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The Space Station Assembly Phase: Flight Telerobotic Servicer Feasibility

Volume 1: Summary

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ABSTRACT

This report addresses a question raised by the Critical Evaluation Task Force (CETF) analysis of the Space Station: "If a Flight Telerobotic Servicer (FTS) of a given technical risk could be built for use during Space Station assembly, could it save significant extravehicular (EVA) resources?" The report identifies key issues and trade-offs associated with using an FTS to aid in Space Station assembly phase tasks such as construction and servicing. A methodology is presented that incorporates assessment of candidate assembly phase tasks, telerobotics performance capabilities, development costs, operational constraints (STS and proximity operations), maintenance, attached payloads, and polar platforms.

A discussion of issues is presented with focus on three potential FTS roles: (1) as a research-oriented test bed to learn more about space usage of telerobotics; (2) as a research-based test bed with an experimental demonstration orientation and limited assembly and servicing applications; or (3) as an operational system to augment EVA, to aid the construction of the Space Station, and to reduce the programmatic (schedule) risk by increasing the flexibility of mission operations.

During the course of the study, the baseline configuration was modified into Phase I (a Station assembled in 12 flights) and Phase II (a Station assembled over a 30-flight period) configurations. This study reports on the Phase I plus the Phase II or CETF design.

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FOREWORD

The Automation and Robotics Systems Engineering Task was established to provide support for analyses of Space Station automation and robotics issues. The objectives of this task were to assess the fundamental issues of feasibility for a Flight Telerobotic Servicer (FTS) during the assembly phase and to assess the elements of such feasibility.

This report describes a methodology for examining the feasibility of an FTS using two assembly scenarios, defined at the EVA task level, for the 30 shuttle flights (beginning with MB-1) over a four-year period. Performing all EVA tasks by crew only is compared to a scenario in which crew EVA is augmented by an FTS. A reference FTS concept is used as a technology baseline and a life-cycle cost analysis is performed to highlight cost tradeoffs.

This report is divided into two volumes. Volume I summarizes the basic approach and results. Volume II documents in detail the methodology, procedures, and data used to complete the analysis.

ACKNOWLEDGMENTS

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CONTENTS

<u>Figures</u>

Tables

SECTION I

INTRODUCTION

There has been continuous interest in the use of telerobotics for Space Station activities from Congress, the Advanced Technology Advisory Committee, and work package contractors as a possible means for reducing extravehicular activity/intravehicular activity (EVA/IVA) and operations costs, increasing safety, and improving the technology base and spin-off potential of telerobotics. A large-scale analysis of the Space Station assembly phase by the Critical Evaluation Task Force (CETF) in the fall of 1986 resulted in the accommodation of a Flight Telerobotic Servicer (FTS) only as an option for possible use starting at First Element Launch (FEL--the first flight in the Station assembly phase). While the CETF recognized that an FTS could make a substantial contribution to reducing EVA during the assembly phase, it was not clear whether such a system built at a given technical risk would be cost-effective. This question was the motivation for initiating the present study.

Although the FTS has been manifested on the first flight since January 1987, no functions had been specifically allocated to it other than selected servicing tasks. Furthermore, during the course of this study, additional revisions have been made to the Station that divide the assembly phase into Phases I and II. Phase I approximates a CETF configuration assembled during flights 1 through 12 and Phase II represents flights 13 through 30. The contents of the present study represent a CETF-derived configuration (Phase I plus Phase II or flights 1 through 30). A forthcoming report will document the results of the current Phase I analysis.

The dividing point between Phases I and II is referred to as the Permanently Manned Configuration (PMC). Table 1-1 presents the list of flights, timelines, and relevant schedule points used in the study. The period from FEL to PMC is severely constrained for EVA resources due to the short (Shuttle-based) time intervals for assembly (approximately one week). There is a need to displace EVA resources where "need" is defined as an FTS capability to reduce crew-EVA time so that absolute Shuttle-based EVA limits are not exceeded. Furthermore, the FTS must accomplish this reduction in a manner that is at least as cost effective and reliable as available alternatives. After PMC, the value of the FTS can be argued to depend on a more complex set of considerations: life-cycle cost, productivity gains, safety improvements, technology spin-offs, and other factors. This study was focused on cost factors: considerations such as safety and technology spin-off benefits were not explicitly addressed.

The current study examines the costs and benefits that could be achieved during the assembly phase (flights 1-30). The objective was to determine if the FTS could break even within this period.

The purpose of this study is twofold. The first purpose is to define a methodology for evaluating the feasibility of using telerobotics during the assembly phase of Space Station construction. The second purpose is

Table 1-1. Assembly Phase Timelines and Definitions

Assembly Flight Number	Assembly Phase Sequence Number	Time
MB-1	1	First Element Launch (FEL)
MB-2	2	5 flights
MB-3	3	
MB-4	4	
	5 Polar Platform	<-- end year 1
MB-5	6	
	7 Outfitting Logistics	
MB-6	8	
	9 Polar Platform	8 flights
MB-7	10	
MB-8	11 Logistics	Permanently manned config. (PMC)
MB-9	12	
	13 Logistics	<-- end year 2
MB-10	14	
	15 Logistics	
MB-11	16	
	17 Logistics	8 flights
MB-12	18	
	19 Logistics	
MB-13	20	
	21 Logistics	<-- end year 3
MB-14	22	
	23 Logistics	
MB-15	24	
	25 Logistics	9 flights
	26 Polar Platform	
	27 Logistics	
MB-16	28	
	29 Logistics	Initial Operating Capability (IOC)
MB-17	30	<-- end year 4

to illustrate the methodology by collecting data and performing a case study analysis. This volume summarizes the detailed results of the study contained in Volume II.

The scope of this study is aimed at answering the question, "Can an appropriately designed FTS operate in a cost-effective manner as early as First Element Launch (FEL) when applied in a routine, operational fashion to expected assembly phase Station tasks?"

The first step toward answering this question involved defining, to the extent possible, a baseline set of Station assembly tasks, maintenance tasks, attached payload setup and servicing tasks, polar platform setup and servicing tasks, logistics, and satellite servicing facility tasks. From these tasks, a telerobotics technology assessment was performed to derive an FTS "Reference System" capable of performing a reasonable subset of the tasks according to explicitly defined criteria. The original task list, called the technically feasible task set, was reviewed in the context of EVA and IVA budget constraints, proximity operations rules, and other operational constraints to derive an operationally feasible task set--those tasks that could be performed by an FTS Reference System.

The operationally feasible tasks were used to estimate the EVA and IVA requirements for two cases: (1) an EVA-Only case in which flights 1 through 30 are performed without an FTS, and (2) an EVA+FTS case in which an FTS is present to displace EVA. The EVA/IVA requirements for the two cases were used in a life-cycle cost framework developed specifically for evaluating the benefits and costs of an FTS in the Station environment. The FTS Reference System costs were estimated using a bottom-up approach, and a variety of scenarios were examined.

The report is divided into two volumes. Volume I is a summary of the study and consists of seven sections. Section I is the introduction; Section II describes the approach; Section III characterizes the FTS Reference System; Section IV summarizes the EVA/IVA resource requirements; Section V presents the results of the cost analysis; Section VI presents the issues and implications of the analysis on future decisions; and Section VII presents the conclusions and recommendations.

Volume II contains the details of the study. Section I introduces the purpose, background, and scope of the study. Section II provides an overview of the methodology. The definition of a reference FTS design for the study is described in Section III. Section IV identifies the operational constraints and operationally feasible tasks. Section V derives the EVA and IVA time estimates for the EVA-Only and EVA+FTS cases. Section VI describes the estimation of FTS costs, and the economic evaluation is presented in Section VII. Section VIII contains the results of the study, followed by the discussion and conclusions in Section IX. References are listed in Section X.

SECTION II

APPROACH FOR COMPARING SPACE STATION TELEROBOTICS OPTIONS

A comparison of Station telerobotics options involves many complex factors. The objective is to provide a systems-level methodology that addresses the important components affecting the value of an FTS to the assembly phase. The study approach is illustrated in Figure 2-1.

A technically feasible task set is derived from the CETF results and modified to include more detail at the subtask level. In parallel with this activity, an FTS Reference System is derived that could perform a subset of the assembly phase tasks at a level of technical readiness corresponding to FEL.

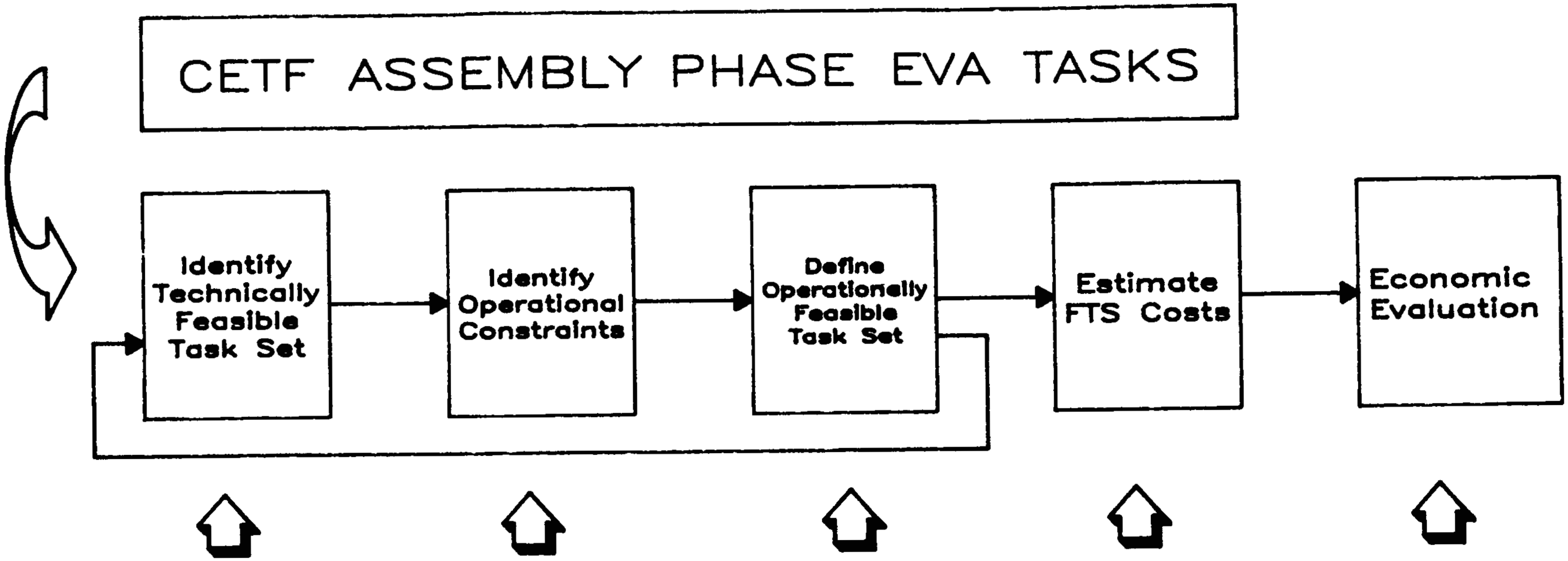
The operational constraints consisting of EVA and IVA budgets and proximity operations rules are applied to the technically feasible task set to obtain an operationally feasible task set. The following categories of activities are examined to estimate the EVA and IVA times for two cases: EVA-Only (no FTS) and EVA+FTS (FTS present).

