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Volume I

Executive Summary

Final Report

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Integrated Orbital Servicing Study for Low-Cost Payload Programs

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FOREWORD

This study was performed under Contract NAS8-30820 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the direction of James R. Turner, the Contracting Officer's Representative. The final report consists of two volumes:

Volume I - Executive Summary

Volume II - Technical and Cost Analysis.

CONTENTS

Figure

Table

I. INTRODUCTION

Much of the Space Transportation System (STS) planning centered around the investigation of various operating methodologies to achieve low-cost space operations. Primary emphasis focused on justifying the STS development on an economic basis. The emphasis was to show that the development investment, initial fleet costs, and supporting facilities for the STS could be effectively offset by exploiting the capabilities of the STS to satisfy mission requirements and reduce the cost of payload programs. Although many items contribute to cost effective payload programs, the maintenance and/or refurbishment question, with its many variables, embraces a majority of the design, operation, and cost questions that must still be resolved before the full potential of the STS can be achieved.

Considerable work has already been done relative to the orbital maintenance question. The large number of maintenance studies performed for NASA and DOD over the past few years formed the basis for this study. These studies generally accented specific maintenance concepts, spacecraft programs, space tug effects, or certain analytical aspects. It was necessary to place all these alternative maintenance concepts on a common basis for effective comparison. This effort included an assessment of the relative value of the previously identified concepts and an overall comparison of the expendable, ground-refurbishable, and on-orbit maintainable modes. Through this process, the most effective concepts were isolated.

The following major conclusions were reached in the study.

- The development of an on-orbit servicer maintenance system is compatible with many spacecraft programs and is recommended as the most cost effective system.
- Spacecraft can be designed to be serviceable with acceptable design, weight, volume, and cost effects.

- Use of on-orbit servicing over the 12 years covered by the 1974 SSPD and the October 1973 Payload Model results in savings gerater than
  - nine billion dollars over the expendable mode, and
  - four billion dollars over the ground refurbishable mode.
- The pivoting arm on-orbit servicer was selected and a preliminary design was prepared.
- Orbital maintenance does not have any significant impact on the space transportation system.
- Users need guarantees that servicing will be available and assurances that it will be cost effective.

The advantages of on-orbit servicing are greatest when there are many similar spacecraft in orbit, when the program time is long compared to the spacecraft lifetime, when the spacecraft availability requirement is similar for comparative modes, and when the spacecraft cost is not too low compared to the launch cost. The study outputs included a one-tenth scale mockup of the on-orbit servicer and three representative spacecraft as well as engineering test units of two forms--side- and bottom-mounting--of module interface mechanisms.

While the study used a NASA mission model representing automated spacecraft, the general conclusions are applicable to sortie missions and to DOD spacecraft. The study has been coordinated, integrated, and data exchanged with a parallel study, Integrated Orbital Servicing and Payloads Study, being conducted by the COMSAT Laboratories of the Communications Satellite Corporation (COMSAT) under the direction of Dr. Gary D. Gordon. The COMSAT study principally looked into on-orbit servicing and STS effects on communications satellite operations. These activities have been most beneficial to the conduct of this study.

II. STUDY OBJECTIVES

The broad objective of this integrated orbital servicing study (IOSS) was --

> to provide the basis for the selection of a cost effective orbital maintenance system supported by the space transportation system.

This objective required the selected mode to be cost effective in the sense of minimizing the total life-cycle spacecraft program costs, including those associated with maintenance, while retaining the spacecraft availability level implied by the payload model. The maintenance approach selected could have been a combination of modes which could be selectively applied to the payload model automated spacecraft programs.

Inclusion of the study add-ons has expanded the objective to include preliminary design of a cost effective servicer, fabrication of a one-tenth scale mockup, evaluation of the control issues pertinent to servicing in orbit, expanded technical emphasis on spacecraft interfaces to better assess the potential effects of spacecraft configuration for servicing, and the design and fabrication of engineering test units of two different space-replaceable unit interface mechanisms and an associated end effector.

The large number of maintenance studies performed for NASA and DOD the past few years form the basis of this study as shown in Table II-1. It was necessary to put the alternative maintenance concepts on a common basis for effective comparison. All cost-generating effects were to be identified so the cost comparison could be complete. The design effort was originally limited to "gap filling" as necessary to form a basis for generating costs.

Of the many approaches to providing servicing functions, module exchange was selected for maintenance concept evaluation because it satisfies the majority of the servicing operations with a single technique. This selection is consistent with the findings of the majority of the prior studies.

Table II-1 IOSS Scope

CONSIDERATIONS	ACTIVITIES
BUILD ON PRIOR STUDY RESULTS	PUT PRIOR WORK ON COMMON BASIS
INCLUDE ALL MAINTENANCE CONCEPTS	PERFORM TECHNICAL EVALUATIONS
ALL AUTOMATED SPACECRAFT IN PAYLOAD MODEL	CONDUCT STS IMPACT ANALYSIS
SHUTTLE ORBITER AND FULL CAPABILITY SPACE TUG	DETERMINE SPACECRAFT INTERFACE DESIGN REQUIREMENTS
PRIMARY SERVICING FUNCTION IS MODULE EXCHANGE	PERFORM CONSISTENT ECONOMIC ASSESSMENT
	EVALUATE PROGRAMMATIC/MANAGEMENT ASPECTS
	PREPARE SERVICER PRELIMINARY DESIGN AND MOCKUP
	IDENTIFY SERVICER CONTROL SYSTEM APPROACH
	DESIGN AND FABRICATE SRU INTERFACE MECHANISMS
	PREPARE STUDY RECOMMENDATIONS WITH SUPPORTING RATIONALE

Module exchange can provide the servicing functions of (1) repair failed equipment, (2) repair degraded equipment, (3) overcome design failures, (4) replace/replenish worn-out equipment, and (5) update equipment with new models. Equipment includes mission equipment as well as subsystem equipment. The maintenance concepts were also evaluated as to their adaptability to such other servicing functions as inspection, cleaning, and fault detection and isolation.

As the various maintenance concepts were identified, it became obvious that very little hard data existed; most concepts were just sketches of the spaceborne equipment and there were no data concerning the associated ground and operations equipment. Thus it was necessary to complete the concept definitions in many areas. Inherent in the activities of Table II-1 is identification of the criteria for the several evaluations. These criteria have been identified and evaluated and have become one of the significant study outputs.

In our examination of the many maintenance concepts, the entire automated spacecraft mission model, full life-cycle costs, the entire range of STS interfaces, and the myriad detail aspects, we found that the resultant breadth of our study permitted depth in only certain limited areas.

We have compensated for this effect by drawing particularly on two excellent concurrent studies, Operations Analysis Study by the Aerospace Corporation, and Servicing the DSCS-II with the STS by TRW Systems Group. These studies concentrated on more limited aspects and provided the depth of analysis needed so we could apply it across the breadth of this study.

The automated spacecraft of the payload model were evaluated to identify those to which maintenance might reasonably be applied. This involved 47 different spacecraft programs with 340 missions. To provide the desired depth of analysis, six spacecraft programs were selected to characterize, or represent, all the maintenance-applicable spacecraft programs. The configurations of the six spacecraft in this characteristic set are shown in Figure II-1. The figure shows each spacecraft in its operating

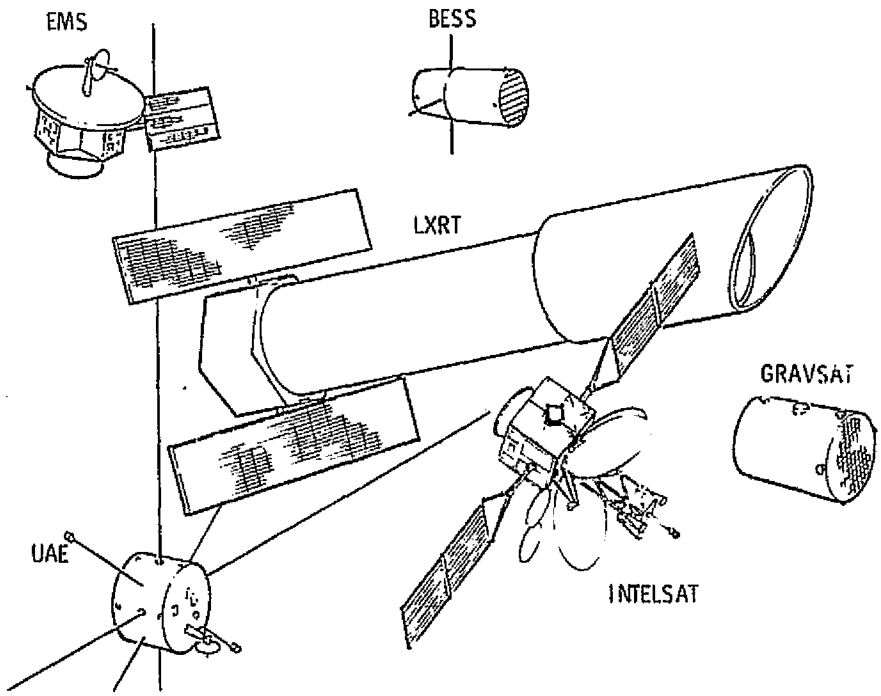


Figure II-1 Configurations of Characteristic Set

configuration to approximately the same scale for each spacecraft. The characteristic set spacecraft designations are biomedical experimental scientific satellite (BESS), environmental monitoring satellite (EMS), gravity satellite (GRAVSAT), international communications satellite

(INTELSAT), large X-ray telescope (LXRT), and upper atmosphere explorer (UAE).

The figure illustrates the variety of shapes, sizes, and configurations of spacecraft that might be involved in servicing. The configurations of the spacecraft considered for maintenance are important for the following reasons:

1) The sizes and shapes of the spacecraft as stowed in the payload bay are necessary to calculate potential launch sharings and costs;

2) The operating configuration of the spacecraft as compared to the stowed configuration in the payload bay is necessary to determine requirements for reconfiguring the operating spacecraft to fit back into the payload bay for ground refurbishment;

3) The operating configuration is necessary for investigating docking considerations and movement of external servicing devices over the spacecraft surfaces; and

4) The current configuration is necessary to help determine if, and how, a spacecraft should be configured for servicing.

Figures II-2 and -3 illustrate serviceable configurations of the large X-ray telescope and the INTELSAT being serviced by an on-orbit servicer where the orbiter and tug are the respective carrier vehicles. These figures show two applications of the pivoting arm servicer, recommended by this study, that can also be applied to an earth-orbital teleoperator system, to a geosynchronous free-flyer, to the solar electric propulsion system, and to some forms of the interim upper stage.

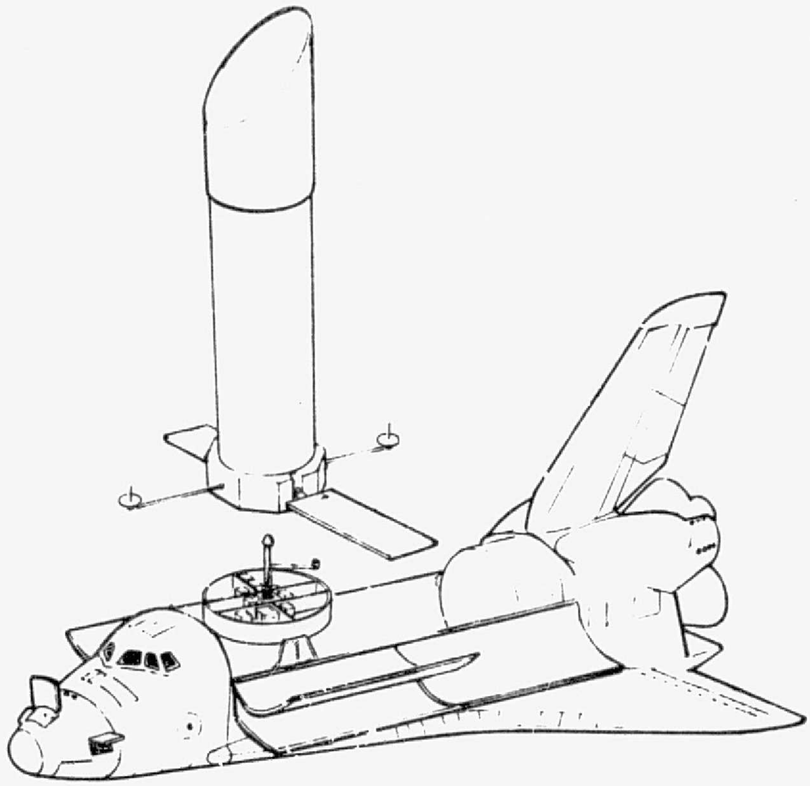


Figure II-2 Servicing the Large X-Ray Telescope at the Orbiter

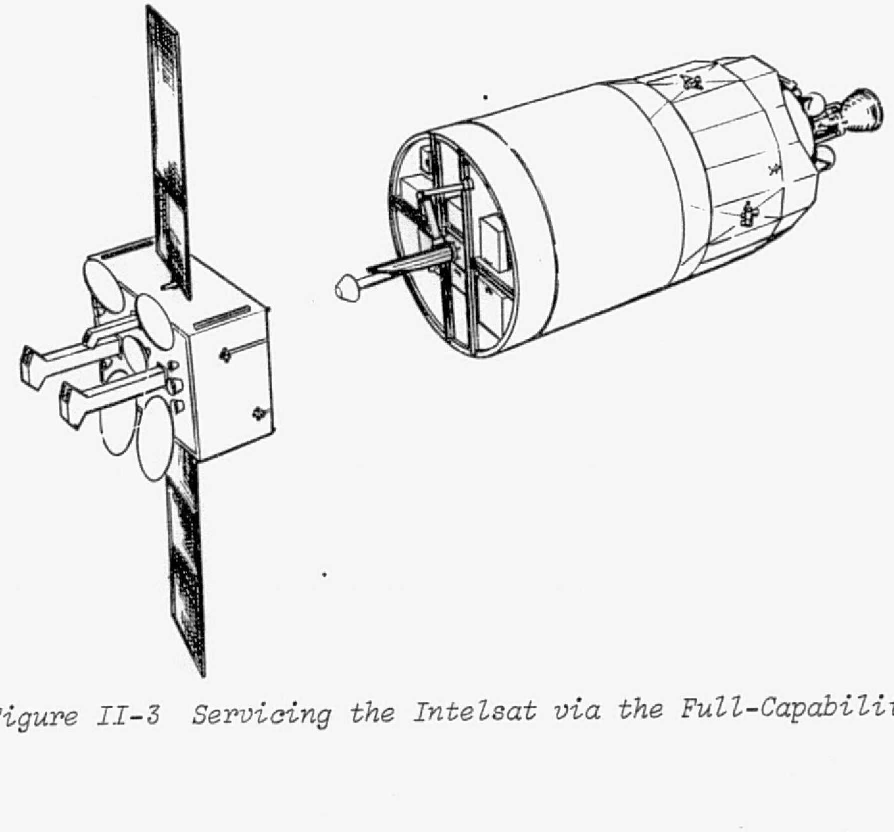


Figure II-3 Servicing the Intelsat via the Full-Capability Tug

III. RELATIONSHIP TO OTHER NASA EFFORTS

The IOSS, with its emphasis on building on prior and parallel study results, had a significant relationship to other NASA efforts. The prime relationship was with the Integrated Orbital Servicing and Payloads Study being performed by COMSAT Laboratories of the Communications Satellite Corporation. These two studies were conducted in parallel for the same MSFC Contracting Officer's Representative, James R. Turner. The studies were coordinated, integrated, and data was exchanged. Monthly coordination meetings were held and all our formal presentations were joint. The purpose of the COMSAT effort is to include a commercial user's perspective and to provide a fuller consideration of the effects of servicing on INTELSAT design and operations.

