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The Space Station Assembly Phase: Flight Telerobotic Servicer Feasibility

Volume 2: Methodology and Case Study

Jeffrey H. Smith
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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.

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 trade-offs.

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.

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INTRODUCTION

A. PURPOSE

During 1986, a Critical Evaluation Task Force (CETF) was convened to evaluate the Space Station (SS) baseline configuration. A conclusion of the CETF was the potential for a Flight Telerobotic Servicer (FTS) to make substantial contributions to the assembly phase of Space Station construction. This contribution was viewed as the potential to displace a severely constrained resource--extra-vehicular activity (EVA) for manned construction of the Station. However, a key question remained: "If an FTS system could be deployed at a given level of risk (that the technologies required could not be developed and integrated in a timely fashion), would such a system be capable of displacing significant EVA resources in a cost-effective manner?" The study described herein addresses this question.

The purpose of this study is to evaluate the potential benefits and costs of implementing an operational FTS for the Space Station at First Element Launch (FEL). FEL refers to the first Space Transportation System (STS) launch that initiates the transport of Station hardware to orbit. The study addresses candidate applications identified by the four work packages and attempts to identify an integrated task set that represents a feasible and beneficial role for the FTS. This study spans a 30-flight period termed the assembly phase - FEL to Initial Operational Capability (IOC) - and is based on the configuration derived by the CETF and the assumptions made for that design. While the configuration was modified again during the course of this study, the present program approach is to arrive at the dual-keel configuration derived earlier in two phases. The assembly sequence used in this study, i.e., the CETF assembly sequence of 30 flights, is approximately equivalent to the present program phases I and II.

Numerous factors affect FTS costs and benefits, including assembly phase task requirements, assembly sequence and STS manifests, EVA and intra-vehicular activity (IVA) time requirements to perform the tasks with and without the FTS, the state of telerobotics technology by First Element Launch, and operations rules and constraints. The study examines these factors to identify the feasibility and possible roles an FTS might serve during the assembly phase. It should be noted that this study uses economic factors to examine these issues--noncost variables that are potential sources of large FTS benefits, such as safety or technology spin-off potential, are not explicitly included. As improvements are made in detailing assembly tasks and proximity operations rules, safety benefits could be examined with alternative methods.

This study also supports the Space Station systems engineering and integration process in several ways.

The method developed will aid in identifying tasks that the FTS could reliably perform in the early Station operating life (the approach can also be applied to later Station evolution periods). Estimates of the assembly phase EVA reduction resulting from FTS implementation support the evaluation of assembly sequence and manifesting options. As more detailed design data become available, the method can also provide an improved basis for performing trades among various EVA-FTS function allocation options, thereby facilitating the definition of quantitative FTS functional requirements.

The approach provides a basis for trades among the FTS and other, nontelerobotic alternatives for accomplishing required assembly phase EVA reduction. Nontelerobotic options include deployable elements, particularly trusses and utilities; increased Mean Time Between Failure (MTBF) to reduce EVA maintenance requirements; relocation of high-maintenance elements to internal locations; or use of launch vehicles with increased lift capacity. Furthermore, this approach will help identify areas in which task redesign could result in significant increases in FTS applicability and value. FTS benefits can be enhanced by redesigning appropriate tasks to better match FTS functional performance characteristics without exceeding those of the EVA crew member. This evaluation also provides a model for assessing implementation of other A&R concepts based upon a cost-effectiveness criterion, and describes the issues associated with such analyses for Station applications.

Finally, the assessment of telerobotic devices in general on a cost-effectiveness basis can assist in the allocation of specific tasks to other telerobotics systems planned for the Station. These systems include the Canadian special-purpose dexterous manipulator (SPDM).

B. BACKGROUND

Recommendations by the Advanced Technology Advisory Committee (ATAC); direction from Congress, including set-aside funding for an FTS (Reference 1); and conclusions of feasibility by work package contractors have supported the implementation of telerobotics technology for various Station assembly phase activities. During 1986 (August 20-September 14), a CETF was convened at the Langley Research Center in Hampton, Virginia. The objective of the Task Force was to "critically evaluate the current baseline configuration and identify options and assembly scenarios which address the identified issues of transportation limitations, EVA constraints, resource allocations, safety, cost, and utilization phasing." Analysis of the Space Station assembly phase by the CETF resulted in accommodation of the FTS only as an option for "possible" use starting at FEL. Although the FTS has been considered a part of the CETF configuration, few, if any, functions have been specifically allocated to it other than selected servicing tasks. This situation presents an important issue. The CETF followed the rule in assessing the assembly sequence and manifesting options that no element would be scheduled for launch before it was required on-orbit. If such a rule were applied to the FTS, specific need for the FTS would have to be established well in advance of FEL. Establishment of such need implies identification of Station functional requirements that the FTS can be shown, by analytical or demonstration means, to best satisfy.

Table 1-1 illustrates the definition and timing of key schedule milestones for this study. The flight rate profile for the four year period assumed in this study was 5, 8, 8, and 9 flights (per year). During the period from FEL to a Permanently Manned Configuration (PMC), when EVA

Table 1-1. Assembly Phase Timelines and Definitions (Source: CETF)

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

resources are severely constrained, "need" means an FTS capability to reduce crew-EVA time so that absolute STS-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 the available alternatives. (After PMC, the value of the FTS can be argued to depend on a more complex set of considerations: life-cycle cost and benefits, where benefits include productivity gains, safety improvements, technology spin-off, etc.)

Identifying the specific tasks and an FTS design appropriate to those tasks that will yield a cost-effective design/operations concept are key early steps in the FTS development process. Early identification of a cost-effective FTS implementation mode affects not only FTS design and Station assembly/operations planning, but will assist the FTS development and demonstration planning process. Cost-effectiveness is the focus of the present report.

C. OBJECTIVE AND SCOPE

The objective of this study is to address the question, "Can an appropriately designed FTS operate in a cost-effective manner beginning at FEL when applied in a routine, operational fashion to expected assembly phase Station tasks?" The question implies the following ground rules for the study approach:

(1) Applications of the FTS will include those for which:

(a) Required technologies of acceptable performance risk are forecast to be available as required by the FTS development schedule.

(b) Maximum value accrues to the Space Station Program; i.e., there are benefits of crew-time savings (especially EVA), safety improvements, etc..

(c) Applications are consistent with NASA operational requirements and constraints.

(2) The actual FTS design concept evaluated will be determined by the specific functional requirements of those tasks that indicate the greatest potential improvements in selected measures of value.

(3) Advanced FTS technologies (those beyond the technologies available to support FTS implementation at FEL) are considered available for operational Station application only when their reliability and cost-effectiveness have been demonstrated.

The present study addresses the assembly phase of the Station operating life, because issues of FTS hardware development, application definition, and operational modes for that phase of the Space Station Program (SSP) represent the most critical FTS planning needs. However, candidate applications for the FTS and other telerobotic systems that go well beyond IOC have also been identified by work package contractors. Assessing the cost-effectiveness of such systems and applications for the station growth period will be important in defining future development directions for evolutionary telerobotics technologies.

The possible inability of an early FTS to operate cost-effectively does not necessarily challenge the present SSP FTS development program, although it might suggest reexamination of immediate goals. For example, an early FTS flight program might well be justified wherein the initial FTS is used strictly as a testbed for the development and demonstration of new technologies that will enable cost-effective operational systems at some later point in the Station operating life. An early FTS might also be justified based on its use to reduce schedule risk by adding contingency time for EVA activities not completed within the flight time budgets.

D. ASSUMPTIONS AND LIMITATIONS

A study of this scope involves a number of assumptions and limitations. The assumptions and limitations are focused on the areas of:

(1) Assembly Phase Tasks

(a) Assembly tasks: Assumptions about some of the missing details or incomplete task descriptions must be made in order to estimate both the EVA-only task time and the EVA+FTS task times. Many of the assumptions in this category are associated with these estimates and methods of estimation.

(b) Maintenance tasks: The focal point of assumptions in the maintenance area rests on estimates of maintenance requirements per flight and whether the FTS can be expected to perform ORU changeouts.

(c) Attached payload setup and servicing tasks: The primary difficulty in the attached payload area is the uncertainty of characteristics of likely payloads. The only available data are the mass and volume available for manifesting. A review of the attached payload flights was performed to synthesize a generic payload set.

(d) Polar platform tasks: The question of polar platforms centers on how they will be transported to and maintained on-orbit. During the course of the study many changes about polar platform assumptions took place. Although estimates were made initially of how much EVA could be displaced by an FTS, the high cost of a second FTS, coupled with the moderate amount of displaced EVA and with significant revisions in polar platform planning, led to a removal of the polar platform benefits (and costs) from the study results.

(2) FTS Reference System: The assumptions of the FTS involve the identification of probable robotics technologies available for

inclusion by FEL. While the FTS synthesized here is not intended to be an optimized system, an attempt was made to identify the primary components of such a system.

(3) Estimation of EVA/IVA Budgets by Flight Interval: The EVA budget assumptions are concentrated in the pre-PMC period as to how the total EVA available would be divided among the task categories. For the most part, the CETF estimates are used.

(4) IVA Constraints During Adjustment Period: A CETF ground rule of 30 IVA hours per flight and no IVA during the first two days of operations for the period FEL to PMC was used. The two-day constraint is to allow the astronauts time for adjustment to weightlessness and so no attempt was made here to assume that any of this time could be used for FTS operations. The effect of this CETF ground rule is to make the results conservative in that additional benefits might be attained if IVA operations were allowed during the first two days.

(5) Estimation of Required EVA/IVA by Flight Interval: The most difficult aspect of this category was obtaining description and time estimates of the component tasks. A number of assumptions were required for the parameters used to estimate task times within each task category: assembly, maintenance, attached payloads, and polar platforms.

(6) Costing of FTS Reference System: The cost assumptions focus on the data used to estimate the FTS cost. The sources of data range from programmatic and technically justifiable estimates to conversations with technical experts to obtain their judgments as to likely costs.

(7) Economic Evaluation of EVA-Only versus EVA+FTS cases (life-cycle cost inputs): The assumptions of the economic approach fall into two categories. While the life-cycle cost methodology makes a number of assumptions about discount rates and other model parameters, the key factors are the operational, performance, and data assumptions.

A central problem was the lack of detailed data for many of the methodology elements. This problem required developing numerous estimation algorithms, each with a set of assumptions, in order to derive the required data. The most difficult area was a lack of detailed task descriptions on a flight-by-flight basis for each of the categories examined in (1).

A key assumption of the study was an emphasis on simply deriving a candidate scenario; no claims are made that the results presented herein are optimal. The aim of the methodology is to identify a feasible task set. The optimization step (which could be performed parametrically) is beyond the scope of the present study.

At a more detailed level, the following assumptions were made:

(1) The 30-flight period corresponds to the following schedule assumption:

    (a) Year 1: 5 flights (1-5).
    (b) Year 2: 8 flights (6-13).
    (c) Year 3: 8 flights (14-21).
    (d) Year 4: 9 flights (22-30).

(2) Attached payloads will be delivered on flights 3, 18 and 30.

(3) Polar platforms on flights 5, 9, and 26 will be launched by either shuttle or ELV; servicing will be supported by an STS-based FTS. This assumption was removed later in the study as the polar platform case and its assumptions changed.

(4) No Orbital Maneuvering Vehicle (OMV) will be available during the assembly phase.

(5) All maintenance and servicing ORU changeouts are designed to be performed by the FTS as stated in the servicing (ORU) requirements.

(6) For the EVA+FTS case, a general assumption is made for Station maintenance (and polar platform servicing) that 20% of EVA could be displaced by an FTS.

(7) Noncritical maintenance prior to PMC can be deferred to PMC and beyond.

(8) The inclusion of the categories of satellite servicing and logistics would improve the attractiveness of the FTS because of the additional servicing opportunities to displace EVA.

E. REPORT ORGANIZATION

The report consists of nine sections. 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 identified the operational constraints associated with the assembly phase and derives the operationally feasible task set. Section V derives the EVA and IVA time estimates for the EVA-Only and EVA+FTS cases. Section VI describes the estimation of FTS Reference System costs, and the economic evaluation is presented in Section VII. Section VIII contains the results of the study, followed by a discussion and conclusions in Section IX. References are listed in Section X.

SECTION II

METHODOLOGY

The approach requires an assessment of the technically feasible tasks that an FTS could be expected to perform in parallel with a technology assessment of FTS technologies that could perform the required functions and be developed by FEL. Operational constraints on EVA and IVA time, together with proximity operations rules, are applied to screen out any tasks that are not operationally feasible. The resulting operationally feasible task set represents a candidate set of tasks which the FTS Reference System (derived from the technology assessment) could perform. The EVA and IVA times are then estimated for the entire task set for two cases: an EVA-Only case (no FTS) and an EVA+FTS case (FTS present during the assembly phase). The operations and maintenance (O&M) costs of the two cases are compared to the investment cost to deliver an FTS to orbit to determine whether a net savings can be achieved (whether the savings achieved by the FTS Reference System exceeds the investment cost).

To assess the cost-effectiveness of an FTS Reference System for assembly phase applications (FEL to IOC), the following steps are involved (Figure 2-1).

A. IDENTIFY TECHNICALLY FEASIBLE TASK SET

This step requires forecasting the performance capabilities of an FTS system at FEL in order to identify specific EVA tasks that the FTS could perform between FEL and IOC. Such an FTS forecast addresses the availability of critical constituent technologies required to support reliable FTS operation at FEL, based on reasonable schedule requirements for system design, integration, verification, and integration into operations.

This step consists of four components:

(1) Assembly phase task identification and task functional analysis.

(2) Telerobotics technology assessment.

(3) Definition of an FTS reference system and its performance capabilities.

(4) Identification of technically feasible tasks.

Because the initial FTS concept is determined by some subset of the range of possible task demands (i.e., the subset that the FTS is capable of performing), identifying suitable technology/task combinations requires that these elements be performed interactively.

The products of this step are a listing of tasks that the FTS would be technically capable of performing in a reliable manner and an FTS Reference System capable of performing those tasks.

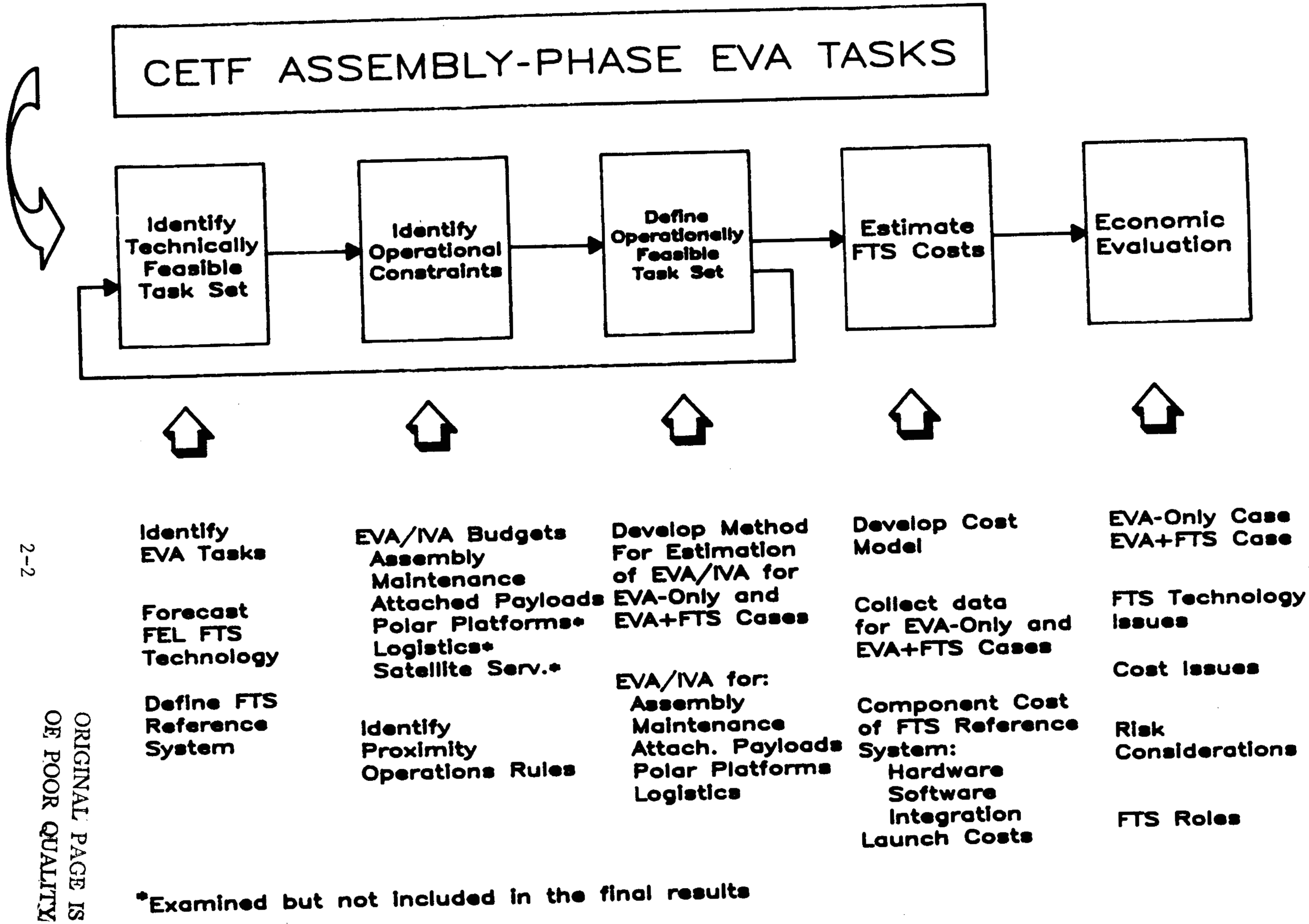

Figure 2-1. FTS Evaluation Methodology

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B. IDENTIFY OPERATIONAL CONSTRAINTS

This step identifies operational constraints that limit the assembly phase task set that an FTS might perform. Examples of such constraints include absolute limits on STS and Station crew IVA resources for each flight, FTS operation time limits, operational safety requirements, and proximity operations rules.

The product of this step is a list of guidelines to be applied to the technically feasible task set as a filter for removing FTS activities constrained by external considerations not directly related to FTS performance capabilities or task demands. In some cases tasks can be summarily removed, and in other cases the task activities must be assessed parametrically due to incomplete task definition information.

C. SELECT AND ASSESS OPERATIONALLY FEASIBLE TASK SET

This step defines an operationally feasible assembly phase task set based on the technically feasible task set and the identified operational constraints. In general, more than one operationally feasible task set may be possible. To assess the FTS, a selection must be made from among these possible sets.

A realistic operational task regimen is identified in this study that utilizes the maximum capabilities of the FTS technology. In general, the FTS task set comprises those tasks that offer the greatest return (EVA hours saved, special safety benefits, etc.) within the constraints imposed by crew resource availability, proximity operations rules, and FTS performance capabilities. The result is a final listing of tasks allocated to an FTS and used to refine the FTS design concept and to estimate operational benefits.

During the definition of the operationally feasible task set, as tasks are eliminated because of proximity operational risk, safety, and other reasons, the requirements for the FTS are modified. These modifications feed back to the FTS reference system concept to maintain consistency between the FTS tasks defined and the FTS technology required. Thus the FTS concept is based on the final set of tasks allocated to the FTS. This concept represents a refinement in which the FTS performance envelope is defined to accommodate the requirements of the specific task set to which the FTS is to be applied. The result helps to generate a conceptual design appropriate to the operationally feasible task set that characterizes the FTS in sufficient detail to enable estimation of FTS first costs and operating costs.

The product of this step is a compilation of FTS task assignments by flight (1-30).

D. ESTIMATE FTS COSTS

This step estimates FTS first costs and operations costs appropriate to the reference FTS conceptual design. First costs refer to all Design, Development, Testing, and Engineering (DDT&E), fabrication, and launch costs of the FTS and associated flight support equipment assignable to the Space Station Program. Operations costs are the continuing costs of operating and maintaining (O&M) the FTS. For cases in which the Station impact of FTS operation cannot be expressed readily in dollar terms, such as the impact of increased IVA resource usage, such impact will be estimated in the most appropriate units (e.g., crew-hour requirements).

The product of this step is a summary of estimated operations and maintenance costs associated with performing assembly phase EVA tasks by crew EVA alone (denoted EVA-Only), and by crew EVA supported by an FTS performing the operationally feasible task set (denoted EVA+FTS).

E. ECONOMIC EVALUATION

This step characterizes and evaluates the benefits of reducing crew EVA by the use of the FTS for the selected subset of EVA tasks. These benefits are compared with estimated costs. As in the cost estimation step, for instances in which benefits cannot be expressed readily in dollar terms, such benefits will be estimated in the most appropriate units (e.g., EVA-hour savings).

The benefits and costs of the FTS are then compared to the benefits and costs for the EVA-Only case using the operationally feasible task set and the EVA/IVA profiles for each flight and flight interval. A life-cycle cost model is derived to examine the cost-effectiveness of the FTS Reference System during the assembly phase. Because the initial costs (and many other cost parameters) are the same in both the EVA-Only and EVA+FTS cases, they subtract out to yield a net savings relationship that simplifies the cost model. The net savings relation compares the O&M costs (discounted) of the two cases against the investment cost (discounted) of the FTS Reference System to answer the question, "Are the savings achievable by an FTS worth the required investment?"

The product of this step is a discussion of issues, conclusions, and recommendations regarding the regions of feasibility and cost-effectiveness of using an FTS during the Station assembly phase, and regarding the role or capacity in which the FTS might best serve the needs of the Space Station Program.

SECTION III

IDENTIFICATION OF TECHNICALLY FEASIBLE TASK SET

The identification of technically feasible EVA tasks occurring during the Station assembly phase that could be performed by an FTS is a multistep process (see Figure 3-1). This section describes the process used to derive the technically feasible task set and the FTS Reference System used in the study.

Step A. Identify the assembly tasks.