(1) Assembly tasks
(2) Maintenance tasks
(3) Attached payload setup and servicing tasks

The areas of logistics and the satellite servicing facility were also examined but were not included due to a lack of data. Polar platform setup and servicing tasks were also examined but later removed due to major changes in polar platform assumptions during the course of the study (such as moth-balling the western launch facility).

The operational constraints are overlaid on the technically feasible task set to derive an operationally feasible task set, and the FTS Reference System definition was revised to reflect the operational constraints. The EVA and IVA times for the two cases were estimated by flight (1-30), category (assembly, maintenance, attached payloads, and polar platforms), and year (1-4).

The FTS Reference System definition is used to generate a bottom-up cost estimate for the economic evaluation of the EVA-Only and EVA+FTS cases. The basis for the evaluation is to examine the operational savings due to the FTS Reference System versus the investment cost to design, build, and deliver the FTS Reference System. Regions of cost-effectiveness are examined in Section IV.



Identify
EVA Tasks

Forecast
FEL FTS
Technology

Define FTS
Reference
System

EVA/IVA Budgets
- Assembly
- Maintenance
- Attached Payloads
- Polar Platforms*
- Logistics*
- Satellite Serv.*

Identify
Proximity
Operations Rules

Develop Method
For Estimation
of EVA/IVA for
EVA-Only and
EVA+FTS Cases

EVA/IVA for:
- Assembly
- Maintenance
- Attach. Payloads
- Polar Platforms
- Logistics

Develop Cost
Model

Collect data
for EVA-Only and
EVA+FTS Cases

Component Cost
of FTS Reference
System:
- Hardware
- Software
- Integration

Launch Costs

EVA-Only Case
EVA+FTS Case

FTS Technology
Issues

Cost Issues

Risk
Considerations

FTS Roles

*Examined but not included in the final results

SECTION III

FLIGHT TELEROBOTIC SERVICER REFERENCE SYSTEM

To assess the benefits and costs of an FTS, a design concept is required to focus the required technology capabilities and estimate costs. An FTS system is needed that is appropriate for specific EVA tasks required for assembly and operation of the Space Station between FEL and IOC. Such an FTS forecast addresses the availability of critical constituent technologies required at FEL, and highlights essential support characteristics such as FTS reliability, maintenance, and associated logistics support. Selection of technology capabilities must also consider schedule requirements (when must the system be operational), technology and system integration, system verification and testing, and system integration into Space Station operations. The objective is to identify a low-risk, technically feasible FTS Reference System that could be ready by FEL and could perform a set of operationally feasible tasks during the Space Station assembly phase (see Figure 3-1).

Before developing a reference configuration, the functional requirements for the system as a whole must be understood. As the desired functional capabilities are explored, obvious conflicts between FEL functions and technologies are identified and used as discriminators to maintain the list of functional requirements within the realm of feasibility (e.g., tasks requiring a considerable amount of on-line planning for fault management, or a large degree of dexterous manipulation, would not have the commensurate technology in place to meet the task needs). Tasks considered technically feasible in the FEL to IOC time frame include (1) basic assembly tasks such as pallet handling, worksite preparation, or truss assembly in a well-defined, almost industrial robotic type environment, (2) simple orbital replaceable unit (ORU) change-out and inspection type tasks on payloads, (3) Space Station support tasks such as surface cleaning and inspection, (4) pick-and-place type logistic tasks such as transferring components or fluid consumables from the Shuttle to the Station, and (5) other support such as transporting equipment from one place to another, holding equipment in place while it is worked on by EVA astronauts, or providing on-site visual monitoring of an EVA task.

Given a set of possible technically feasible tasks, telerobot technologies are matched against those tasks. The key variables in selecting the technologies are:

(1) Level of technology readiness (i.e., with FEL being the deadline for delivery)
(2) Degree of system integration
(3) Accuracy and repeatability requirements
(4) Reliability
(5) Retrofit considerations in terms of future growth in capabilities

An important element of technology readiness is whether the technology has the potential for being flight-qualified by FEL. Empirical data gathered

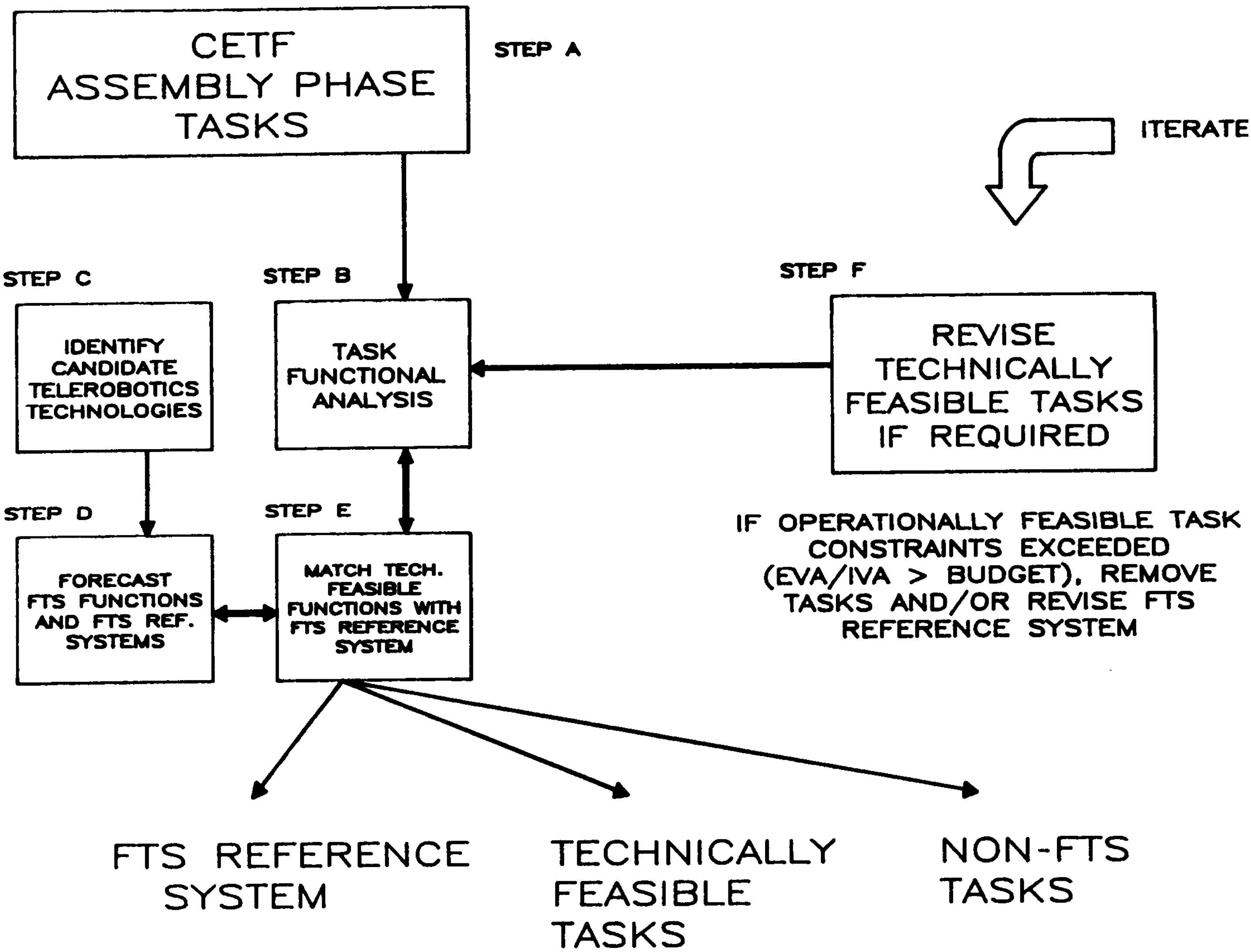


Figure 3-1. Procedure for Identification of Operationally Feasible Tasks and FTS Reference System

on system development elapsed time from concept to full operational capability (i.e., space qualification) suggest a time frame between five and ten years for moderately complex systems, and ten to twenty years for complex systems. Therefore, considering the FTS system as a moderate-to-complex design with an appropriate logistics support program in place by FEL, it was determined that likely FTS robotic technologies would probably not exceed the present state-of-the-art unless a flight test program or other experience gathering mechanism were introduced to reduce risk.

The next step in identifying a reference system is to develop an array of "strawman" FTS configurations that contain the required robotic technologies while meeting the projected task requirements. It was understood that the same tasks could be done in different ways, depending on the FTS configuration. For example, employing a more sophisticated configuration such as a mobile FTS versus a fixed FTS offers greater flexibility and a wider range of applicability in task performance. More importantly, by developing several strawman configurations, it is possible to understand how other factors such as operational constraints (e.g., FTS operations in proximity to EVA) might influence the selection of a particular configuration over another. Although this study focuses on providing a methodology for performing FTS trade-offs, the reference configuration activity provides a basis for application of the methodology in the future to a variety of FTS designs.

Several design configurations are developed in case options prove infeasible when operational or cost constraints are considered. In this study it is likely that EVA-FTS proximity operations constraints could severely limit the possibility of any type of free-flying FTS being deployed. System control constraints imposed by the task environment and available technology could also limit the ability of the system to compensate for self-induced or environmentally induced dynamic disturbances or changes in the preplanned task environment. For control and vision purposes, the approach is to select the most reasonable reference configuration from the subset of strawman designs having a fixed base in which the fixed base is fastened and the FTS is transported manually to the base using the Shuttle RMS or the MSC where it is connected for operations.