The major part of the prior work, which included over three million dollars of contracted effort, is well represented by the seven studies of Table III-1. The recommendations from these studies and the types of data contained in the study reports are shown in Table III-2. These recommendations were useful because they provided a tentative set of conclusions the IOSS could support or reject. The study agrees with most of the stated recommendations as explained in Chapter V.

Table III-1 Significant Prior Studies

PAYLOAD SUPPORTING STUDIES FOR TUG ASSESSMENT MSFC IN-HOUSE, 1973
IN-SPACE SERVICING OF A DSP SATELLITE SAMSO/TRW, MARCH 1974
UNMANNED ORBITAL PLATFORM MSFC/RI, SEPTEMBER 1973
PAYLOAD UTILIZATION OF TUG MSFC/MDAC, GE AND FAIRCHILD, MAY 1974
OPERATIONS ANALYSIS NASA/AEROSPACE, JULY 1974
SERVICING THE DSCS-II WITH THE STS SAMSO/TRW, MARCH 1975
EARTH OBSERVATORY SATELLITE SYSTEM GSFC/IN-HOUSE AND CONTRACTED, CONTINUING

Two of the studies were particularly helpful. The operations analysis study by Aerospace defined a set of standardized modules and the complement of those modules for 29 spacecraft. It also provided weight and reliability data for these modules. The data were extrapolated to our set of 47 spacecraft programs.

Table III-2 Results of the Significant Prior Studies

THEIR RECOMMENDATIONS INCLUDED:
ON-ORBIT SERVICING IS THE MOST PROMISING MAINTENANCE APPROACH (ALL);
SPACECRAFT SHOULD BE DESIGNED FOR SERVICING (ALL);
GROUND REFURBISHMENT IS NOT AS PROMISING (SIX);
HIGH RELIABILITY MAY BE MORE COST EFFECTIVE (THREE);
ON-ORBIT SERVICING SHOULD BE FURTHER INVESTIGATED (ALL).
TYPES OF DATA AVAILABLE:
SERVICER CONCEPTS (ALL);
SERVICEABLE SPACECRAFT CONCEPTS (ALL);
COST DATA (ALL);
SERVICER EVALUATION CRITERIA (SIX);
RELIABILITY ASSESSMENT (FIVE);
MODULE SIZES AND WEIGHTS (SIX).

Table III-3 Concurrent Studies

MULTI-MISSION SUPPORT EQUIPMENT MSFC/MMC, JUNE 1974, 10 MONTHS
ORBITAL ASSEMBLY AND MAINTENANCE JSC/MMC, AUGUST 1974, 12 MONTHS
STUDY TO EVALUATE THE EFFECT OF EVA ON PAYLOAD SYSTEMS AMES/RI, JULY 1974, 6 MONTHS
MULTI-MISSION SUPPORT EQUIPMENT (LAUNCH SITE) MSFC/MMC, SEPTEMBER 1974, 8 MONTHS
EARTH ORBITAL TELEOPERATOR SYSTEM (EOTS) CONCEPTS AND ANALYSIS MSFC/MMC, JANUARY 1975, 12 MONTHS

The DSCS-II study by TRW was based on existing TRW spacecraft and provided much detailed data on designs, costs, and schedule effects. These data helped us to extrapolate the NASA-provided spacecraft cost numbers from the expendable form to the ground-refurbishable and on-orbit serviceable forms of spacecraft.

The statement "high reliability may be more cost effective" can be interpreted in two ways. Two of the studies concluded that high reliability may be more cost effective than orbital servicing, while the third study concluded that orbital servicing is more cost effective than the other two modes and, within this mode, the reliability increases considered provided additional savings for the spacecraft system considered.

Table III-3 lists five concurrent studies that provided additional data helpful to the IOSS and to which the IOSS provided significant and useful data.

IV. STUDY APPROACH

The objective of maintenance is to increase a system's availability, which is a measure of the time that a system is ready to perform its intended mission. Maintenance, or servicing, is one way to reduce the cost of availability. The many approaches to obtaining spacecraft availability are shown in Figure IV-1. This tree of approaches is easily divided into

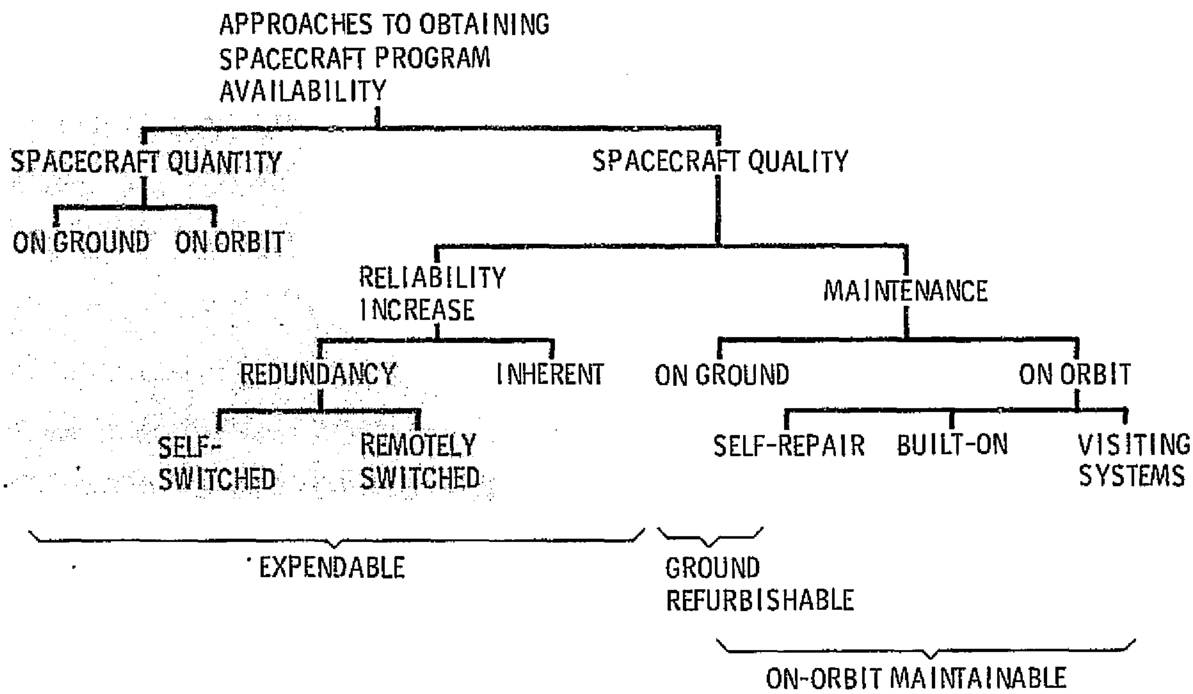


Figure IV-1 Spacecraft Program Availability Approaches

the maintenance modes of the study--expendable, ground-refurbishable, and on-orbit maintainable. Two maintenance concepts shown were considered and found to have little application--built-on and self-repair. Built-on is a maintenance concept in which the spacecraft has its own spare modules and the failed modules are replaced mechanically. Self-repair is an extension of built-on where the spacecraft has a second manipulator that is used to repair the failed modules. Note that the availability approaches in the shaded area are not considered part of the study effort; those in the unshaded area were addressed.

In the expendable mode, spacecraft are launched until the desired on-orbit fleet size is obtained and then each failed spacecraft is replaced with a new spacecraft. The ground-refurbishable mode starts as with the expendable mode until a spacecraft fails. Then the failed spacecraft is returned to earth, repaired, and relaunched. (If an extra spacecraft has been procured, then it is sometimes possible to launch the replacement spacecraft and retrieve the failed spacecraft on one mission.) The on-orbit maintainable mode is also like the expendable mode until a failure occurs. Then replacement modules are taken into space, exchanged with the failed modules, and the spacecraft returned to normal operation. The method used for exchanging the modules, called visiting systems, has been the subject of much study.

The overall study task identification and interrelationships shown in Figure IV-2 demonstrate the highly interactive approach necessary for the technical and economic evaluations to support the study objective--provide the basis for selection of a cost effective orbital maintenance system supported by the STS. The desired results are tradeoff studies, rationale, evaluations, criteria, spacecraft configuration data, and cost structure formats to support the selection of maintenance concepts to be used in the actual cost determination of on-orbit serviceable versus expendable and ground-refurbishable alternatives that will provide the desired spacecraft availability.

After the first quarterly review the study effort was increased to include an increment to task 3, spacecraft interface requirements; task 6, servicer control issues: and task 7, servicer preliminary design and mockup. These activities were added to meet the important needs of providing an effective on-orbit servicing demonstration device; i.e., a servicer mockup, an initial evaluation of the controls problem, and expanded

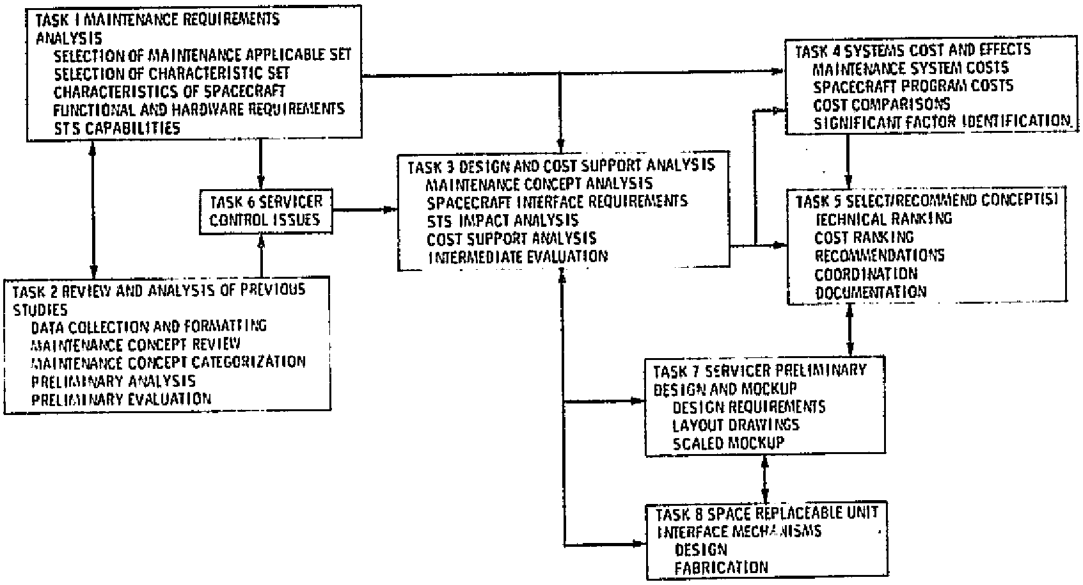
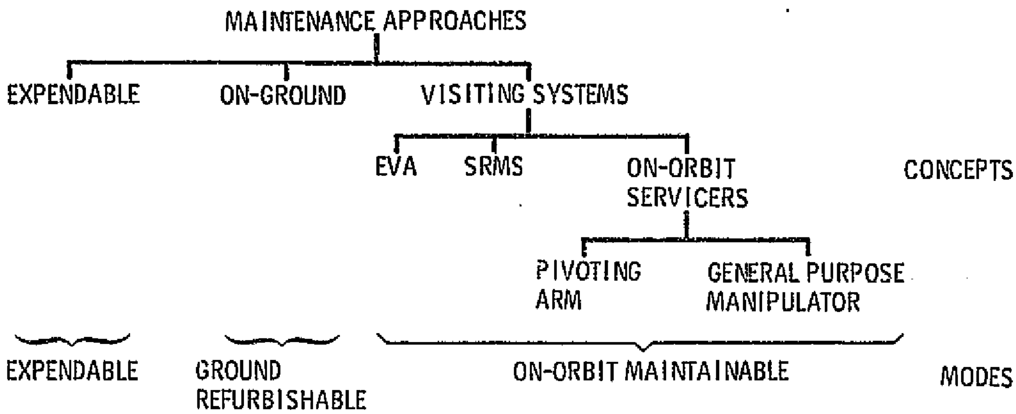


Figure IV-2 Study Task and Flow

definition of the effect on the spacecraft interfaces resulting from the on-orbit servicing scenario. After the third quarterly review, task 8, space-replaceable unit interface mechanism design and fabrication, was added to provide engineering test units for two approaches to the important mechanical fastening interface between the space-replaceable units and the spacecraft and stowage rack.

While the study involved many facets, iterations, and evaluations, the flow of the major tradeoffs is shown in Figure IV-3. The three *modes* are shown across the middle of the figure. Each *mode* can be achieved by one or more maintenance *concepts*. The primary tradeoff is between the three *modes*, but the maintenance *concept* for the visiting system level--EVA versus shuttle remote manipulator system vs on-orbit servicer--also had to be selected. While Figure IV-3 expresses the on-orbit servicer tradeoff as being between the pivoting arm and the general-purpose manipulator maintenance *concepts*, these two concepts are the result of a screening/categorization/evaluation process that started with 15 different concepts. The considerations shown on the figure were used in the evaluations depicted as well as in most of the other study evaluations.



EVALUATION CONSIDERATIONS:

1. SPACECRAFT DESIGN ASPECTS
2. STS IMPACTS
3. TECHNICAL
4. OPERATIONAL AREAS
5. PROGRAMMATIC
6. COST

Figure IV-3 Study Evaluation Flow

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The significant conclusions and results reached in the two Integrated Orbital Servicing studies are presented below with the major conclusions shown in italics. Many secondary results and supporting conclusions are given in the rest of this chapter and in the technical volume. The following significant conclusions and results were generated by both COMSAT and Martin Marietta in their two companion studies. These conclusions, where Martin Marietta has performed a significant part of the work, are discussed and their supporting rationale are presented in the remainder of this chapter.

