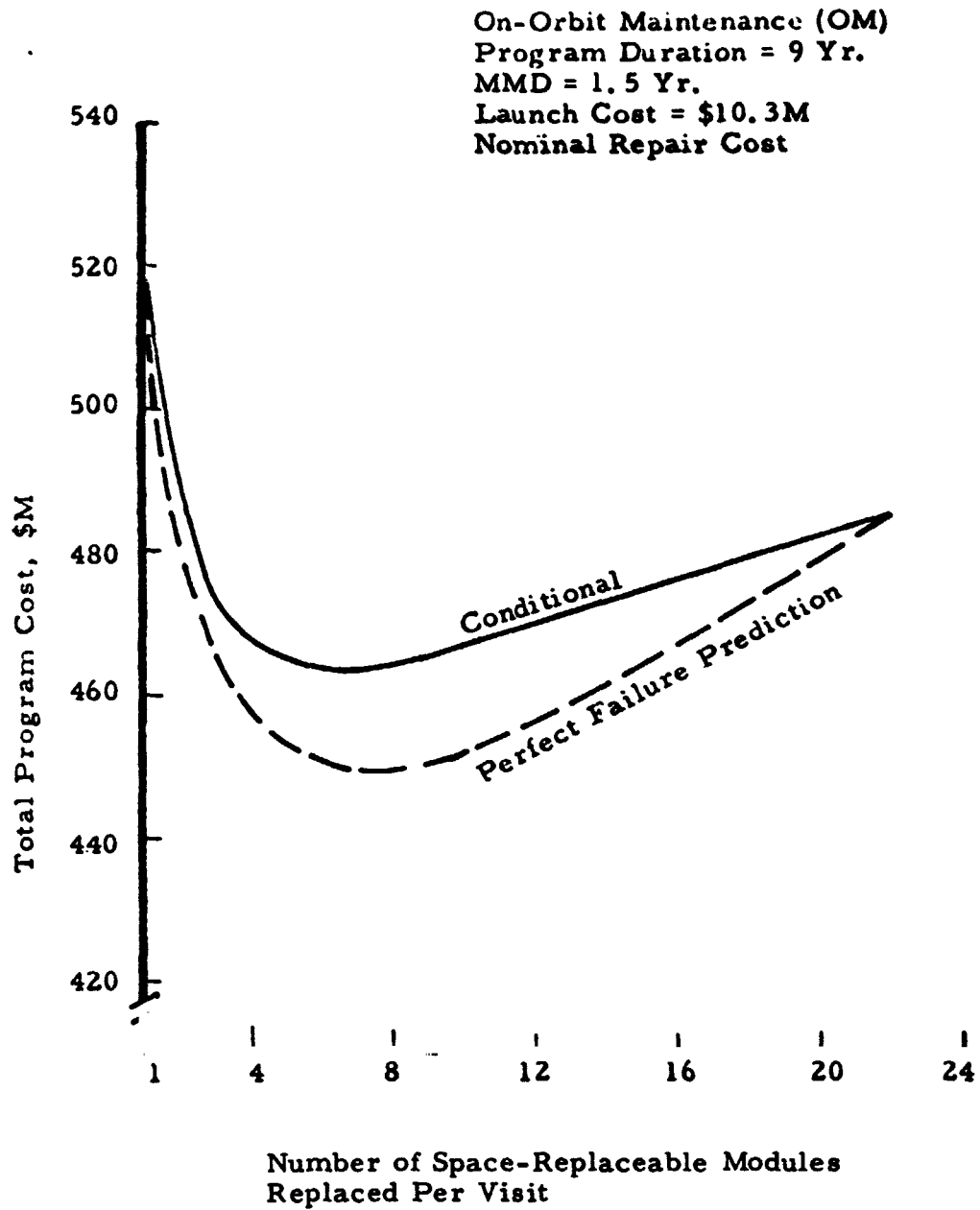


Figure 5-4. Optimum Number of Modules Replaced for LST with 22 Space-Replaceable Modules