A total of twelve basic configurations are developed, ranging from a simple component/tool handler and site visual monitor, to a free flyer that could transport components/materials, and perform the suggested assembly, ORU replacement, and support tasks. The final reference configuration selected as the FTS Reference System is a design more limited than the mobile options, but more capable than the fixed position (nonmobile/zero arm) or single-arm manipulator options. The design (see Figure 3-2) is a fixed-base configuration that can be moved from one worksite to another via the Mobile Remote Manipulator System (MRMS) and once inserted in the worksite adaptor, the power plugs on the base of the FTS automatically mate with the power plugs on the adaptor (which would be attached to a truss member). The selected design has dual-arm master/slave control with two auxiliary arms (one for lighting and one for vision), which are not coupled to the upper arms. The two auxiliary arms represent technology hooks for eventual growth to multiple-arm coordinated control. In the interim, it is envisioned that the two

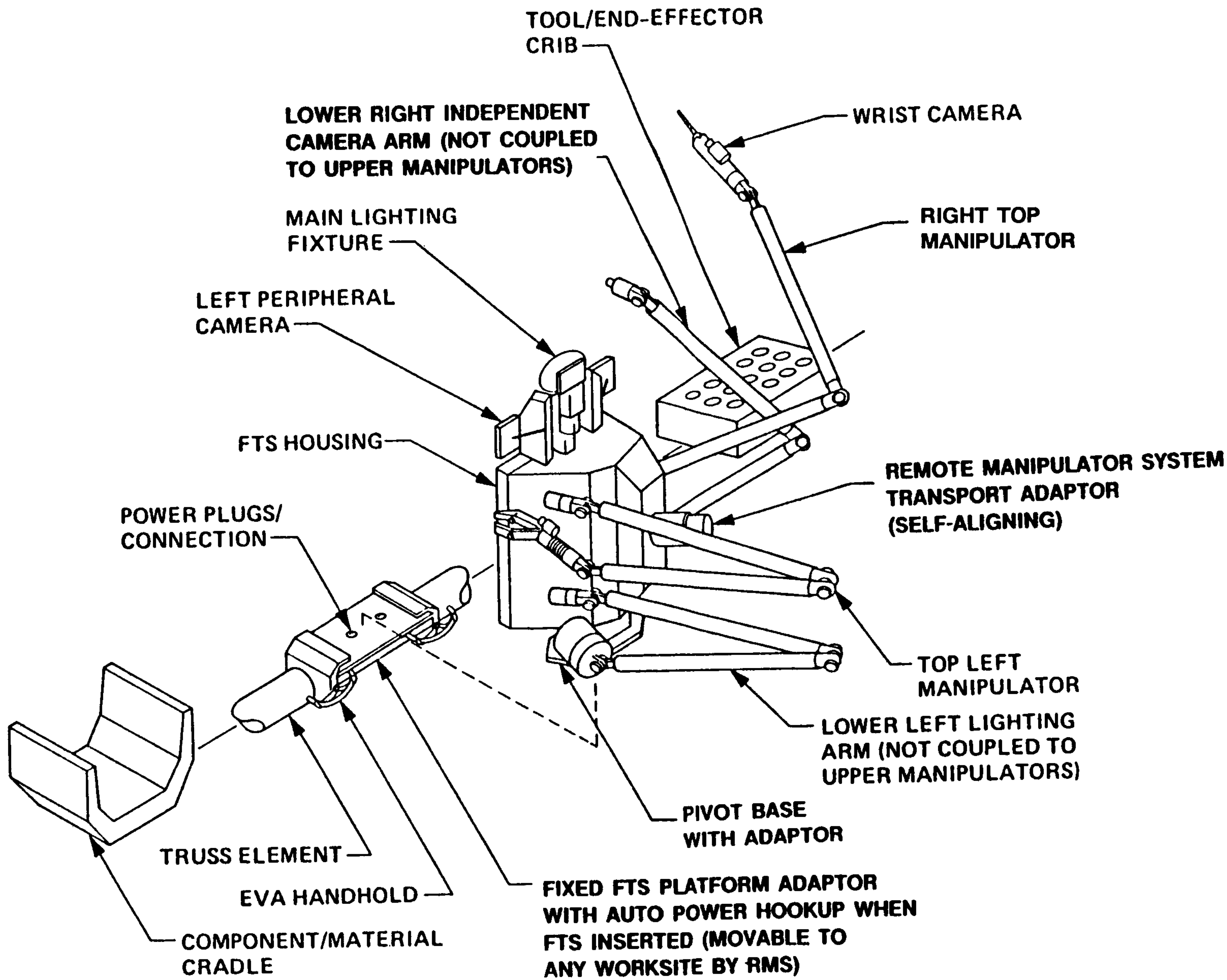


Figure 3-2. FTS Reference System Components

auxiliary arms would be independently controlled by voice or teleoperation and would only act in a support role to the master/slave arms with no grasping functions.

The operational scenario for the FTS Reference System is: (1) the FTS is positioned in the adaptor by the MRMS; (2) the FTS is then loaded with the specific control routine for that specific worksite; and (3) with the adaptor position representing a known set of reference coordinates to the telerobot, the FTS then proceeds to perform its pick-and-place, assembly, or ORU change-out tasks within a well-defined work envelope. Use of structural jigs, object labeling, or compliantly (robot friendly) designed assemblies is considered acceptable as a means of further structuring the work environment.

In summarizing this section, it should be noted the FTS Reference System selected for evaluation is selected primarily as an example. However, as an example, it is important to show, through the analysis, that the example is representative of a possible configuration that meets sound design, functional, and safety criteria. The example also provides a reasonable starting point for attempting to establish the actual cost regime of a system such as the FTS. Other available designs for a servicer presently emphasize the teleoperation portion of FTS control. The FTS Reference System selected for this study addresses both autonomous and teleoperation aspects of FTS design.

SECTION IV

ASSEMBLY PHASE EVA/IVA RESOURCE ESTIMATES

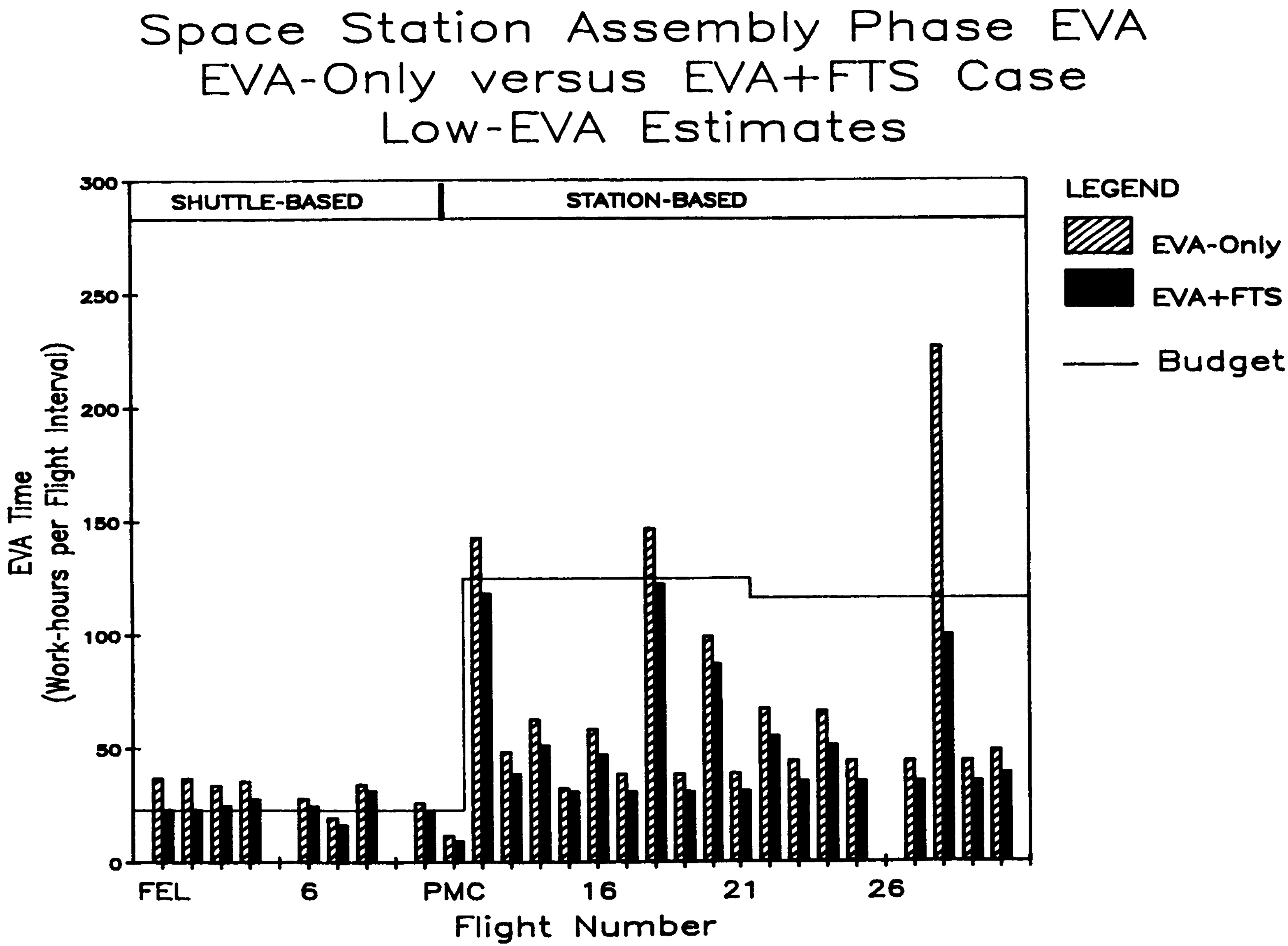
Due to large uncertainties in some of the data components, ranges are used to bound the results. Where indicated, the range of uncertainty applied to an estimate is arbitrarily chosen as $\pm$ 20%. The size of the range used is a parameter of the methodology and can be varied as the situation warrants. It should be noted that a formal analysis of these uncertainties was not performed. Hence, estimates with narrow ranges or point estimates should <u>not</u> be construed as having less uncertainty than estimates with wider ranges.

Figures 4-1 and 4-2 illustrate the total EVA times per flight for the EVA-Only and EVA+FTS cases. Figure 4-1 represents the total EVA times for the <u>low-range</u> EVA estimates for assembly, maintenance, and attached payloads. Figure 4-2 represents the total EVA times for the <u>high-range</u> EVA estimates. The low-range values represent the lowest estimates for the EVA range obtained by adding all the low values together and the high-range estimates represent the highest values of each range obtained by adding all the high values together. The aim was to bound the actual values by examining the extreme low and high values.

The low-range estimates of Figure 4-1 are troubling. The estimated EVA required on five flights prior to PMC exceeds the budgeted amounts of 24 hours. This finding supports the argument that the CETF assembly sequence does not manifest within the CETF constraints for at least three early flights. This is due primarily to assembly on flights 1 and 2 and maintenance and attached payload contributions on subsequent flights. The implication is that for the CETF design to work, one or more shuttle flights must be added, the current shuttle flights must be extended (unlikely), or there must be a remanifesting of assembly EVA to meet the constraints. A combination of remanifesting and additional flights is examined here. It is the cost of additional shuttle flights that tends to make the FTS an attractive option. Figure 4-1 also shows how increased EVA budgets after PMC dramatically increase the amounts of available EVA through flight 22.

However, after flight 22, there is a dramatic drop due to (1) the "catching up" of maintenance required to handle numerous start-up failures during assembly, a reduction in assembly (only two out of seven flights, and more nonassembly related flights for logistics (23, 25, 27, and 29), and attached payloads (30). The exception is flight 28, when the transverse boom is erected. Notice also that most of the FTS-displaced EVA occurs in flight intervals 12, 18, and 28, when trusses are installed.

Although assembly might be a prime candidate for FTS application, Figures 4-3a and 4-3b indicate that maintenance, by far, is the largest consumer of EVA time during the assembly phase. Maintenance EVA ranges from 54% to 57% of the total EVA time. Further analysis could indicate that configuring the FTS to perform general maintenance on a Station-wide basis would prove beneficial. Assembly is the second largest consumer of EVA time at approximately 32% to 36% of assembly phase EVA.