Step B. Identify functional capabilities and commonalities among the assembly tasks to focus the search for required FTS functions.

Step C. In parallel, identify telerobotic technologies available currently and over next 10+ years and the kinds of functions these technologies can perform.

Step D. Identify the FTS functions in (C) that could be developed within the FEL time frame. Each configuration of functions represents an increasingly complex FTS over time. Twelve FTS configurations were developed and a median configuration selected to minimize technical and performance risk.

Step E. Match the functions of the FTS configuration in (D) against assembly sequence functions from (B). Apply selection criteria and revise lists of assembly functions and FTS functions as needed to refine the correspondence between tasks and FTS. The result of Step (E) is the identification of technically feasible tasks (the tasks for which there is a match between the assembly functions and the FTS configuration functions); the FTS Reference System (the refined FTS configuration); and remaining tasks which constitute the remaining non-FTS-related assembly tasks.

Step F. Revise the technically feasible task set as required. If there are tasks in the operationally feasible task set that exceed the EVA or IVA constraints and tasks must be removed, it may be possible to simplify the technical requirements on the FTS simultaneously. This step is a review process to check the correlation between the task set and the FTS Reference System design.

Each of these steps is detailed below.

A. EVA TASK DEFINITION (STEP A)

For this study, the following categories of tasks were considered:

(1) Assembly tasks.
(2) Maintenance tasks.

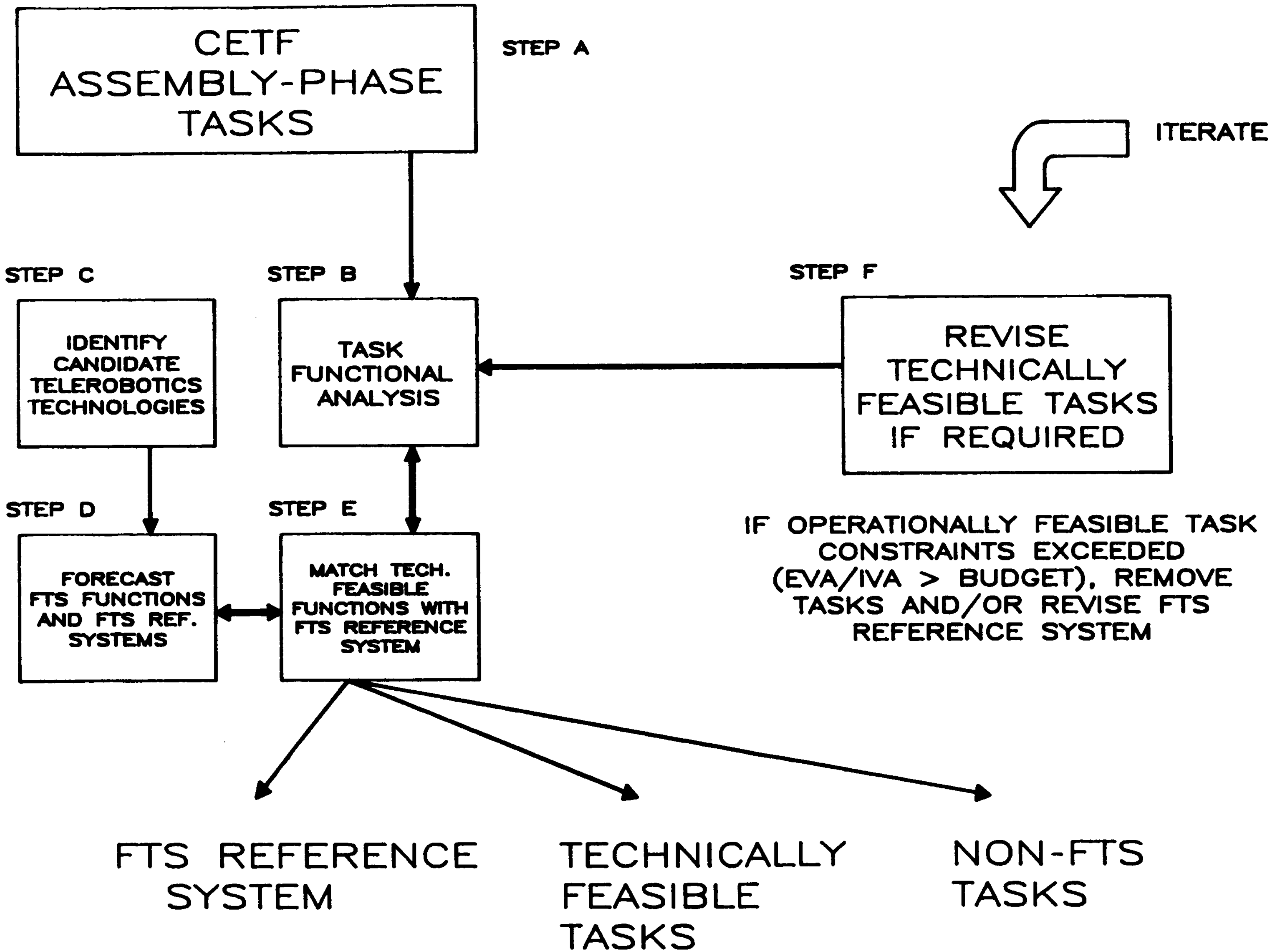

Figure 3-1. Procedure for Identification of the Reference System and Technically Feasible Task Set

(3) Attached payload tasks (setup and servicing).
(4) Polar platform tasks (setup and servicing).
(5) Logistics tasks.
(6) Satellite servicing facility tasks.
(7) Miscellaneous tasks.

During refinement of the assembly sequence, only the assembly tasks (1) are listed explicitly. The other categories (2-7) were reviewed using descriptions and estimates from a variety of sources. As more detailed data are obtained, these categories could be further refined at the task level.

1. Assembly Tasks

For purposes of this evaluation, assembly tasks comprise all tasks required to construct, check out, and verify the Station facility at each assembly stage. Assembly tasks typically require removal of equipment from the STS, setting up a workstation, grappling objects, moving the objects, aligning and fastening objects, and bolting them down. These generic functions were examined and detailed for each flight using the CETF manifests and estimated EVA/IVA times.

2. Core Station Maintenance Tasks

Maintenance tasks include those preventive and corrective maintenance tasks associated with the core Station that must be performed by EVA. Prior to PMC, the STS will provide on-orbit repair for high-criticality items. Maintenance items that present no immediate risk to the unmanned Station will be deferred until PMC, and, in general, be performed by Station-based crew. Examples of core Station maintenance tasks are ORU changeout, truss strut removal and replacement, and puncture reseal.

An additional important maintenance category will consist of maintenance of the various Station robotic devices: mobile servicing system (MSS), servicing facility, etc. Such maintenance will include ORU changeout on elements such as joints and avionics.

3. Attached-Payload Tasks

There are three flights manifested with attached payloads: Flights 3, 18 and 30.

The servicing activities for the attached payload equipment fall into two general categories: payload setup and payload servicing. Payload setup refers to the installation of payloads upon arrival at the Station. Payload servicing includes payload operations support, maintenance, and consumables replenishment. Payload operations support may include conveyance/relocation required for operation; reconfiguration; initiation or termination of selected operations modes; or collection of samples or products of payload experiments.

Payload maintenance comprises those preventive or corrective actions required to maintain a payload system in its operational state. Examples include lubrication, inspection, calibration, and filter changeout (preventive actions), and ORU removal and replacement (corrective action).

Consumables replenishment consists of resupply or replacement of various gases, liquids, or solids utilized in the conduct of experiments, or fuels used for stabilization or control of experiments.

For the purposes of this study, candidate attached payloads were used to obtain a profile of the EVA/IVA requirements for each of the three attached payload flights (3, 18, 30). The details of this procedure are described in Section V-C.

4. Polar Platform Tasks

There are three polar platform flights manifested during the assembly phase (flights 5, 9, 26). The activities associated with these flights are divided into installation and servicing categories. Installation consists of deployment from the shuttle to an OMV and servicing consists of scheduled and unscheduled maintenance composed largely of ORU changeouts. However, during the course of the study, as the SSP moved to a shorter, Phase I and II design, many assumptions regarding the availability of an OMV, a western launch site, and other complexities made it clear that the polar platform role would be limited during the assembly phase. Although an attempt was made to examine potential polar platform FTS benefits, the benefits of performing polar platform EVA were not included in the final results.

5. Logistics Support Tasks

For purposes of this study, logistics support is defined as replenishment of consumables to the Station (not including attached payloads), i.e., the replacement of expendable resources to a Station system or subsystem. Included are fuels used for Station stabilization or control. However, due to limited data on EVA tasks and the likelihood that most logistics transfer will be performed by STS and Station-based remote manipulators, logistics operations were not included at this time. While the FTS could assist in large object transfers, providing lighting and improved video field of view, the results of the study are conservative in that additional tasks might be aided by an FTS, but were not specified. In particular, the handling of fluid transfer carries important safety considerations and benefits if performed by an FTS rather than by IVA. There may be non-cost issues for which the FTS provides very large, but somewhat intangible benefits such as increased safety, additional flexibility in mission planning, and reduction of schedule risks. These benefits are discussed further in Section IX.

6. Satellite Servicing Tasks

Satellite servicing tasks consist of various activities required to operate and maintain user-owned equipment. The user equipment of interest in this evaluation consists of payloads attached to the core

Station at external unpressurized locations. Servicing of satellites was not addressed in this study, either in situ or in the Station satellite servicing facility.

The satellite servicing facility is assumed to rely on operation primarily by dedicated telerobotic devices, largely independent of the FTS. In the CETF assembly sequence, operation of the servicing facility is scheduled to begin after Phase 1 facility outfitting during assembly flight No. 18 (MB-12) (Reference 2).

If, on the other hand, the FTS is applied extensively to tasks within the satellite servicing facility prior to the completion of Station assembly, the effect on the results of this study would be of a conservative nature. That is, the appearance of additional task candidates for the FTS, in the form of satellite servicing tasks within the servicing facility, allows operations planners more flexibility in FTS task allocation. This situation ensures that the level of cost-effectiveness estimated for the FTS need be no less than that estimated in the absence of the satellite servicing option. (Of course, this conclusion assumes that planners will base their allocation on the cost-effectiveness of the outcome.)

7. Miscellaneous Tasks

A number of additional EVA tasks were identified that may be feasible for the FTS to perform. These include such tasks as erecting or tearing down workstations in support of EVA tasks, and capturing debris or cleaning up hazardous material leaks. Only the workstation tasks were examined here (and included under assembly tasks) because of a lack of detailed information on the nature of the other tasks. Again, any benefits that might accrue from these tasks were not considered; thus the results are conservative in terms of expected O&M savings in the EVA+FTS case.

B. TASK FUNCTIONAL ANALYSIS (STEP B)

Ideally, the feasible-task identification step would utilize detailed task descriptions that included sequence data at the level of task primitives. These performance requirements would be compared to specific system performance capabilities forecast for the FTS at the time of initial implementation (FEL). Those tasks whose performance requirements did not exceed forecasted capabilities would comprise the technically feasible FTS task set.

Unfortunately, at the time of this evaluation, detailed task data were available for only a few servicing tasks, since the actual Station design had not yet begun. Consequently, Station tasks were characterized in more general terms, according to higher-level operational constituents (grasping, translating, positioning, aligning, etc.). The Station Program generally will require that tasks be designed to not exceed EVA crew performance limits, even in areas where FTS performance capabilities could be designed to exceed those of the crew member. This approach attempts to ensure that no task is created which the crew could not back up if the FTS temporarily could not operate. This condition defines the limits on the envelope of performance requirements imposed by EVA tasks, which is useful in certain tasks in assessing whether FTS capabilities might be exceeded.

The task functional analysis is based on four major resources:

(1) The CETF draft reference assembly sequence provides the Station assembly sequence and associated projected EVA hours; these data are useful for understanding (1) relative object sizes and masses; (2) serial task progression; and (3) EVA requirements on a per-flight basis.

(2) The work package assembly studies provide an understanding of the hardware components associated with Station assembly as well as timelines and characteristic task durations for EVA (Reference 3).

(3) Projected payload servicing data from the Mission Requirements Data Base (Reference 4), along with actual Shuttle/Skylab experience, provide perspective on the more detailed task elements that might be associated with Station assembly (e.g., bolting, module removal, component assembly/disassembly, and cable/electrical connections).

(4) The JPL telerobotic functional task/technology trades analysis, which provides a basis for understanding limitations on task performance as a function of telerobotics technology constraints (References 5, 6).

In order to evaluate the suitability of each CETF assembly phase EVA task for performance by the FTS, these tasks were initially categorized by the general functional requirements involved in performing them. These requirements included (Reference 7):

(1) <u>Dexterous manipulation</u>: Any sequence of translating, rotating, positioning, or grappling of Space Station hardware requiring manual performance consistent with human capabilities (e.g., ORU changeout). (Nondexterous manipulation, or simply manipulation, by contrast, refers to similar actions in which the size or mass of the hardware exceeds normal human capabilities (e.g., module berthing).)

(2) <u>Transportation</u>: Relocating Station hardware requiring greater than manipulator reach envelope (e.g., retrieval of attached payload).

(3) <u>Tracking</u>: Acquiring a specified object or location on the Station for purposes of inspection, servicing, etc.

(4) <u>Capture</u>: Securing an object structurally to the Station.

(5) <u>Holding</u>: Restraining or securing an object for the purpose of temporary positioning to enable operations.

The task list initially was reduced in size by identifying those tasks that could likely be done with the STS-RMS or Station-RMS without the specific dexterity, arm-span, dual-arm capability, or vision potential offered by the FTS. Thus, the list of assembly tasks can be divided into a higher-level list of functions that can be matched against FTS functions in Step E. For example, there are numerous tasks that involve grappling of objects. After eliminating the tasks that could be performed with a Remote Manipulator System (RMS) or that exceeded the holding requirements (e.g., the Habitation Module is too big for the FTS), the remaining grappling tasks constitute a technically feasible set under the holding function. When the FTS functions are identified in Step D, the expected FTS holding capabilities available by FEL are matched against only those holding tasks that the FTS Reference System could perform.

C. TELEROBOTICS TECHNOLOGY CAPABILITIES AT FIRST ELEMENT LAUNCH (STEP C)

Forecasting the availability of useful telerobotics technology requires evaluation of candidate technologies against desired performance, cost limits, and other characteristics of the overall FTS system. These considerations give rise to a set of "concept-related" selection rules that assist in screening out inappropriate FTS concepts and reducing the number of technologies to be evaluated. The FTS concept-related selection rules require the FTS concept to have:

(1) Consistency with expected FTS development resources.

(2) Low technical and development risk.

(3) High performance reliability.

(4) Acceptable level of design impact on the core Station.

Consequently, the evaluation of FTS technologies considered the following availability factors in assessing the availability of specific FTS performance capabilities required to perform possible Station assembly phase tasks.

(1) Level of technology readiness: Whether the technology can move from its present state of development to a space-qualified configuration by the required deadline (FEL).

(2) Degree of system integration: The degree of FTS engineering complexity associated with the configuration, space, volume, and work environment constraints.

(3) Accuracy/repeatability: The required capability of the FTS to move to, and manipulate, objects within a reasonable positional/dynamic control envelope; also includes the accuracy with which repeated returns to the same positional/dynamic control end-points can be executed (this criterion has both control and safety implications).

(4) Reliability: The degree of reliable operation, expected maintenance, and failure modes (failsafing) (this criterion has both control and safety implications).

(5) Retrofit considerations: Addresses the system hardware and software hooks and scars that should be present to allow FTS growth for post-IOC.

Specific constituent technologies that were considered are summarized in Table 3-1.

The approach involved mapping each of the possible FTS functions against appropriate telerobotic technologies (Table 3-1), considering each of the preceding five factors, in order to identify those capabilities available at FEL required to perform expected EVA tasks. The associated technologies form the basis of an FTS Reference System concept.

An example of a telerobotic technology that is consistent with the four selection rules and affords capabilities useful in performing candidate EVA tasks would be the vision system (third column from the right in Table 3-1). In order to remove and replace a module on an attached payload, a vision sysem must recognize it or the teleoperator must be able to see it. Looking down the column under vision, the vision supervisor must contain, for example, PIFEX/gray-scale technology (which is state-of-the-art) that would be available by FEL and IOC for recognition of objects. Object labels would also be possible for control of the worksite/environment.

D. DEFINITION OF AN FTS REFERENCE SYSTEM (STEP D)

Given the range of state-of-the-art and advanced automation and robotic technologies that exist on near and far time horizons, there are milestones imposed by FEL availability when targeting various technologies for a usable FTS FEL configuration. By present planning guidelines, that milestone appears to be approximately 1992 to 1994, with IOC occurring around 1996 to 1998. Under ATAC auspices, several technology projections were assembled by members of both NASA and the private sectors. Technology availability done as part of the ATAC effort and the Space Station Reference Configuration Study/RFP were used to examine technology availability for the early 1990s envelope (References 6 and 8). Additionally, a standard technology readiness/time plot which typifies flight-qualified systems (Reference 9) was employed to extrapolate standard technology development time frames. Using the approach of Reference 9 (known as the THURIS or The Human Role in Space approach), the time frame needed to fully develop and space-qualify a supervised/teleoperated system is on the order of 10-15 years. This implies that technology being evaluated in current research and development programs will be the front-runner components of the first FEL telerobot version.

Superimposing the THURIS model over the potential early-1990s robotic technology roster resulted in the telerobot configuration matrix of Table 3-1. The required generic technology categories are listed across the top of the matrix, and the generic functions (from the previous functional analysis) are listed in the first vertical column. While these

Table 3-1. Telerobotic Functions versus Technologies for IOC

Telerobot Configuration Matrix for IOC (1994-1996)

Generic Technologies / Generic Functions	Telerobot System Housing	Thrusters/ Motor Drive	Guidance Navigation and Control (GN&C)	Battery Pack/ Power Distrib.	Dual Arm Manipulators with Vision Arm	Processor/ Software/Data Storage (Distributed Hierarchical Design)
Move to worksite and dock/hold station	Standard, self-aligning docking fixture	Inert gas thrusters; or, telerobot on track with elec. motor drive	Coarse trajectory control between worksites with stationkeeping to within 3m of docking pt. or worksite	NiH_2/NiCad storage batteries; standard power distribution	--	SOA 8086/80286 micro-processors: pre-determined flight trajectory and stop pts. for different worksites/tasks* (SEU hardened)
Control peripheral work environment at worksite	Telerobot housing frame of reference relative to work-site is predeter-mined and accurate to within 1 mm	--	--	--	--	--
Sense o Obj. prox. o Obstacles o Posit./rate o Force/torque o Power level o Fuel Level o Inertial char. o Compliant force/ posit., force/ torque	Proximity/align/ contact sensors provide positive hard dock feedback and also monitor surrounding obj. in work environ-ment	Fuel/power consumption (Standard Tech.)	*Inertial changes due to grasping and transporting objects of vari-ious sizes/masses	Power consump-tion (Standard Tech.)	Standard joint position/rate encoding: proximity sen-sing	Fused sensor capa-bility for force/ posit., posit./rate, and force/torque (SEU hardened)
Acquire/Verify o Fixtures o Obj. labels o Objects	--	--	--	--	--	SOA 8086/80286 (Microprocessors with CAD database tailored to given worksite) Task/Set of objects (SEU hardened)
Calculate/Plan o Manip. kinem. o Manip. dyn. o Servo control algor. o Obj. locat./orient. trajec./safe state o Optim. arm config. o Compliant motion o Inertial charact.	--	Δt before fuel reserve reached (Standard Tech.)	*Thruster control compensation for coupled inertial characteristics of telerobot/ grasped obj.	Δt before power reserve reached (Stan-dard Tech.)	Arm kinematics/ dynamics (*with dynamic damp-ing servo con-trol algor./ obstacle free trajec. for each task set)	SOA 8086/80286 microprocessors: short term archival memory tailored to specific task set (SEU hardened)
Grasp/move/remove/ replace o Large obj. (pal-lets, airlock, gimbal assy.) o Subsyst. modules (batteries, payload component) o LRU (circuit panel)	Support structures on housing provided for manipulators, tailored end-effectors and special tools	MMU type thrusters com-pensate for variable dyna-mics introduced by inertial changes caused handling large obj.	--	--	7 DOF dexterous arm (as rigid as possible to reduce insta-bility induced by flexibility)	--
Perform Teleop. o Switch mode (aut. to teleop.) o Operate hand con-trollers o Place telerobot in safe state	Teleop. can be per-formed from a posi-tion on (or in) the housing; or from the station command/ control module	--	Direct human control switch-over	--	--	SOA 80286/32000 Microprocessors for 7 DOF HCs; shared memory interface for Aut./Teleop. switch-over (SEU hardened)

*Note: Potential IOC High Risk Technology

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Table 3-1. Telerobotic Functions Versus Technologies for IOC (con't)

Telerobot Configuration Matrix for IOC (1994-1996)

Generic Technologies / Generic Functions	Servo/ Actuators	Sensors	I/O	Vision	End-Effecting/ Tooling	Teleoperation
Move to worksite and dock/hold station	Standard Motor Tech.	--	--		--	Direct human control switchover (stick control)
Control peripheral work environment at worksite	--	--	Voice I/O standard technology for: o lighting control o camera position	Obj. labels on large objects/ modules	All end-effectors and special tools labeled/placed in known locations on housing	--
Sense o Obj. prox. o Obstacles o Posit./rate o Force/torque o Power level o Fuel Level o Inertial char. o Compliant force/ posit., force/ torque	Servo overheating (Standard Tech.)	Standard sensor Tech.; compliant sensing suite(s) (Standard Tech.)	--	--	Standard contact sensing technology	--
Acquire/Verify o Fixtures o Obj. labels o Objects	--	--	--	Pifex/gray scale type technology (incluttered/ uncluttered task environment)	--	Direct visual location/ verification of objects with standard video/ stereo tech.
Calculate/Plan o Manip. kinem. o Manip. dyn. o Servo control algor. o Obj. locat./orient. trajec./safe state o Optim. arm config. o Compliant motion o Inertial charact.	--	--	Standard Touch keyboard data/ program entry	--	--	--
Grasp/move/remove/ replace o Large obj. (pallets, airlock, gimbal assy.) o Subsyst. modules (batteries, payload component) o LRU (circuit panel)	Standard servo/ actuator tech.	--	--	*Vision-servoing linkup	Tailored/exchangeable end-effectors and tools for specific task sets (non-dexterous)	Shared memory processor capability allows 7 DOF hand controllers to be back driven to allow correct position rate, and force/torque to be sensed
Perform Teleop. o Switch mode (aut. to teleop.) o Operate hand controllers o Place telerobot in safe state	--	Force/torque/ rate feedback	Voice interrupt for teleop./aut. control switchover (emergency manual stop/ station hold command)	Stereo imaging standard video image feedback for peripheral cameras	--	Aut. to teleops. handover accomplished by voice I/O or keyboard (or both); teleop. tasks tailored to constraints imposed by hardware/task environment complexity/endurance

*Note: Potential IOC High Risk Technology generic functions are listed independently, it was assumed that the potential difficulties of integration were included in the technical and performance risk assessments during the syntheses of the FTS Reference System in Section III-E. Note that the matrix still shows high risk in the following areas:

(1) Compensation for changes in inertial characteristics (e.g., nonrigid connection to Station) once the telerobot has grappled an object of unknown mass and unknown center of gravity; since the grapple point could also represent a nonrigid attachment point, the compensation problem becomes extremely complicated.