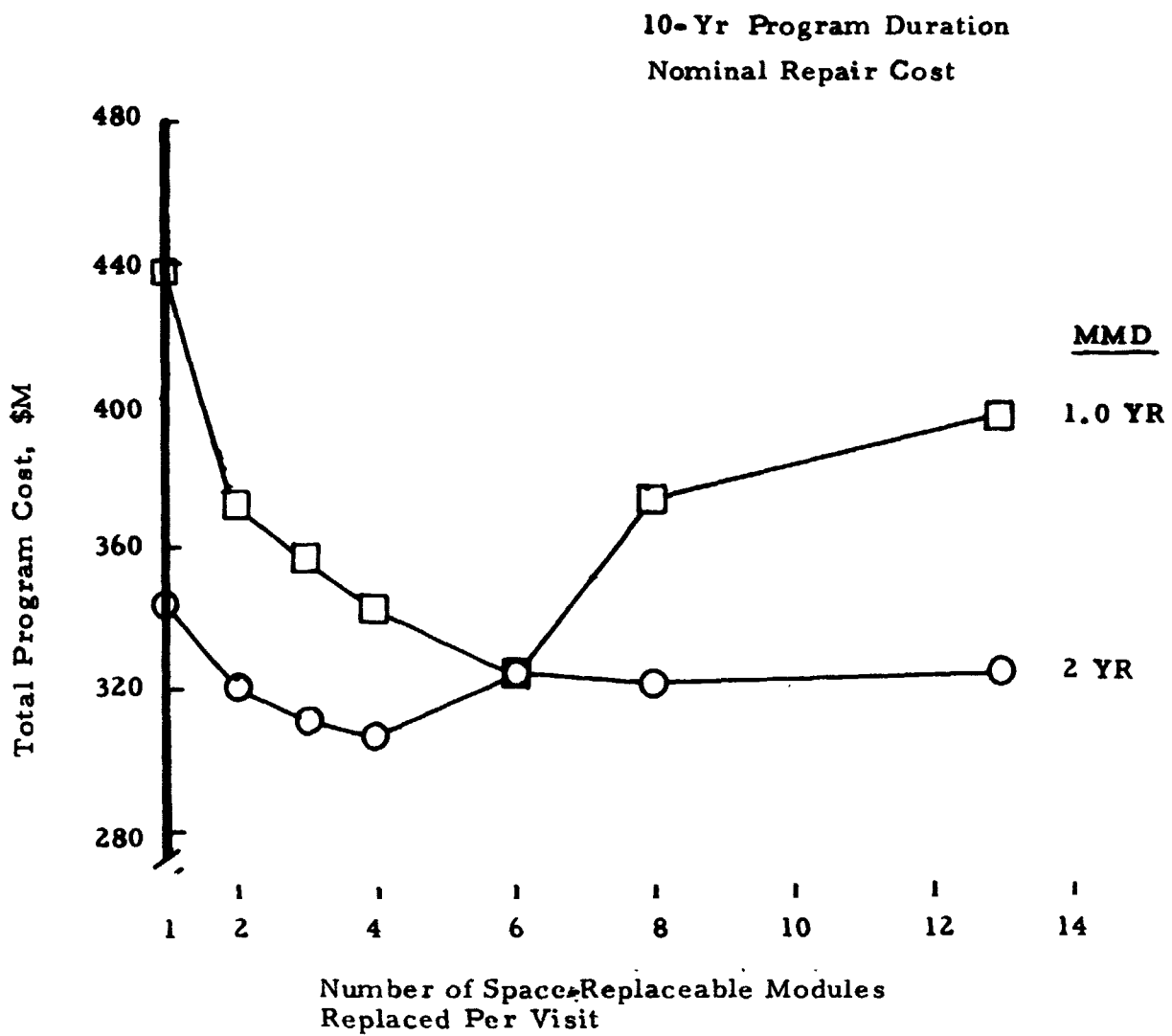


Figure 5-5. Effect of Modules Replaced on Total Program Cost for SLDSP With 13 Space-Replaceable Modules