Space Station Assembly Phase EVA
EVA-Only versus EVA+FTS Case
Low-EVA Estimates
SHUTTLE-BASED
STATION-BASED
LEGEND
EVA-Only
EVA+FTS
Budget
EVA Time
(Work-hours per Flight Interval)
0
50
100
150
200
250
300
FEL
6
PMC
16
21
26
Flight Number

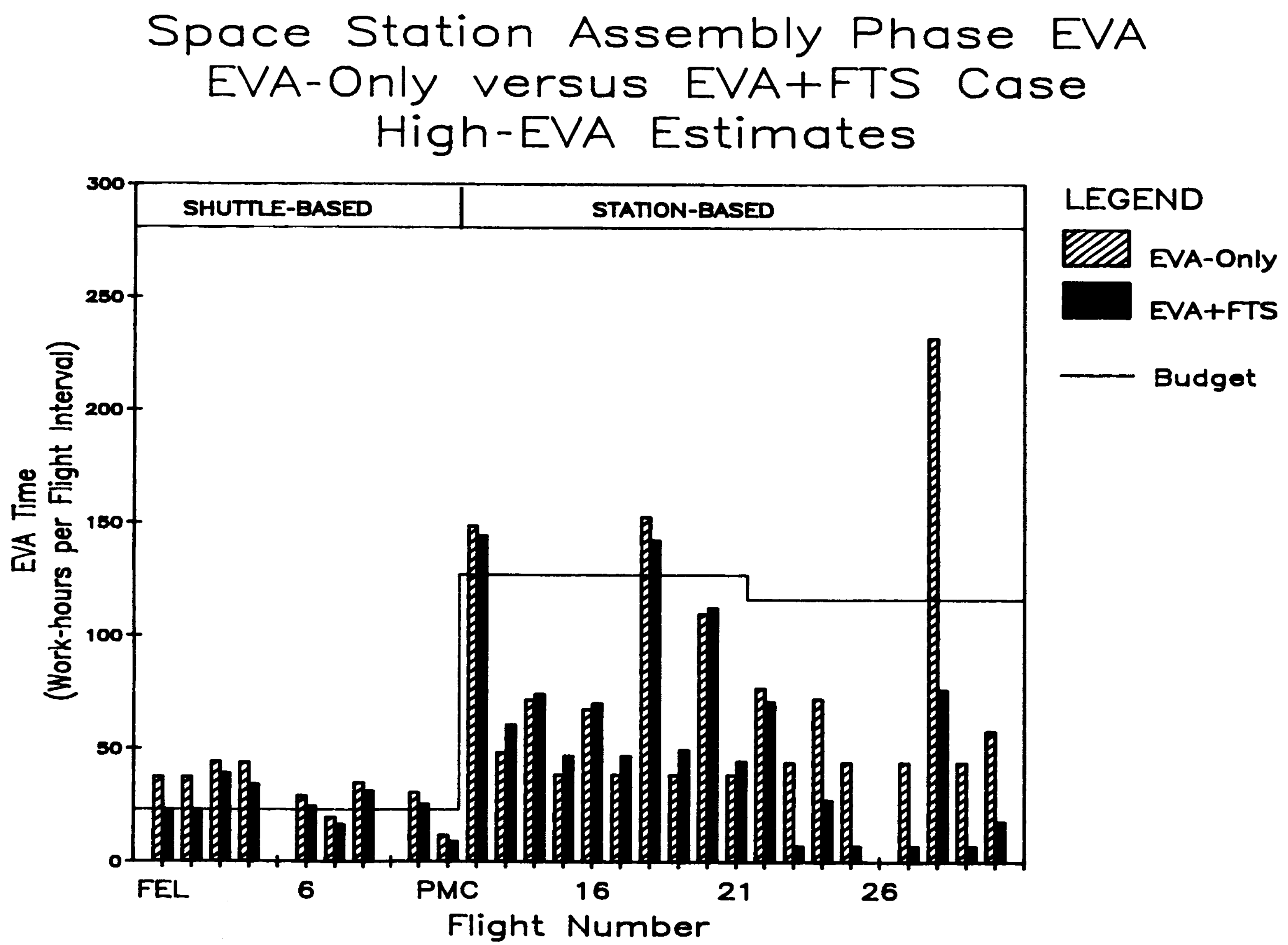


Figure 4-2. High-Range EVA Estimates

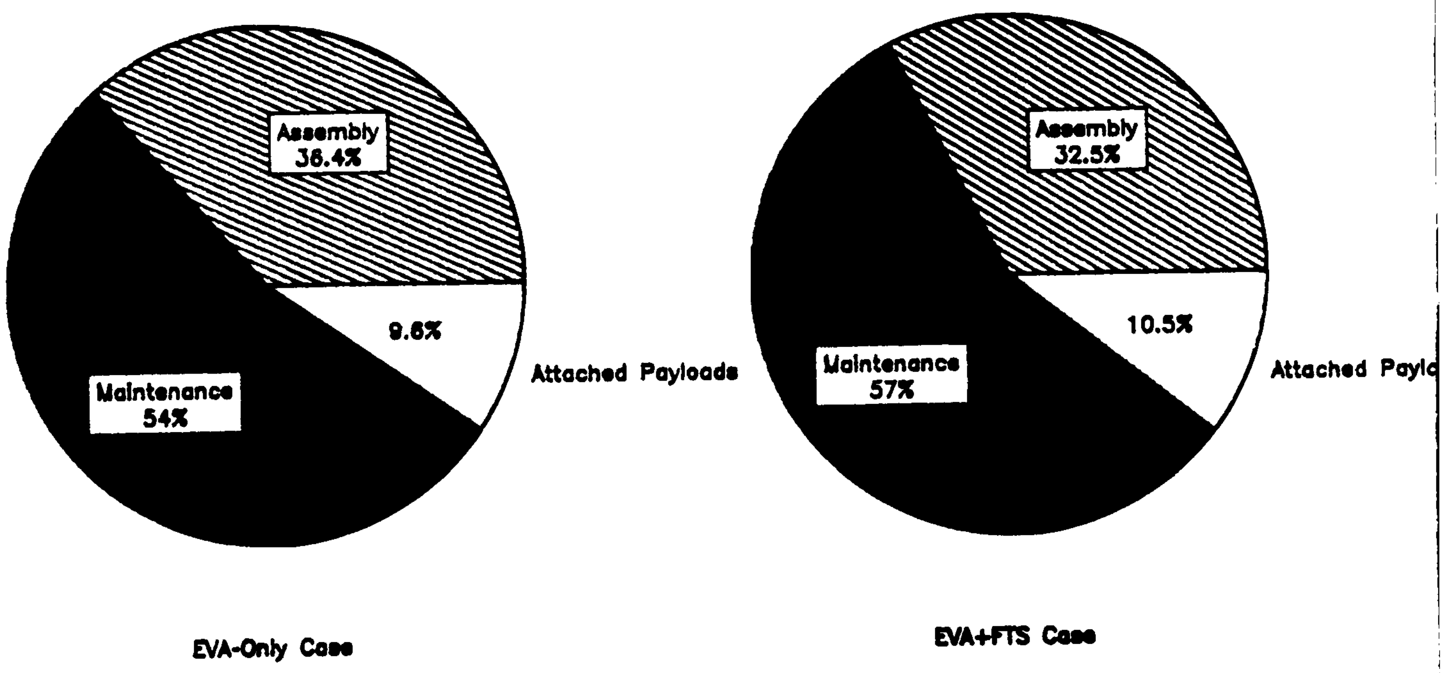


Figure 4-3a. Low-Range EVA Distribution, FEL-IOC

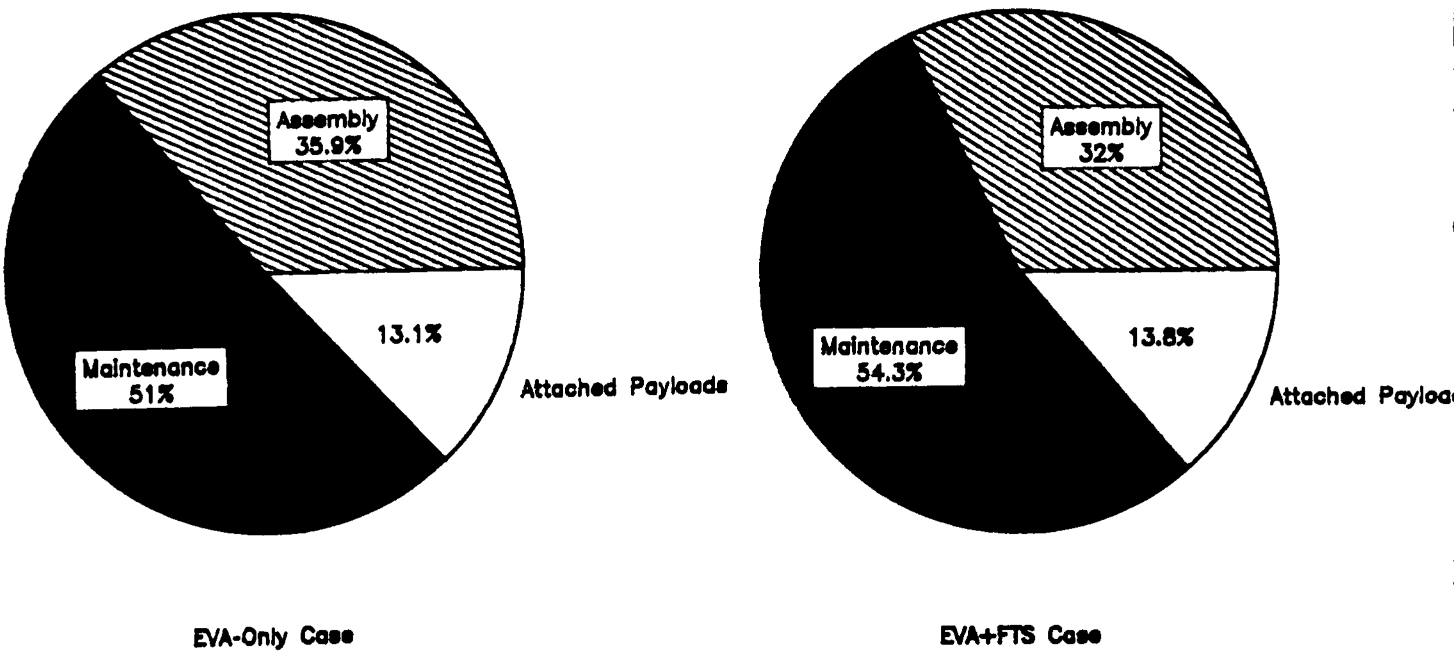


Figure 4-3b. High-Range EVA Distribution, FEL-IOC

The focus on assembly EVA occurs during the period FEL to PMC, when EVA is Shuttle-based. During this period, assembly EVA ranges from 59% to 65% while maintenance ranges from 30% to 31%.

IVA time estimates are not as severely constrained as EVA. Figure 4-4 displays the budget distribution of IVA for the assembly phase, showing significant resources allocated to user payloads. This result highlights the assumption that much of the user support will occur within pressurized volume rather than the space environment. Figures 4-5a and 4-5b present the IVA estimates for FEL-IOC. While the allocation for attached payloads is below the budget of 45% (25% to 31%), there is an imbalance between the assembly and maintenance categories as shown below (derived from Tables 4-1 and 5-6 in Volume II).