(2) Dynamic position and force damping/compensation during manipulation of an object.

(3) Vision servoing (i.e., coupling visual feedback target tracking data with position/rate control of the manipulator arms) during object grappling.

The first risk element above addresses the problems associated with a free-flying FTS that grapples components and moves them to a different worksite. This risk area has both control and safety implications and may require technology (and subsequent testing) not actually space-qualified until IOC or beyond. The second risk element refers to the problem of potential dynamic coupling between a nonrigid attachment for the FTS (such as another set of manipulator arms) and the upper dual arms. The last risk area addresses the limitations of existing vision systems to accurately track (and provide control feedback) objects spinning (or precessing) at a rate greater than 2-5 rpm. Clearly, in space applications the FTS would need to be flexible and handle a wide range of object motion.

In the first technology risk area, it appears that the best way to circumvent the inertial compensation problem by FEL is to have the FTS operate on a fixed, rigid track, or from a fixed platform. Additionally, during the handling of large-mass objects such as airlocks, it appears more practical to perform by teleoperation. For the second technology risk area, again it appears that the most practical solution for FEL is to provide a fixed, rigid platform for the FTS to perform its assembly, component handling or ORU replacement functions. The last technology risk area, the vision servoing, appears manageable by a similar solution. By fixing the FTS position and constraining the vision environment to static acquisition and verification, the FTS could still perform its vision function without the uncertainty associated with the previously described dynamic environment.

In summary, it appears that the kinds of technologies shown in the configuration matrix (Table 3-1), with consideration given to the above technology constraints, are representative of a feasible set of FEL system components that meet (1) the stated functional needs derived earlier; (2) the availability factors used to constrain the functional and technological mapping; and (3) the FEL time schedule deadline.

For costing and cost-benefit assessment purposes, a matrix of potential FTS configurations was assembled. This matrix identified 12 major configurations that could be built out of the technologies listed in the functional configuration matrix presented earlier. Considering the earlier described limitations, a midpoint "Reference" system was selected that provided the above suggested capabilities while reducing technical and performance risk to a level consistent with FEL schedule constraints. The components of this FTS Reference System are shown in Figure 3-2.

The last step in this portion of the analysis was to break down the reference FEL FTS system into detailed components for costing. This breakdown was achieved by drawing on the present JPL Telerobot Testbed Functional Requirements and Interface Specifications (References 10, 11). The detailed hardware and software component breakdown and costs are shown in Section VI (Table 6-1).

E. TECHNICALLY FEASIBLE TASKS (STEP E)

An additional set of selection rules were applied to derive the technically feasible task set. In Section III-B, FTS concept-related selection rules were applied to screen out telerobotic technologies not expected to afford satisfactory or useful performance in an FTS system at FEL. In this section, task-related selection rules are applied to identify a reduced set of tasks, any of which would be possible and reasonable to perform, given the projected performance capabilities of the FTS system. Again, it is emphasized that development of the FTS Reference System concept is done in an iterative fashion that continually refines both the concept and the associated set of technically feasible tasks.

The task-related selection rules are as follows:

(1) Tasks requiring manipulatory dexterity exceeding that of the RMS end effector. (This includes any need for dual-arm capability.)

(2) Tasks that can be performed within the reach envelope of a temporarily "fixed" FTS, or the FTS mounted on an RMS.

(3) Tasks that can be performed in their entirety by the FTS, or by the FTS in conjunction with the RMS. This mode potentially could reduce the <u>frequency</u> of EVA excursions, and the attendant crew preparation overhead.

(4) Tasks in which, by assisting crew EVA, the FTS could significantly reduce the <u>amount</u> of EVA required (duration of individual excursions), by providing task setup, cleanup, or cooperative (co-EVA) support.

(5) Tasks within the functional performance envelope of the FTS with reasonable (low-risk) margins.

Tasks suitable for teleoperator performance, those sufficiently structured for autonomous control, or those performed by trading between these control modes were all considered.

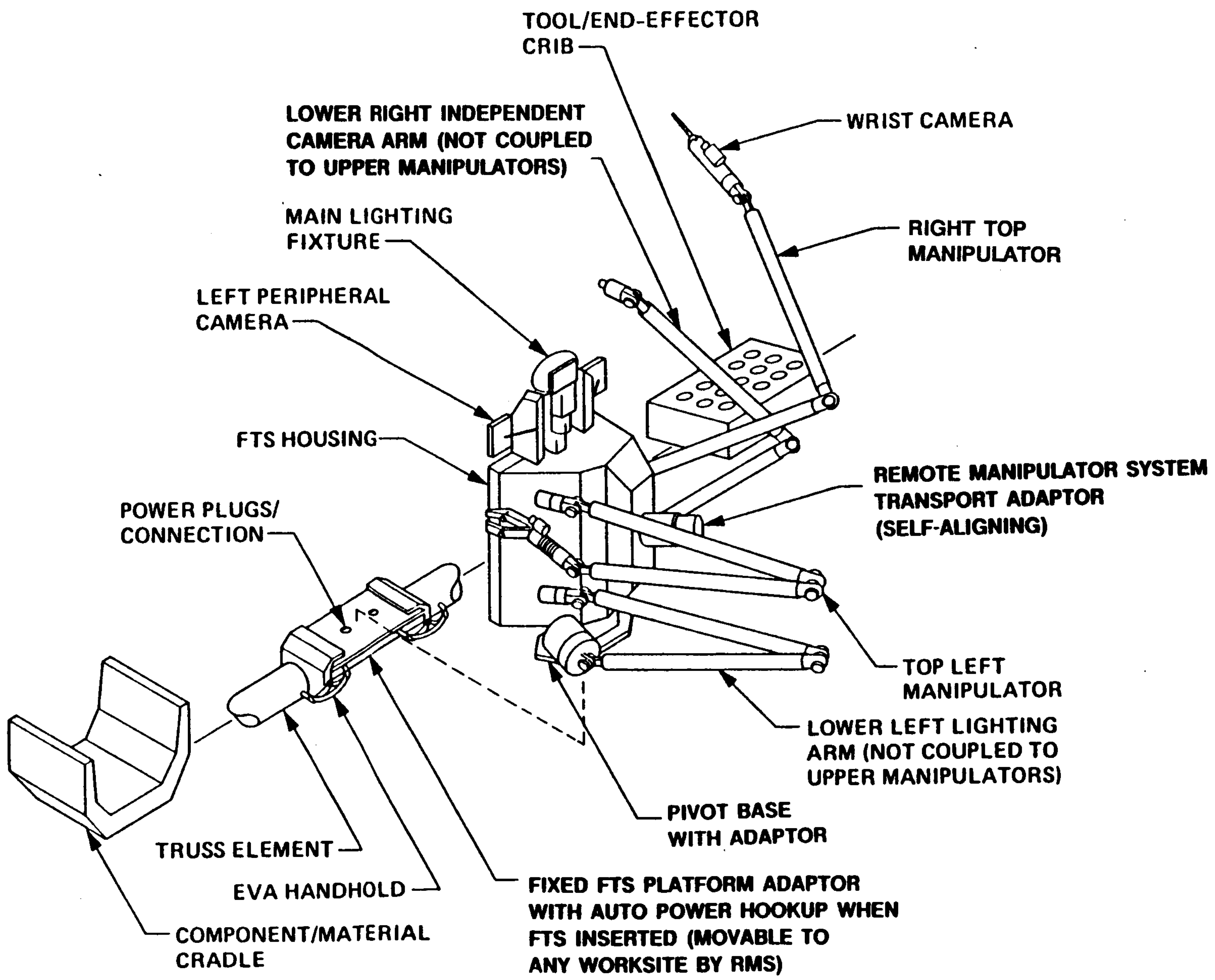

Figure 3-2. FEL/FTS Reference System (Components)

Tasks that were eliminated as candidates were:

(1) Tasks that can be performed by the RMS unassisted.

(2) Tasks requiring initiation and completion by crew EVA, in which FTS involvement during the task would simply idle the EVA crew temporarily.

(3) Tasks with a small margin between functional demands and expected FTS capability (i.e., tasks that could not be performed by the FTS with a high degree of reliability).

(4) Tasks exceeding the functional reach envelope of the FTS or RMS/FTS, such that frequent crew intervention would be required to reposition the FTS. (The introduction of the Mobile Transporter on Flight MB-3 will alleviate this constraint, assuming STS-based control of an FTS located on the Station is provided for.)

Reexamination of the reference concept capabilities relative to the task-related selection rules resulted in a list of feasible FTS functional applications. Specific assembly phase activities identified by CETF and the work packages were examined in detail and compared to the above functions. The results of the analysis suggest that potential FTS functions for FEL to IOC could include:

(1) Handling and unloading of STS pallets,

(2) Deployment of special support equipment and construction components,

(3) Assembly of trusses,

(4) Specific inspection tasks,

(5) Specific handling of modules under traded teleoperator control (providing additional stabilization/grappling points, camera field-of-view, or lighting), and

(6) Limited replacement of ORUs on those payloads that are FTS-compatible.

These six functional applications were judged feasible at FEL because (1) they do not require inordinantly high accuracy in terms of FTS system control; (2) they can be performed largely by state-of-the-art technology; and (3) they can be partitioned such that distinct hardware and software modules can be built for specific tasks and control modes.

Eliminated from contention were tasks such as general exterior inspection and the transfer of logistics launch packages where such packages utilize STS attach fittings that permit operation by the RMS end effector. Regarding inspection activities, it has been estimated that these will comprise approximately 90% of the exterior maintenance tasks (Reference 12). However, the benefits of doing inspection by an FTS will not be realized fully until these can be done autonomously by an FTS having unrestricted mobility about the Station exterior. As long as the FTS is restricted to (1) supervised operation, and (2) the reach envelope of the SS RMS, it is not clear that the FTS would have any advantage over a relatively simple closed circuit TV/lighting system mounted on the SRMS. For the latter case, logistics transfer, it is expected that the Flight Releasable Grapple Fixture supplied for each launch package will be designed to accommodate RMS operations on-orbit (Reference 13). As a specific example, the STS/core Station docking/berthing mechanism is expected to be designed to allow full operation and transfer of payloads without EVA intervention or, in general, use of the FTS.

Tasks such as large module, airlock, or node handling and positioning were left to teleoperation because the analysis of Section III-B suggested potential technology and safety risks. Additionally, more detailed tasks such as utility installation, bolt down, module attachment, and payload installation were considered risk areas (from the standpoint of technology availability, reliability, safety, and accuracy/repeatability) and therefore left to EVA. Note, however, that Table 3-2 does show a potential application of the FTS to the logistics supply and payload tasks. For example, the FTS could off-load supply canisters from a logistics pallet onto a special logistics canister transport (similar to the moving of an assembly pallet from the Shuttle to a cradle). This task could be structured into a "pick-and-place" type automated function similar to existing manufacturing environments. The payload applications include the ORU removal function identified earlier in this section.

The data in Table 3-2 suggest some rather significant savings in some areas. These areas are, by importance, (1) truss construction, (2) moving (deploying) special support equipment and materials to the worksite, and (3) removing the component storage pallet from the Shuttle bay and placing it in a cradle to facilitate deployment of materials.

These results seem to imply the proposed FTS functional capabilities are limited in comparison to still-large investment in EVA (and subsequent remaining conflicts with allowable EVA work schedules). However, it is important to understand that the combined match of assembly phase functions with available technologies (particularly considering the above trade-off criteria) is such that the window of FTS-executable functions is fairly small.

This process established the list of technically feasible FEL FTS tasks. These tasks are summarized in Table 3-3. ("Technically feasible" means that the FTS would be capable of performing any given task in the set, although it may be unable to perform all such tasks for reasons of time limitation, or prohibition based on certain proximity operations rules. Application of these constraints to the technically feasible task set determines the "operationally feasible" task set derived in Section IV.)

F. REVISION OF THE TECHNICALLY FEASIBLE TASK SET (STEP F)

It is apparent that applying many of these task selection rules is related to the forecast of the performance potential of the FTS at FEL

Table 3-2. Summary of Proposed Assembly Task Time Splits For EVA+FTS Case (work-hours)

Flight Number (Type)		EVA Savings (Assembly-Only) with FTS
1	Truss assembly/alpha joints/modules	13.7-14.4
2	Truss assembly/alpha joints/modules	13.7-14.4
3	Radiator/airlock/antenna/payloads	5.6- 5.9
4	Airlock/CERV	4.5- 4.9
5	(Polar platform launch)	-
6	Lab module berth/attach	0.9-2.1
7	Lab module outfitting	0.7
8	Hab module berth/attach	0.5-1.2
9	(Polar platform launch)	-
10	Install 2 nodes	1.4-2.3
11	(First crew/logistics)	potential application of FTS
12	Truss assembly/EMU/SD module	13.0-13.4
13	(Logistics)	potential application of FTS
14	JEM berth/attach	1.8-2.7
15	(Logistics)	potential application of FTS
16	ESA berth/attach	1.6-2.5
17	(Logistics)	potential application of FTS
18	Servicing facil install	4.5-4.9
19	(Logistics)	potential application of FTS
20	Outfit serv facil/log mod	3.2-5.1
21	(Logistics)	potential application of FTS
22	JEM facil/ESA log module	1.9-2.9
23	(Logistics)	potential application of FTS
24	MSC install/manip install	4.9-5.8
25	(Logistics)	potential application of FTS
26	(Polar platform launch)	-
27	(Logistics)	potential application of FTS
28	(Truss assembly)	116.8
29	(Logistics)	potential application of FTS
30	(Payloads)	potential application of FTS
	Total Assembly EVA Savings	189-201 hours

Table 3-3. Technically Feasible Tasks for Performance by FTS at FEL

Assembly Tasks
- Pallet handling and unloading
- Flight support assembly
- Worksite preparation
- Truss assembly
- Specific module handling under teleoperator control

Payload Servicing Tasks
- ORU replacement (selected tasks) (see Note 1)
- Non-ORU maintenance: inspection, cleaning, lubrication, calibration/alignment, filter changeout, re-pointing or positioning
- Removal and transport for purposes of operation, maintenance, or storage

Core Station Maintenance Tasks (see Note 2)
- ORU replacement (selected tasks) (see Note 1)
- Non-ORU corrective maintenance: structures and instrumentation alignment and calibration; parts welding; interface, puncture, and tear reseal; utility lines attachment/detachment (selected tasks)
- Preventive maintenance: surface cleaning, inspection, consumables monitoring (selected tasks)

Logistics Support Tasks
- Transfer of fluid consumables (e.g., fuels)

Miscellaneous/Special Operations Tasks
- EVA support: erect workstations; transport tools, materials, and support equipment; erect a supply bin; lay out work environment
- Berthing/deployment
- Facilities support: monitor processing functions, transport material to other process points
- Hazardous material handling
- Chemical release decontamination, e.g., use a "vacuum cleaner"
- Provide on-site visual monitoring of hazardous/critical operations

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NOTES:

1. Current PDRD requirements call for ORU R&R to be designed compatible with FTS capabilities.

2. Prior to the Permanently Manned Configuration (PMC), the Space Transport System (Shuttle) provides on-orbit repair for high-criticality items.

(particularly the manipulatory performance) under both teleoperator and autonomous control (Step (D)).

Note that in the overall study methodology (Figure 2-1) there is feedback from the operationally feasible task set to the technically feasible task set. This feedback is also displayed as Step (F) in Figure 3-1.

When estimating the EVA and IVA times for the operationally feasible task set, the total times may exceed the available budget. In such cases, low-priority tasks may be eliminated from the technically feasible task set. If this is the case, the FTS Reference System may or may not be revised, depending on the degree to which the FTS Reference System design supports the task to be removed. If the FTS design is highly dependent on the task(s) to be removed, there is potential to simplify and thus reduce technical and performance risk by revising the FTS. If the FTS design does not depend a great deal on the task to be removed, it may not be possible to achieve significant improvements in technical and performance risk by revising the FTS Reference System.

As a guideline, the degree of FTS-task design dependency is related to the total time for such tasks during the assembly phase. If the technically feasible task set is to be reduced because of EVA or IVA constraints, the place to begin is with small, infrequent tasks requiring small amounts of EVA/IVA. This approach retains the FTS for repetitive, long-duration tasks for which it is well-suited.

SECTION IV

OPERATIONAL CONSTRAINTS AND THE OPERATIONALLY FEASIBLE TASK SET

Operational constraints are additional factors, not directly related to FTS performance capabilities, that may prevent the FTS from performing those tasks judged technically feasible (Table 3-3). The operational constraints addressed in this section are: (1) crew resource constraints, (2) constraints on proximity operations, and (3) operations-related priority selection rules.

The crew resource constraints consist of two categories: EVA and IVA. There are limits on EVA that all operations must recognize, but the limits on IVA time are most relevant to FTS operation. Because the tasks in the technically feasible task set could be performed by either EVA or IVA (using an FTS), limits for both EVA and IVA are reported here.

The proximity operations rules refer to constraints imposed by physical operating envelopes and safety that might preclude specific tasks from being performed by an FTS.

A number of different task sets, all comprising technically feasible tasks, might satisfy these constraints during the FTS life cycle. Therefore, additional operations-related priority selection rules are suggested to identify a prioritized task set that includes some notions of safety and hazard exposure.

A. EVA AND IVA TIME LIMITATIONS

The CETF-derived EVA/IVA budgets are presented in Table 4-1. The values shown represent the maximum amount of available EVA/IVA at each flight-interval milestone. The values presented here are the budgeted amounts available to complete the assembly phase. The entries in the table after PMC were obtained by taking the CETF weekly estimates and multiplying by the number of weeks in each flight interval. The weeks per flight interval is obtained by dividing 52 weeks per year by the number of flights assumed per year. Thus for flights 12-21 we have 52/8 = 6.5 weeks per flight interval. Table 4-2 presents a summary of the EVA constraints for STS versus Station-based EVA.

One crew resource item was considered as an FTS operations constraint in this evaluation: crew IVA time. Specifically, crew IVA support must be provided for FTS operation in order to (1) control the FTS during the teleoperation mode, (2) monitor the FTS during operation, (3) provide on-orbit maintenance/servicing of the FTS, and (4) potentially assist replacement crew members in FTS operations checkout.

Obviously, crew IVA resources devoted to FTS operation and support must not exceed the total IVA crew-hour resources available. These resources estimated to be available for application to the FTS are also summarized in

Table 4-1. Study EVA/IVA Budgets for Assembly Phase
(work-hours per flight interval)

Assembly Flight	Assembly Phase Sequence No.	Assembly EVA	Assembly IVA	Other IVA Maintenance	Other IVA User	Other IVA Unassigned	
MB-1	1	24[a]	30	12	--	--	
MB-2	2	24[a]	30	12	--	--	
MB-3	3	24[a]	30	12	--	--	
MB-4	4	24[a]	30	12	--	--	
	5	24[a]	30	12	--	--	
MB-5	6	24[a]	30	12	--	--	STS-
	7	24[a]	30	12	--	--	Based
MB-6	8	24[a]	30	12	--	--	(hours per
	9	24[a]	30	12	--	--	STS flight)
MB-7	10	24[a]	30	12	--	--	
PMC--> MB-8	11	130[b]	1274	410	390	475	
MB-9	12	130[b]	1274	410	390	475	
	13	130[b]	1274	410	390	475	
MB-10	14	130[b]	1274	410	390	475	
	15	130b	1274	410	390	475	
MB-11	16	130[b]	1274	410	390	475	
	17	130[b]	1976	501	780	696	
MB-12	18	130[b]	1976	501	780	696	Station-
	19	130[b]	1976	501	780	696	Based
MB-13	20	130[b]	1976	501	780	696	(hours per
	21	130[b]	1976	501	780	696	flight
MB-14	22	116[c]	1756	445	693	618	interval)
	23	116[c]	1756	445	693	618	
MB-15	24	116[c]	2380	445	1317	618	
	25	116[c]	2380	445	1317	618	
	26	116[c]	2380	445	1317	618	
	27	116[c]	2380	445	1317	618	
MB-16	28	116[c]	2380	445	1317	618	
	29	116[c]	2380	445	1317	618	
MB-17	30	116[c]	2380	445	1317	618	
TOTALS		2,738	37,996	9,090	16,845	11,902	

[a] Estimated: 2 crewmen x 6 hours/day x 2 days for flights 1-11.
[b] 52 weeks/yr/8 flight intervals/yr x 20 EVA hrs/week = 130 hrs/flight interval.
[c] 52 weeks/yr/9 flight intervals/yr x 20 EVA hrs/week = 116 hrs/flight interval.