1. Top-level conclusions

   a) *On-orbit maintenance is the most cost-effective mode.*
   b) *Spacecraft can be designed to be serviceable with acceptable design, weight, volume, and cost effects.*
   c) The module exchange form of servicing is applicable to repairing failed satellites, improving reliability of operating satellites, and updating equipment.
   d) Analysis, design, engineering test unit fabrication, and evaluation of on-orbit servicers should continue.
   e) On-orbit servicing can increase program flexibility and satellite reliability, lifetime, and availability.
   f) Ground refurbishment is not cost effective for most geosynchronous satellites.

2. Maintenance concepts

   a) *The on-orbit servicer maintenance concept is recommended.*
   b) The on-orbit servicer, extravehicular activity, and shuttle remote manipulator system are all technically feasible.
   c) Only the on-orbit servicer is applicable to both tug and orbiter based missions.

d) Remote control of module exchange with an on-orbit servicer is technically feasible.

3. On-orbit servicers

a) *The pivoting arm on-orbit servicer was selected and a preliminary design was prepared.*

b) On-orbit servicer concepts exist that will permit a broad range of spacecraft design alternatives.

c) On-orbit servicing is compatible with standardized modules or spacecraft, but does not require them to be cost effective.

d) Side- and bottom-mounting forms of space replaceable unit interface mechanisms are useful and have been designed.

4. Economics evaluations

a) *Use of on-orbit servicing over the 12 years covered by the 1974 SSPD and the October 1973 Payload Model results in savings greater than*

- *nine billion dollars over the expendable mode, and*
- *four billion dollars over the ground refurbishable mode.*

b) The life cycle costs of the on-orbit servicer represent approximately one percent of the overall savings and these costs can be fully recovered by 1982.

c) Cost sensitivity analyses showed that wide variations in cost data, especially mission model size and fraction of spacecraft replaced, affect specific savings but do not change the major study conclusions.

d) A long-life free-flying servicer at geostationary orbit is potentially cost effective.

e) Specific launch cost reimbursement policies can be an important factor in which form of servicing is adopted for individual spacecraft programs.

f) Expendable satellites are cost effective where satellite lifetime meets program lifetime requirements.

5. Development implications

   a) *A single development of an on-orbit servicer maintenance system is compatible with many spacecraft programs and is recommended.*

   b) *Orbital maintenance does not have any significant impact on the space transportation system.*

   c) On-orbit maintenance with the pivoting arm servicer is compatible with a variety of delivery vehicles such as the orbiter, full capability tug, free-flying servicer, solar electric propulsion system, earth orbital teleoperator system, and some forms of the interim upper stage.

6. User acceptance

   a) *Users need guarantees that servicing will be available and assurances that it will be cost effective.*

   b) A deeper understanding of the orbital servicing cost structure is required before initiating drastic changes in conventional satellite construction and operations methods.

   c) Scheduling delays of several months are tolerable for many servicing requirements.

   d) Development of the on-orbit servicer should include early in-space demonstrations of module exchange along with rendezvous and docking.

   e) Building, flying, and servicing a serviceable satellite is needed to obtain widespread acceptance of orbital servicing.

A. TOP-LEVEL CONCLUSIONS

The results of this study have shown that on-orbit maintenance is a more cost effective mode than the expendable or ground-refurbishable maintenance modes. Each of the three maintenance modes was investigated for the six evaluation considerations: (1) spacecraft design aspects, (2) STS impacts, (3) technical, (4) operational areas, (5) programmatic, and (6) cost. The results from investigating considerations (1) thru (5) provided the basis for establishing the associated cost impacts to be incorporated in the cost considerations. It was determined that each of the three modes is technically feasible and that spacecraft can be designed for each maintenance mode. Acceptable development programs and operational methods are also possible for each mode.

The total program costs for each maintenance mode are:

1) On-orbit maintainable - $15.9 billion;
2) Ground-refurbishable - $20.2 billion;
3) Expendable - $24.9 billion.

These costs are predicated on all 47 spacecraft programs being flown in each mode. The on-orbit maintainable mode results in a cost savings of 9 billion dollars, or 36%, over the expendable mode and 4.4 billion dollars, or 22%, over the ground-refurbishable mode.

Spacecraft can be designed to be serviceable with acceptable design, weight, volume, and cost effects. This same conclusion was drawn in seven other studies that were reviewed. Several of the studies (Aerospace Corporation and TRW DSCS-II) went into considerable depth as to the effect of servicing on spacecraft design. The expendable and on-orbit serviceable configurations of COMSAT INTELSAT, shown in Figure V-1, are representative of the transition of a spacecraft to a serviceable configuration. It was also found that on-orbit servicers can accommodate a sufficient variety of module metrics to avoid an excessive spacecraft modularization penalty. A wide range of spacecraft characteristics can be accommodated by a servicer without excessive configuration penalties. Even the effect of three-axis stabilization as opposed to spin stabilization does not show an excessive penalty; some data show that three-axis stabilization results in lighter and less expensive spacecraft.

To a first level, spacecraft can be made serviceable without mission objective penalties; it is more a management challenge to coordinate development. Weight penalties of 600 to 800 pounds are incurred in going from an expendable to a modular spacecraft for servicing. Spacecraft configurations established along the policy lines of "status quo" or "maximum STS efficiency" have more effect on the spacecraft than the servicer. There is an indicated cargo bay length and accompanying cost benefit when spacecraft are designed for "maximum STS efficiency".

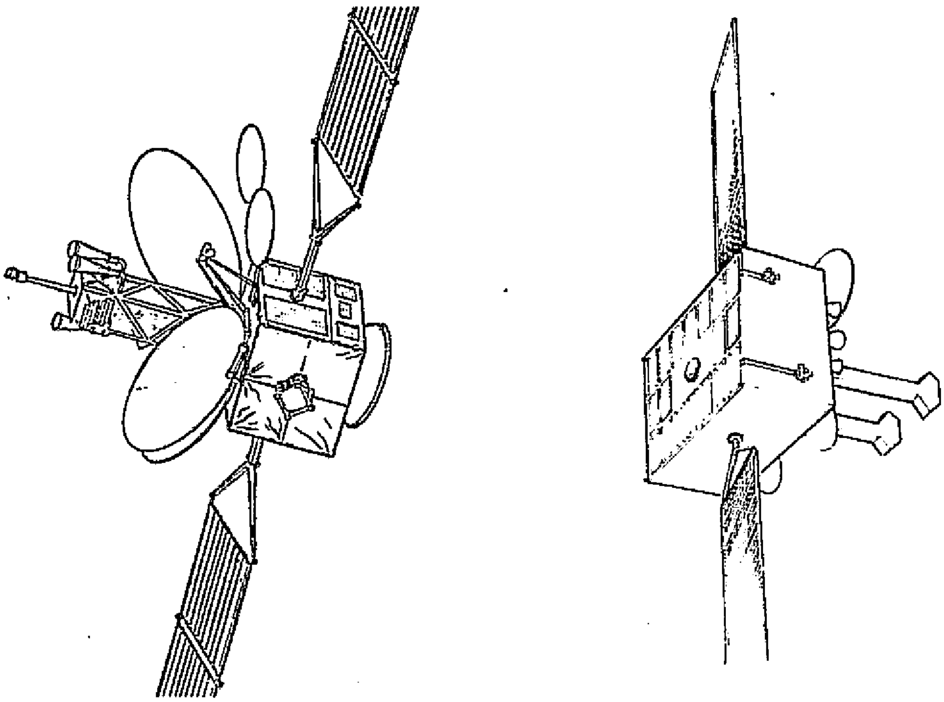


Figure V-1 INTELSAT Configurations

The recommendation that an on-orbit servicer maintenance concept should be used, when combined with the existing schedule constraints relative to establishing user's acceptance of on-orbit maintenance early in the spacecraft development cycle, dictates the requirement for continuation of analysis, design, engineering test unit fabrication, and evaluation of on-orbit servicers. This continuation of effort will provide the most effective, and thus the most cost efficient, means of providing engineering data for establishing (1) a realistic servicer final design, and (2) user acceptance.

Launching of STS-delivered spacecraft will start in 1980. The early phases of development for many of the spacecraft to be launched by the STS have already started. To avoid double development costs resulting from changing over a spacecraft design to on-orbit maintainable at some later date, user acceptance of maintenance must be established now. This requires an early management decision to implement on-orbit maintenance to allow the greatest benefits to be realized.

On-orbit maintenance is compatible with standardized spacecraft subsystems but does not require them. A spacecraft designed for on-orbit maintenance will be modular. Modularization of a spacecraft requires many of the same design factors as standardization. Two common design factors for a replaceable module and a standardized subsystem are structural and thermal independence. Also, both approaches would benefit from standardized electrical connectors and tend to favor a data bus approach to minimize the number of pins required. Standardized spacecraft subsystems could be integrated into a modular spacecraft design with a minimum impact. However, the SRUs of on-orbit servicing need not be standardized subsystems; they need only have standardized interfaces.

B. MAINTENANCE CONCEPTS

The three maintenance concepts within the classification of visiting systems are (1) on-orbit servicer (OS), (2) extravehicular activity (EVA), and (3) shuttle remote manipulator system (SRMS). Each of these systems can operate in low earth orbit out of the orbiter cargo bay. However, only the on-orbit servicer can also operate in high earth orbit.

A technical comparison of the maintenance concepts operating in low earth orbit was performed. For each maintenance concept it was necessary to (1) establish servicing guidelines, (2) select a representative maintenance technique, (3) define the operating region in the orbiter cargo bay, (4) determine the equipment required, and (5) summarize the advantages and disadvantages.

Since EVA and SRMS are baselined for the STS program, the JSC *Space Shuttle System Payload Accommodations* document (July 3, 1974) was used to establish servicing guidelines for these two maintenance concepts. Several significant facts were observed. Even though EVA and SRMS are STS-baselined, no spacecraft maintenance approach is specified. Further, the SRMS design has been driven by deployment and retrieval of spacecraft. An improvement in positional accuracy and in operational utility would be required for efficient use of the SRMS for module replacement.

A representative maintenance technique, as shown in Figures V-2, V-3, and V-4, was synthesized for each of the maintenance concepts. Also, the

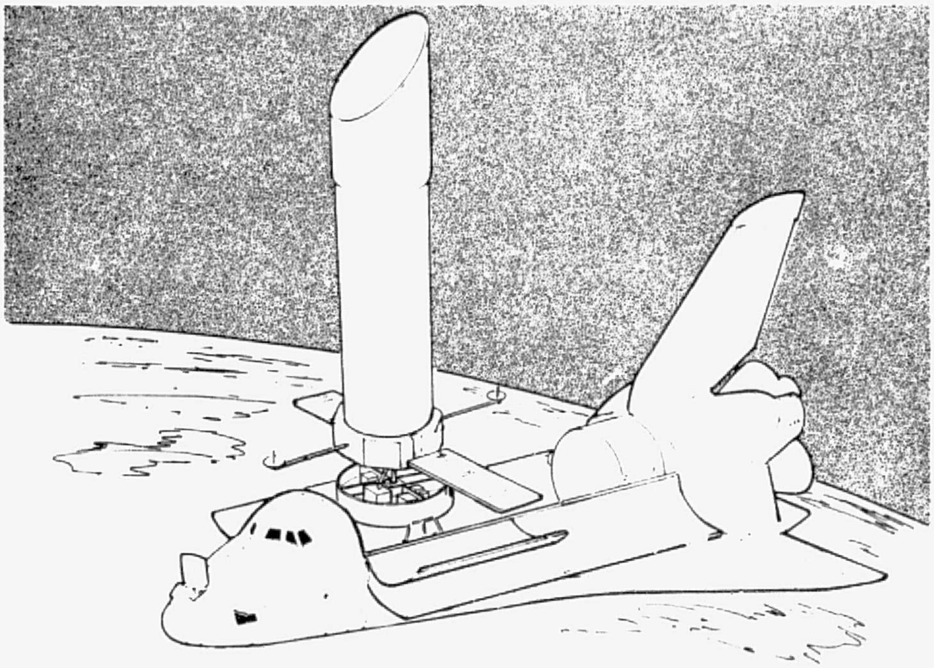


Figure V-2 On-Orbit Servicer Concept

operating regions within the cargo bay were defined. This was done for two modular spacecraft and the pivoting arm stowage rack. The effects of large (large X-ray telescope) and small (solar maximum mission spacecraft) were investigated. The objectives of this evaluation were to provide a basis for establishing the equipment in the areas of spacecraft, STS, and servicing and to determine the advantages and disadvantages of each maintenance concept. EVA can be considered as a backup for either SRMS or

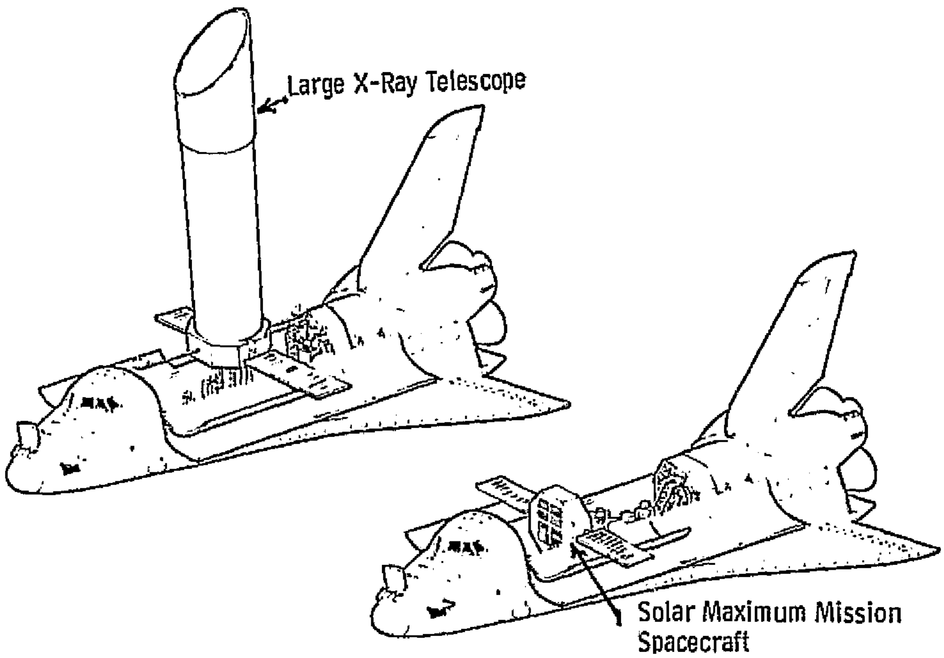


Figure V-3 EVA Maintenance Concept

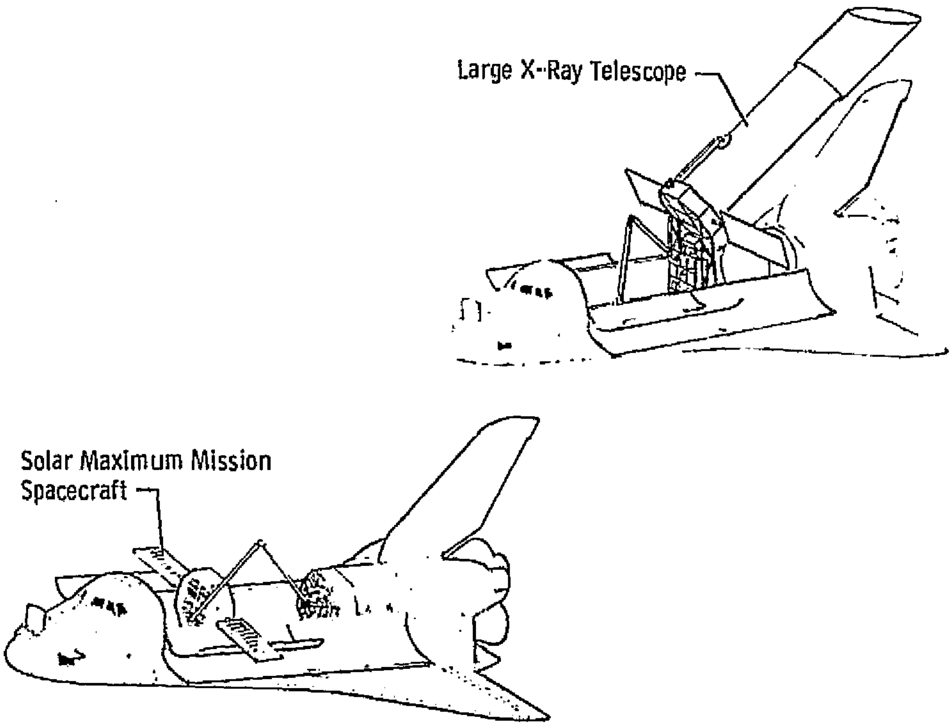


Figure V-4 SRMS Maintenance Concept

the on-orbit servicer in the orbiter cargo bay. The module exchange techniques, designs and operations of these two concepts were made compatible with EVA backup. However, the direct costs for EVA backup have not been included.