	Budget	Estimates
Assembly	31.5%	27% to 29.6%
Maintenance	24.0%	40.8% to 47.7%
Attached Payloads	44.5%	25.3% to 30.6%

The assembly values are within the budget but outweighed by the maintenance estimates. Less time is required for attached payloads but more is required for maintenance.

The estimates for the two cases are used to compute the operations cost savings in the next section.

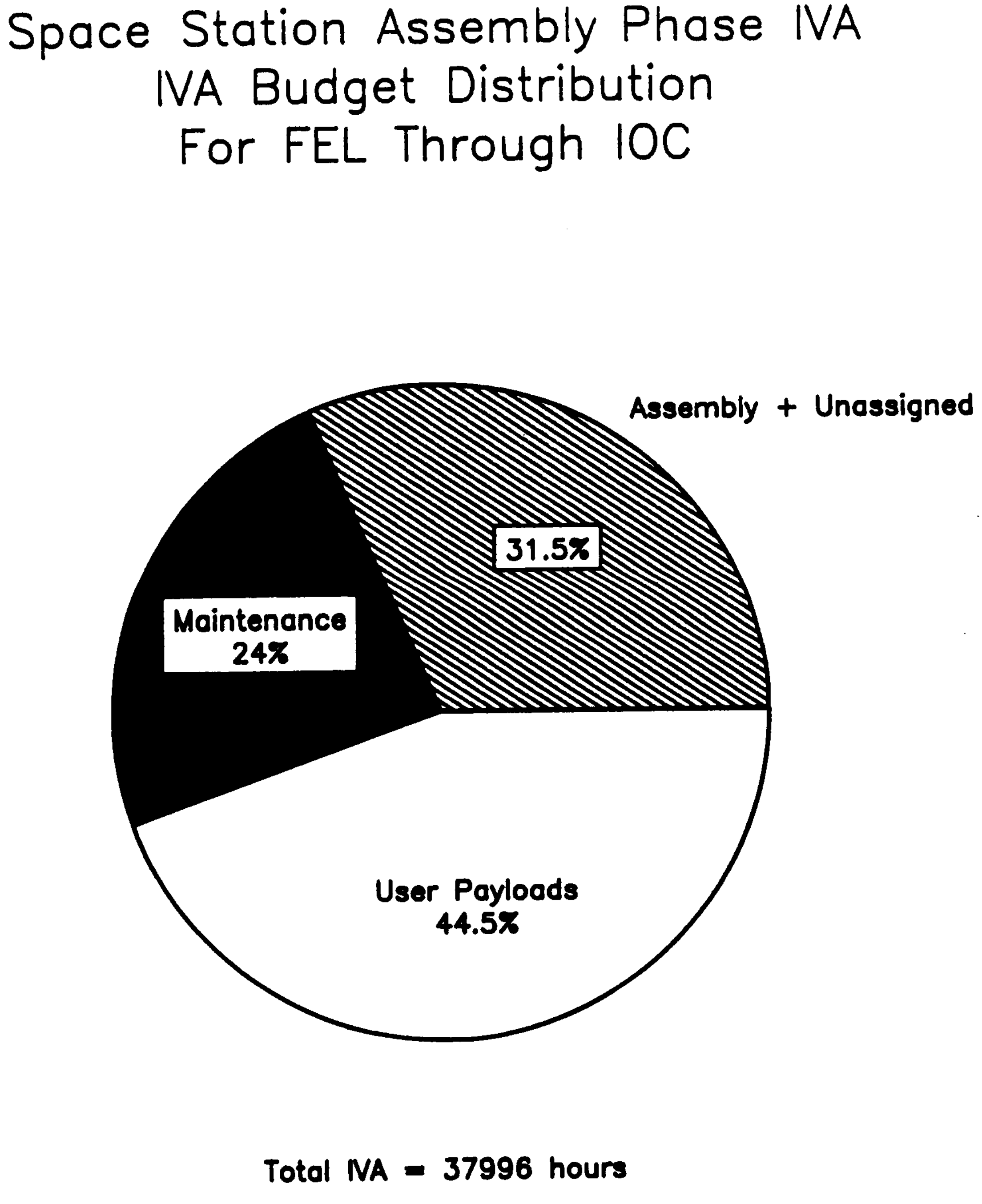


Figure 4-4. IVA Time Budget Distribution, FEL-IOC

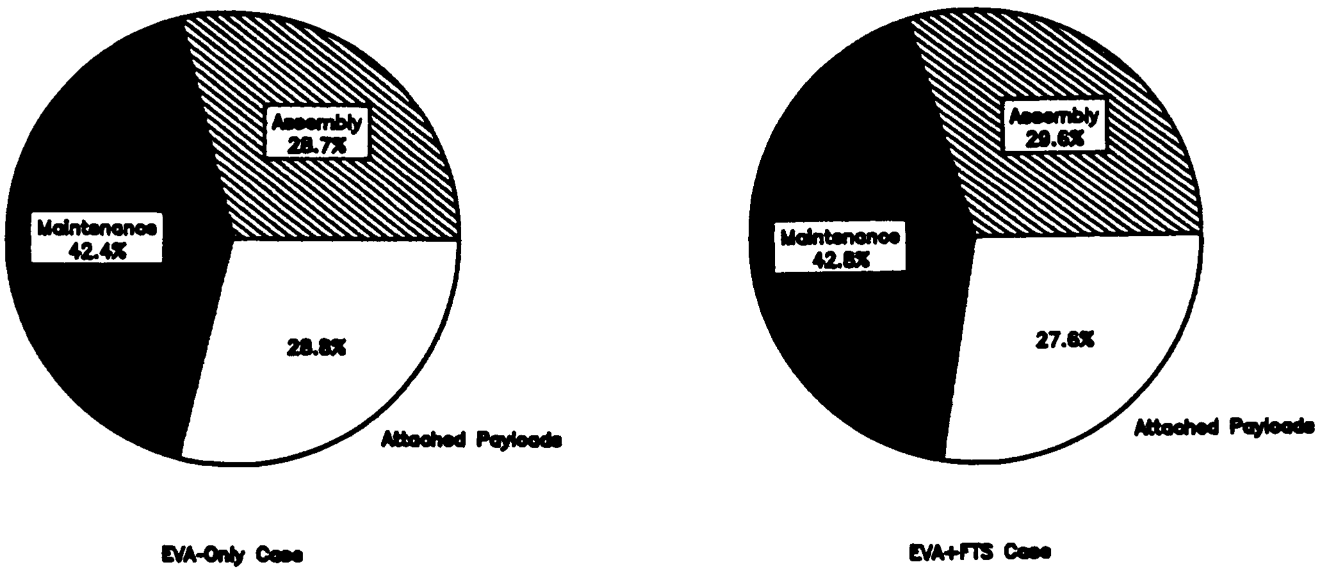


Figure 4-5a. Low-Range IVA Distribution, FEL-IOC

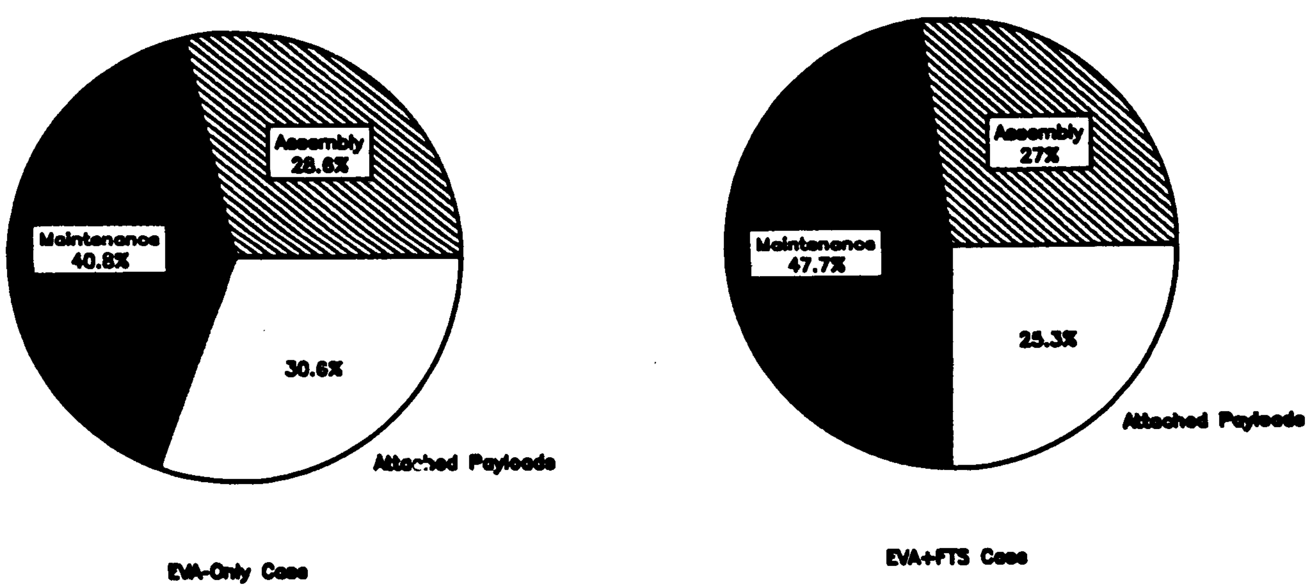


Figure 4-5b. High-Range IVA Distribution, FEL-IOC

SECTION V

ASSEMBLY PHASE COMPARISON WITH AND WITHOUT THE FTS

An economic model was developed to examine the cost-effectiveness of the FTS Reference System and to determine whether the FTS could be cost-effective during the assembly phase using two cases. The two cases defined are denoted the EVA-Only case (no FTS) and the EVA+FTS case (FTS present). The Net Savings model is:

> Net Savings Due to the FTS Reference System -
> (Operations and Maintenance Cost of EVA-Only Case
> minus
> Operations and Maintenance Cost of EVA+FTS Case)
> minus Investment Cost of the FTS.

If the Net Savings is positive, the FTS Reference System is cost-effective.

The economic approach is summarized by Figure 5-1. The use of this approach required a cost estimate of the FTS Reference System. A bottom-up cost estimate was made using the component list for the FTS Reference System defined in Section III. An estimate of $277 million (M) to $304 M was obtained for the FTS (excluding nonprime costs and spares costs).

The approach used here examined the costs and benefits from the development of the FTS up to the completion of the assembly phase. The issue was the feasibility of using the FTS to assist in the assembly process only, so the benefits to users or the Station after the assembly phase were not examined. FTS ground operations costs were included using estimates of FTS operating costs, but explicit estimates of ground support were subsumed into the EVA and IVA cost estimates.

Using these cost estimates and the EVA and IVA profiles from Section IV, a series of analyses were performed to determine the feasible region for the FTS Reference System.