10-Yr Program Duration  
Nominal Repair Cost

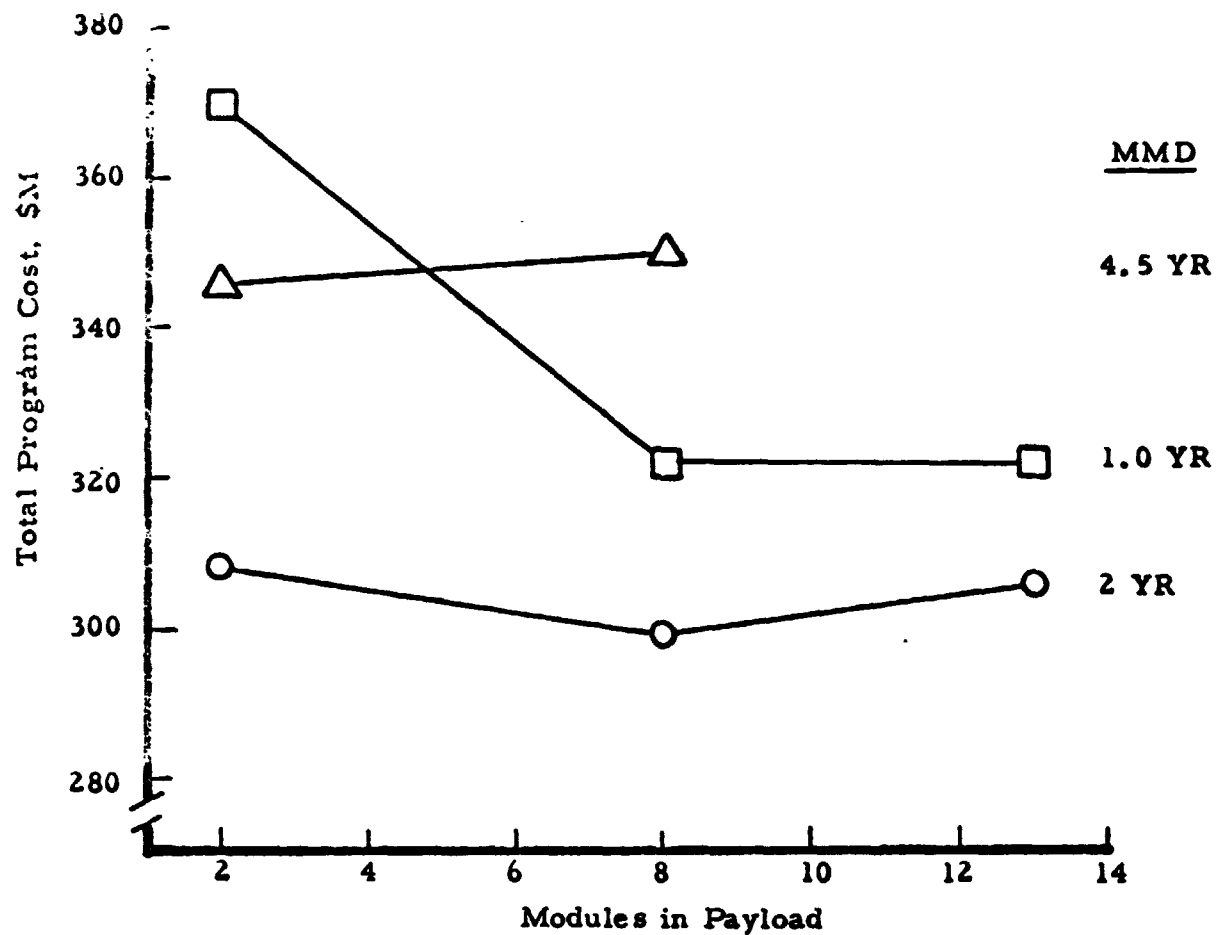


Figure 5-6. Effect of Number of Modules in SLDSP on Total Program Cost

Considering all of the system variables analyzed, the type of payload appeared to have the largest identifiable cost impact while the program duration appeared to establish the type of payload resulting in the lowest cost payload concept. The other system guidelines such as reliability, modularity, common hardware, ground operation time, and launch site testing are areas in which approaches are provided for potential savings, but they were not quantified in the study. Of these, the common hardware concept is the most promising.

The policy of commonality and standardization should be employed in all housekeeping subsystems of the expendable, ground-refurbishable, and on-orbit maintainable payloads. This approach should reduce cost and development time and still maintain reliability. This method of using common hardware that will lead to standardized modules should be employed wherever feasible.

The common hardware study indicated that the current "off-the-shelf" and "flight-proven" assemblies in the stabilization and control subsystem can accommodate 85 percent of the satellites of the NASA missions. This capability could be provided for 85 percent of the missions with the use of only 12 stabilization and control assemblies which could be further combined into 8 subsystem configurations. The balance of 15 percent will require special component development because of the unique mission requirements. Commonality of hardware will facilitate checkout and maintenance during fabrication, acceptance, and operational phases. The applicability of this concept to Sortie payloads is limited since Sortie payloads consist of mission equipment; i. e., Sortie Lab provides the housekeeping function. Mission equipments are generally developed to perform specialized functions and do not lend themselves to standardization.

## C. SUBSYSTEM GUIDELINES

### 1. STRUCTURES

The factor of safety and structural design criteria for the structures subsystem have been developed for each of the four Shuttle payload types



considered: expendable, on-orbit maintainable, ground refurbishable, and Sortie. The safety factors are presented for each type of test option and for a range of subjectively defined classes of structural complexity. The three approaches to test options are: qualification, acceptance, and no test. Stress analysis is required for all of the development approaches including the no-test option. Since the structural integrity is based only on analysis for the no-test option, the factor of safety is varied in accordance with the structural complexity. While these factors are to an extent arbitrary, they are suitable as initial values for structural design and trade studies.