Table 4-2. STS and Station EVA Constraints
(Source: CETF)

EVA Constraints

STS-Based (first 8 assembly phase flights: 7 assembly, 1 logistics)

24 work-hours planned EVA for Space Station

Station-Based (Values are ground rules used by the CETF)

20 work-hours per week planned

Note: Typical STS-Based Assembly Timeline

(Assumes:

- Five STS EMUs
- STS airlock operations
- Seven crew members
- Four EVA crew members)

Day	Activity
1 & 2	STS operations, SS rendezvous and docking
3	EVA preparation
4 & 5	Planned 24 work-hours EVA (two six-hour shifts, 2 crew members per shift)
6	Assembly contingency (12 work-hours EVA for SS)
7	Return preparation / STS contingency 12 work-hours EVA
8	Return

Table 4-1. CETF concluded that one EVA excursion (12 work-hours) per week satisfies maintenance and user needs.

Figure 4-1 displays a breakdown of the IVA budgets for maintenance, user payloads, and assembly (which includes unassigned IVA).

The time constraints are provided here for reference and comparison with the estimated requirements derived in Section V.

B. PROXIMITY OPERATIONS RULES

Certain tasks may be off-limits based on violation of constraints for proximity operations. This section identifies proximity operations rules that might impinge on the choice of candidate EVA tasks for augmentation or replacement by the FTS. The objective is to use such rules to filter out those EVA tasks that could not be performed by or in conjunction with the FTS.

Using References 14 and 15, a general set of rules/constraints that could be expected for a telerobotic device were synthesized. The constraints fall into two general categories:

(1) Device (FTS) operation, and

(2) Device (FTS) operation in presence of EVA crew (co-EVA) operations.

These "synthesized" constraints are based on the Shuttle Operational Flight Rules and the Remote Manipulator (RMS) constraints.

1. FTS Rules

(1) Positional limits on FTS. No part of the FTS will be positioned within a specified distance of any thruster due to possible contamination and loading. This also depends on the type of propellant. In addition, there would be limits on the physical envelope of the FTS specific to the work area (like keeping the arms from banging into the shuttle radiators).

(2) No part of the device (FTS) can be manipulated outside the field of view of the camera systems or direct line-of-sight of an either IVA or EVA crewman unless allowed by specific alternative requirements.

(3) The device (FTS) shall not be left unattended unless the following conditions are met:

(a) A single point failure cannot allow the FTS to move on its own;

(b) There are sufficient inhibit modes that the device (FTS) can be left unattended for a specified length of time.

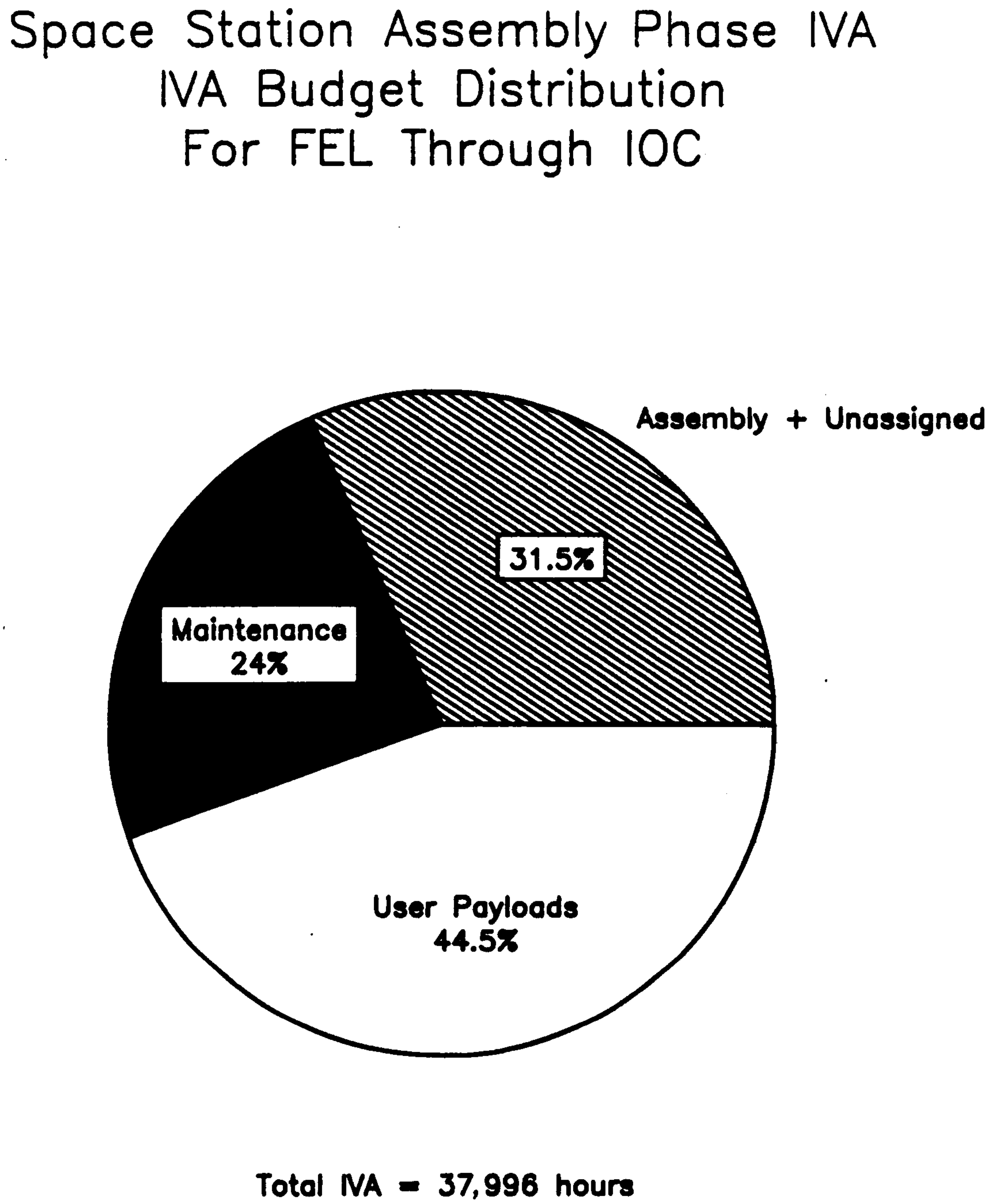

Figure 4-1. IVA Budget Distribution for Assembly Phase

(4) During crew sleep periods and device nonoperations periods beyond a specified length of time, the FTS must be stowed.

(5) Device (FTS) operations will be terminated outside the specified temperature regime.

(6) In a Shuttle [or Station] emergency mode, if the device (FTS) cannot be stowed within a specified length of time (probably well under 30 minutes), the capability must exist to jettison the device clear of the Shuttle and/or Station (even if it is attached to the Shuttle bay).

(7) A payload may be grappled and berthed if there are at least two ways to release it. This is especially true of operations within the Shuttle bay and may also be true for FTS if operations are to be performed within some period of time prior to a scheduled reboost.

(8) If the device (FTS) is self-mobile, there will likely be constraints on either its holding power or its reboost configuration (so it can hang onto the Station during a reboost!).

(9) Failures in FTS supporting systems (video lines, cameras, DMS, etc.) will terminate FTS operations.

(10) An appropriate level of "safing" capability is required to avoid the consequences of single-point failures.

2. <u>Possible FTS Co-EVA Operations Rules</u>

(1) Potentially hazardous modes or equipment (FTS) will be verified safe in the event of co-EVA. This will depend on safety assurance and might require two ways to prevent FTS translation during EVA.

(2) There must be live communications between the FTS operator and EVA crew in the vicinity of the FTS. If communications are lost, FTS operations must be discontinued.

(3) There must be visual verification of the FTS position and clearance required between FTS and a crewman. This verification must be provided by either an EVA crewman or an IVA crewman with cameras and/or direct line-of-sight. (There are currently no rules governing the physical envelope between the FTS and a crewman.)

(4) If there is any degree of FTS autonomous operation, there will probably be a rule that an EVA crewman could not invade the physical envelope (to be specified) of the FTS while it was operating. This may preclude a large number of tasks where the FTS would be co-located next to an EVA crewman.

(5) There might be a constraint on moving (translating) the FTS while crew are in the vicinity. If there are sufficient safety inhibits to prohibit uncommanded motion, then translation might be allowed within a specified envelope in the present of a crewman.

Applying these rules to the technically feasible task set is difficult because of a lack of detailed data on positional limits and physical envelopes associated with each task description. As such data become available, the rules would be applied.

There are a number of related points to be made regarding FTS operating modes. For example, when designing and locating movable, actuating, or similar mechanical devices, adequate clearance must be provided to prevent interference with any structure; puncture of fluid lines, valves, and tanks; and contact with electrical wiring and components or other subsystem components. In particular, when working with hypergolic fuels, Space Station Program personnel will have to be on "alert" status when loading such propellants. The implication, if the FTS is used at all in this mode, is a requirement of full-time supervision, even if the task can be performed autonomously by the FTS.

There are several possible application modes for telerobotics. In the "concurrent" mode, the telerobotic devices will be operated under IVA control during EVA operations. The more likely version of this option will consist of operation at locations fairly remote from the EVA center of activity, or solely involve the transport of parts and materials to the EVA site. Alternatively, however, the telerobot could be operated to perform tasks cooperatively with the EVA worker at the job site.

Another possible mode of operation is the "separate shift" mode, in which the telerobot is operated only before or after EVA shifts, but not during. This mode primarily would involve (1) site preparation for the EVA workers: materials delivery or worksite button-up/safing at the end of an EVA shift, (2) post-assembly inspection or maintenance, or (3) actual assembly tasks that do not require direct EVA involvement and would be scheduled for off-EVA shifts.

Finally, a telerobot might be operated in a "combined mode," involving activity both during and outside of EVA shifts.

As mentioned above, tasks that may be prohibited under the proximity operations rules early in the FTS operating life are difficult to assess. It is likely that proximity operations rules will be applied conservatively due to lack of on-orbit FTS operating experience. It is expected that such rules might be modified significantly as FTS operating experience accumulates. However, it should also be noted that each replacement crew will experience its own FTS operation learning periods, so that proximity operations rules may be relaxed very slowly.

There are a number of tasks in this study that were ruled out on technical feasibility grounds (e.g., cooperative EVA dexterous alignment tasks) that might also be ruled out due to operations constraints when a future FTS with greater capabilities might be used. Such tasks would need to maintain a distance between the physical envelopes of EVA crew and FTS for safety reasons.

The constraints identified in this section are applied to the technically feasible task set (Table 3-2) to derive an operationally feasible task set.

C. ADDITIONAL OPERATIONS-RELATED SELECTION RULES

The application of the EVA/IVA time and proximity operations rules can provide a number of alternative task sets that are feasible. However, in order to select a prioritized set, a second category of selection rules could be applied to the technically feasible tasks subject to the operational constraints to derive a prioritized operationally feasible task set.

The designation of a "priority" task set is not intended to imply a set of FTS applications criteria currently endorsed by the Space Station Program. A variety of A&R selection criteria have been proposed over the course of Phase B, but no single set has been adopted generally for use. The term "priority" is applied relative to the specific issue: "Can the FTS be operated during Station assembly in a cost-effective manner under some reasonable set of assumptions about how EVA time might be valued?"

Consequently, FTS applications could be selected much in the same manner as a planner might use to maximize the usefulness of the FTS. Because the fundamental purpose of the FTS is to reduce EVA demands on the crew, EVA time reduction is the primary factor in the selection process. However, not all EVA tasks are equally valuable in that each of the following factors may vary by task or by time of occurrence in the assembly phase:

(1) Station resources for EVA plus overhead per EVA hour (e.g., duration of EVA excursion will affect this ratio),

(2) Degree of risk to EVA crew, and

(3) Program consequences of insufficient EVA time availability (e.g., slippage of early assembly tasks could affect the entire assembly schedule).

Selecting an FTS task application set of high value relative to these considerations requires specifying the relative value of each EVA task according to its overhead cost, schedule risk, and crew risk. Table 4-2 identifies four priority ranking rules that could be used for selecting a high-value set of operationally feasible FTS tasks.

It is important to reiterate that these priority ranking rules are not part of an "official" Program selection procedure, nor do they represent all factors of interest in selecting FTS configurations or applications. Their sole purpose is to establish a reasonable basis for selecting a set of operationally feasible tasks in order to determine whether an FTS might perform such a task set cost-effectively. As such, the selection scheme is not

Table 4-3. Example Criteria for Selecting a Prioritized, Operationally Feasible FTS Task Set

PRIORITY	EVA TASK CHARACTERISTIC
1.	Tasks that would cause EVA demands to exceed available EVA resources, possibly necessitating costly schedule adjustments. Applied in this study solely to pre-PMC assembly period, when EVA is strictly limited, such that task deferrals might result in additional assembly flights. Examples: selected assembly tasks on Flights 1 and 2 that would otherwise exceed available EVA limits.
2.	Tasks of greater than average hazard to crew (but excluding Criticality 1 items that will likely be allocated to EVA crew). Examples: toxic fluid handling; operation of mechanisms involving release of stored energy. Additionally, use of the FTS in tasks involving EVA hazards (propulsion thrusters, antennas, electrical systems) may in some circumstances be preferable to safing those systems to allow crew EVA in the area.
3.	Tasks that can be performed in their entirety by the FTS, thereby reducing the total number of EVA shifts per time period, and the consequent EVA overhead. Example: selected ORU changeout operations.
4.	EVA tasks that reduce the EVA excursion duration for crew members and may or may not be performed independent of EVA. Example: EVA workstation setup and post-task cleanup.

offered as the means of identifying a programmatically "optimum" FTS configuration or applications mode, but rather these rules are intended to faciliate the process of identifying and characterizing an FTS con-ept and applications scenario for the purpose of determining its cost-effectiveness for situations in which there are multiple alternatives for performing required tasks. Such priority rules can aid in at least ranking the tasks so that higher priority tasks are considered first.

The next step is to take the operationally feasible task set together with the non-FTS tasks and characterize two cases: an EVA-Only (no FTS) case and an EVA+FTS case. The next section describes the process of estimating the EVA and IVA times for these cases.

SECTION V

ASSEMBLY PHASE EVA AND IVA TIME ESTIMATES

This section is concerned with estimating the EVA and IVA times for a set of EVA-Only and FTS-performed EVA tasks between FEL and IOC that were identified as being technically feasible, meet the operational constraints, and conform to the priority ranking rules in Table 3-2. That is, the derived tasks summarize the high-value set of operationally feasible FTS tasks selected for the cost-effectiveness evaluation. The values derived are:

(1) The time required to perform each task by EVA,

(2) The time required to perform each task by the FTS, and

(3) The IVA times for task performance by both EVA crew and the FTS.

These times are listed both by task and by time period (per flight interval). The times are derived for both the EVA-Only and EVA+FTS case for: (1) assembly, (2) maintenance, (3) attached payloads, and (4) polar platforms. As described earlier, logistics operations and satellite servicing were not included. The values for the polar platform category were estimated, but, due to changes in the SSP, were not included in the final results.

The detailed task estimates were available only in the assembly task case. The task descriptions for an FTS in the maintenance, attached payload, and polar platform cases and the task time estimates were more difficult to find or were unavailable. The basic procedure used in these (nonassembly) cases was:

(1) Estimate the EVA-Only-case values of EVA and associated support IVA.

(2) Assume that 20% of the EVA-Only-case times could be displaced by an FTS.

(3) For the EVA+FTS case, compute the remaining EVA (EVA_R) and the EVA savings due to the FTS (EVA_A).

(4) Because the values in (3) are specific to the EVA+FTS case, calculate the EVA and IVA times for the EVA-Only and EVA+FTS cases using performance ratios algorithms to translate to a common basis. The performance ratio algorithms are used to translate equivalent task times between using an EVA crew member and using the FTS. These algorithms are described further in subsection V-B.

(5) In cases in which uncertainty was especially high, the estimates derived in (4) are bounded by an interval of $\pm 20\%$.

As noted earlier, the purpose of the study is not to determine an optimal solution but to provide an approach to bounding the problem.

A. ASSEMBLY TASKS

The candidate assembly tasks are summarized in Appendix Table C-2 by flight interval. These tasks were derived from the CETF data and analyzed to determine further detail at the subtask level. As shown, the tasks share a number of common operations, such as removing the necessary pallets, erecting workstations, deploying special grappling/berthing fixtures, grasping objects, positioning, and bolting down.

The task times were derived from task estimates for the EVA+FTS case using performance time ratio algorithms. The performance ratios represent the amount of time the task category would take if controlled and supervised telerobotically (IVA) using an FTS divided by the time taken by an EVA crew member to perform the same task (References 9, 16). These ratios represent the conversion time between the FTS IVA crew member and one EVA crew member measured in clock time. However, EVA is always performed with crews of two people. Although the two-crew-member rule is accounted for when estimating IVA time, it should be noted that only one-person/one-task is assumed in the performance algorithms used here. If more detailed task descriptions are forthcoming, a weighted split between the two crew members could be used to assess possible synergistic benefits of teamwork versus the solo FTS. For the purposes of the present study, the additional crew member is assumed to be for safety, handling lighting or cameras, for inspection, or working on an unrelated task. This assumption is not unreasonable for many of the dexterous tasks because such tasks are best performed by one crew member. However, some cooperative tasks, such as grappling or moving objects, do involve more than one crew member working on the same task. The possible effects of these differences was not examined.

Using the task times for the FTS-performed tasks, performance ratios (Appendix Table C-1) for a variety of task functions (Reference 16) were used to translate the FTS task estimates into the EVA-Only and EVA+FTS case time estimates displayed in Appendix Table C-2.

The terms used to refer to the tabulated values are defined as follows:

EVA_O - EVA required for the EVA-Only case

IVA_O - IVA required for the EVA-Only case

EVA_F - EVA required in the EVA+FTS case

IVA_F - IVA required in the EVA+FTS case

FTS - EVA hours saved (displaced) by FTS (EVA_O-EVA_F)

The performance ratios in Table C-1 are difficult to allocate to specific tasks without more detailed task descriptions. Each task was reviewed to identify the possible performance categories used for the task, and a range of performance ratios was used to bound possible subtask values in the absence of information regarding duration and frequency of the tasks. For example, if an activity was composed of four subtasks with performance ratios ranging from 1.4 to 2.2, a range of 1.4-2.2 was used to obtain a range of EVA and IVA estimates.

The totals by flight are summed and displayed in Table 5-1. The values summarized in Table 5-1 reflect the range format due to the varying performance ratios. The values in Table 5-1 are based on the original CETF point estimates and form a study database for the methodology used. The primary differences from the original CETF estimates are due to a review and assessment of key assembly tasks by flight in terms of actual EVA and IVA time if performed by an FTS. There is little difference in most cases because the number of FTS tasks with large EVA displacements is small (e.g., Flight 28).

Note that for those tasks with large EVA displacement times, the effect of the ranges will be more pronounced. Uncertainties in the ranges for these cases could be significant and the narrow ranges for many of the estimates should not be construed as narrow uncertainty or indicative of the degree of accuracy.

The ranges are more critical on the pre-PMC flights, when EVA is STS-based. The values prior to Flight 12 (PMC) are for STS-based operations and must be accomplished during the flight duration. After PMC, the hours are those occurring during the interval between flights and are Station-based. The values shown in the table are the total time estimates per flight interval. Although some cases appear large (Flight 28) relative to the 20-hour-per-week EVA constraint, it must be remembered that the estimates are per flight interval. The estimate of 174 hours for Flight 28 is actually distributed over 5.8 weeks (52 weeks/year / 9 flights/year). Because EVA will be Station-based, there will be more more flexibility in rescheduling EVA operations over time than during the Shuttle-based period (FEL-PMC).

B. MAINTENANCE TASKS

Maintenance tasks can be categorized as scheduled and unscheduled maintenance. Estimates of EVA and IVA required to perform core Station maintenance are based principally on data presented from Reference 17.

A conservative peak value of approximately 1,700 corrective events per year has been estimated (all criticality levels) by IOC, which yields a yearly average of approximately 975 events/year during the Station assembly phase (Reference 17). These estimates were based on C-5 aircraft reliability data, and correspond to a MTBF of 203 hours to retain "partial mission capable" availability status. However, spacecraft hardware is approximately 16 times more reliable, which implies a corresponding MTBF of 3,248 hours. Further, the estimates used the CETF conclusion that the number of externally maintainable items could be reduced to 110. With these modifications, the Station was estimated to require the following:

77 maximum corrective events/year by IOC (all criticality levels)

and

39 yearly average during assembly

Table 5-1. EVA/IVA Assembly Estimates by Flight (Flights 1-11) and by Flight Interval (after Flight 11) (work-hours) (ranges due to range of performance ratios used)

		EVA-Only Case		EVA+FTS Case		
	Flight	EVA_O	IVA_O	EVA_F	IVA_F	FTS Hrs.
	1*	37.2-37.9	18.8-19.2	23.5	21.1-29.1	13.7-14.4
	2*	37.2-37.9	18.8-19.2	23.5	21.1-29.1	13.7-14.4
	3	18.8-19.1	9.4-9.6	13.2	12.4-15.2	5.6-5.9
	4	19.9-20.3	10.0-10.1	15.4	11.0-13.9	4.5-6.4
STS-	5	0	0	0	0	0
Based	6	16.3-17.5	8.2-8.7	15.4	11.0-13.9	0.9-2.1
	7	7.9	4.0	7.2	4.0-4.7	0.7
	8	22.6-23.3	11.3-11.7	22.1	12.3	0.5-1.2
	9	0	0	0	0	0
	10	12.7-16.6	6.4-8.3	11.3-14.3	8.8-10.3	1.4-2.3
	11	0	0	0	0	0
PMC	12	83.8-84.7	41.9-42.3	70.8-71.3	43.0-51.2	13.0-13.4
	13	0	0	0	0	0
	14	13.6-17.5	6.8-8.8	11.8-14.8	8.8-11.0	1.8-2.7
	15	0	0	0	0	0
	16	9.4-13.3	4.7-6.67	7.8-10.8	7.2-8.4	1.6-2.4
	17	0	0	0	0	0
	18	44.2-44.6	22.1-22.3	39.7	22.2-25.5	4.5-4.9
	19	0	0	0	0	0
	20	50.7-55.6	25.4-27.8	47.5-50.	29.6-31.8	3.2-5.1
Station-	21	0	0	0	0	0
Based	22	13.3-17.3	6.7-8.7	11.4-14.4	8.6-10.9	1.9-2.9
	23	0	0	0	0	0
	24	13.3-14.2	6.7-7.1	8.4	7.8-11.0	4.9-5.8
	25	0	0	0	0	0
	26	0	0	0	0	0
	27	0	0	0	0	0
	28	174.0	87.0	57.2	87.0-157.4	116.8
	29	0	0	0	0	0
	30	0	0	0	0	0
	TOTALS	575-602	288-301	386-402	316-436	189-201

* Assumes erectable trusses and utilities

Based also on Reference 17 data, the corresponding figures for critical events (i.e., "not mission capable" failures) are as follows:

> 2.7 critical events/year by IOC

and

> 1.5 yearly average during assembly (approximately 6 critical events during the assembly phase)

(Critical events are tallied separately, since these events in general are not deferrable. The occurrence of nondeferrable events will be particularly important during the pre-PMC period, when available EVA resources will be very limited.)