The equipment required and the advantages and disadvantages were examined to determine if any state of the art advancements were indicated. It was concluded that none of the three maintenance concepts presented any major technical problems. The on-orbit servicer, extravehicular activity, and shuttle remote manipulator system are all technically feasible. However, several aspects of EVA and SRMS that could have significant cost impacts were identified.

Design of spacecraft for EVA maintenance involves a small percentage cost increase for each spacecraft, but a significant increase across the 26 low earth orbit spacecraft programs. EVA design aspects, which are sometimes called man-rating, are those over and above what is required to launch the spacecraft in the orbiter, which is the same for all three maintenance concepts. This delta design for EVA results from the need for a suited astronaut to move around/over the surface of the spacecraft. The exterior equipment and thermal control surfaces that are subject to damage from physical contact would have to be protected or avoided. Sharp edges and appendages that could damage the astronaut's suit would have to be removed or covered. Remotely controlled covers would also have to be provided for optical surfaces that could be contaminated by moisture expelled from the life support system.

The support structure for large spacecraft for EVA and SRMS maintenance requires a large stowage volume with a concurrent launch cost penalty. The on-orbit servicer does not require any support structure that increases stowed length. Figures V-5, V-6, and V-7 show layouts in the cargo bay for each of the maintenance concepts. For the on-orbit servicer, large and small spacecraft can be docked to an Apollo-type docking mechanism

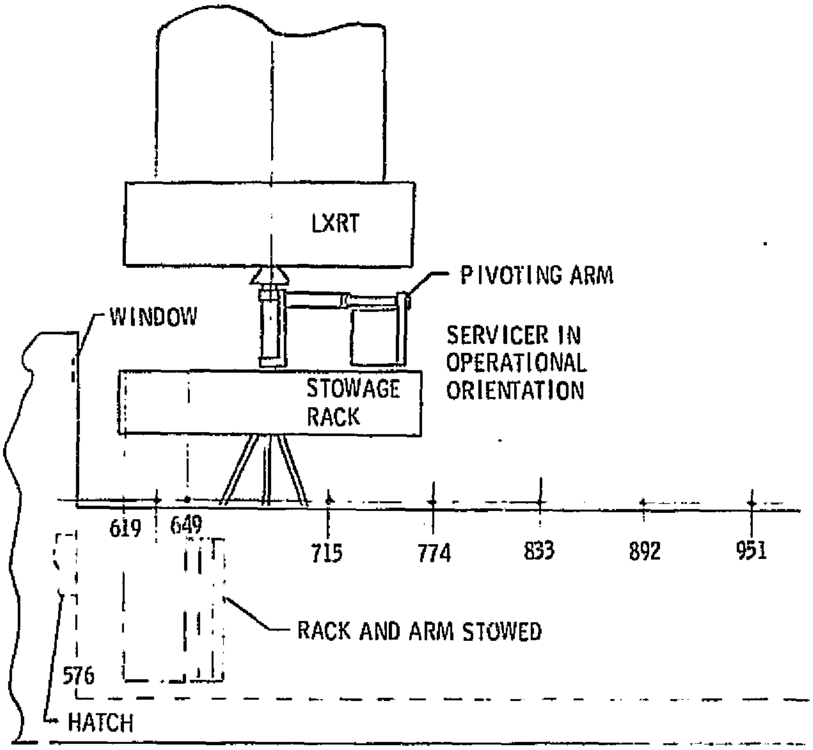


Figure V-5 Cargo Bay Layout, On-Orbit Servicer

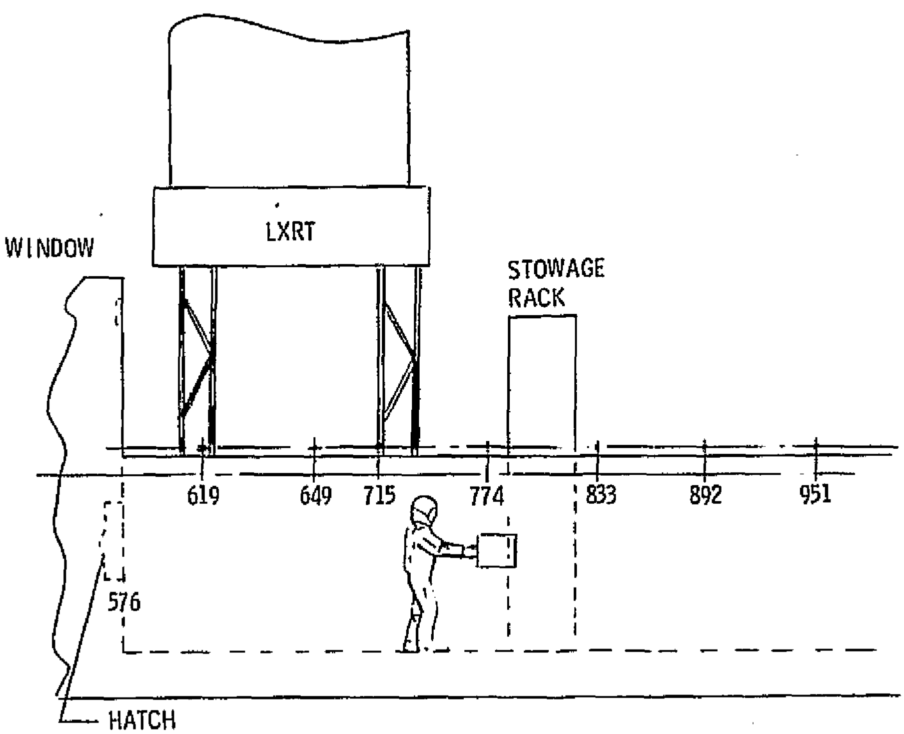


Figure V-6 Cargo Bay Layout, EVA Maintenance

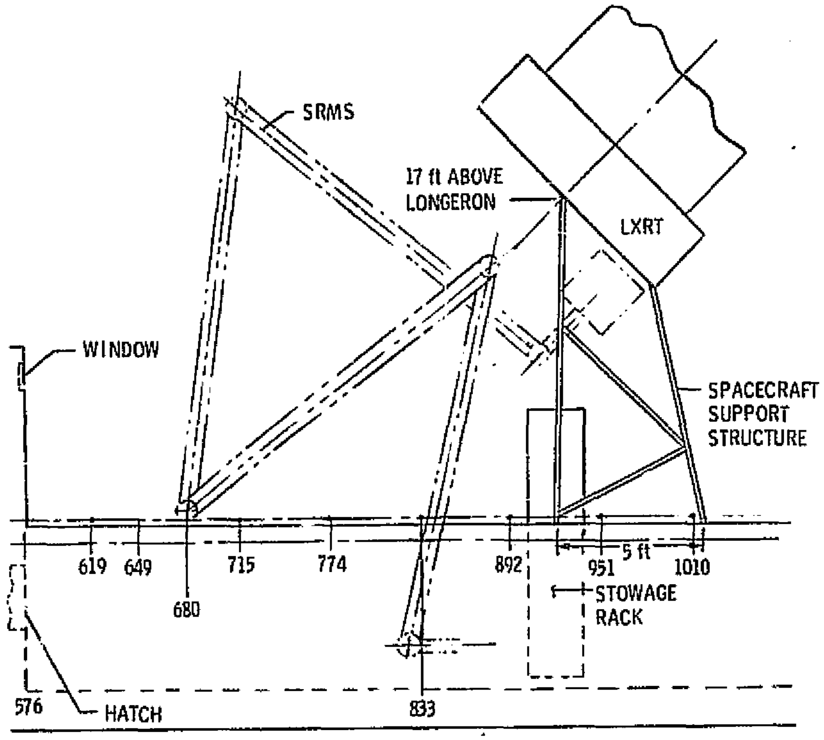


Figure V-7 Cargo Bay Layout, SRMS Maintenance

using the SRMS. The docking mechanism can be designed to fold up against the face of the stowage rack as an integral part of the servicer mechanism, resulting in no stowed length increase. However, in the case of the SRMS and EVA, a support structure that projects above the envelope of the cargo bay and that bridges from longeron to longeron is required. The structure will vary in height and complexity depending on interference problems with appendages and the need to reposition the spacecraft to provide access to the servicing areas. The structure's size indicates a large stowage volume (>17-ft long) in the orbiter cargo bay or a moderate stowage volume (≈ 5-ft long) along with the capability to fold the support structure. The moderate stowage volume approach was used in the cost analysis.

The remote control system selected to be used with the on-orbit servicer mechanism for module exchange can strongly affect the servicer's operational utility and its versatility. The recommended system combines the best qualities of each of two modes, and thus overcomes each of their deficiencies by using supervisory control as the primary mode and remotely manned control to provide backup operation for failures and operational contingencies. Because the remotely manned control is only a backup mode and will not be used frequently, longer operating times can be accepted. This permits use of a simplified TV camera(s) with very low frame rates (say three per minute) as well as using the TV system instead of proximity sensors for the alternative hazard avoidance system in this backup mode. Tolerance compensation can be handled by the operator using his ground-based computer. The major advantage of this combined mode is the availability of different and completely separate backup functions to obtain the highest probability of successful module exchange over the widest range of operating conditions.

C. ON-ORBIT SERVICERS

1. On-Orbit Servicer Selection

Fifteen on-orbit servicer concepts (Fig. V-8) were identified from the literature, screened, and evaluated to arrive at the final selection of

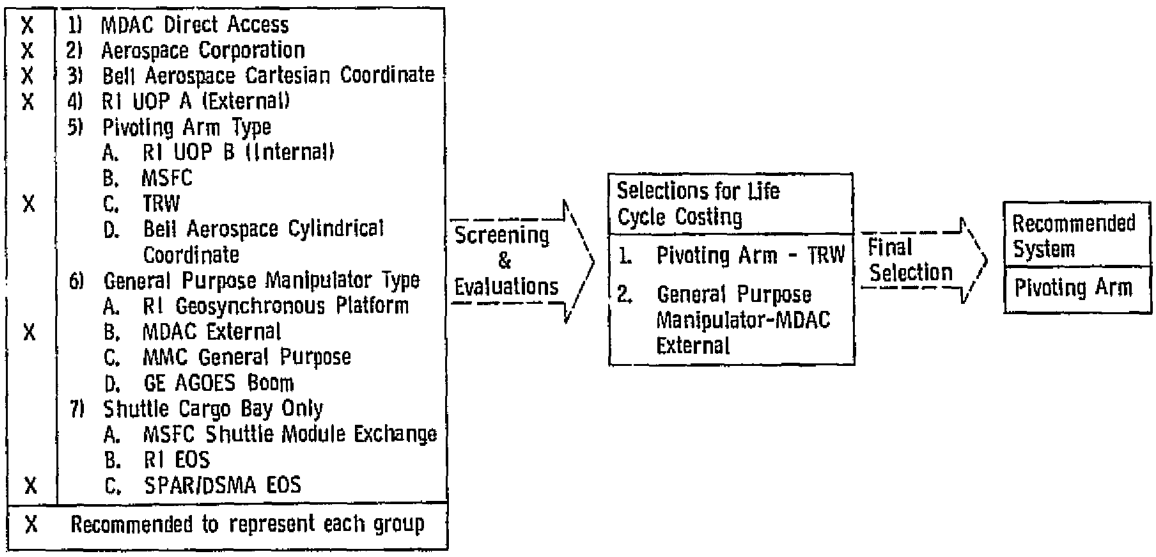


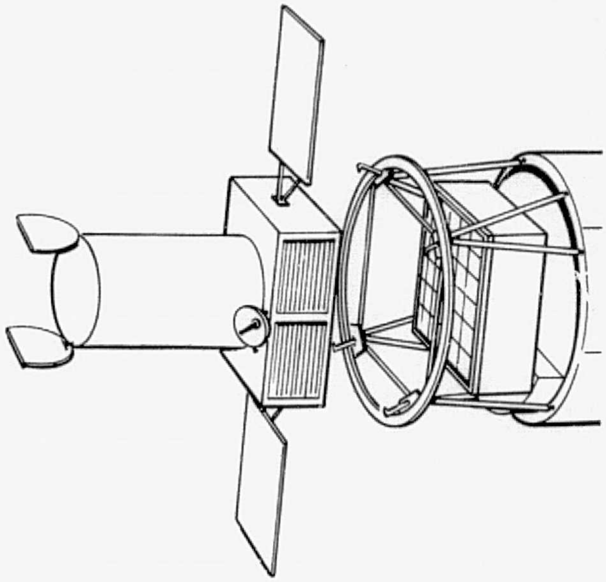
Figure V-8 On-Orbit Servicer Concept Selection the pivoting arm on-orbit servicer. Analysis of on-orbit servicer literature showed that the diverse collection of alternative servicers contains many related types that may be categorized into groups. Within each group one concept was selected to represent the group after the initial evaluation. These representative concepts are indicated in Figure V-8 by the Xs. Illustrations of each of the representative on-orbit servicer concepts are shown in Figure V-9.