The results indicate that a key trade-off is between the cost of the FTS and the cost-per-flight of the STS. Because there are cases in which the estimated EVA exceeds the budget of 24 hours during FEL to PMC, additional flights must be added to make up the difference. The cost of any added flights is a major factor in the cost-effectiveness of the FTS. Figure 5-2 presents one such trade-off region using the low-range estimates of EVA/IVA and the FTS cost over a range of STS costs per flight from $105M to $178M. It was difficult to determine an estimate for STS prices. Estimates have ranged from below $100M to $150M during the pre-Challenger era. A reasonable assumption is that the price will be higher in the post-Challenger era due to increased safety and reliability requirements, component redesigns, and quality control constraints. However, a range of price curves is presented to provide a generalized result. The FTS cost ranges from a low $232M (NASA estimate) to $340M (National Research Council estimate); the endpoints were selected merely to limit the scope of the

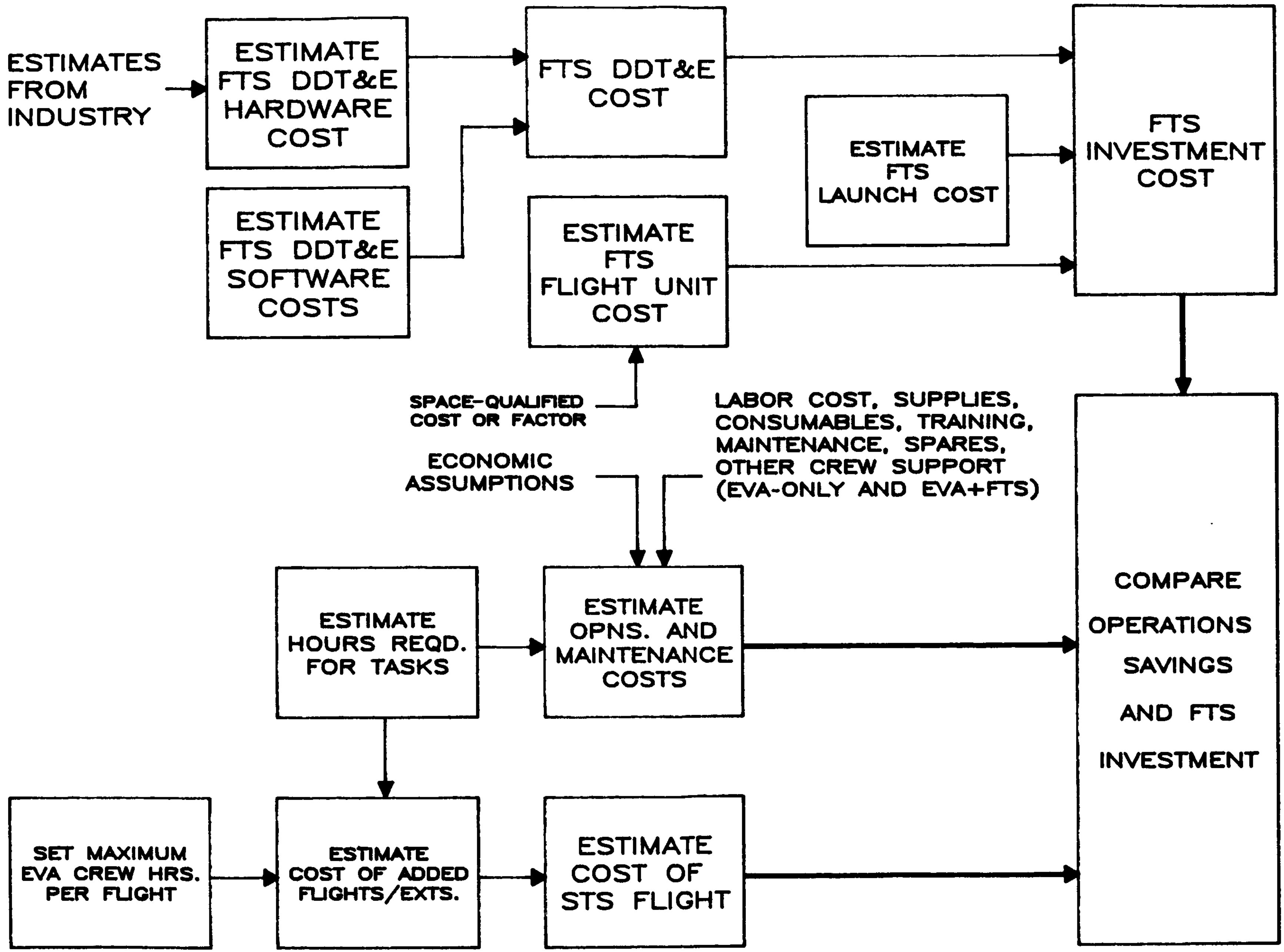


Figure 5-1. Economic Evaluation Procedure

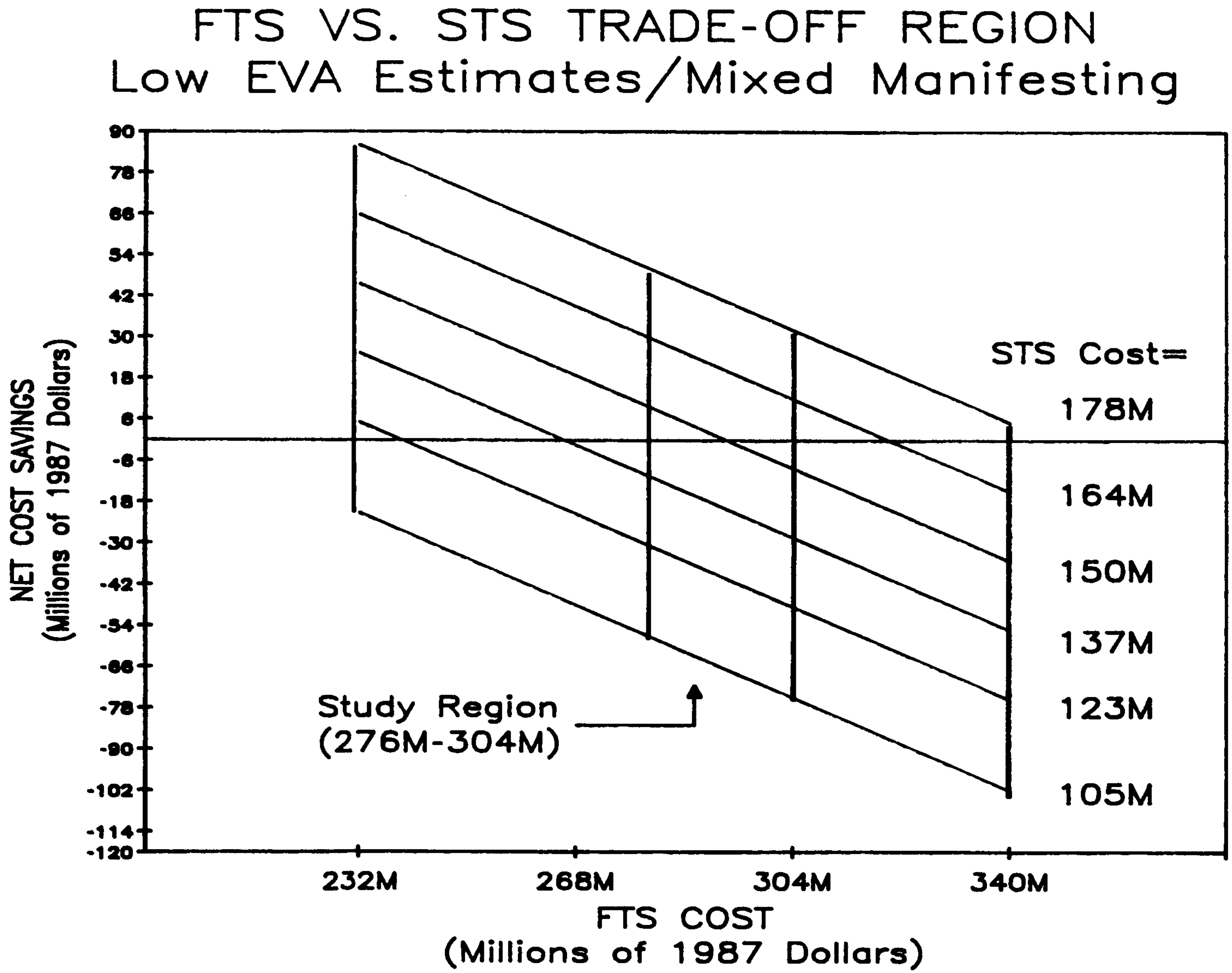


Figure 5-2. FTS versus STS Trade-Off Region--Low EVA Values

trade-off region. The area in the center of the region bounds the FTS Reference System costs estimated in the study. As an example, if we assume a STS cost of $150M, the FTS will break even if it can be built for a cost of $292M or less. If the FTS costs more than $292M, it will not be cost-effective (unless the STS price is actually higher). For the other points on any of these curves, the estimated net savings can be read from the axis on the left.

Also note the term "Mixed Manifesting" on Figure 5-2. This refers to the assumptions made regarding how excess EVA is remanifested on subsequent flights if an additional flight is required. There are three cases. The inflexible manifesting case assumes that it is extremely difficult to remanifest or carry forward any excess EVA not used on a required flight. This scenario tends to require more additional flights than the flexible manifesting case. The flexible manifesting case assumes it is easy to remanifest excess EVA--any subsequent requirement for more EVA simply absorbs what it needs from the excess. In other words, the EVA is treated like work-hours. If Flight 3 needed 4 additional hours, a flight would be added, leaving an excess of 24 - 4 = 20 hours. Then if Flight 8 needed 6 additional hours, instead of adding another flight (as in the inflexible case), the 6 hours would be taken from the current balance of 20 hours, leaving 14 (20 - 6 = 14) hours remaining for any subsequent excess demands. Obviously both the inflexible and flexible cases are extremes. The mixed manifesting case is between the two. If EVA is required on the early flights (1-5), the inflexible assumption is invoked. After Flight 5, a flexible scenario is assumed.

If the scenario is moved toward the flexible manifesting assumption, the trade-off region moves down (toward less cost-effective) because fewer overall flights are required. If the scenario is moved toward the inflexible manifesting assumption, the region moves up (more STS flights are required). Furthermore, as the difference between the number of additional flights in the EVA-Only case and the EVA+FTS cases (if any) becomes larger, the width or spacing between the curves also becomes larger. The constant slope of the curves (approximately -0.75) is an indication that for each reduction in FTS cost of one dollar, there is an increase in net savings of only $0.75. The remaining 25% is the discounted delivery cost.

The region in Figure 5-1 is for the low-range EVA values. If the high-range EVA values are used, the region moves down. Similarly, as the estimated cost of the FTS increases, cost-effectiveness drops (the region shifts downward).

Another parameter of interest is the EVA cost per hour used to estimate the cost of EVA hours used. As with the STS cost, the estimation of such a value is difficult. To examine the sensitivity of the results to EVA cost per hour, three cases are displayed in Figure 5-3, using $45,000 ($45K), $35K, and $25K per hour. Note the apparent insensitivity of the region to this parameter. This is due to the magnitudes of the numbers between the FTS and STS costs. A decrease in the cost per hour simply places less value on the resource benefits the FTS can displace and thus makes the FTS region move down.