Corrective events were estimated to require 3 hours on the average, including overhead, for a two-person EVA crew (= 67 work-hours of EVA time). Maintenance EVA requirements during the assembly phase are summarized below by year of occurrence:

Year	Critical Events:		Noncritical Events:		Totals:	
	Events	EVA work-hours	Events	EVA work-hours	Events	EVA work-hours
1	1	6	9	54	10	60
2	1	6	28	168	29	174
3	2	12	46	276	48	288
4	2	12	65	390	67	402

Table 5-2 provides a more detailed breakout, by year when actually performed, of the EVA and supporting IVA associated with core Station maintenance (note that some deferral of maintenance was assumed in order to accommodate EVA limitations in early flights).

Using these estimates, the values are prorated over each flight interval as follows: 12 hours/week of EVA for maintenance on Flights 3 through 11, 7.5 hours/week for EVA on Flights 12 and 13, 6.0 hours/week for Flights 14 through 21, and 7.7 hours/week after Flight 21.

Noncritical item maintenance will likely be deferred until PMC and, because of uncertainties in EVA/IVA requirements for Flights 1 through 5, the estimates of 12 EVA hours were converted to range estimates using a factor of ±20%. Table 5-3 lists the EVA and IVA times derived using the performance ratio algorithms from Section 5-A with a range of performance ratios from 1.4 to 5.0. It was assumed that in the EVA+FTS case approximately 20% of the maintenance tasks could be performed by the FTS based on the current requirement that ORU changeouts be performable by the FTS. This is a parametric assumption which could be modified as new data become available. During the post-PMC period the total maintenance by flight interval was computed using a weighted sum of the maintenance per week and the number of weeks in each flight interval. The totals by flight interval are presented in Table 5-3.

Table 5-2. Assembly Phase Maintenance Assumptions

Year	EVA Excursions	EVA work-hours	IVA Support work-hours	
1	2	12 each, on Flights 3-5	6 each, on Flights 3-4	(assumes 60% (= 6) of pre-PMC actions can be deferred to post-PMC: 2 to the second year; 4 to the third)
2	16	12 each, on Flights 6-10 7.5/week, post-PMC	6 each, on Flights 6-10 3.8/week, post-PMC	(year 2, post-PMC = 20 weeks)
3	26	6/week	3/week	
4	34	7.7/week	3.9/week	

Notes:

1. One excursion = 2 corrective actions = 12 EVA work-hours = 6 IVA work-hours.

2. McDonnell Douglas (McDAC) estimated approximately 2.9 EVA work-hours/week for the CETF "Revised Assembly Sequence" case for the third year (Reference 18).

3. The CETF estimated 240 work-hours/year (= 4.6 work-hours/week) of EVA would be required for core Station maintenance.

Table 5-3. EVA/IVA Maintenance Estimates by Flight (Flights 1-11) and by Flight Interval (after Flight 11) (work-hours)

	Flight	EVA-Only Case EVA_o	EVA-Only Case IVA_o	EVA+FTS Case EVA_F	EVA+FTS Case IVA_F
	1	0	0	0	0
	2	0	0	0	0
	3	9.6-14.4	4.8-7.2	7.7-11.5	5.2-13.0
	4	9.6-14.4	4.8-7.2	7.7-11.5	5.2-13.0
STS-	5	9.6-14.4	4.8-7.2	7.7-11.5	5.2-13.0
Based	6	12.0	6.0	9.6	6.5-10.8
	7	12.0	6.0	9.6	6.5-10.8
	8	12.0	6.0	9.6	6.5-10.8
	9	12.0	6.0	9.6	6.5-10.8
	10	12.0	6.0	9.6	6.5-10.8
	11	12.0	6.0	9.6	6.5-10.8
PMC	12	48.8	24.7	39.0	26.4-44.0
	13	48.8	24.7	39.0	26.4-44.0
	14	39.0	19.5	31.2	21.1-35.1
	15	39.0	19.5	31.2	21.1-35.1
	16	39.0	19.5	31.2	21.1-35.1
	17	39.0	19.5	31.2	21.1-35.1
	18	39.0	19.5	31.2	21.1-35.1
	19	39.0	19.5	31.2	21.1-35.1
	20	39.0	19.5	31.2	21.1-35.1
Station-	21	39.0	19.5	31.2	21.1-35.1
Based	22	44.5	22.5	35.6	24.6-41.0
	23	44.5	22.5	35.6	24.6-41.0
	24	44.5	22.5	35.6	24.6-41.0
	25	44.5	22.5	35.6	24.6-41.0
	26	44.5	22.5	35.6	24.6-41.0
	27	44.5	22.5	35.6	24.6-41.0
	28	44.5	22.5	35.6	24.6-41.0
	29	44.5	22.5	35.6	24.6-41.0
	30	44.5	22.5	35.6	24.6-41.0
TOTALS:		909-924	458-466	729-740	498-521

C. PAYLOAD SETUP AND SERVICING TASKS

The payload EVA tasks were derived from a review of the potential payload candidates for Flights 3, 18, and 30 contained in a JPL-modified version (MRDB*) (Reference 19) of the Mission Requirements Data Base (MRDB) (Reference 4). The modifications involved translation of the database to a series of subdatabases sorted by key fields and a case by case review of the records for each data set for inconsistent, erroneous, or missing entries. For the cases in which information to support corrections was available, entries were made. However, even after modification, the quality of data in the JPL-modified MRDB is still in question and perhaps can only provide an indication of the types of payloads and the parameters that might be associated with Station attached payloads.

The approach consisted of defining sort indexes for likely candidates on Flights 3, 18 and 30, sorting the candidates, generating a reference payload, and multiplying by an expected number of payloads. The payload setup and servicing times were then prorated over the number of year-specific flights as described below.

The assumptions used to derive the representative payloads for each flight are:

(1) No selection/recommendation of candidates is made, but rather a set of candidates is generated to estimate typical mass, and EVA and IVA hours required by each payload. The estimates are reviewed to determine if the representative servicing activities can be displaced by the FTS.

(2) Although unused mass and volume have been identified on other Space Station assembly flights, only those flights with <u>scheduled</u> attached payloads are considered here. These include Flight 3 (2,954 kg), Flight 18 (14,267 kg), and Flight 30 (18,181 kg) (Reference 19).

(3) Because the time period of this study extends from Assembly Flight 1 through IOC, only attached payloads scheduled during that time frame are considered.

With these assumptions in mind, the JPL-modified Mission Requirements Data Base (MRDB*), containing over 300 proposed payloads (Reference 19), was searched.

1. <u>Candidates for Assembly Flight 3</u>

The sorting indexes for Flight 3 were:

(1) Launch during 1992-1993 (equivalent to the first year of assembly).
(2) All mass located at an unpressurized external location.
(3) No individual attached payloads weighing more than 2954 kg.
(4) No individual power requirements > 17 kW.
(5) Service interval > 90 days.

The average mass, EVA times for setup and servicing, and IVA times for setup and servicing were computed for the resulting list of six viable candidates. The averaged estimates for Flight 3 to be done without an FTS (as per the MRDB) were:

average mass of payload	-	300 kg
average EVA setup time	-	2.5 hrs
average IVA setup time	-	4.2 hrs
average EVA servicing	-	none required
average IVA servicing	-	none required

As a check for consistency, similar values were also computed using projected payload types from an independent CETF presentation. For the nine candidates in this sample, the values compared favorably:

average mass of payload	-	376 kg
average EVA setup time	-	2.3 hrs
average IVA setup time	-	4.5 hrs
average EVA servicing	-	5.6 hrs/90 days
average IVA servicing	-	12.9 hrs/90 days

Based on these values and constraints on payload mix, number, and timing, it was assumed that three payloads would be launched on Flight 3. Furthermore, opportunities for FTS involvement would be limited during Flight 3, since the RMS might perform most of the FTS-type tasks. The estimates of EVA/IVA time are:

Payload Setup-Flight 3 (year 1)

3 payloads x 2.5 EVA hrs/payload = 7.5 EVA hrs for setup
3 payloads x 4.2 IVA hrs/payload = 12.6 IVA hrs for setup

Servicing (year 1)
none assumed

2. Candidates for Assembly Flight 18

A similar procedure was used for Flight 18 with the following sort indexes:

(1) Launch during 1994 (year 3) time frame.
(2) No more than five payloads launched.
(3) All mass located at internal pressurized, internal unpressurized, or external unpressurized locations, but not associated with a free-flyer or OMVs.
(4) No individual attached payloads weighing more than 14,627 kg.
(5) No individual power requirements > 57 kW.
(6) No restriction on service interval.

From the resulting list of 18 viable candidates, the average mass, EVA times for setup and servicing, and IVA times for setup and servicing were computed. The averaged estimates for Flight 18 (no FTS assumed) were:

average mass of payload	-	2047 kg
average EVA setup time	-	10.8 hrs
average IVA setup time	-	25.3 hrs
average EVA servicing	-	7.1 hrs/payload/yr
average IVA servicing	-	4.9 hrs/payload/yr

Because minimal servicing is required for the payloads delivered in Flight 3, it was assumed that the majority of payload service EVA/IVA would be required after Flight 18. Using the average values computed above and assuming that five payloads are delivered, the following estimates of payload servicing times are calculated for the period between Flight 18 and 30:

Payload Setup-Flight 18 (year 3)

5 payloads x 10.8 EVA hrs/payload - 54 EVA hrs for setup
5 payloads x 25.3 IVA hrs/payload - 126.5 IVA hrs for setup

Servicing (years 3-5/IOC)

5 payloads x 7.1 EVA hrs/payload/yr x 2 yrs to IOC/52 weeks/yr
- 1.4 hr/week EVA for payload servicing

5 payloads x 5.9 IVA hrs/payload/yr x 2 yrs to IOC/52 weeks/yr
- 1.1 hr/week IVA for payload servicing

3. Candidates for Assembly Flight 30

A similar procedure was used for Flight 30 with the following sort indexes:

(1) Launch during 1995-1996 (year 4-5) time frame.
(2) No more than five loads launched.
(3) All mass located at internal pressurized, internal unpressurized, or external unpressurized locations, but not associated with a free-flyer or OMVs.
(4) No individual attached payloads weighing more than 18,181 kg.
(5) No individual power requirements > 57 kW.
(6) No restriction on service interval.

From the resulting list of eight viable candidates, the average mass, EVA times for setup and servicing, and IVA times for setup and servicing were computed. The averaged estimates for Flight 30 (no FTS) were:

average mass of payload	-	2781 kg
average EVA setup time	-	0.0 hrs
average IVA setup time	-	7.3 hrs
average EVA servicing	-	0.0 hrs/payload/yr
average IVA servicing	-	39.4 hrs/payload/yr

The average payload is again larger, but requires little if any EVA (perhaps due to use of deployment, the RMS, or the Mobile Servicing System).

Payload Setup (year 4-5)

5 payloads x 0 EVA hrs/payload = 0 EVA hrs for setup
5 payloads x 7.3 IVA hrs/payload = 36.5 IVA hrs for setup

Servicing (year 4-5/IOC)

5 payloads x (7.1+ 0) EVA hrs/payload/yr x 1 (current) yr to IOC/52 weeks/yr = 1 hr/week EVA for payload servicing

5 payloads x (5.9+39.4) IVA hrs/payload/yr x 1 yr to IOC/52 weeks/yr = 4.4 hr/week IVA for payload servicing

This concludes the estimation of total required EVA/IVA time for attached payloads in the EVA-Only case. The next step is to estimate the fraction of time that could be displaced with the FTS. The majority of payload setup tasks consist of medium and large item movement of payloads from the STS bay to the Station, where handoff is performed to an EVA crew-man or the FTS. It was assumed the FTS would not be used to transport the payload to the desired location--the RMS would serve this purpose. The FTS could, however, be placed at the mounting location on the Station and receive or hold the payloads transported from the STS bay to the work area. If the only functions are receiving and holding, the manipulators on the MSC would probably be used. If there is a need for dexterous actions such as bolt-down, then the FTS could be used as long as the applicable proximity operations rules were not violated.

It was assumed that the FTS could displace approximately 20% of the Flight 3 setup EVA or 1.5 hrs by simply receiving and holding the payloads, speeding up the mounting process, and making it more productive by providing another view (IVA) and additional lighting, again assuming no difficulties with proximity operations.

It was further assumed that the FTS could displace approximately 20% of the Flight 18 setup EVA or 10.8 hours. The FTS could be especially helpful as an additional hold-down considering the larger average mass of the payloads (2,450 kg versus 2,047 kg on Flight 18).

The assumption of 20% displacement was also used for the Flight 30 pay-loads. Assuming that all changeouts can be made by the FTS, a displacement of configuration change time can also be made. The IVA is assumed to be constant due to the additional time requirements for unstowing and stowing the FTS between the EVA-Only and EVA+FTS cases. The following subsections itemize the procedure followed for the derivation of EVA/IVA estimates for the setup and servicing portions and summation to the flight-interval level.

4. Attached-Payload Setup Support Tasks

The first step involved constructing a generic task breakdown structure consistent with the operations to be performed and the reference attached-payload times. The basic procedure was to estimate the EVA-Only case, assume a 20% EVA savings by the FTS (multiply by 0.8), translate to the performance ratio form, and compute the task times for a range of performance ratios. Refer to Appendix D for the intermediate calculations.

Table D-1 presents a task breakdown used to estimate EVA and IVA times using the assembly sequence tasks as a model. Because CETF also made estimates, a combined range of values was used as shown in the summary Table D-2. The values in Table D-2 were translated to the form required by the performance ratio algorithms (a performance ratio range of 1.4-5.0 was used).

5. Attached-Payload Servicing Support Tasks

The derivation of servicing times follows a similar procedure, using the estimates in Table D-3. The values in Table D-3 were projected to the flight intervals on the flight schedule, combined with the CETF values (which represent the maximum budget), and translated to ±20% ranges as shown in Table D-4. Table D-5 shows the step translation to the performance ratio input form and the resulting values.

6. Attached-Payload Setup + Service Times by Flight

Table 5-4 summarizes the totals derived by weighting the time per week by the appropriate number of weeks for each flight interval and adding any applicable setup time (Flights 3, 18, and 30) from Tables D-2 and D-5.

D. POLAR PLATFORM SETUP AND SERVICING TASKS

As described earlier, the programmatic environment for the polar platform missions changed dramatically during the course of the study. Nonetheless, the objective was to be as comprehensive as possible and polar platform FTS benefits were examined. It became apparent that under currently evolving scenarios, use of an FTS for polar platform servicing during the assembly phase is highly unlikely. The estimates of limited potential benefits presented in this section illustrate the high-cost trade-off between a minimal displacement of EVA for polar platform servicing and the cost of a second FTS. It should be noted that while a polar platform FTS may not appear cost-effective, no conclusions can be drawn regarding polar platforms based on the study performed here. The polar platform issue is discussed further in Section IX. Because the polar platform estimates were not included in the final results, the values derived in this subsection are for informational purposes only.

It was assumed for the purposes of this study that the EVA requirements for polar platforms are minimal, based on the servicing requirements outlined in Reference 20. The scenario calls for three polar platform launches in years 1, 2, and 4 (Flights 5, 9, and 26), with servicing missions in years 3 and 4 (for platforms 1 and 2). While the availability of an OMV was not assumed in the study and ELVs may be used for platform launch, the polar platforms were included per the CETF manifest. It was assumed that because servicing could be either shuttle- or platform-based, an FTS could be used to assist in servicing. This second FTS would either be shuttle-based or be a part of the polar platform.

Table 5-4. EVA/IVA Attached Payload Estimates by Flight (Flights 3-11) and by Flight Interval (after Flight 11) Totals of Setup and Servicing (work-hours)

Flight			EVA-Only Case EVA_O	EVA-Only Case IVA_O	EVA+FTS Case EVA_F	EVA+FTS Case IVA_F
	1		N/A	N/A	N/A	N/A
	2		N/A	N/A	N/A	N/A
	3		5.7-11.1	2.7-5.6	4.3-8.9	2.9-10.0
	4		6.4-9.6	3.2-4.8	5.1-7.7	3.5-8.6
STS-	5	Polar Platform	N/A	N/A	N/A	N/A
Based	6		N/A	N/A	N/A	N/A
	7	OF-1	N/A	N/A	N/A	N/A
	8		1.6-2.4	0.8-1.2	1.3-1.9	0.9-2.2
	9	Polar Platform	N/A	N/A	N/A	N/A
	10		1.6-2.4	0.8-1.2	1.3-1.9	0.9.2.2
PMC	11		N/A	N/A	N/A	N/A
	12		10.4-15.6	5.2-7.8	8.5-12.4	5.9-14.3
	13	Logistics	N/A	N/A	N/A	N/A
	14		10.4-15.6	5.2-7.8	8.5-12.4	5.9-14.3
	15	Logistics	N/A	N/A	N/A	N/A
	16		10.4-15.6	5.2-7.8	8.5-12.4	5.9-14.3
	17	Logistics	N/A	N/A	N/A	N/A
	18		63.8-69.6	32.2-34.8	51.7-55.6	34.4-62.9
	19	Logistics	N/A	N/A	N/A	N/A
	20		9.8-15.6	5.2-7.8	8.5-12.4	5.2-14.3
Station-	21	Logistics	N/A	N/A	N/A	N/A
Based	22		9.8-15.6	5.2-11.0	8.5-12.4	5.2-14.3
	23	Logistics	N/A	N/A	N/A	N/A
	24		8.7-13.9	4.6-7.0	7.5-12.0	4.6-12.8
	25	Logistics	N/A	N/A	N/A	N/A
	26	Polar Platform	N/A	N/A	N/A	N/A
	27	Logistics	N/A	N/A	N/A	N/A
	28		8.7-13.69	4.6-7.0	7.5-12.0	4.6-12.8
	29	Logistics	N/A	N/A	N/A	N/A
	30		4.6-13.9	214.0-218.7	3.5-11.0	214.0-224.5

The procedure consisted of summing the EVA/IVA requirements for the EVA-Only case from Reference 20, prorating the estimates by 0.8 (assuming a 20% displacement of EVA/IVA by the FTS), and summing the servicing times during years 3 and 4. Because there are no specified servicing schedules for the polar platforms (e.g., every 3 months, 67 months, 12 months), the total service times were spread across the number of appropriate flight periods. Thus, some polar platform servicing is assumed for each flight interval rather than every 6 or 12 months.

It is assumed that the bulk of polar platform servicing will be performed using Shuttle-based RMS telerobotics; however, there is also potential for use of the FTS to displace ORU replacement time. Using the estimates of Reference 20, the total EVA-performed ORU replacements for the three polar platform launches scheduled during the assembly phase comprises approximately 18.25 hours.

The polar platform EVA/IVA estimates are derived by year as shown in Table 5-5. The procedure assumes that setup of polar platforms is similar to deployment of Habitation (HAB) or the Japanese (JEM) modules with three subtasks (erect workstation, grapple, and release). A performance ratio algorithm was used with a range of 1.4-5.0 to compute the time estimates for each subtask.

Year 1. <u>Flight 5 - Platform 1 Launch Setup</u>

The EVA-Only case values range from 2.1 hours for EVA to 24 hours (upper-limit EVA budget for a single flight prior to PMC). The IVA range is 1.1-12 work-hours. The EVA+FTS case is 0-19.2 hours for EVA and 1.5-9.6 hours for IVA. The EVA+FTS estimates are obtained by assuming a 20% displacement of EVA/IVA.

Year 2. <u>Flight 9 - Platform 2 Launch Setup</u>

The EVA-Only case values are 2.1-24 hours for EVA and 1.1-12 hours for IVA. The EVA+FTS case is the same as Year 1, Flight 5 --0.0-19.2 and 1.5-9.6 for EVA and IVA, respectively.

Year 3. <u>Platform 1 Servicing</u>

During Year 3, Mission 2, servicing of platform 1 is performed requiring a total of 50 EVA hours, with 13.75 hours of potential EVA displaced by ORU changeouts. As noted earlier, the totals are spread across the eight flights of Year 3 so an average amount is allocated per flight interval.

The EVA-Only case requires 6.3 hours servicing per flight interval for EVA and 3.1 hours IVA. The EVA+FTS case requires 4.5 hours per flight interval EVA and 3.5-6.6 hours IVA.