## 2. PRESSURE VESSELS

Current pressure vessels for space application are principally designed for single use. Design factors of safety for reusable vessels cannot be based on past experience, since no previous space vehicle system has been designed for reuse. These safety factors can be determined by linear elastic fracture mechanics principles and were computed for several representative weldable materials. The values of the proof factors and factor of safety are dependent upon the mechanical properties, fracture toughness, flaw growth rates, type of use, environmental effects, and proof test procedure. Using these principles, the factor of safety for the weldable materials studied for single use ranged from 1.20 to 1.33, which agrees with current conventional values.

## 3. THERMAL CONTROL SUBSYSTEM

The thermal control design should emphasize improving temperature control to increase payload performance and reliability over reducing thermal control subsystem cost. The concept of improving thermal control performance and reliability to provide better temperature control is applicable to expendable, ground-refurbishable, and on-orbit maintainable payloads. Cold side bias with a heater provides this capability when payload weight and volume are not constrained. The Sortie payloads can use the Sortie Lab thermal control system and the crew to provide servicing in event of malfunctions.

#### 4. REACTION CONTROL

Reaction control with low specific impulse propellants should be considered for payloads requiring attitude control propulsion because of higher reliability and lower costs in the low total impulse range. This concept is possible with the large payload weight and volume available with the Shuttle and the Shuttle revisit capability which permits replenishment or replacement of Reaction Control Subsystem (RCS) modules. For on-orbit maintainable and ground-refurbishable payloads, the safety and servicing methods should also be factored in the system analysis of the payload to select the type of RCS. Reliable fluid quick disconnects for remote servicing do not appear promising. The leak problems with fluid disconnects on the Apollo program indicate that RCS modules for on-orbit replacements should not be designed with quick disconnects.

#### 5. ELECTRICAL POWER

Standardization of the solar array can show substantial cost savings over current customized array designs. The major savings would result from large annual production orders by a single agency for all users. This approach can reduce array costs by over 50 percent. Standardization can also apply to batteries and decentralized converters/inverters. Further reductions are possible with periodic battery replacements for low earth and elliptical orbit payloads which have a large number of charge and discharge cycles. For synchronous orbit payloads, the batteries should be designed to payload design life because of the low number of discharge cycles.

#### 6. BACKUP CONTROL FOR RETRIEVAL

If any of the payload subsystems used for the docking maneuver become inoperative, retrieval cannot be accomplished for on-orbit maintainable and ground-refurbishable payloads. Functions such as the command receiver, attitude control, propulsion, and electrical power

which are necessary to accomplish docking, must have some form of backup. The backup system may take the form of partial or total redundancy in the primary system or a simplified and independent backup system used specifically for docking.

To assess the backup system, an analysis was conducted on the LST to control loss of electrical power, thruster control, and attitude control. This analysis indicated that the success of any backup system depends on automatically switching off the failure causing the uncontrolled situation. Once the failure can be switched off, the backup system will provide the necessary control for retrieval. The stability requirement for retrieval need be limited only to Orbiter/Tug docking requirement. The ability to retrieve a malfunctioning payload is mandatory if servicing is to be performed.

#### D. SIGNIFICANT RESULTS

The design guidelines that were quantified and presented in this study have been shown to be useful in producing a low-cost payload concept for the Shuttle, using the EOS as an example satellite. The guidelines appear to have utility in that the EOS yielded cost trend data similar to the LST and SLDSP satellites. This verification provides confidence; however, the result is dependent on the amount of available data on the mission equipment and spacecraft description. In the satellites studied, the available data were at the component and assembly level. This degree of granularity in describing the payload data in the conceptual design phase should provide cost trend data that are sensitive to design approaches.

The cost trend data indicated that the program duration established the type of low cost payload. For long duration programs, the on-orbit maintainable concept was the lowest cost approach. For short duration programs that are less than two to three years, the expendable payload concept was the lowest cost for a one satellite on-orbit system. The ground-refurbishable payload cost was generally between the expendable and on-orbit maintainable payload costs; the ground-refurbishable concept was never a

low cost type. For on-orbit maintainable payloads, the program cost was relatively insensitive to mean mission duration but showed an apparent low cost at lower MMD than expendable payloads for a one satellite on-orbit system.

The expendable payloads are sensitive to mean mission duration. As the mean mission duration is increased, the program cost decreases substantially; however, the minimum cost does not reach the on-orbit maintainable cost. Some programs may effectively attain long life at which time the cost may become competitive; however, in the satellite studied, the expendable satellites could not be extended effectively by redundancy, based on current data.