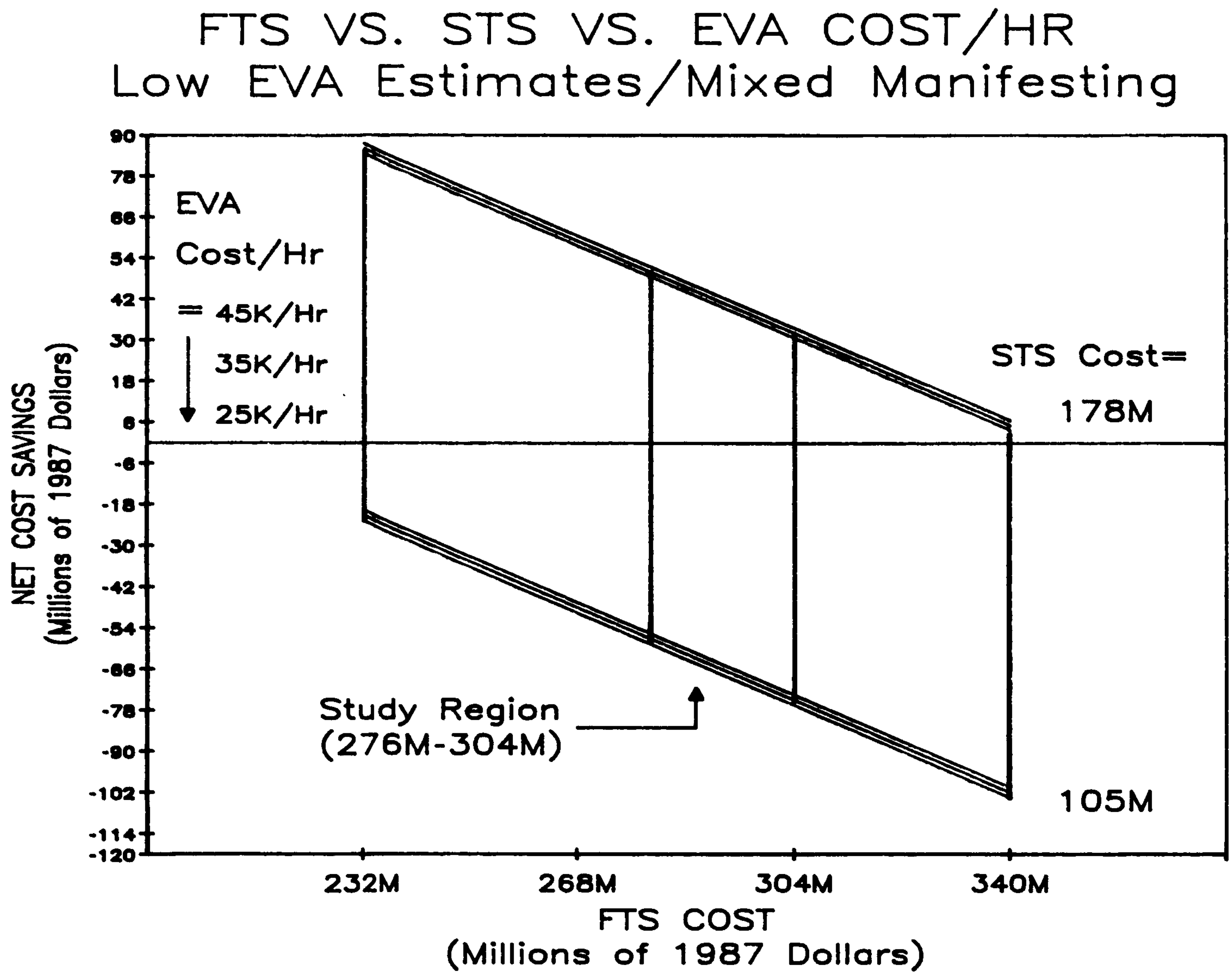


Figure 5-3. FTS Cost versus STS Cost versus EVA Cost per Hour

The discount rate used in the above results is the Office of Management and Budget (OMB) value of 10% used for cost-benefit analysis on government projects. The effect of varying the discount rate was also examined using a 6% rate (Figure 5-4). The effect of reducing the discount rate is to move the trade-off region up significantly. This indicates that a lower discount rate would have a significant impact on improving the cost-effectiveness of the FTS.

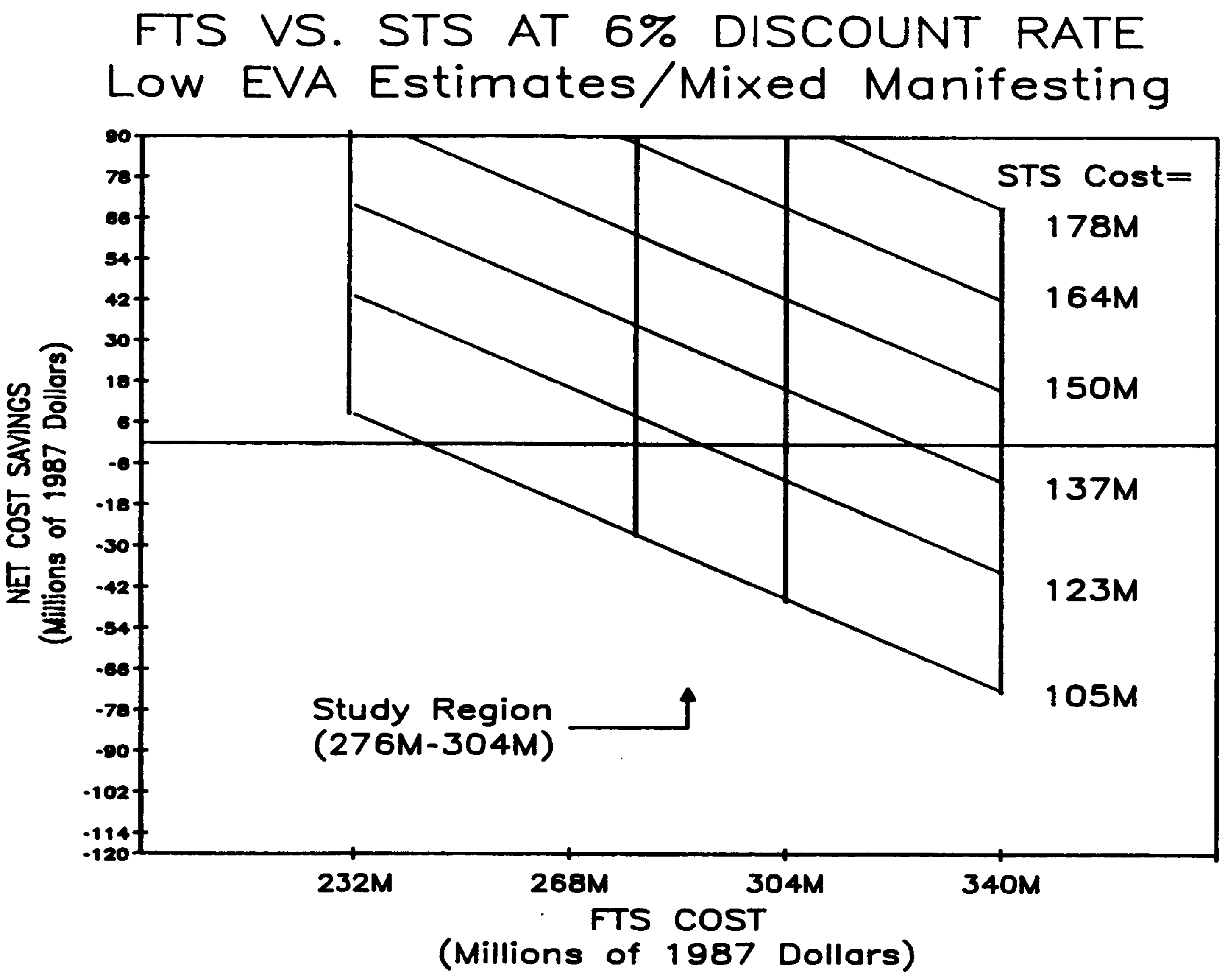


Figure 5-4. FTS versus STS Cost Trade-Off Region for a 6% Discount Rate

SECTION VI

ISSUES AND IMPLICATIONS OF THE ANALYSIS FOR FUTURE DECISIONS

To place the results of the study in context with the Space Station Program, there are two issues:

(1) What are the goals (values to be maximized) that should be used to evaluate the FTS?

(2) What steps need to be taken to correlate the study results with the current assembly phase scenario (Phase I)?

If the value to be maximized in FTS development is the commercial benefit to be derived from technology advances (i.e., spin-off potential), then a different value equation (than net savings) will need to be constructed in order to accommodate those technologies to be stimulated, and thus the activities that the FTS can be used to demonstrate.

It was assumed here that the objective was to maximize the overall value of the FTS to the Station. Thus, technology development programs need to be instituted that enable FTS performance upgrades in areas that directly enhance FTS value to the Station. This could be done by identifying high-payoff applications amenable to acceptable-risk FTS system configurations. This assumption need not minimize the role of the FTS program in stimulating automation and robotics (A&R) technology development, since both terrestrial spin-off and Station benefits can accrue from development of intelligently selected advanced technologies.

It is likely the Program will follow a middle ground by implementing an operational FTS of demonstrable benefit to the Station while serving to perhaps host technology advances, evaluate operational procedures for new concept assessment, and use simple reliable systems to pave the way for newer, more complex systems to be implemented later.

The second issue is one of logistics. The current study was performed over a period of time in which the Station design moved from the CETF concept to a Phase I and Phase II configuration. While some of the overall conclusions might still hold for the combined Phase I and Phase II design, current interest is focused on Phase I, the results of the study are somewhat limited, if not dated. However, the methodology has been developed and an application to Phase I will require a review and revision of existing data. Because the FTS is cost-effective due to additional STS flights required during FEL through PMC, it is likely that the FTS may still be cost-effective, but at a lower level (the feasible region will move down). The drop will be due to the loss of EVA displaced benefits not counted during Phase II. However, this is conjecture and should be verified by performing the additional analysis.

It is important to keep in mind that whether or not the FTS is cost-effective for the assembly phase, there are legitimate uses under a number of scenarios. If the FTS is not cost-effective, it could still serve as a research and development testbed for post-IOC applications. If it is cost-effective, it could be used as an applications-oriented tool. Earlier studies have highlighted some of these role differences varying from a low-cost orbiter-based operational system to a space-based testbed for evolving telerobotics technologies. Although there is a range between an applications-oriented versus a demonstration-oriented FTS, even if marginally cost-effective, the FTS could still serve as a backup that could reduce schedule risks by providing a flexible option for some additional EVA activity if needed.

Note that the analysis performed herein is inherently conservative. Limiting the time frame of the analysis to FEL through IOC underestimates the actual benefits of an FTS by excluding any post-IOC benefits. If the FTS is assumed to continue operations after IOC, the FTS feasibility region will tend to move upward (towards more feasible) for all the cases described.