Table 5-5. Polar Platform EVA/IVA Task Estimates

Flight	EVA-Only Case EVA_O	IVA_O	EVA+FTS Case EVA_F	IVA_F
Flight 5: Platform #1-year 1 (setup)	2.1-24.0[a]	1.1-12.0[a]	0-19.2[b]	1.5-9.6[b]
Flight 9: Platform #2-year 2 (setup)	2.1-24.0[a]	1.1-12.0[a]	0-19.2[b]	1.5-9.6[b]
Platform #1 servicing-year 3				
Total EVA required = 8.5+10-0.25+19+12.25 = 50 hours				IVA_{FS} = 0
ORU replacement EVA for FTS = 13.75 hours				EVA_A = 13.7
EVA_R = 50-13.75 = 36.3				PR = 1.4-5
The resulting service estimates are:	50.0	25.0	36.3	27.8-52.5
and if distributed over the eight flights of year 3 (per flight interval)[c]:	6.3	3.1	4.5	3.5-6.6
Flight 26: Platform #3-year 4 (setup)	2.1[d]	1.1[d]	0.0[d]	1.5-5.3[d]
Platform #2 servicing-year 4				
Total EVA required = 6.75+10.75+11.0+10.75 = 39.25				IVA_{FS} = 0.0
ORU replacement EVA = 3.75				EVA_A = 3.75
EVA_R = 39.25-3.75 = 35.6				PR = 1.4-5.0
The resulting service estimates are:	39.3	19.7	35.6	20.4-27.2
and if distributed over the nine flights in year 4 (per flight internal)[c]:	4.4	2.2	4.0	2.3-3.0

[a] Lower-limit values analogous to HAB and JEM modules (see assembly) using EVA_R=0, IVA_{FS}=0, EVA_A=0.7 for EVA+FTS case and PR=1.4-5.0. Results multiplied by 3 for 3 subtasks involved (erect workstation, grapple, and deploy). Upper-limit values are EVA/IVA budget constraints for pre-PMC flights.

[b] Derived from EVA-Only case values by factor of 0.8 (20% of task times displaceable by FTS); lower limit of zero used for EVA+FTS for contingency of no EVA servicing.

[c] This is done for uniformity and to avoid selecting a particular servicing strategy. For the purposes of life cycle costing, there will be minor differences between spreading the servicing costs and expending them all at the end of the year.

[d] Does not include the upper-limit EVA/IVA budget constraint since timing is post-PMC. Also, the total transferred to Flight 26 is the sum of the setup for Platform #3 and the servicing component of Platform #2.

Year 4. <u>Flight 26 - Platform 3 Launch Setup and Platform 2 Servicing</u>

Year 4 involves deployment of platform 3 and the service mission for platform 2. The totals are computed as before except the servicing is distributed across nine flights (Table 5-5).

5. <u>Summary</u>

Table 5-5 summarizes the values for polar platform setup and servicing.

E. LOGISTICS TASKS

As mentioned earlier, there is potential for using the FTS during logistics flights (11, 13, 15, 17, 19, 21, 23, 25, 27, 29). However, since most logistics transfers appear to be anticipated as RMS/MSC tasks and since information regarding the nature of expected EVA tasks is lacking, this category could be refined at a future time, when more data are available. The expected effect of ignoring logistics is to undervalue the benefits of the FTS, because any or all of the possible benefits of the FTS to displace logistics EVA are not included. However, it may be that the vast majority of logistics transfers would be performed by the RMS--the possibility of using the FTS for logistics transfers is a subject for further study.

F. SATELLITE SERVICING FACILITY TASKS

There is potential for using the FTS for satellite servicing, and while a satellite servicing facility is manifested, the possible lack of adequate satellite retrieval capability might preclude such a system in the finalized configuration. The principal benefits of using an FTS within the servicing facility will not be realized until after IOC (the end of the scope of this study). This is an area for additional analysis and was not addressed in the present study.

G. TOTAL EVA/IVA REQUIREMENTS BY FLIGHT INTERVAL

This section collects the estimates for the EVA-Only and EVA+FTS cases derived in the previous sections to provide a summary by flight and flight interval. These values are used as a component of the life-cycle costing model, which is based on time periods equal to the flight intervals. Table 5-6 displays the breakdowns and total EVA/IVA by flight for the two cases studied. Note that additional assembly flights are implied by the EVA-Only case for Flights 1 or 2, implying a need for remanifesting the assembly sequence. The excesses on Flights 16 and 28 are not as critical, since these occur after PMC, when EVA can be performed weekly throughout the year. This confirms an emerging belief that the CETF-derived sequence does not fit within the manifest as currently designed for reasons other than assembly. That is, the addition of requirements for maintenance, attached payloads, polar platforms, etc., contribute to the conflicts over EVA resources.

Table 5-6. Total EVA/IVA Estimates By Flight (Flights 1-11) and by Flight Interval (after Flight 11) (work-hours)

Flight		EVA-Only Case EVA_O	IVA_O	EVA+FTS Case EVA_F	IVA_F	FTS
1	assembly	37.2-37.9	18.8-19.2	23.5	21.1-29.1	13.7-14.4
	maintenance	0	0	0	0	0
	att. pylds .	0	0	0	0	0
	polar plfms.	0	0	0	0	0
	total	37.2-37.9	18.8-19.2	23.5	21.1-29.1	13.7-14.4
2	assembly	37.2-37.9	18.8-19.2	23.5	21.1-29.1	13.7-14.4
	maintenance	0	0	0	0	0
	att. pylds.	0	0	0	0	0
	polar plfms.	0	0	0	0	0
	total	37.2-37.9	18.8-19.2	23.5	21.1-29.1	13.7-14.4
3	assembly	18.8-19.1	9.4-9.6	13.2	12.4-15.2	5.6-5.9
	maintenance	9.6-14.4	4.8-7.2	7.7-11.5	5.2-13.0	1.9-2.9
	att. pylds.	5.7-11.1	2.7-5.6	4.3-8.9	2.9-10.0	1.4 2.2
	polar plfms.	0	0	0	0	0
	total	34.1-44.6	16.9-22.4	25.2-33.6	20.5-38.2	8.9-11.0
4	assembly	19.9-20.3	10.0-10.1	15.4	11.0-13.9	4.5-4.9
	maintenance	9.6-14.4	4.8-7.2	7.7-11.5	5.2-13.0	1.9-2.9
	att. pylds.	6.4-9.6	3.2-4.8	5.1-7.7	3.5-8.6	1.3-1.9
	polar plfms.	0	0	0	0	0
	total	35.9-44.3	18.0-22.1	28.2-34.6	19.7-35.5	7.7-9.7
5	assembly	0	0	0	0	0
	maintenance	9.6-14.4	4.8-7.2	7.7-11.5	5.2-13.0	1.9-2.9
	att. pylds.	0	0	0	0	0
	polar plfms.	2.1-24.0	1.1-12.0	0.0-19.2	1.5-9.6	2.1-4.8
	total	11.7-38.4	5.9-19.2	7.7-30.7	6.7-22.6	4.0-7.7
6	assembly	16.3-17.5	8.2-8.7	15.4	11.0-13.9	0.9-2.1
	maintenance	12.0	6.0	9.6	6.5-10.8	2.4
	att. pylds.	0	0	0	0	0
	polar plfms.	0	0	0	0	0
	total	28.3-29.5	14.2-14.7	25.0	17.5-24.7	3.3-4.5
7	assembly	7.9	4.0	7.2	4.0-4.7	0.7
	maintenance	12.0	6.0	9.6	6.5-10.8	2.4
	att. pylds.	0	0	0	0	0
	polar plfms.	0	0	0	0	0
	total	19.9	10.0	16.8	10.5-15.5	3.1

Table 5-6. Total EVA/IVA Estimates By Flight (Flights 1-11) and by Flight Interval (after Flight 11) (continued) (work-hours)

Flight		EVA-Only Case EVA_O	IVA_O	EVA+FTS Case EVA_F	IVA_F	FTS
8	assembly	22.6-23.3	11.3-11.7	22.1	12.3	0.5-1.2
	maintenance	12.0	6.0	9.6	6.5-10.8	2.4
	att. pylds.	1.6-2.4	0.8 1.2	1.3-1.9	0.9-2.2	0.3-0.5
	polar plfms.	0	0	0	0	0
	total	36.2-37.7	18.1-18.9	33.0-33.6	19.7-25.3	3.2-4.1
9	assembly	0	0	0	0	0
	maintenance	12.0	6.0	9.6	6.5-10.8	2.4
	att. pylds.	0	0	0	0	0
	polar plfms.	2.1-24.0	1.1-12.0	0.0-19.2	1.5-9.6	2.1-4.8
	total	14.1-36.0	7.1-18.0	9.6-28.8	8.0-20.4	4.5-7.2
10	assembly	12.7-16.6	6.4-8.3	11.3-14.3	8.8-10.3	1.4-2.3
	maintenance	12.0	6.0	9.6	6.5-10.8	2.4
	att. pylds.	1.6-2.4	0.8-1.2	1.3-1.9	0.9-2.2	0.3-0.5
	polar plfms.	0	0	0	0	0
	total	26.3-31.0	13.2-15.5	22.2-25.8	16.2-23.3	4.1-5.2
11	assembly	0	0	0	0	0
	maintenance	12.0	6.0	9.6	6.5-10.8	2.4
	att. pylds.	0	0	0	0	0
	polar plfms.	0	0	0	0	0
	total	12.0	6.0	9.6	6.5-10.8	2.4
12	assembly	83.8-84.7	41.9-42.3	70.8-71.3	43.0-51.2	13.0-13.4
	maintenance	48.8	24.7	39.0	26.4-44.0	9.8
	att. pylds.	10.4-15.6	5.2-7.8	8.5-12.4	5.9-14.3	2.0-3.2
	polar plfms.	0	0	0	0	0
	total	143.0-149.1	71.8-74.8	118.3-122.7	75.3-109.5	24.8-26.4
13	assembly	0	0	0	0	0
	maintenance	48.8	24.7	39.0	26.4-44.0	9.8
	att. pylds.	0	0	0	0	0
	polar plfms.	0	0	0	0	0
	total	48.8	24.7	39.0	26.4-44.0	9.8
14	assembly	13.6-17.5	6.8-8.8	11.8-14.8	8.8-11.0	1.8-2.7
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	10.4-15.6	5.2-7.8	8.5-12.4	5.9-14.3	1.9-3.2
	polar plfms.	6.3	3.1	4.5	3.5- 6.6	1.8
	total	69.3-78.4	34.6-39.2	56.0-62.9	39.3-67.0	13.3-15.5

Table 5-6. Total EVA/IVA Estimates By Flight (Flights 1-11) and by Flight Interval (after Flight 11) (continued) (work-hours)

Flight		EVA-Only Case EVA_O	IVA_O	EVA_F	EVA+FTS Case IVA_F	FTS
15	assembly	0	0	0	0	0
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	0	0	0	0	0
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	45.3	22.6	35.7	24.6-41.7	9.6
16	assembly	9.4-13.3	4.7-6.6	7.8-10.8	7.2-8.4	1.6-2.5
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	10.4-15.6	5.2-7.8	8.5-12.4	5.9-14.3	1.9-3.2
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	65.1-74.2	32.5-37.0	52.0-58.9	37.7-64.4	13.1-15.3
17	assembly	0	0	0	0	0
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	0	0	0	0	0
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	45.3	22.6	35.7	24.6-41.7	9.6
18	assembly	44.2-44.6	22.1-22.3	39.7	22.2-25.5	4.5-4.9
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	63.8-69.6	32.2-34.8	51.7-55.6	34.4-62.9	12.1-14.0
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	153.3-159.5	76.9-79.7	127.1-131.0	81.2-130.1	26.2-28.5
19	assembly	0	0	0	0	0
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	0	0	0	0	0
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	45.3	22.6	35.7	24.6-41.7	9.6
20	assembly	50.7-55.6	25.4-27.8	47.5-50.5	29.6-31.8	3.2-5.1
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	9.8-15.6	5.2-7.8	8.5-12.4	5.2-14.3	1.3- 3.2
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	105.8-116.5	53.2-58.2	91.7-98.6	59.4-87.8	14.1-17.9
21	assembly	0	0	0	0	0
	maintenance	39.0	19.5	31.2	21.1-35.1	7.8
	att. pylds.	0	0	0	0	0
	polar plfms.	6.3	3.1	4.5	3.5-6.6	1.8
	total	45.3	22.6	35.7	24.6-41.7	9.6

Table 5-6. Total EVA/IVA Estimates By Flight (Flights 1-11) and by Flight Interval (after Flight 11) (continued) (work-hours)

Flight		EVA-Only Case		EVA+FTS Case		
		EVA_O	IVA_O	EVA_F	IVA_F	FTS
22	assembly	13.3-17.3	6.7-8.7	11.4-14.4	8.6-10.9	1.9-2.9
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att. pylds.	9.8-15.6	5.2-11.0	8.5-12.4	5.2-14.3	1.3-3.2
	polar plfms.	4.4	2.2	4.0	2.3-3.0	0.4
	total	72.0-81.8	36.6-44.4	59.5-66.4	40.1-68.3	12.5-15.4
23	assembly	0	0	0	0	0
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att.pylds.	0	0	0	0	0
	polar plfms.	4.4	2.2	4.0	2.3-3.0	0.4
	total	48.9	24.7	39.6	26.3-43.1	9.3
24	assembly	13.3-14.2	6.7-7.1	8.4	7.8-11.0	4.9-5.8
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att. pylds.	8.7-13.9	4.6-7.0	7.5-12.0	4.6-12.8	1.2-1.9
	polar plfms.	4.4	2.2	4.0	2.3-3.0	0.4
	total	70.9-77.0	36.0-38.8	55.5-60.0	38.7-66.9	15.4-17.0
25	assembly	0	0	0	0	0
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att. pylds.	0	0	0	0	0
	polar plfms.	4.4	2.2	4.0	2.3-3.0	0.4
	total	48.9	24.7	39.6	26.3-43.1	9.3
26	assembly	0	0	0	0	0
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att. pylds.	0	0	0	0	0
	polar plfms.	6.5	3.3	4.	3.8-8.3	2.5
	total	51.0	25.8	39.6	27.8-48.4	11.4
27	assembly	0	0	0	0	0
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att. pylds.	0	0	0	0	0
	polar plfms.	4.4	2.2	4.0	2.3-3.0	0.4
	total	48.9	24.7	39.6	26.3-43.1	9.3
28	assembly	174.0	87.0	57.2	87.0-157.4	116.8
	maintenance	44.5	22.5	35.6	24.0-40.1	8.9
	att. pylds.	8.7-13.9	4.6-7.0	7.5-12.0	4.6-12.8	1.2-1.9
	polar plfms.	4.4	2.2	4.0	2.3-3.0	0.4
	total	231.6-236.8	116.3-118.7	104.3-108.8	117.9-213.3	127.3-128.0

Table 5-6. Total EVA/IVA Estimates By Flight (Flights 1-11) and by Flight Interval (after Flight 11) (continued) (work-hours)

Flight	EVA-Only Case EVA_O	IVA_O	EVA_F	EVA+FTS Case IVA_F	FTS
29 assembly	0	0	0	0	0
maintenance	44.5	22.5	35.6	24.0-40.1	8.9
att. pylds.	0	0	0	0	0
polar plfms	4.4	2.2	4.0	2.3- 3.0	0.4
total	48.9	24.7	39.6	26.3-43.1	9.3
30 assembly	0	0	0	0	0
maintenance	44.5	22.5	35.6	24.0-40.1	8.9
att. pylds	4.6-13.9	214.2-218.7	3.5-11.0	214.0-224.5	1.1- 2.9
polar plfms	4.4	2.2	4.0	2.3- 3.0	0.4
total	53.5-62.8	238.7-243.4	43.1-50.6	240.3-267.6	10.4-12.2
Assembly-Phase Totals:	1,734.0-1,881.9	1,083.4-1,159.1	1,311.6-1,425.2	1,155.2-1,781.0	422.4-456.7
Polar platform[a] Subtotals:	96.3-140.1	47.9-69.7	72.0-110.4	53.2-104.3	24.3-29.7
Study Totals[b]: (Excluding polar platforms)	1,572-1,671	1,002-1,054	1,187-1,258	1,066-1,613	385-413

[a] Excluding maintenance on Flights 5, 9, 26.

[b] Excluding polar platform Flights 5, 9, 26.

There is an EVA savings between 422 and 457 EVA hours provided by the FTS Reference System (including the polar platform values) and with the polar platform values removed, the EVA savings drops slightly, to 385 to 413 hours.

The assumptions of the preceding sections apply to these summary values and it should again be noted that for assembly tasks, a narrow range or point estimate does not imply greater accuracy than a value with a larger range. The size of the range for the maintenance, payload, and polar platform categories is somewhat more representative of the degree of uncertainty, but is not meant or believed to be very accurate. The effect of these variations on estimates of FTS cost-effectiveness is, however, minimal, as will be shown in Section VIII.

Figures 5-1 and 5-2 summarize Table 5-6 using the low- and high-range EVA values, respectively. The difference between the two figures is the range of values used. These figures are the sum of assembly, maintenance, and attached-payload EVA. Prior to PMC the estimates are per Shuttle-based EVA flights. After PMC, the estimates are per flight interval. Thus on Flight 12, the estimates are based on a 6.5-week flight interval (52 weeks/year divided by 8 flights per year). The EVA budget constraint is also plotted, showing the requirement for additional EVA time on Flights 1, 2, 3, 4, 6, 8, and 10 for both the low and high EVA-Only case. Notice that the EVA+FTS case reduces the EVA so that additional EVA is only required on Flights 3, 4, 6, and 8 (and 10 for the high-range EVA values). There are three ways to meet the EVA constraints during the early flights: extend the length of stay (unlikely); remanifest the assembly sequence; or insert another STS flight to complete the required EVA. Three scenarios are defined to bound the alternatives: flexible manifesting, in which excess EVA from one flight can be carried over to another; inflexible manifesting, in which excess EVA from one flight cannot be carried over or remanifested onto a subsequent flight; and mixed manifesting, in which early Flights 1-4 are characterized as inflexible because of the need to build the fundamental system elements and later flights take advantage of the flexible manifesting assumption. Such a mixed manifesting case is a more reasonable assumption, but nonetheless requires additional flights. These additional flights play a key role in the cost-effectiveness of the FTS Reference System (Section VIII). The requirement for an additional flight prior to PMC can be seen for Flights 1 and 2. On the other hand, the large times required on Flights 12, 18, 20, and 28 are not as critical because the required times occur after PMC and can be distributed over a longer period of time. The potential contribution of the FTS on Flight 28 is dramatic for reducing the extensive truss assembly EVA time.

Figures 5-3 and 5-4 display the distribution of EVA hours by category for the low- and high-range EVA estimates. The figures characterize a key result--maintenance is more significant than originally believed, as it represents more than 50% of the total EVA. This will depend in part on how much of the assembly-phase EVA could be deferred and whether the SSP will have the flexibility to defer large numbers of noncritical maintenance tasks that could degrade the performance or lifetimes of the systems involved.