Four ground rules were established for evaluating the on-orbit servicers:

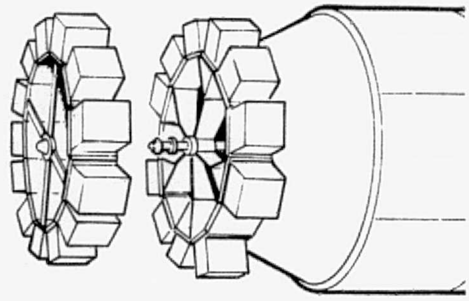
1) Spacecraft are designed to be serviceable;
2) Servicer performs module exchange only;
3) All modules are located in one or two separate docking faces or in one or two adjacent tiers;
4) Large antennas and solar panels are assumed to have long life and high reliability and therefore do not need replacing.

The criteria initially selected for screening the on-orbit servicers are shown in Table V-1. The selected concept should be the one that achieves the best balance between maximum simplicity and maximum versatility. Although a simple system with high reliability is very desirable, the servicer must not be too restrictive on the spacecraft designer. The length of the servicer mechanism when stowed in the cargo bay is important because it occupies space otherwise usable by other payloads, and its weight is equally important because it subtracts from orbiter and tug capabilities.

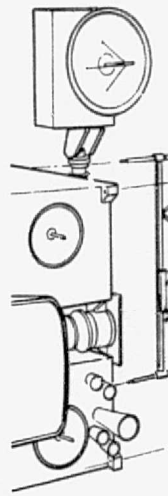
The servicer analysis results, with three level ratings in each category for each servicer, are given in Table V-2. This was done for each of the seven screening criteria. An additional criteria--number of mechanical functions--was added to augment mechanical advantage. The servicer mechanism should have the least number of actuators possible to be simple and reliable, and yet be versatile enough to not overly restrict the spacecraft designer.



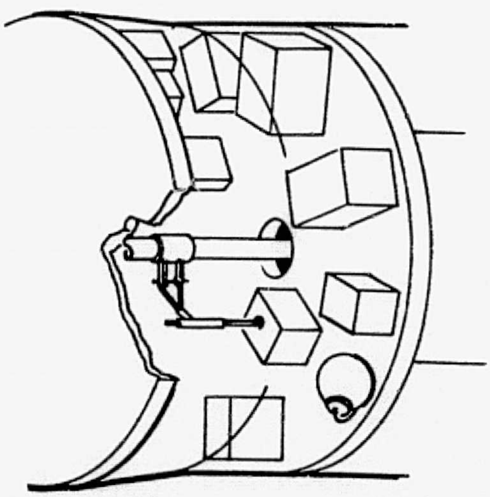
a) MDAC Direct Access



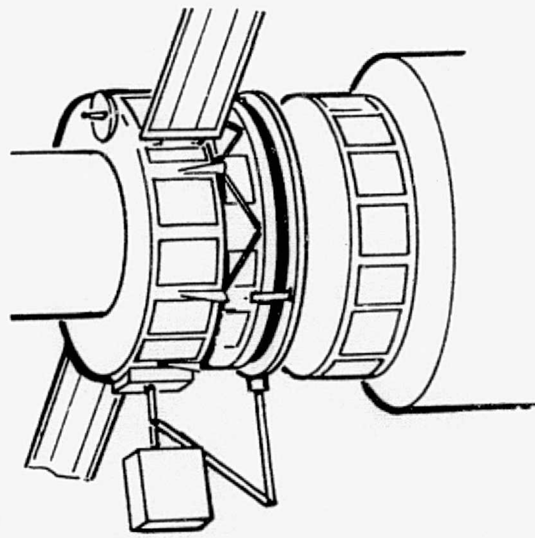
b) Aerospace Corporation



c) Bell

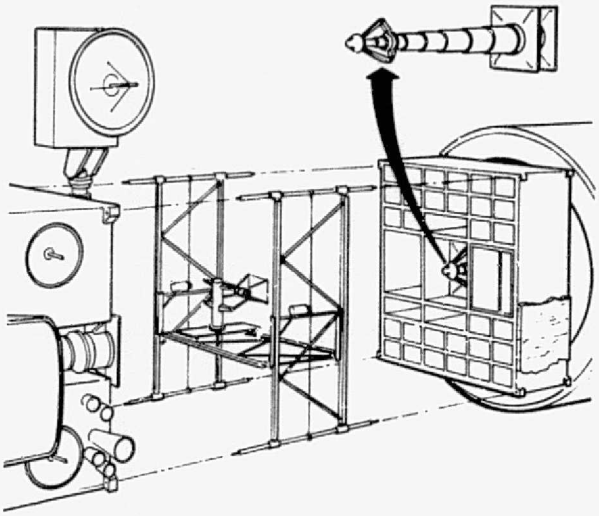


e) TRW - Pivoting Arm

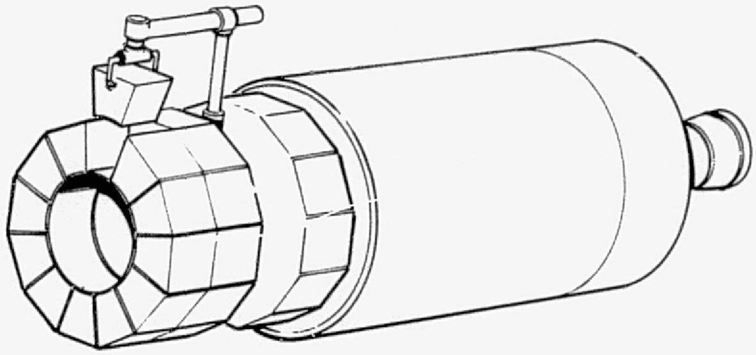


f) MDAC - General Purpose Manipulat

Figure V-9 On-Orbit Servicer Concepts

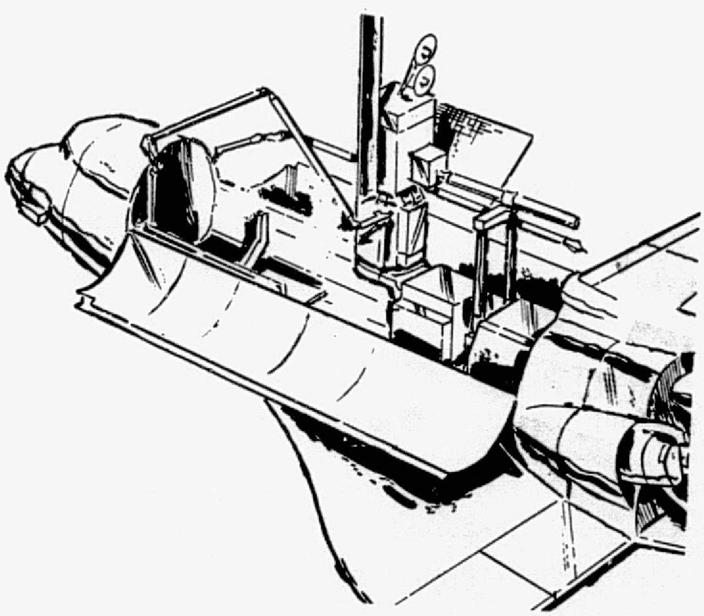


c) Bell Aerospace Cartesian Coordinate



d) RI UOP A (External)

ose Manipulator



g) SPAR/DSMA - Shuttle Cargo Bay Only

Table V-1 Screening Criteria for On-Orbit Servicers

VERSATILITY
- Minimum Constraints on Spacecraft Design - Number, Sizes, Shapes, and Location of Modules
- Minimum Constraints on Docking Device Design

SIMPLICITY
- Mechanical Advantage - actuator concept, motion type, force levels, temporary stowage, operations time
- Structural Flexibility - of docked spacecraft/servicer assembly, of mechanism itself
- Reliability - design simplicity, number of degrees-of-freedom and actuators, synchronization requirements

LENGTH
- Minimum Length when in Operation or when Stowed in Cargo Bay

WEIGHT
- Efficient Use of Tug Capability

Table V-2 Servicer Evaluation Summary

	VERSATILITY	MECHANICAL ADVANTAGE	NUMBER OF MECHANICAL FUNCTIONS	DOCKING MECHANISM DEPENDENCY	STIFFNESS	SIZE	WEIGHT	RELIABILITY
MDAC DIRECT ACCESS SERVICER	POOR	MEDIUM	HIGH	POOR	LOW	SMALL	MEDIUM	POOR
AEROSPACE CORPORATION	POOR	MEDIUM	HIGH	GOOD	LOW	MEDIUM	MEDIUM	POOR
BELL AEROSPACE CARTESIAN COORDINATE	FAIR	MEDIUM	MEDIUM	FAIR	LOW	LARGE	HIGH	FAIR
RI UOP A EXTERNAL	FAIR	MEDIUM	LOW	GOOD	HIGH	MEDIUM	MEDIUM	GOOD
TRW PIVOTING ARM	GOOD	HIGH	LOW	GOOD	HIGH	MEDIUM	LOW	GOOD
MDAC EXTERNAL MANIPULATOR	FAIR	MEDIUM	MEDIUM	POOR	MEDIUM	SMALL	MEDIUM	FAIR
SHUTTLE CARGO BAY ONLY SERVICER	FAIR	MEDIUM	MEDIUM	GOOD	MEDIUM	LARGE	LARGE	FAIR

This means that about four degrees of freedom plus an end effector for latching and unlatching modules is about the optimum servicer mechanism. Also, the use of rotary actuators is usually preferred over linear actuators when possible. These factors favor the pivoting arm-type over the others. The pivoting arm can exchange modules of most any size or at most any position on a satellite end with axial exchange motion. Also the pivoting arm servicer is the most easily modified for additional capability when considering future growth potential, and it can accommodate to various types of docking devices.

2. Selected On-Orbit Servicer Design

A preliminary design of a pivoting arm on-orbit servicer (Fig. V-10) has been established. The TRW pivoting arm servicer design was used as a basis for the improved design. The new des.gn meets the on-orbit servicer design requirements shown in Table V-3. The pivoting

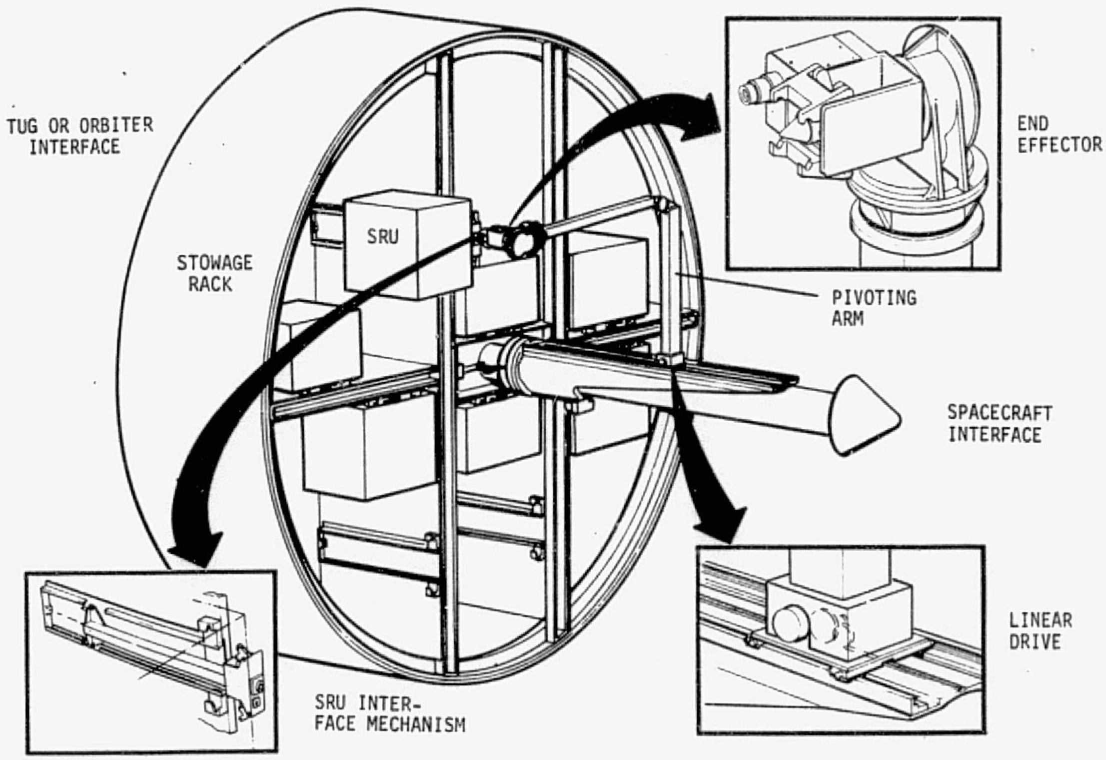


Figure V-10 Pivoting Arm On-Orbit Servicer

Table V-3 On-Orbit Servicer Design Requirements

Minimize Degrees-of-Freedom
Module Mass Range 0 to 700 Pounds
To Handle and Stow Modules of the Following Size Characteristics:
Large - 40 X 40 X 40 Inches
Medium - 26 X 26 X 40 Inches
Small - 15 X 15 X 40 Inches
Minimize Stowed Length
Tip Force > 20 Pounds In Worst Configuration
Attach/Latch Actuator Located In End Effector
Time to Replace One Module - 10 Minutes
Generate Operational Status Signals
Minimize Sliding Friction Areas
Be Compatible With Orbiter/Tug/EOTS Electrical Power
Be Compatible With Automatic, Supervisory, and Remotely Manned Control
Satisfy All Latch/Attach Mechanism Guidelines
Compatible With Operations at Orbiter, Tug (IUS, FCT), EOTS
Compatible With Most Automated Spacecraft
Multiple Spacecraft Capability per Mission
Probability of Mission Success = 0.98
Reusable for 100 Missions
Lifetime of Five Years
Provide Failed Module Temporary Stowage
Provide Module Environmental Control (Thermal, Radiation, Contamination)
Operate Module Latches
Compatible With EVA
Compensate for Tolerances/Misalignments In 6 DOF
Withstand Orbiter Crash Loads
No Ability to Exchange Modules In One-G
Operable In One-G, No Modules
Lightweight

arm mechanism (Fig. V-11 thru V-14) has been designed to overcome two major problems in the TRW design--long stowage length (105 in.) and long module turnaround distance (132 in.). The long stowage length resulted from the fact that the TRW pivoting arm did not incorporate a folding capability for launch. In the recommended design, the pivoting arm mechanism folds against the face of the stowage rack during launch, resulting in a stowage length of 21 inches (Fig. V-14). The operating distance be-