When the trip charge was varied from \$2 million (representing sharing of the launch cost by five missions) to \$10 million for dedicated missions, the cost ranking did not change. The on-orbit maintainable payload remained the low cost approach. It was also observed that the program cost increase with trip charge increase was relatively small. Programs that require high availability or immediate servicing can operate on a dedicated mission approach without an excessive program cost penalty over the program duration; however, this observation may not apply to the multi satellite on-orbit servicing concept.

The repair cost variation showed a trend similar to the trip charge in that the cost ranking did not change. The on-orbit maintainable payload cost is lower than the ground-refurbishable payload cost at the same repair cost factor due to the smaller percentage of modules overhauled in on-orbit servicing compared to the ground-refurbishment mode which overhauls all of the modules.

For the on-orbit maintainable payloads, an optimum number of modules to be replaced per visit was clearly noted. This optimum is about 30 percent of the total number of space-replaceable modules and includes both failed modules and selected additional modules. The obvious

method is to select the failed modules, penultimate failed modules, and expendable modules on the basis of module mean mission duration. With instrumentation and telemetry, additional data on module status can be obtained to assist in the selection procedure. Perfect failure prediction techniques provide only a relatively small economic gain over the conditional prediction approach.

## 6. STUDY LIMITATION

The spacecraft synthesis program that was developed with the interim weight estimating equations was not used extensively in the study because the payload attributes could be better defined by the system optimization program which uses the payload reliability model, parts failure rate, and parts weights to relate the design life and subsystem weights. If such reliability data were not readily available, then the spacecraft synthesis program could use the interim weight estimating relationships which are based on the correlation analysis of actual NASA and DOD payloads.

The system optimization program allocates part redundancy to improve system reliability and amount of expendables to extend system life in an optimal manner by weight or cost. This study selected weight as the optimizing parameter because of the availability of data. The reliability model and part reliability data with the weight of the part must be provided as input to this program. The input values were based on the best set of current available data on satellites. Historically, it is generally recognized that actual flight data on satellite reliability have been better than predicted. Furthermore, reliability improves with advances in manufacturing techniques and technology, which were not factored into this study. This study did not attempt to reflect these observed characteristics and therefore the mean mission duration calculations should be considered as conservative.

The Aerospace cost model used throughout the study is based on actual cost data from several expendable satellites. This data base was extended to ground-refurbishable and on-orbit maintainable satellites by careful examination of the design changes and resulting weight changes in converting from the expendable payloads. Information on detail design, development, manufacturing, and flight operations is needed on Shuttle payload concepts to provide confidence in the cost estimates. Because of the necessity to project the expendable payload data, the cost data should be reviewed as cost trend data rather than absolute values.



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## 7. SUGGESTED RESEARCH AND ADDITIONAL EFFORT

Since on-orbit maintainable payloads were found to provide economic gains with the Shuttle, research should be conducted to assist in developing space-replaceable modules. Many design advances are needed in the remotely replaceable modules to provide a simple and reliable mechanical and electrical interface with the spaceframe, service unit, and modules. In addition, the module design should be directed towards standardization to simplify the on-orbit servicing operation and permit ground refurbishment of modules economically.

In general, modularity will require fluid disconnects, electrical connectors, and thermal energy transfer across modules that can be engaged remotely. Currently there is no reliable, leakproof fluid quick disconnect for gases and liquids that can be used even under ground installation conditions. To reduce the number of electrical cables for power and data transmission to certain modules, data buses will be required. A data bus concept which consists of modulators, a control unit, and demodulators can accommodate the transfer of signals, commands, and data between modules through a single coaxial cable. The technology for this approach exists, but development is needed to study the various levels of data transfer capability and to tradeoff single cable versus multi cables to reduce data bus complexity. The range of data rate transfer is 1 kbps to 100 mpbs.

It is not obvious at what level standardization would be an optimum. Standardization at the module level will assist on-orbit maintenance. However, in the process of providing good servicing features, the ability to meet mission objectives may be compromised due to inflexibility in module modifications to changes in performance requirements. The concept of standardizing at component and assembly level appeared to be feasible and desirable because it permitted flexibility in meeting mission requirements



by changes at component level. In addition, off-the-shelf and flight-proven hardware can be used to initiate this concept. Both approaches must support the concept of simplifying module assembly, checkout, repair, calibration, and refurbishment operations. It is recommended that standardization and modularization be studied from the aspect of utility, serviceability, and cost.

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