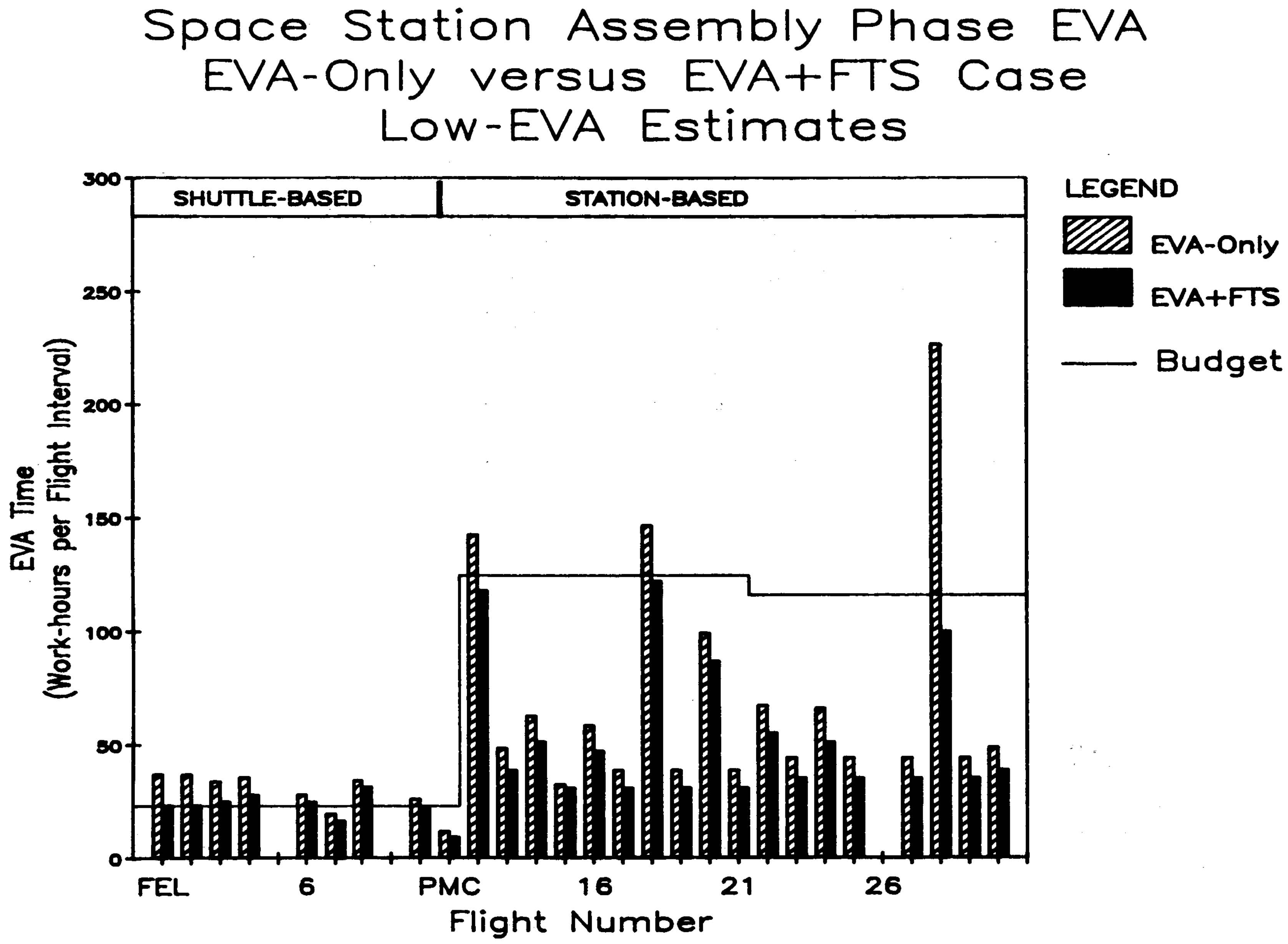

Figure 5-1. Low-Range EVA Estimates for EVA-Only versus EVA+FTS Cases

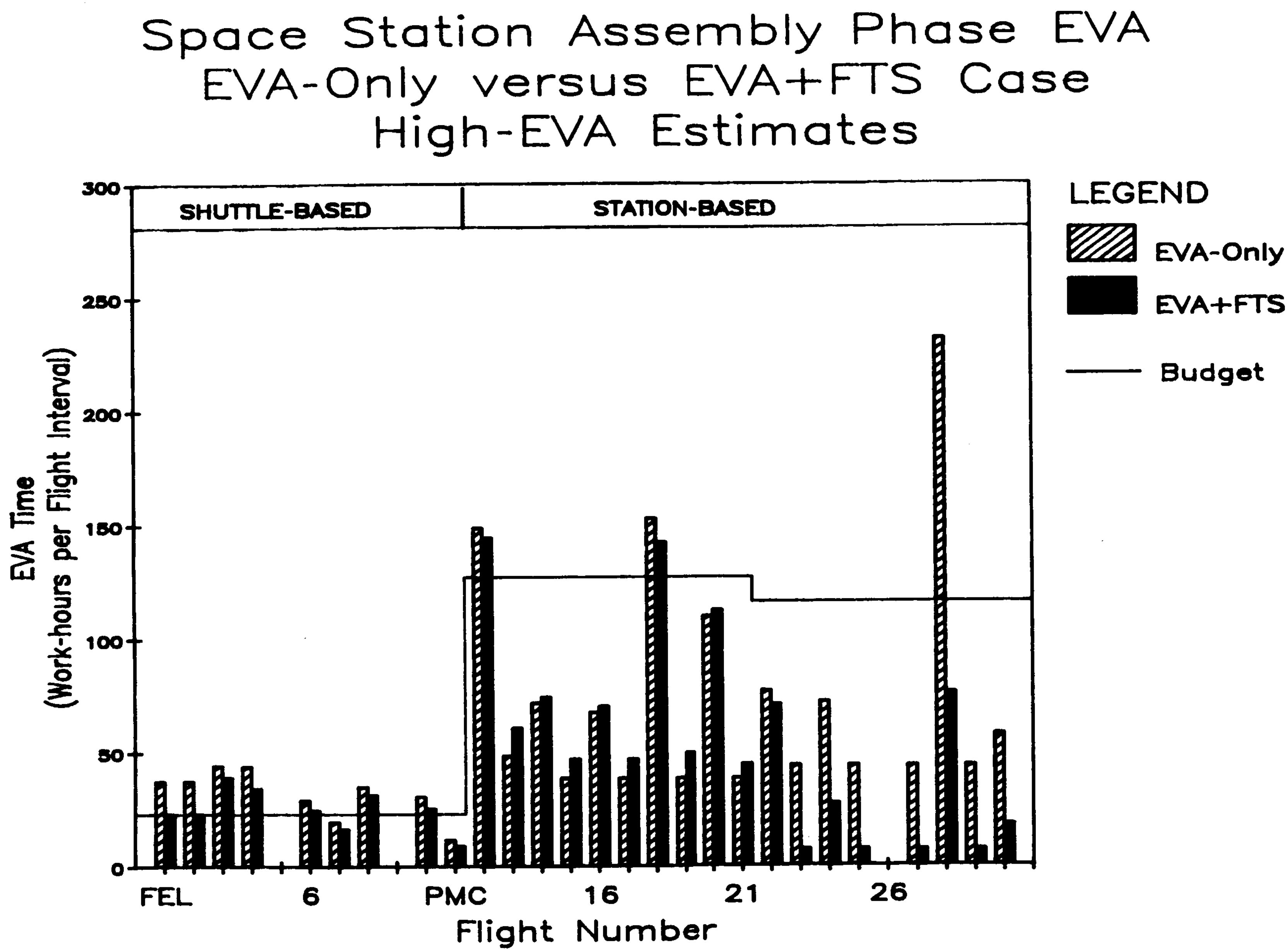

Figure 5-2. High-Range EVA Estimates for
EVA-Only versus EVA+FTS Cases

Space Station Assembly Phase EVA
EVA-Only versus EVA+FTS Case
Low-EVA Estimates

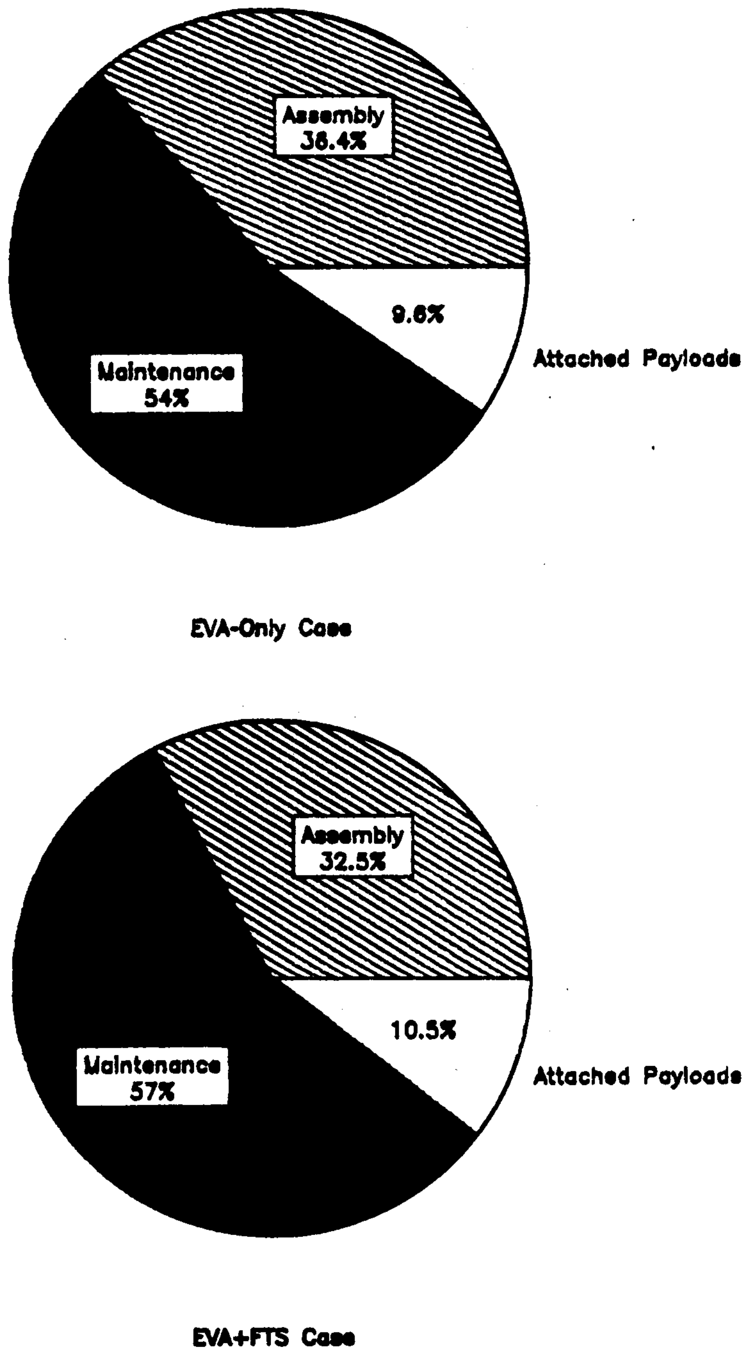

Figure 5-3. Low-Range EVA Time Distribution During the Assembly Phase

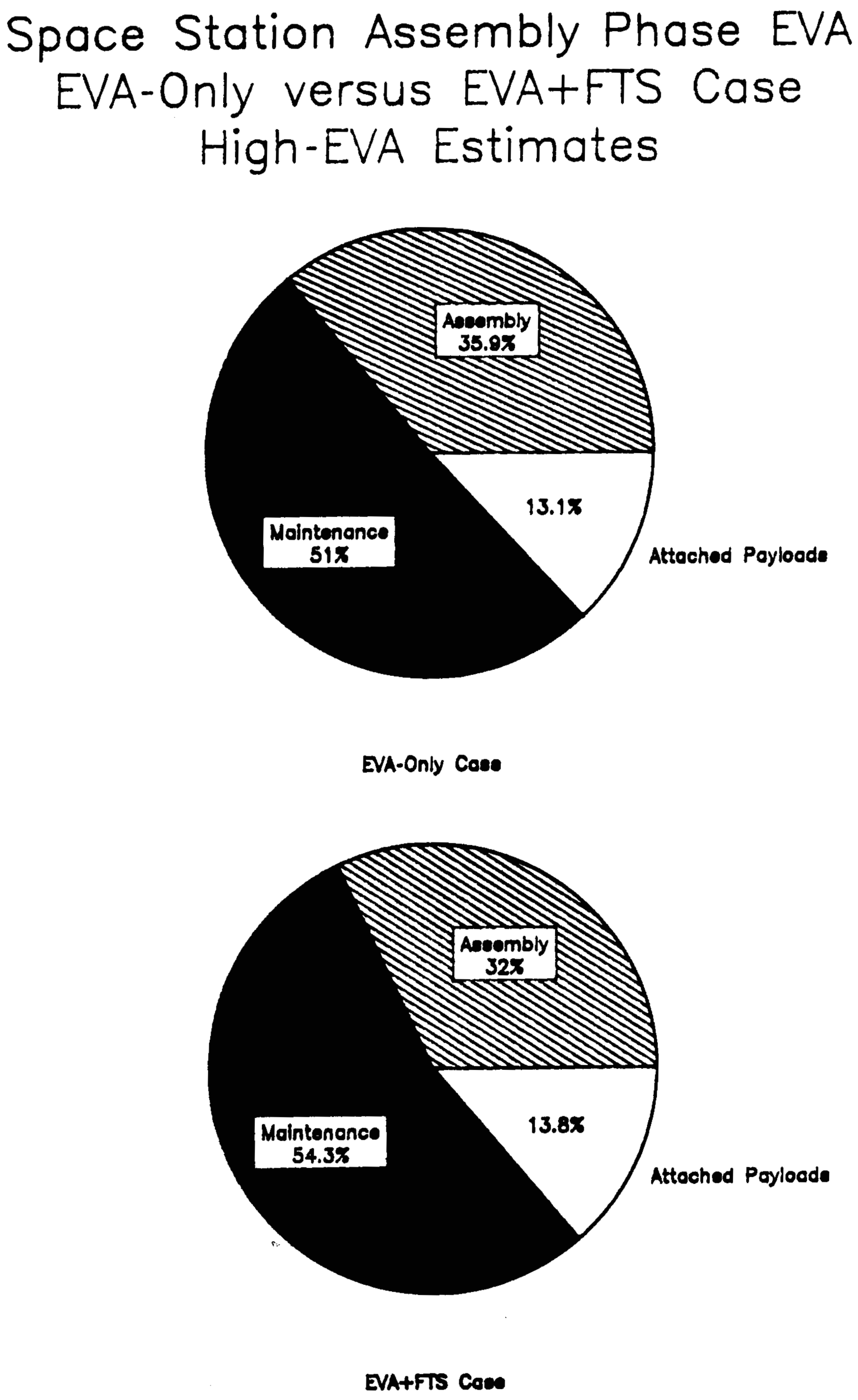

Figure 5-4. High-Range EVA Time Distribution During the Assembly Phase

Figures 5-5 and 5-6 show that for FEL to PMC (flights 1-11), assembly is the dominant factor in EVA, representing more than 60% of the total EVA during that period. Turning to IVA time, the same pattern can be seen in Figures 5-7 and 5-8 (the entire assembly phase) versus Figures 5-9 and 5-10 (FEL through PMC) with a 40-30 split between maintenance and assembly for the assembly phase and a 30-60 split for the more assembly-intensive FEL-PMC period.

It should also be noted that, if included, polar platform estimates comprise less than 7% of the total EVA, and thus the impact of removing polar platforms from the analysis is minimal. On a cost basis only, it appears that the additional cost of a second FTS ($100 million [M]) for polar platform servicing must be traded against a relatively small savings in EVA hours. However, there are other factors that could be considered, involving the length of the FTS life beyond IOC, the higher cost of polar platform EVA due to higher transportation costs, and whether noncost considerations are paramount (e.g., safety).

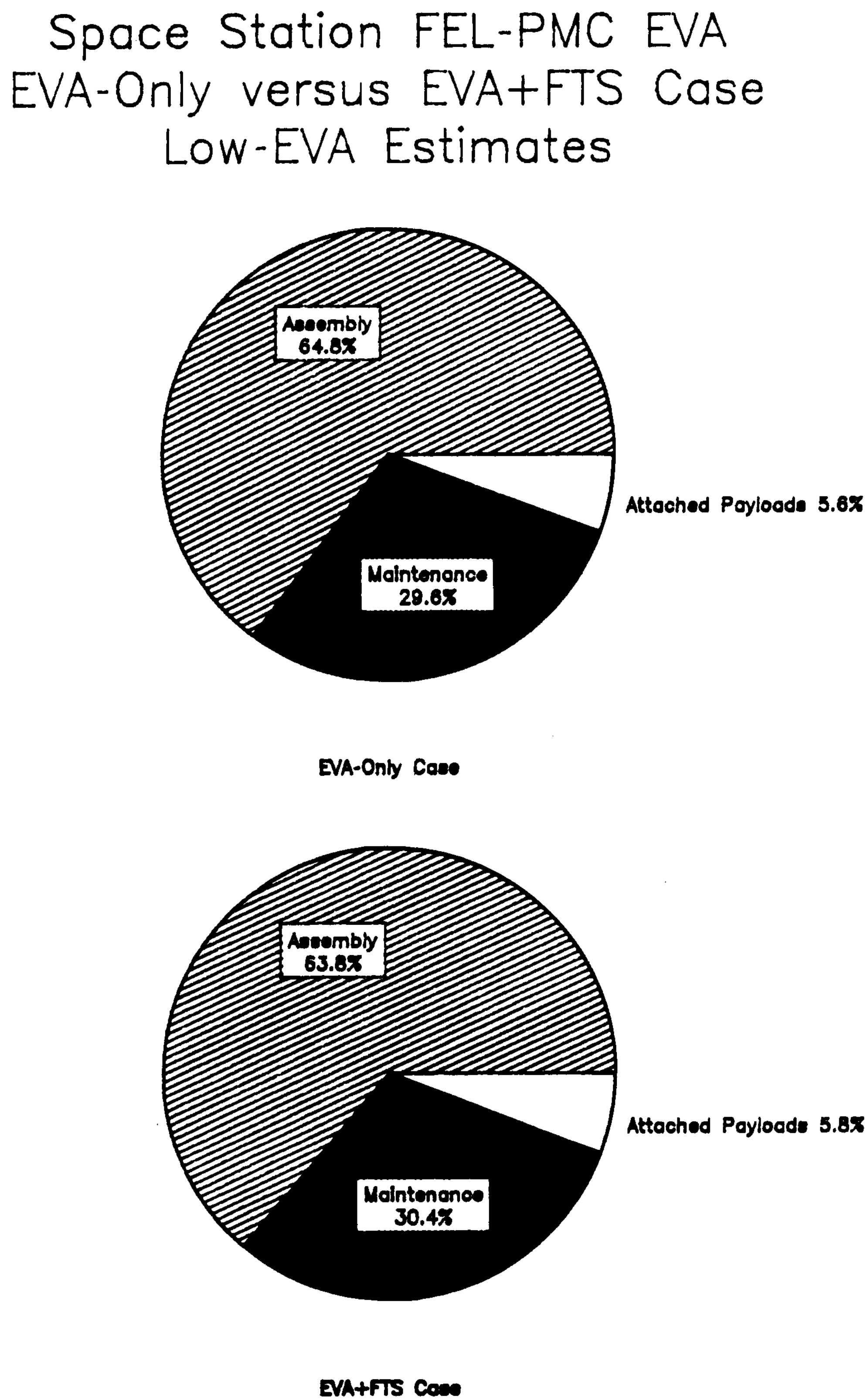

Figure 5-5. Low-Range (Shuttle-Based) EVA Time Distribution for the Period FEL-PMC

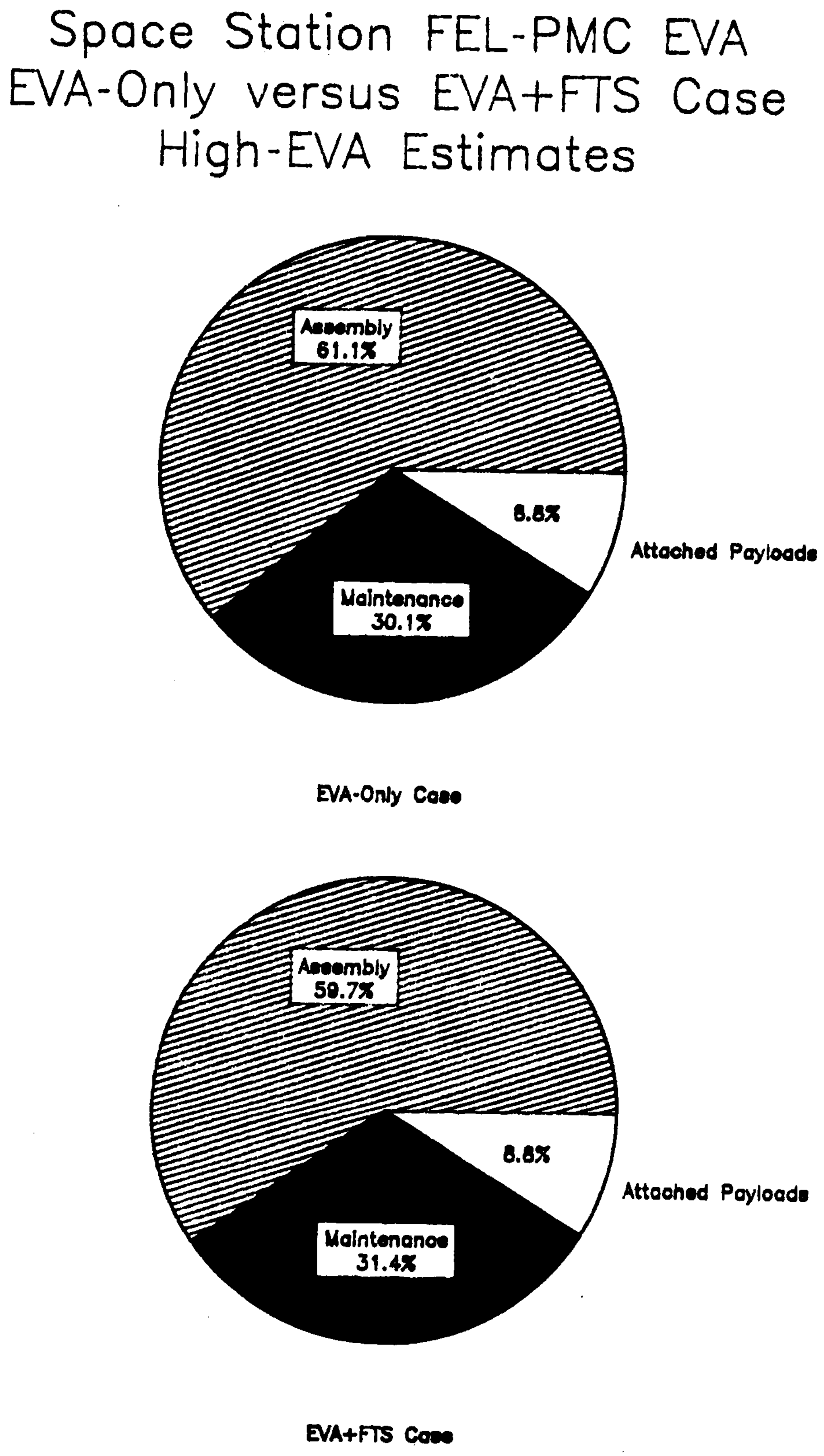

Figure 5-6. High-Range (Shuttle-Based) EVA Time Distribution for the Period FEL-PMC