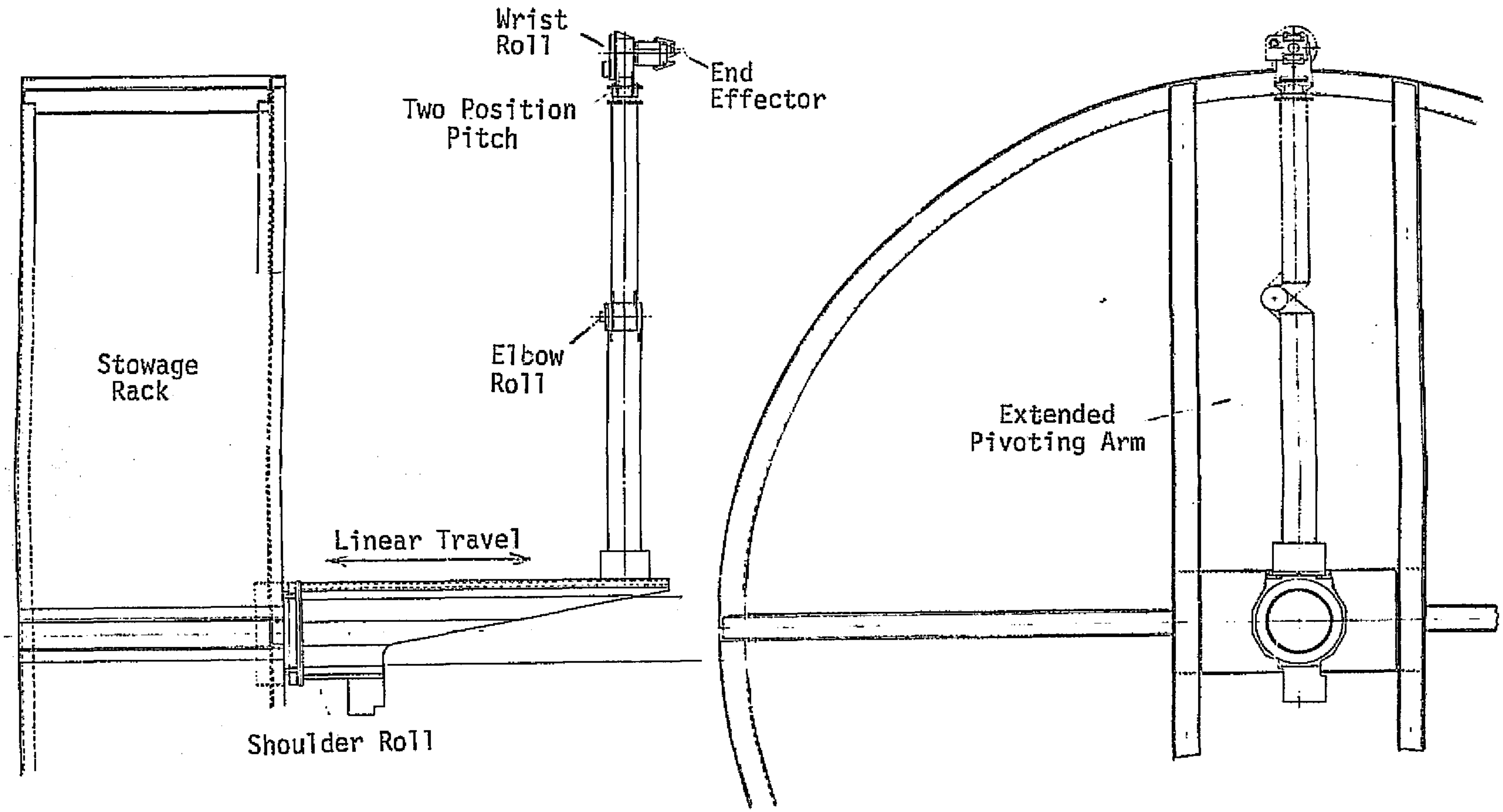
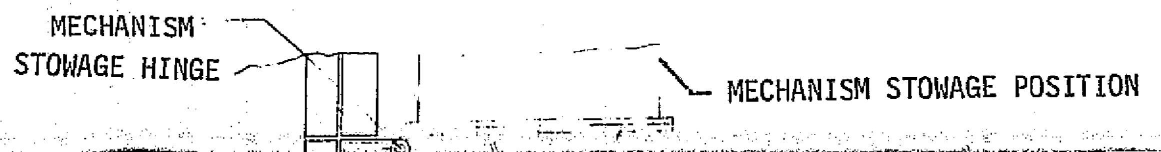


Figure V-11 Pivoting Arm Layout



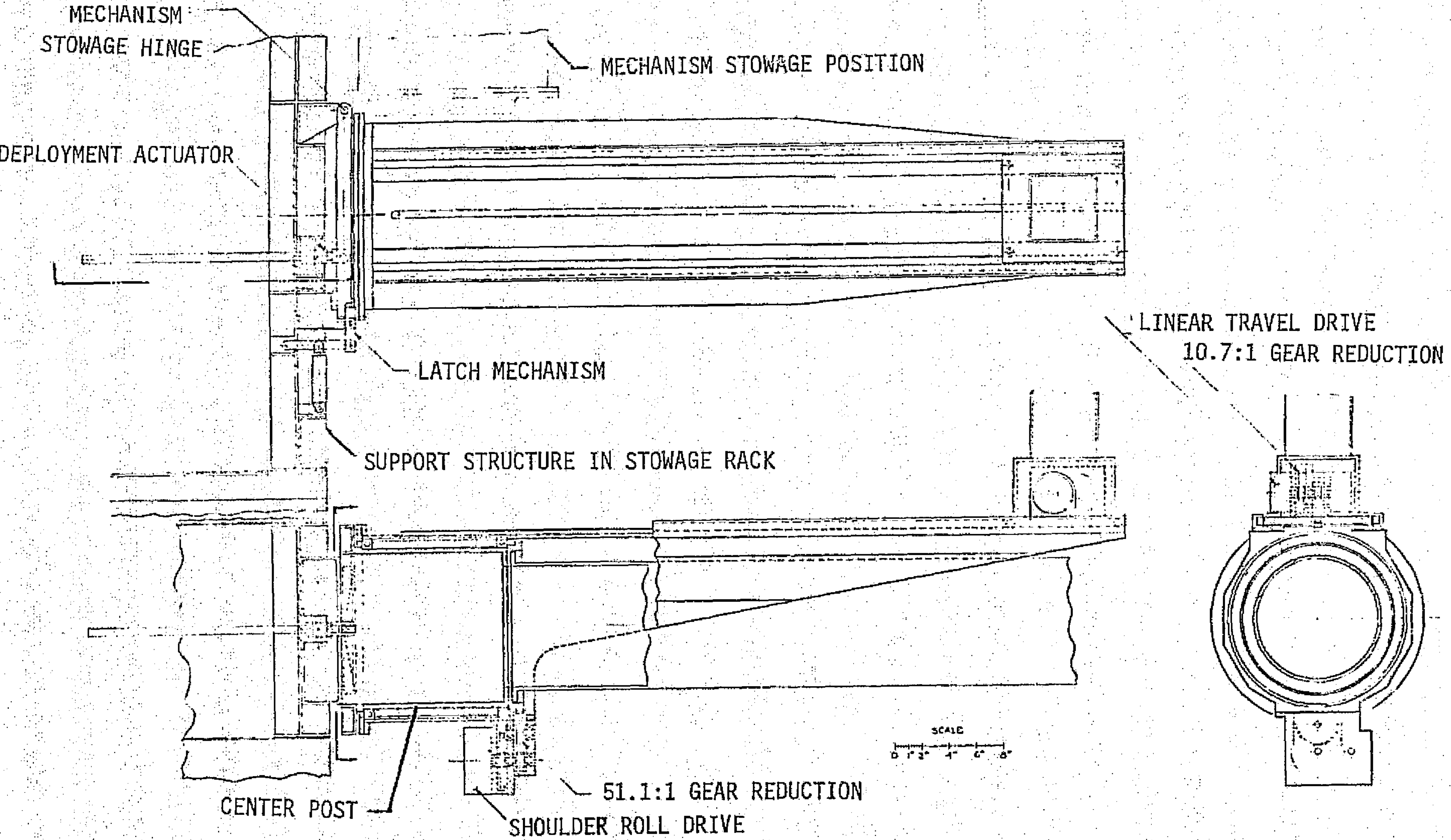


Figure V-12 Pivoting Arm - Shoulder Details

FOLDOUT FRAME 2

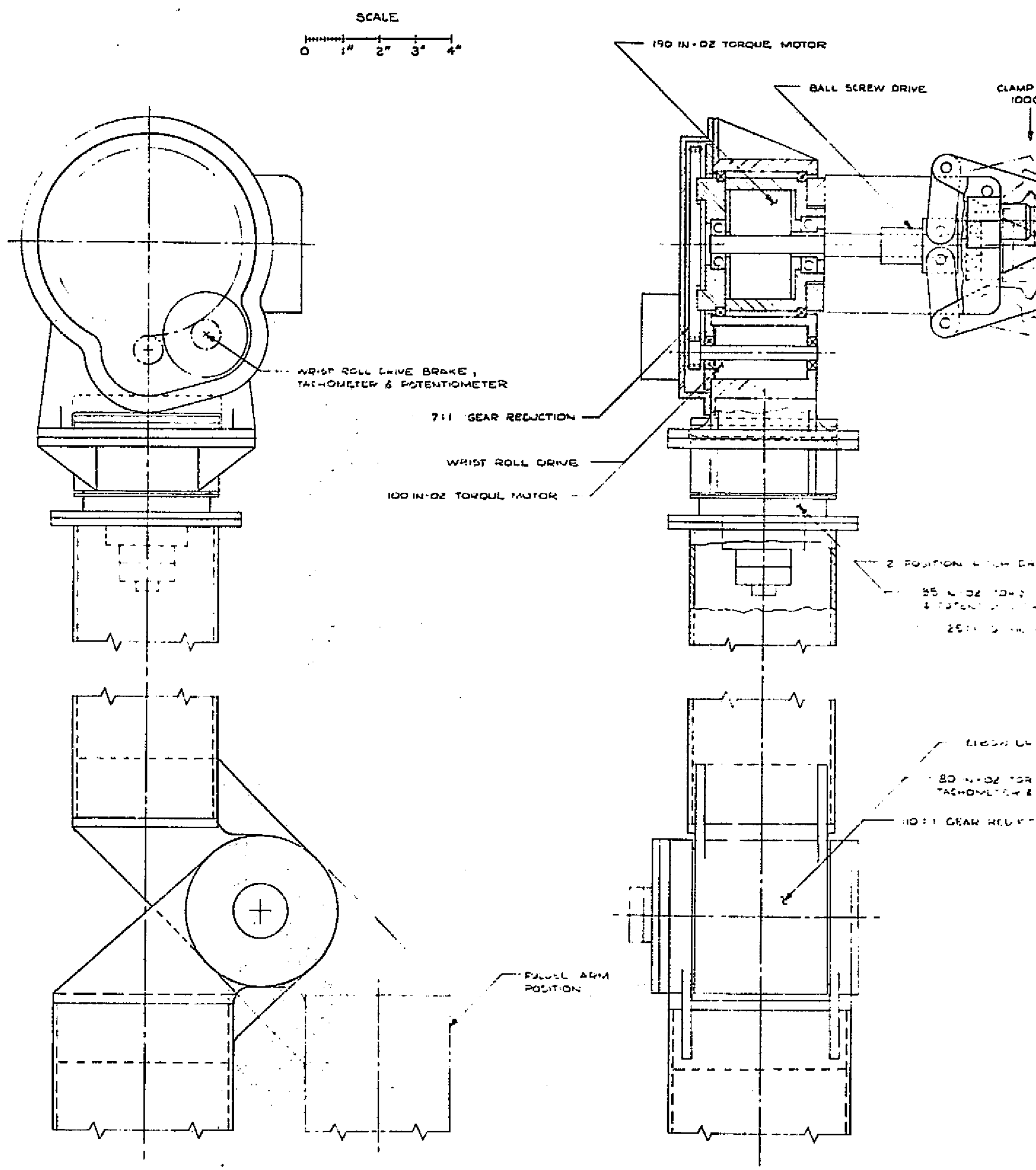


Figure V-13 Pivoting Arm - Details

FOLDOUT FRAME /

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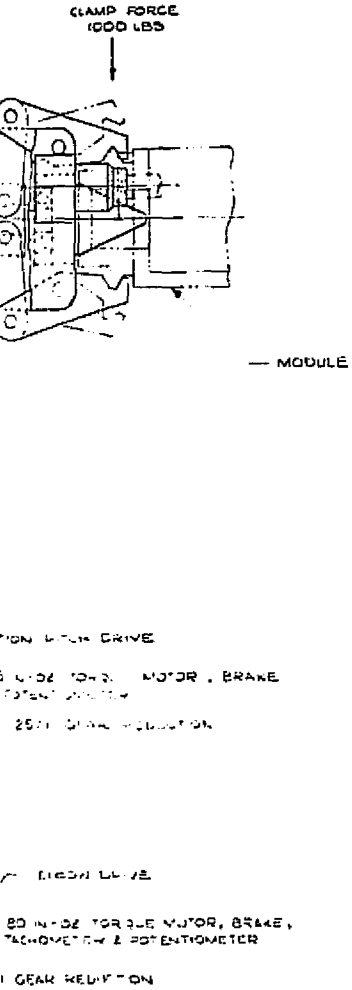