If it is assumed that FTS operations are terminated at IOC or that the FTS is not used for Station operations but rather for research and demonstration purposes, there are benefits that this study made no attempt to quantify. One class of benefits is the development lessons learned that can be utilized to develop a future FTS that does play an integral role in a wider variety of Station and on-orbit operations. Another class of benefits is the on-orbit operations experiences obtained by working with an early FTS in either a demonstration or applications mode. The interfaces between the human operators, the equipment, and the task requirements can be refined or revised to make better use of the synergistic potential of redesigned tasks coupled with FTS capabilities specifically designed for those tasks. Such experiences would provide a valuable database for examining the issue of EVA-equivalence--that the FTS should perform at a level compatible with human performance. The EVA-equivalence issue (also known as the "fallacy of the anthropomorphic robot") argues that the tasks and telerobotic functions can be designed together such that the overall performance exceeds the human performance. An example of this is the requirement that any task performed by the FTS must be designed such that it can be accomplished by EVA astronauts equipped with tools. For instance, a high speed socket driver "hand" coupled with a standardized bolt size might be used instead of a more complex, highly articulated hand/vision system (i.e., fingers). If there were a sufficient number of bolts to be installed or removed, the socket driver option would outperform the articulated hand/vision system. The experiences of operating an FTS in a weightless environment on actual tasks would provide useful guidance for the design of future tasks and FTS capabilities.

This study presents a single solution out of many possible ones, and the results described are by no means optimal. The FTS option selected here was based on an analysis of estimated task requirements and estimated functional requirements. The focus was to identify the components that ought to be examined when comparing FTS options. Nonetheless, a number of recommendations are made.

First and foremost would be a complete review of the data for the Phase I definition of the current program to bring the results in line with current plans. The major differences would be a revision of EVA/IVA times. If the same FTS Reference System were used, the entire study could be updated. If a different FTS configuration were used, a new cost estimate would be required, as well as new EVA/IVA estimates for the EVA-Only and EVA+FTS case to account for variations in the performance time ratios across FTS configurations. As more data become available, an improved technology assessment of telerobotics technologies could be performed to examine alternative FTS configurations.

There is also a need to examine the effects of risk on the results presented here. Cost risk can be viewed directly using the net savings or operations and maintenance (O&M) equations with simulation techniques to generate probability estimates for net savings and O&M costs. Then, as assumptions of the problem (such as software/integration costs) are varied, the impact on the probability of breaking even can be computed. Technical risk could also be studied in terms of the uncertainties in performance and reliability. In addition, the effects of specific risk elements, such as the introduction of suits requiring no prebreathe step, EVA overhead, and the effects on EVA if such a suit is not ready on schedule, could be singled out. An understanding of the risk and uncertainty effects would show how the FTS could help reduce program risk by adding flexibility to operations planning and contingency planning--especially during FEL-PMC. There is value and benefit of having an FTS for the flexibility it provides for dealing with unscheduled events. A study of the risk elements would quantify those benefits.

Further study is also needed for the allocation of automation and robotics functions. Very different results can be achieved by locating such functions on the ground. With improved autonomous operations, Station IVA could be reduced. One question is whether to pursue advanced and technically risky autonomous or semiautonomous options versus a less sophisticated on-the-ground remote telerobot operation capability.

Such a study would identify the issues related to the human factors and control technology problems of dealing with time delays in teleoperation feedback. It may be possible to mitigate the problems of such time delays with autonomous time-delay handling technologies or alternative cost-effective technology-based solutions. The present study has shown the magnitudes of the savings to be potentially large enough that a dedicated FTS relay system to provide real-time response might be an alternative worth consideration. This will depend on the potential for extending the displacement of IVA and EVA task times while minimizing the technical risk of developing the system. If extended operations can be performed from the ground, the risk of requiring additional flights may be reduced and provide a schedule margin during the early FEL-PMC period when assembly elements must be completed within fixed, short term flight periods or risk mission failure.

The area of allocation of autonomous and robotic functions and resources needs further examination to help designers select whether A&R upgrades are performed on the Station, incorporated into the FTS, or operated on the ground.

A related allocation problem that requires further understanding is the allocation of work among and between multiple robots (FTS, RMS, MSC, SURFAC) and crew EVA (co-EVA). Data on performance time ratios for such mixed tasks should be collected for a variety of tasks using neutral buoyancy studies and (eventually) on-orbit experience. The proximity operations rules for such operations will also have to be identified in detail.

There is a need for an accessible, detailed assembly-sequence that identifies the current list of assembly, maintenance, attached payload, and any other tasks together with the EVA/IVA times as manifested with information on locations, dimensions, masses, etc. pertinent to each task. Hopefully, as the Station continues toward FEL, such information will become available for wide use.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

There are a number of conclusions that can be drawn from the present study, which is based on a CETF-derived (30-flight) assembly phase. Noting that the study was conservative in that benefits after IOC were not examined; logistics benefits were not considered; safety benefits were not considered; and the effects of the satellite servicing facility were not examined; the following conclusions were drawn:

(1) The FTS Reference System identified herein appears to be technically feasible for development by FEL.

(2) The FTS Reference System is cost-effective under a variety of conservative scenarios.

(3) The STS cost is the primary factor for FTS cost-effectiveness due to avoidance of extra STS flights by EVA reductions.

(4) Cost-effectiveness of the FTS is not sensitive to EVA cost per hour due to dominance by STS costs. As the EVA-IVA time estimates increase toward the high-range values, the FTS feasible region moves down (towards less feasible). It is not the EVA cost per hour that makes a difference, but rather the product of the EVA cost per hour and the number of EVA hours.

(5) The FTS is cost-effective at a 10% OMB discount rate but even more cost-effective at a 6% rate.

(6) As the ability to remanifest becomes more flexible, the FTS is less cost-effective because fewer additional flights are required.

(7) The total estimated EVA savings due to the FTS Reference System is 385-413 hours.

(8) The assembly-phase is a maintenance problem (50% of total EVA is for maintenance versus 33% for assembly). FEL-PMC is the primary assembly problem.

(9) The FTS Reference System defined here is most suitable for performing:

    (a) Truss assembly tasks
    (b) Limited ORU replacement tasks
    (c) Deployment of special equipment
    (d) Pallet handling, loading, and unloading tasks

    The potential exists for transferring some on-orbit tasks to ground operations given that appropriate technology and human engineering constraints are considered.

(10) The total estimated cost of the FTS Reference System is $277 - $304M (does not include nonprime costs or spares).

(11) There is a need for improved and more detailed data on task descriptions, timelines, manifests, etc. updated quarterly or semi-annually and available via electronic mail, for example.

(12) A methodology for comparing autonomous options has been developed with specific applications to the FTS and its technical and cost feasibility for use during the assembly phase. Other A&R elements could be analyzed in a similar manner.

Based on the study results, a number of recommendations are made:

(1) A review of FTS feasibility should be performed using new data for the Phase I Station design to determine the effects of different projected tasks, STS flight rates, and the possible inclusion of heavy lift vehicles on FTS feasibility. Refinement of projected activities after the assembly phase could be used to extend the period of analysis to include additional operational benefits in the post-assembly period. Such an analysis should be performed as far in advance of procurements as possible.

(2) A review such as (1) above should examine the role of the FTS as a risk reduction tool. The FTS could offer significant benefits by providing operational flexibility not available to an EVA-Only environment. The balance between the risks posed by the presence of an FTS and those risks that an FTS might be used to mitigate need to be understood. A related issue is the need to understand uncertainty effects from cost model parameters and EVA/IVA activities on conclusions regarding FTS feasibility. Again, a full understanding of these risk elements (to the extent possible) should be obtained far in advance of procurements.

(3) A growing problem arising in the A&R area is the question of allocation of functional capability. For example, an A&R function could be built into the FTS, the data management system of the Station, or the ground system. It is recommended that methodologies be developed to assist or guide designers in making these allocations. A related area to this is the allocation of functions between FTS and crew (co-EVA), or between FTS and other robotic systems.

(4) A study should also be undertaken to assess the feasibility and requirements for operating the FTS from the ground. An understanding of the technology limitations and roles the ground system could perform is required to determine the match between FTS tasks and technology requirements.

(5) Finally, as the program enters the next phase of design, it is recommended that the details of the assembly sequence (EVA tasks, time requirements, tools, work envelopes, sequencing, and manifesting, among others) be made available on a wide basis (via electronic mail) so that related studies can be performed using a uniformly available database.

This evaluation is intended to assist in the characterization of a role for which an early FTS might best be designed. Potential for cost-effective early operation argues for an FTS and host environment designed to facilitate performance of the selected FTS tasks. On the other hand, marginal early operating benefits suggest the option of treating the FTS initially as a test bed for development of advanced technologies that will later serve the Station in a more cost-effective manner.

The second issue is that of reliability, or more accurately, program confidence in the reliability of the FTS to perform tasks determined analytically to be cost-effective. This issue was particularly in evidence during the CETF process. The Advanced Technology Advisory Committee and Space Station work package contractors have been remarkably consistent in their conclusions regarding which tasks were within the capabilities of telerobotic devices. Program personnel, citing the criticality of early (pre-PMC) EVA tasks, are considerably more skeptical. The CETF, for example, ultimately based its results on the use of deployable utilities in preference to use of an FTS, on the grounds that on-orbit assembly by telerobotic devices had never been attempted. This suggests that the subject of both ground and flight demonstrations of the FTS should be directed specifically toward whatever tasks the FTS might be applied to initially, particularly in cases of high task criticality.

Finally, multiple competing goals have been articulated for the mandated FTS development program and it is not clear that the program adequately addresses this issue. For example, the goal of increased Station productivity and decreased operational cost implies a high-reliability, low-risk, low-maintenance FTS that can be brought on-line early in the Station operating life. This approach cannot be easily reconciled with the current program focus on implementing advanced technologies and system concepts in an operating environment for which no prior operating experience is available. While of potentially higher technology spin-off value (a separate FTS goal), the technology-driven approach is also of higher risk and possibly of considerably smaller direct value to the Station. Maximizing spin-off value may isolate development attention on technologies that are not particularly applicable to high-payoff Station tasks; also, systems utilizing complex, advanced technologies tend to require larger amounts of maintenance until those systems are mature and well-proven. This could constitute a significant additional burden on Station resources. Finally, any lack of confidence in the reliability of the FTS may cause it to be relegated to "elective" or demonstration functions, rather than being accorded full operational status and assigned to important routine Station tasks.

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16. Abstract

This report addresses a question raised by the Critical Evaluation Task Force (CETF) analysis of the Space Station: "If a Flight Telerobotic Servicer (FTS) of a given technical risk could be built for use during Space Station assembly, could it save significant extravehicular (EVA) resources?" The report identifies key issues and trade-offs associated with using an FTS to aid in Space Station assembly phase tasks such as construction and servicing. A methodology is presented that incorporates assessment of candidate assembly phase tasks, telerobotics performance capabilities, development costs, operational constraints (STS and proximity operations), maintenance, attached payloads, and polar platforms.

A discussion of issues is presented with focus on three potential FTS roles: (1) as a research-oriented test bed to learn more about space usage of telerobotics; (2) as a research-based test bed with an experimental demonstration orientation and limited assembly and servicing applications; or (3) as an operational system to augment EVA, to aid the construction of the Space Station, and to reduce the programmatic (schedule) risk by increasing the flexibility of mission operations.

During the course of the study, the baseline configuration was modified into Phase I (a Station assembled in 12 flights) and Phase II (a Station assembled over a 30-flight period) configurations. This study reports on the Phase I plus the Phase II or CETF design.

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