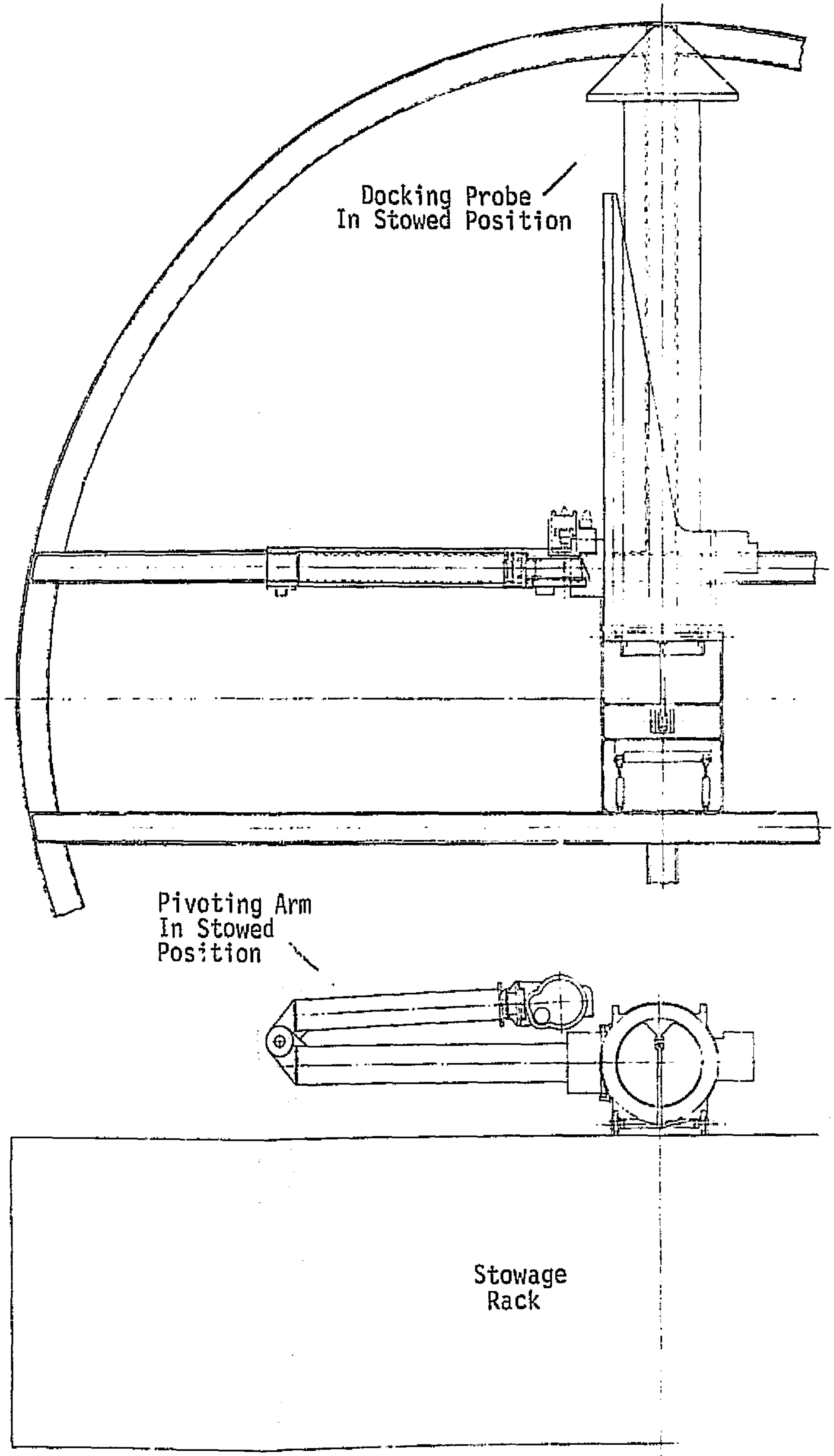

Figure V-14 Pivoting Arm - Stowed Configuration

FOLDOUT FRAME

tween the spacecraft and the stowage rack has been reduced to 58 inches by incorporating the linear drive at the shoulder as opposed to at the wrist as in the TRW design. The total stowed length of the tug-mounted version of the on-orbit servicer is 61 inches.

3. Space-Replaceable Unit Interface Mechanisms

Two complementary forms of space-replaceable unit interface mechanisms have been designed and are shown in Fiqures V-15 and V-16. The interface mechanism is used to fasten space-replaceable units into space-serviceable spacecraft and into the associated stowage rack of the on-orbit servicer.

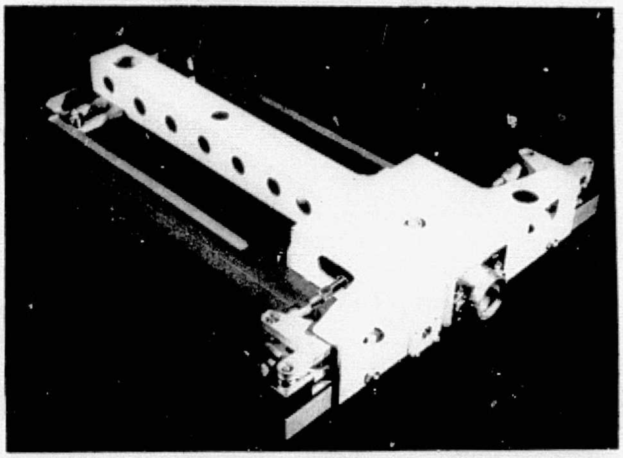

Figure V-15 SRU Interface Mechanism, Side Mount

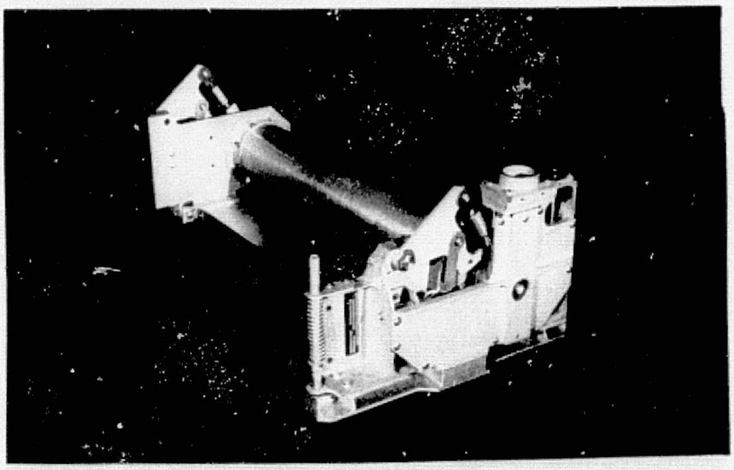

Figure V-16 SRU Interface Mechanism, Bottom Mount

This design effort was initiated because a survey and evaluation of 12 interface mechanisms concluded that no concept fully met all the interface mechanism design criteria (Table V-4). The two interface mechanisms represent bottom- and side-mounting approaches. The two designs rather than

Table V-4 SRU Interface Mechanism Design Guidelines

ATTACH-LATCH SYSTEM LEVEL DESIGN GUIDELINES
Impose Minimum Restrictions on the Spacecraft and Module Designers
- Allow Flexible and Efficient Packaging of Modules on Spacecraft and Stowage Device
- Accommodate a Wide Range of Module Sizes and Masses
- Baseplate Transmits All Forces and Moments
- Accommodate a Range of Connector Types and Forces
Accommodate Misalignment in Six Degrees of Freedom
Minimize Weight and Volume
Require Servicer Mechanism Forces of Less Than 20 lbs
Be Compatible with Operation by Astronaut
Provide Nonredundant Module Support
Accommodate Orbiter Crash Loads
Allow for Thermal and Structural Deflections
ATTACH-LATCH ELEMENT DESIGN GUIDELINES
APPLICABLE TO ATTACH AND LATCH
Provide a Two-Stage Engagement: Capture and Lockup
Provide Separation Forces
Generate Operational Status Signals
Utilize an Actuator Located in End Effector
Accomplish Capture under Required Misalignment Tolerances (6 DOF)
Make Final Alignment to Required Accuracy (6 DOF)
Minimize Sliding Friction Areas
ATTACH ONLY
Use a Passive Interface on Baseplate
LATCH ONLY
Use a Passive Interface on Spacecraft
Provide Load Paths at Final Alignment to Handle Orbiter Crash Loads
Avoid Initial Module to Opening Close-Fit Requirement
Provide Positive Lockup Device
Provide Connector Make/Break Forces

either one were performed so viable alternatives would be available to spacecraft designers. The bottom-mount interface mechanism is applicable to a spacecraft structural configuration where all the SRUs are mounted to a single plane or plate, whereas the side-mounted concept is applicable to a spacecraft designed in the form of deep intersecting webs with the SRUs mounted on the sides of the webs. Both the interface mechanisms are applicable to other spacecraft structural configurations, e.g., the exterior surface of a cylindrical polygon.

D. ECONOMIC EVALUATIONS

The main results of the economic evaluations show that over nine billion dollars, or 36 percent, can potentially be saved by flying most of the 340 automated spacecraft during the shuttle era in an on-orbit maintainable mode rather than in an expendable mode. When compared to ground refurbishment, on-orbit maintenance saves 4.2 billion dollars, or 21 percent. Figure V-17 presents a brief description, in the form of a work breakdown structure (WBS), of the costing elements that went into costing the three maintenance modes. This WBS format was used to cost flying all the spacecraft programs in the

Spacecraft Program		Expendable	Ground Refurbishable	On-Orbit Maintainable
Orbiter		Launch S/C	Launch, Retrieve & Relaunch S/C	Launch S/C, Launch & Return Servicer & Modules
Tug		Launch S/C	Launch, Retrieve & Relaunch S/C	Launch S/C, Launch & Return Servicer & Modules
Spacecraft	DDT&E	Basic	Modified Basic	Modified Basic
	Production	Basic	Modified Basic for Fleet Size	Modified Basic for Fleet Size
	Operations	Launch C/O, Sustaining	Launch C/O for Fleet Size	Launch C/O for Fleet Size
Spacecraft/Module Refurbishment	Operations	N/A	Refurbish S/C, Launch C/O of Refurbished S/C, Sustaining	Replace Modules, Launch C/O of Modules, Sustaining
Maintenance Concept	DDT&E	N/A	N/A	Develop for Servicer
	Production	N/A	N/A	Develop for Servicer
	Operations	N/A	N/A	Launch C/O Servicer, Sustaining Servicer

Figure V-17 Cost Estimation - Organization expendable, ground-refurbishable, and on-orbit maintainable modes. Table V-5 presents a cost summary of flying the 47 spacecraft programs and 340 missions in the study mission model. In the first column, all missions are flown expendably and the total life-cycle cost for all the programs is 25 billion dollars. In the second column, most missions are flown in the ground-refurbishable mode, although some are still flown in an expendable mode (those that would be cheaper to fly in an expendable mode), and the total life-cycle cost is about 20 billion dollars, a savings of almost 5 billion dollars. The third column represents most programs being flown in the on-orbit maintainable mode (as typified by the pivoting arm servicer). Some programs are still cheaper to fly in an expendable mode, but none are cheaper in the ground-refurbishable mode. The total cost is less than 16 billion dollars and that represents a savings of some 9 billion dollars over flying all spacecraft expendably. In addition, the costing analysis indicated that the savings could increase from such additional considerations as the capability to repair design failures, multiple spacecraft servicing, expendable servicers, or increases in shuttle launch costs. The nine billion dollars in savings represents a total of about 36% of the budget required to fly all programs expendably.

Cost estimates comparing the three visiting-system concepts of EVA, SRMS, and the on-orbit servicer (pivoting arm) indicated that for low earth orbit (LEO) only, the on-orbit servicer could be 90 million dollars cheaper than the SRMS and 180 million dollars cheaper than EVA. When viewed across the total mission model, including medium/high earth orbit (MEO/HEO)

Table V-5 Maintenance Mode Cost Summary (billions of dollars)

	EXPENDABLE	GROUND REFURBISHABLE	ON-ORBIT MAINTAINABLE
LEO SPACECRAFT	16.3	12.5	9.3
MEO/HEO	8.5	7.6	6.4
MAINTENANCE CONCEPT	--	--	0.1
TOTAL	24.9	20.1	15.9
	--	4.8	9.0

orbits, the on-orbit servicer could save an additional two billion dollars over the EVA and SRMS. Table V-6 presents a summary of visiting-system cost comparisons. The total cost to develop, build, and utilize the pivoting arm servicer during the 1980's and early 1990's will be 103 million dollars if used to service the entire mission model, or 90 million dollars if used only in LEO. The EVA and SRMS can only be used in LEO. The costs to develop, build, and utilize the EVA and SRMS maintenance concepts, over the STS baseline, will be about 80 million dollars each, plus an additional 100 million dollars for additional orbiter launch charges for each system, and an additional 90 million dollars in spacecraft costs for EVA over those costs associated with the pivoting arm on-orbit servicer. The incremental spacecraft costs for EVA design are to provide a payload safe-work station and include 1) provision of EVA load bearing surface for hand/foot restraints and pushoff, 2) additional structural protection where orbital conditions differ from ground, and 3) secondary power and/or AC power protection. The EVA operations costs also include a $60K per service item in accordance with a recent Rockwell International report.

The total life-cycle costs for the pivoting arm servicer of 103 million dollars represents approximately 1% of the nine billion dollars that can be saved by utilizing on-orbit maintenance instead of flying all spacecraft expendably.

Table V-6 Visiting System Cost Comparisons (millions of dollars)

MAINTE-NANCE CONCEPTS	DDT&E	PRODUC-TION	OPERA-TIONS	MAINTE-NANCE CONCEPT SUBTOTAL	Δ S/C DDT&E AND PRO-DUCTION EFFECTS	Δ ORBITER LCRP EFFECTS	TOTAL
PIVOTING ARM LEO/MEO/HEO	29	17	57	103	0	0	103
PIVOTING ARM LEO ONLY	29	14	47	90	0	0	90
SRMS, LEO ONLY	22	20	40	82	0	100	182
EVA, LEO ONLY	18	11	51	80	90	100	270

The performance of a sensitivity study on the cost analysis showed that the greatest effects on the savings from on-orbit maintenance were caused by changes in the mission model. The mission model used to perform the nominal cost analysis consisted of 47 automated spacecraft programs with 317 missions from 1979 through 1991 and an additional 23 missions after 1991 and was based on the July 1974 SSPD and the October 1973 payload model. The standard traffic model lists a total of 725 shuttle missions, also based on the SSPD and payload model. More recent traffic models have suggested a reduction in the number of shuttle flights to 572, a reduction of about 21%. Although this does not necessarily mean that the number of missions in the maintenance mission model will be reduced by 21%, a 25% reduction in the number of missions was investigated. In addition, a reduction of up to 50% in the number of missions was investigated. Cost sensitivity study results, for reductions of 25 and 50% in the number of missions flown, indicated that savings of on-orbit maintenance would be reduced from nine billion dollars to about six billion and three billion dollars respectively. Even with these large reductions in the mission model, on-orbit maintenance can still show significant savings over flying all spacecraft in the expendable mode.

The cost sensitivity study also investigated expected variations in the other cost parameters and the effects of these variations on the savings. It was found that variation in parts factors, which represent the fraction of the spacecraft replaced, and in the values used to calculate launch cost reimbursement policy charges could also affect the total savings of the on-orbit maintainable mode, but would not change the major study results. The parts factors used varied from 0.06 to 0.38 with an average value of 0.16. Variations as large as ± 0.08 in parts factors, which represent the maximum expected limits, were found to have an effect of $\mp$ one billion dollars in the total savings. The launch cost reimbursement policy charges could vary due to changes in shuttle launch costs, changes in load factors, and changes in expendable and serviceable spacecraft and module weights and lengths. If expected changes in all the parameters were summed separately, the total effect on savings could be as large as three billion dollars. However, it is anticipated that shuttle launch costs will increase and load factors will probably decrease from the values used in the study, and that both of these factors will increase the savings of on-orbit maintenance over the expendable modes.

Several forms of launch cost reimbursement policy were investigated, ranging from no charge at all to a full charge for each flight required. The major approach based launch costs on length in the orbiter cargo bay and weight to and from orbit. For some spacecraft programs the launch cost reimbursement policy used can affect which of the maintenance modes is least expensive.

E. DEVELOPMENT IMPLICATIONS

Forty-seven types of spacecraft were included in this study and it was determined that the development of one on-orbit servicer maintenance concept would be compatible with almost all of them. No technical reasons were determined that would definitely make any of the spacecraft incompatible with the on-orbit servicer.

The primary maintenance function identified was module replacement--the replacement of a failed module with a functioning module. Both axial and radial module replacement were investigated. Although advantages and disadvantages were found for each type, axial replacement appeared to be better and was the recommended approach. All spacecraft investigated could be made compatible with the pivoting arm and with axial module removal. The important point to be noted is that no problems or constraints were discovered that indicated that any of the spacecraft investigated, or any future spacecraft program, could not be made technically compatible with a module exchange maintenance concept. Certainly some mission equipment items or subsystems on an individual spacecraft might not lend themselves to module exchange as easily as others, but, if necessary, they could be included as part of the nonreplaceable unit (NRU) and still leave the bulk of the spacecraft systems (both standard subsystems and mission equipment subsystems) as space-replaceable units or modules.

A few programs were noted in which an expendable spacecraft would prove more economic under current program plans, but should those plans change, they too could be made compatible with an on-orbit servicer. Seventeen spacecraft in the 47 studied were incompatible with EVA and SRMS maintenance concepts because of the costs associated with bringing these spacecraft to the orbiter.

Specific studies of the effects of including orbital maintenance in the STS show no significant impacts on the STS. Not only were space operations of the orbiter and tug considered, but also detailed ground operations and handling at ETR and WTR. These studies included ground and flight operational functions and support items (ground equipment, logistics, and facilities). Figure V-18 presents a schematic in block diagram form of how an on-orbit servicer might fit into the STS ground processing flow.

Minor impacts were identified (such as additional storage space at the launch site or additional support structures), but no significant impacts were found. As a whole, the pivoting arm maintenance concept is compatible with the space transportation system requirements and plans.

The preliminary design of the pivoting arm servicer concept involves the use of a central docking system. However, a central docking system is not a requirement for the pivoting arm; it can also operate with a peripheral docking system. Figure V-12 presents a schematic of the shoulder details for the pivoting arm mechanism design where a central docking probe system is used. Note that the central docking probe can be removed, and a peripheral docking system mounted to the exterior circumference

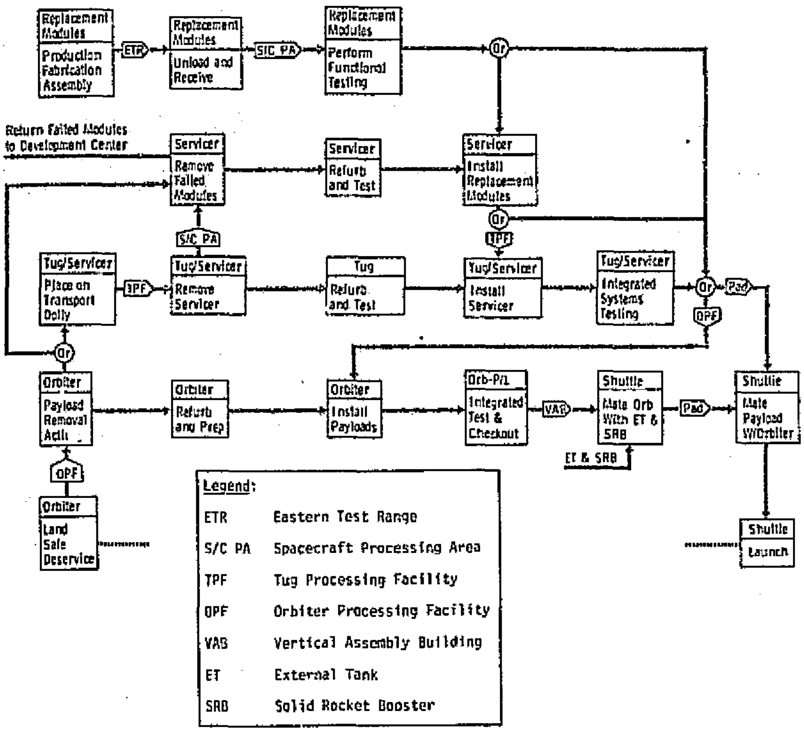

Figure V-18 On-Orbit Servicer Ground Processing Flow

of the stowage rack, without affecting design or operation of the rest of the system.

Although several possible items are suggested for supporting research and technology (SRT) for the development of the on-orbit servicer, no real advances in the state of the art are required for the servicer. One of the purposes of performing the preliminary design of the servicer was to help investigate whether advances in the state of the art would be required. None were identified.

The on-orbit servicer can be thought of as consisting of three separate main subsystems--the stowage rack for the modules and the supporting structure, the mechanism that provides the means to exchange modules, and the control electronics. Several associated subsystems such as docking, telemetry and communications, and power are also included. Interface items between modules/stowage racks, modules/spacecraft, and pivoting arm mechanism/modules are also required. The interface items include latch/

attach mechanisms (SRU interface mechanisms), and electrical, waveguide, and possibly fluid connectors. Although some SRT may be required for each of the subsystems and some development work must be performed, none represent advances in the state of the art.

For the stowage rack and supporting structure, standard aerospace materials and construction techniques are applicable. The pivoting arm mechanism will employ components that have been well-proven in both ground and space activities such as gear drives (gears, shafts, and bearings), torque motors, tachometer generators, brakes, and position sensors. This also applies to materials, finishes, and lubricants.

The recommended control system involved supervisory control with remotely manned backup control and would involve relatively standard force and position sensors feeding into a control electronics assembly. A simplified TV camera(s) with very low frame rates ($\approx$ 3 per minute) can help simplify the communication requirements and system. Ground-based controls and displays are certainly well within the state of the art. Power will be provided by the carrier vehicle (orbiter, tug, IUS, EOTS) and current indications are that sufficient capability will be available, requiring only distribution to the servicer.

Some interface mechanism and connector development will be required, but again these represent no real advancements in the state of the art. A form of a data bus system for electrical signal distribution is expected to simplify the electrical connector and several methods of constructing waveguide connectors have been suggested that are based on already developed systems. The SRU interface mechanisms represent standard mechanical designs and devices including links, rollers, push rods, bell cranks, worm gears, spring-loaded ball detents, and guide rollers. None imply an advancement in the state of the art.

Although the prime thrust of this study served to show that the pivoting arm servicer will be fully compatible with both orbiter operations and full-capability tug operations, it was also noted during the study that the pivoting arm servicer could also be compatible with the proposed earth-orbiting teleoperator system, a geosynchrorous free-flying servicer, the solar electric propulsion system, and potentially with the interim upper stage. A comparison of servicer mechanism production costs with the launch charges to return the servicer from geostationary orbit showed that if enough servicers can be built, it may be cheaper to expend the servicer than return it. This indicates that it could be economically feasible to use servicers on expendable IUS missions. Although the current concepts of IUS may not include a rendezvous and docking capability, if this capability is eventually included, additional savings over the nine billion dollars may be realized by flying expendable servicers on IUS missions. Comparison of the data and requirements from this study with other previous and on-going study contracts at Martin Marietta indicate that a pivoting arm servicer can also be compatible with EOTS operations.

F. USER ACCEPTANCE

One of the development facets noted early in the study was that user acceptance of servicing was a prerequisite before servicing would gain the wide acceptance required to obtain as much of the potential economic benefits as possible. To help obtain early user acceptance, this study concurs with the thoughts of many others that early demonstrations of the capabilities of the on-orbit servicer maintenance concept would be very beneficial. This is particularly true for the designers and builders of geostationary and other tug-delivered spacecraft, which present the opportunity to obtain the full advantages from the on-orbit servicer. Although the prime thrust of the study only considered use of the servicer with the orbiter and full-capability tug, possible additional economic benefits were also shown to exist from the use of the servicer with the IUS. For the entire range of spacecraft, whether low or high earth orbits, it is important that user acceptance of servicing be established as soon as possible, because designs of spacecraft that will be flying in the early portion of the shuttle era will begin in the very near future.

Demonstrations of module exchange with an on-orbit servicer should range from early one-g ground demonstration programs in the next few years to early orbital demonstrations in or near the orbiter soon after IOC of the shuttle, and away from the orbiter soon after. These orbital demonstrations should involve activities with an operational serviceable spacecraft and should include and be complemented with remote demonstrations of rendezvous and docking.

To obtain the maximum economic benefits from the on-orbit servicer (9 billion dollars and above), the capabilities of the servicer must be demonstrated to potential servicer users as soon as possible.

VI. STUDY LIMITATIONS

As noted in Chapter II, the IOSS addressed a very wide range of subjects and, while depth has been developed or obtained in most of the critical areas, many detail aspects have not been addressed completely. Our approach was to apply the analysis and evaluation techniques to the level required to derive the conclusions drawn. Sometimes an engineering judgment was made and an approach selected and used without the suboptimization that will properly occur as orbital servicing develops.

This study addressed the application of maintenance to spacecraft programs to reduce costs while maintaining availability. However, it recognized (Fig. IV-1) that there are other ways to maintain availability with possible reductions in cost, the common approach being a higher level of redundancy in mission-critical components. Whether this approach, when applied across the 47 spacecraft programs, is more cost effective than orbital maintenance is not known. However, orbital maintenance can be used to correct wearout and design failures which redundancy cannot overcome.

While not specifically addressed in this study, the literature (and the COMSAT work) indicates that on-orbit servicing and high redundancy together are cost effective when very high availability is required.

In the latter phase of the study, questions were raised as to whether the mission model considered was too large. These questions were answered in our sensitivity analysis by considering drastic cuts in the size of the mission model. The other side of the coin was not addressed. However, it is valid to question to what extent our recommended maintenance approach might be applied to:

1) DOD spacecraft;
2) Sortie missions;
3) Planetary spacecraft (before leaving low earth orbit);
4) Lunar surface bases;
5) Large structures in space; or
6) Space stations.

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VII. IMPLICATIONS FOR RESEARCH

All of the on-orbit servicers considered, especially the one recommended, used approaches, components, techniques, and arrangements that are well within present day state of the art. However, several associated aspects have been identified as candidate supporting research and technology items in the advanced development category. These are discussed in the following sections.

A. CONTROL TECHNIQUES FOR ON-ORBIT SERVICERS

This study recommended a combination of supervisory and remotely manned control. These techniques should be further considered to ensure that the most effective system of control of the module exchange process is employed.

B. SPACE-REPLACEABLE UNIT INTERFACE MECHANISMS

The mechanical interface between space-replaceable units and the spacecraft and stowage rack needs a level of standardization if a single servicing concept is to be used across many spacecraft programs. Although two versions of the SRU interface mechanism have been designed and engineering test units fabricated, a significant amount of technology and development work must be performed before any interface mechanism can be established as a standard.

C. CONNECTORS

When modules or SRUs are exchanged, connectors will be demated and mated with a single push-or-pull action. No such connectors suitable to this use were found, and they must be developed. In addition to the usual electric power and electronic signal connectors, waveguide connectors are needed. There is also a probable need for fluid connectors and some consideration should be given to thermal connectors.

D. ON-ORBIT SERVICING ONE-G DEMONSTRATION FACILITY

This facility is needed to study the exchange of modules in one-g so control systems, latches, trajectories, connectors, and tolerances can be investigated and basic data developed for application to flight hardware development.

E. LONG-TERM SPACE ENVIRONMENTAL EFFECTS

The long-term effects of the space environment on the ability to replace modules and on continued operation of the various parts of the nonreplaceable units are not known. It is desirable to verify predictions that modules can be replaced and that the nonreplaceable units will have an adequately long life.

F. CONTAMINATION PROTECTION

The contamination limits for spacecraft during on-orbit servicing should be established so the appropriate limits for the on-orbit servicer and its carrier vehicle can be established. The servicer itself and the stowage rack can be kept clean by proper shrouding if necessary. However, the carrier vehicles, i.e., orbiter and tug, are not so easily kept clean and development of a "clean" earth orbital teleoperator system should be considered if contamination limits are too stringent.

G. SPACE-REPLACEABLE SOLAR ARRAYS AND DRIVES

Solar arrays and drives are expensive items that were considered as part of the nonreplaceable units but that possibly should be considered for development into space-replaceable units.

VIII. SUGGESTED ADDITIONAL EFFORT

A review of the IOSS efforts and conclusions identified a number of areas that merit consideration for substantial additional effort. They are as follows:

1) Engineering aspects,

   a) Analysis, design, engineering test unit fabrication, and evaluation of on-orbit servicers,
   b) Development of SRU interface mechanisms,
   c) Development of electrical, waveguide, and fluid connectors compatible with SRU interface mechanisms,
   d) Simulations of module exchange including full-scale SRU interface mechanisms,
   e) Investigation of on-orbit servicer control following the approach that has been suggested,
   f) Design of representative serviceable spacecraft,
   g) Development of spacecraft structural configurations that are compatible with space-replaceable units,
   h) Investigation of multiple payload rendezvous techniques and energy requirements,
   i) Evaluation of need for, and possible development of, a thermal connector,
   j) Investigation of alternative materials in on-orbit servicer designs;

2) Economic aspects,

   a) Development of better cost data including spacecraft standardization, flight density, and scheduling effects,
   b) Generation of confidence limits on cost data,
   c) Application to DOD programs,
   d) Investigation of potential servicer benefits with other spacecraft not in the mission model considered herein; i.e., sortie lab payloads, planetary, lunar, and heliocentric spacecraft,

e) Determination of effects of the continuing development of NASA launch cost reimbursement policy plans on economics and operations of servicing,

f) Investigation of availability, lifetime, and servicing strategies with a reliability simulation;

3) Management aspects,

a) Development of on-orbit servicer implementation plan,

b) Investigation of programmatic/scheduling aspects of the STS,

c) Consideration of operational mode alternatives,

d) Evaluation of compatibility of interim upper stage with on-orbit servicing,

e) Consideration of orbit-based servicers (chemical vs solar electric propulsion),

f) Development of techniques for spacecraft program manager selection of maintenance modes,

g) Identification of safety implications,

h) Evaluation of adaptability of the on-orbit servicer to central or peripheral docking systems;

4) User aspects,

a) Development of an on-orbit servicer demonstration plan including on-orbit demonstrations,

b) Identification and fabrication of equipment for concept verification and test facility.