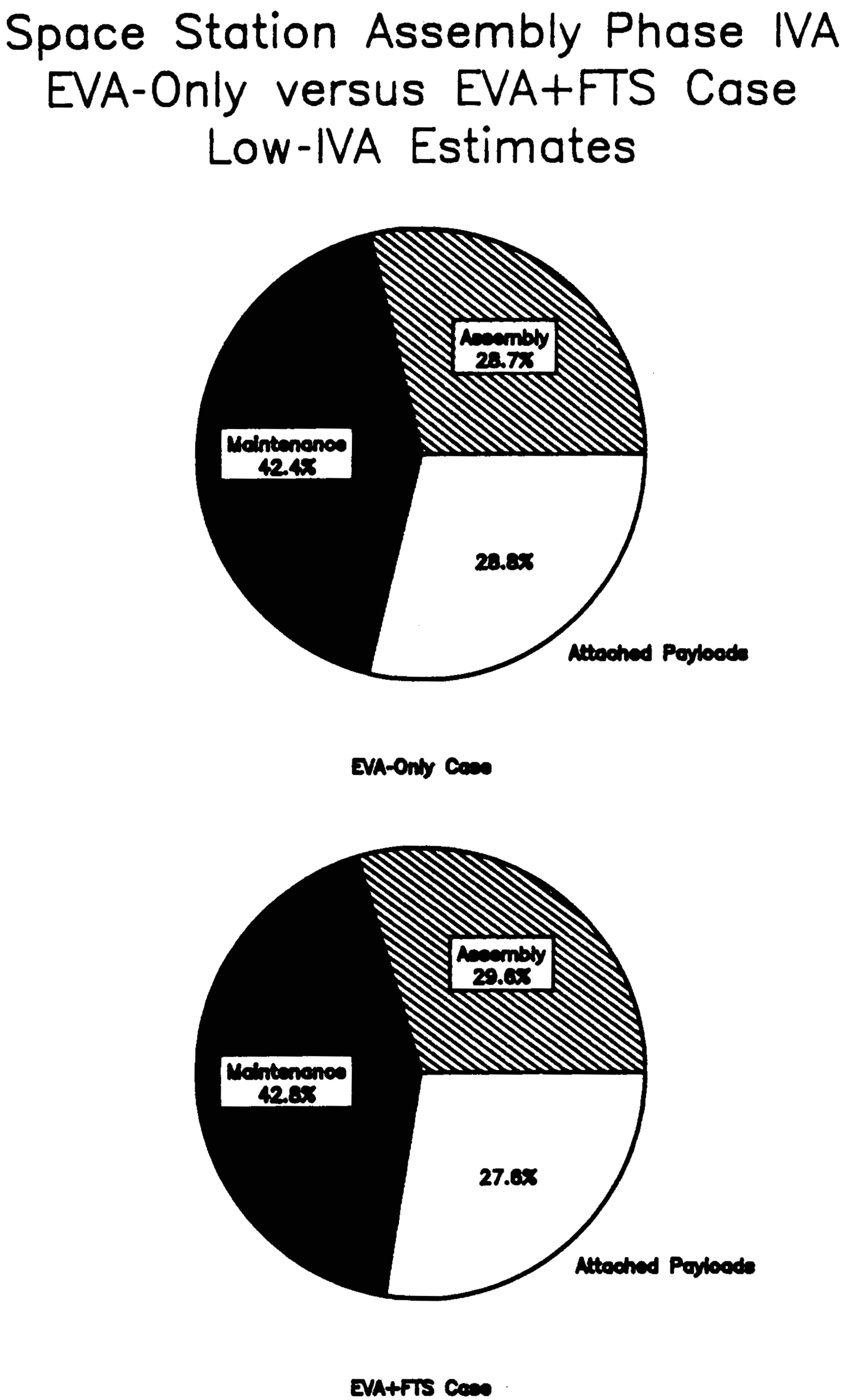

Figure 5-7. Low-Range IVA Time Distribution During the Assembly Phase

Space Station Assembly-Phase IVA EVA-Only versus EVA+FTS Case High-IVA Estimates

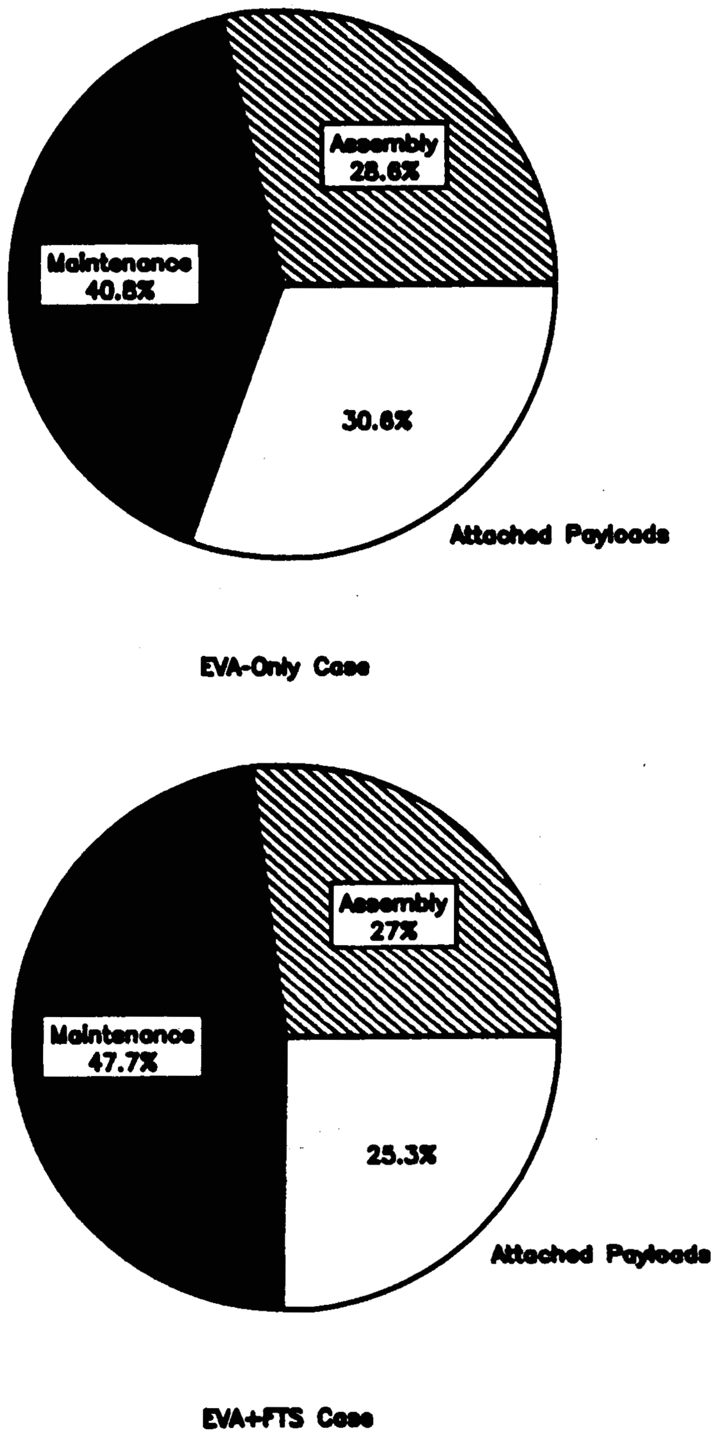

Figure 5-8. High-Range IVA Time Distribution During the Assembly Phase

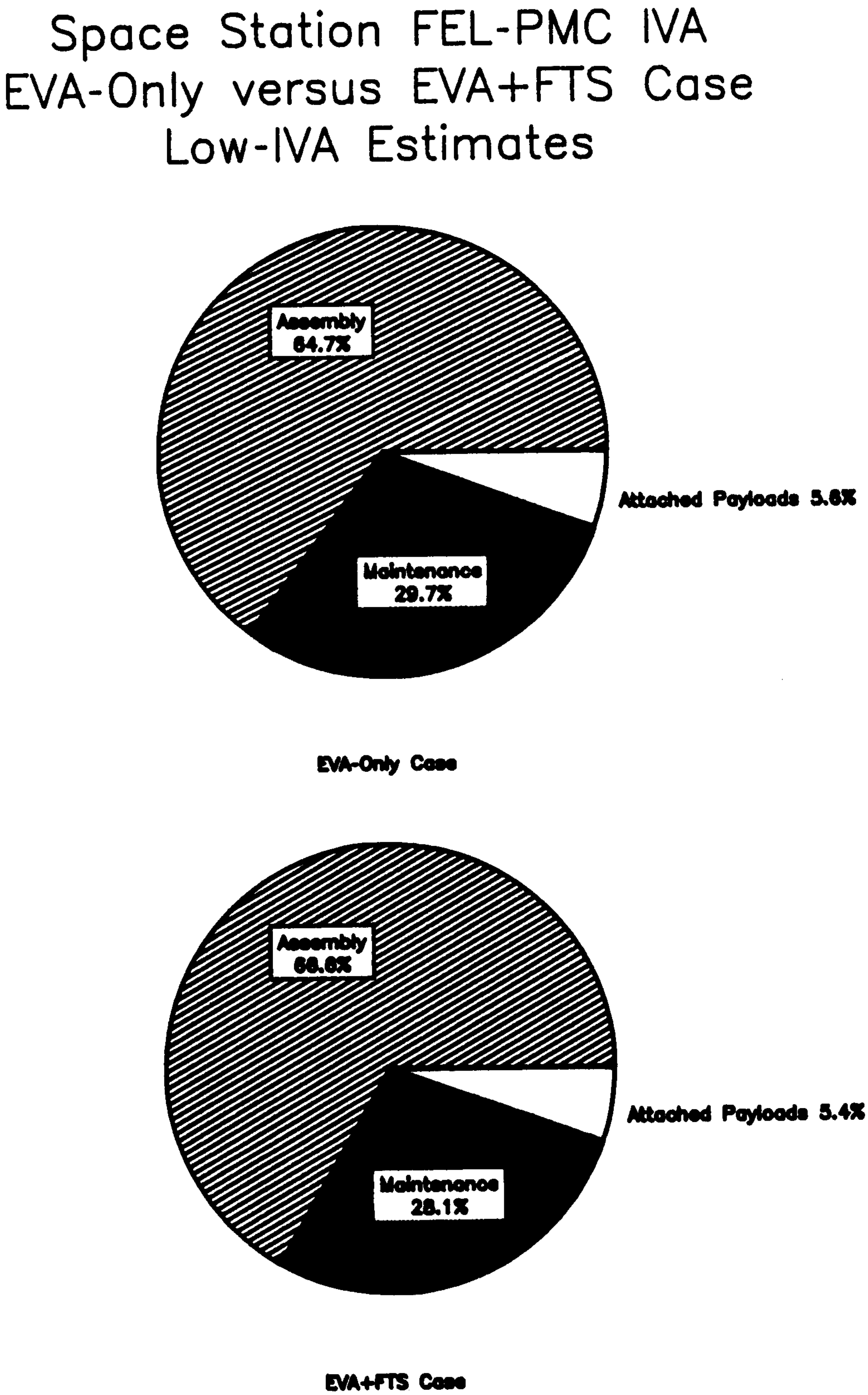

Figure 5-9. Low-Range (Shuttle-Based) IVA Time Distribution for the Period FEL-PMC

Space Station FEL-PMC IVA
EVA-Only versus EVA+FTS Case
High-IVA Estimates

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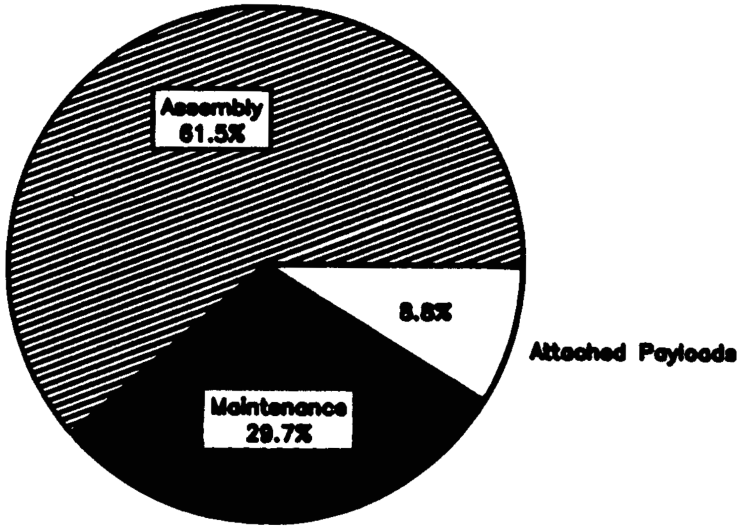
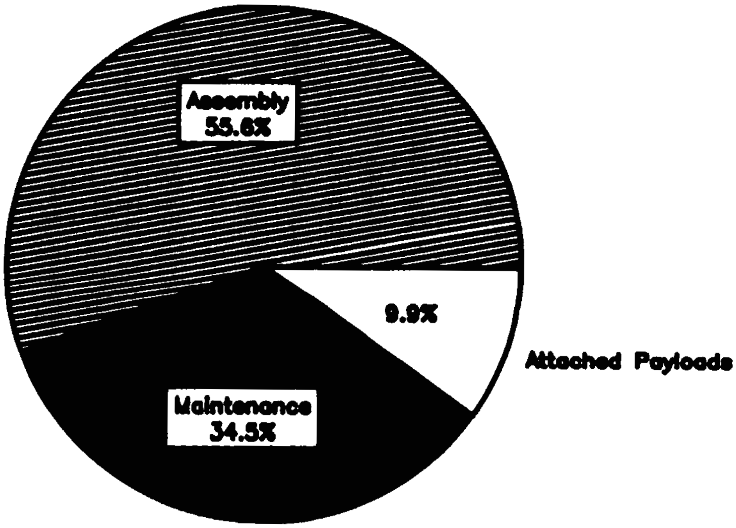


EVA-Only Case



EVA+FTS Case

Figure 5-10. High-Range (Shuttle-Based) IVA Time Distribution for the Period FEL-PMC

SECTION VI

FTS REFERENCE SYSTEM COST ESTIMATION

There are two requirements for examining the cost-effectiveness of an FTS during the assembly phase: a measure of any cost savings achievable by using an FTS and an estimate of the cost of development of the FTS. If the cost savings exceed the development (investment) cost, then a net savings indicates a net benefit. The details of the economic comparison are described in Section VII. This section describes the process of costing the FTS Reference System defined in Section III. The result of this section is a range of cost estimates for such an FTS that is used as a component of the net savings relationship presented in Section VII.

The FTS is the first completely integrated telerobotic system to be built for use in space. In the early concept phase of such a system, approximate cost figures are required to estimate system costs for development, production, operation, and maintenance. The cost estimating process at this phase is difficult due to inadequate knowledge of the mission, design, operational, and environmental parameters. Cost methods used in the past include component Cost Estimating Relationships (CERs), system or subsystem CERs, cost per pound in orbit, budget constraint analysis, complexity analysis, and bottom-up costing by component. The approach used here involved a bottom-up costing by component for the list of FTS Reference System components identified in Section III.

Estimates of the DDT&E and Flight Hardware Unit (FLT) costs of an FTS need to include numerous factors such as: the cost of similar systems, the cost of systems performing similar functions, the additional capabilities to be incorporated in the design of the FTS beyond that of an industrial telerobot, the timing and availability of technologies needed for development, budget allocation for the development of FTS, and FTS development schedule. A source for this study of extensive and similar data is the Shuttle RMS. Functionally, the RMS has arms similar to those of the FTS, although the FTS will be designed to have more sophisticated subsystems and components. The cost of the RMS is used as a basis for estimating the cost of the FTS because of its functional similarities. It is anticipated that the FTS would make use of existing industrial telerobot technologies as well as incorporate advanced and evolutionary technologies. As described in Section III, the timing and availability of these technologies entail uncertain technological and schedule risks that affect FTS cost.

Because of these uncertainties, ranges were used to bound the cost and data estimates. The approach developed to estimate the cost of the FTS Reference System is:

(1) Divide the FTS system into hardware and software components.

(2) Estimate the component or subsystem hardware costs using available NASA and contractor data, estimates from JPL costing experts, and industrial sources.

(3) Estimate the software cost using the COCOMO1 (Reference 21) software cost-estimating methodology.

(4) Estimate the costs of system integration and testing for the FTS Reference System.

(5) Derive the FTS cost by summing the hardware, software and integration, and testing costs. Table 6-1 presents estimates for hardware, software, and spares costs of the FTS Reference System.

Recognizing that there are uncertainties in cost estimates, a range of cost estimates is derived rather than point values for the FTS. For example, many of the industry component cost experts suggested adding a 10%-20% additional cost factor to account for uncertainty in cost estimates. This cost factor was chosen after discussion with industry, JPL, and NASA experts familiar with robot development. A cost factor was applied to such cases to produce a range in which the low value was the original estimate obtained for the component (no uncertainty) and the high value was obtained by applying the 10%-20% uncertainty value. Note that the FTS costs used in the economic evaluation do not include the cost of spares or nonprime costs. (Nonprime costs are the nondirect costs of developing the system.)

In a similar manner, a cost factor of 20% for the systems integration cost (the cost of assembling and testing the integrated system) was applied to the development and flight unit cost. Relative to the total (DDT&E+FLT) cost, the systems integration percentage drops to 16.6%. Again, in the high-range case, a value of 20% was assumed to account for uncertainty in the percentage itself.

After accumulating the component costs and distributing them over the investment (development) period, a discounted (1987 dollars) FTS cost of $277M-304M was computed. The low-range value ($277M) for DDT&E and FLT unit cost of the FTS Reference System is $160.5M and $69.9M, respectively. The systems integration cost is estimated at $46.8M, for a total low-range value of $277M. The corresponding high-range estimates are $254M for DDT&E+FLT and $50.8M for systems integration, for a total high-range value of $304M. Table 6-1 illustrates the cost categories that make up the total cost.

Software cost accounted for approximately 18% of the total cost. The system was designed to include spares as backup; these spares amount to approximately 58% of the cost of the system. The large cost drivers are systems integration cost, $46M (16.6%); the manipulator arms, $32M (11.6%); and the Artificial Intelligence (AI) planner, $18M (6.5%). The FTS Reference System cost derived by this process is compared with the FTS budget allocation to check for differences.

Figure 6-1 summarizes the distribution of these cost components.

Table 6-1. FTS Reference System Hardware Components and Costs (millions of 1987 dollars)

Component	Quantity	Development Cost $M	Flight Unit Cost $M	Spares Cost $M
FTS Hardware-				
7 DOF manipulator arms[a] (see Fig. 3-2)	4	32-33	6-6.2	0
FTS main shell or housing[b]	1	1.74-2	4-4.8	0
- Contains radiation/SEU shielding (cost incl. in shell)[b]		--	--	--
- Contains adaptors for manipulator attachment[b]	4	.20-.24	.02-.024	.06-.07
- Contains adaptors for power interface[b]	3	.05-.06	.005	.01-.012
- Contains adaptor for interface with support base[b]	1	.10-.12	.01-.012	--
- Contains self-aligning adaptor for RMS[b]	1	.20-.24	.02-.024	--
- Contains adaptor for antennae (telemetry)[b]	1	.10-.12	.01-.012	--
- Contains adaptors for peripheral cameras[b]	2	.05-.06	.005-.006	.005-.006
- Contains adaptors for proximity sensors[b]	4-6	.02-.024	.002	.008-.009
- Contains adaptor for main lighting fixture[b]	1	.10-.12	.01-.012	--
- Contains temp. control medium (heat fins/pipes)[c]				
Dedicated arm/end-effector servo microprocessors[a]	4(+4bu)	1-1.2	4-4.8	4-4.8
Dedicated camera servo microprocessors[a]	4(+4bu)	1-1.2	4-4.8	4-4.8
Dedicated lighting servo microprocessors[a]	2(+2bu)	1-1.2	2-2.4	2-2.4
Dedicated temp. control microprocessors[a]	2(+2bu)	1-1.2	2-2.4	2-2.4
Dedicated power distribution/monitoring processor[a]	1(+1bu)	1-1.2	1-1.2	1-1.2
NiH_2 storage batteries (4 hours of service)[b]	6-10 kW tot.	16-17.0	16-17.0	32-38.4
Power conditioning (switching, routing, etc.)	1 set	20-21	20-21	40-48
Servos/actuators				
- FTS base pivot	1	0.04	--	--
- Manipulators (included in complete arm assy.)		--	--	--
- Temperature control[b]	2 sets	.2-.24	.2-.24	--
- Camera control (wrist, lower arm, and peripheral)[b]	5(+5bu)	.2-.24	.2-.24	--
- Lighting control (lower arm and housing)[b]	2(+2bu)	.2-.24	.2-.24	--
Sensors/encoders				
- Proximity (end-effec., wrist, elbow, housing)[b]	16-18(+18)	--	.18-.22	.18-.22
- Joint position/orientation (incl. in arm assy.)	--	--	--	--
- Main housing orientation[b]	1(+1bu)	--	.010	.010
- Position (peripheral cameras, main lighting)[b]	6(+6bu)		06-.07	.06-.07
Subtotal		76.2-80.7	59.9-64.7	85.7-102.8

[a] Industry estimates
[b] JPL estimates
[c] Costs included under shell/housing

Table 6-1. FTS Reference System Hardware Components and Costs (continued)

Component	Quantity	Development Cost $M	Flight Unit $M	Spares Cost $M
- Velocity (included in arm assembly)			--	
- Lighting level (lower arm, main housing)[b]	6 (+6 backup)	--	.06-.07	.06-.07
- Temperature (main housing internal)[b]	4 (+4 backup)	--	.04-.048	.04-.048
- Power level[b]	1 (+1 backup)	--	.01-.012	.01-.012
- Force/torque (at each end-effector)[b]	2 (+2 backup)	--	.2-.24	.2-.24
Movable FTS support platform/adaptor	1 or 2			
- with power adaptors built-in[b]		.35-.42	.035-.42	.07-.08
- with expandable adaptors to fit in EVA handholds[b]		.350-.42	.035-.42	.07-.08
I/O Telemetry				
- Antennae, receiver/transmitter, signal conditioning and distribution[a,b]		3.3-4.0	3.3-4.0	--
Short-term archival memory (ROM)[b]	1 for each microprocessor	--	.6-.72	--
End-effectors (task-tailored, nondexterous)	assume 4 sets			
- Basic grasping		2.5-3.0	1.0-1.2	--
- Inspecting/testing		2.5-3.0	1.0-1.2	--
Tools (tailored)	assume 4 sets			
- Latch removal[a,c]		0	.006-.007	--
- Bolt removal[a,c]		0	.006-.007	--
- Screw removal[a,c]		0	.006-.007	--
- Inspection probe[a,c]		0	.006-.007	--
- Object accommodation (capturing/controlling)[c]		0	.006-.007	--
FTS special support equipment	assume 2 sets			
- End-effector/tool crib[b]		0	002-0.002	--
- Component/material crib[b]	assume 2 sets	0	.002-0.002	--
FTS Workstation Hardware-				
Monitors[b]	5 (+2 backup)			
- Left peripheral camera[b]		0	.005-.006	--
Subtotal		9.0-10.8	6.3-8.4	.45-.53

[a] Industry estimates
[b] JPL estimates
[c] Johnson Space Center (JSC) estimates

Table 6-1. FTS Reference System Hardware Components and Costs (continued)

Component	Quantity	Development Cost $M	Flight Unit $M	Spares Cost $M
Right peripheral camera		0	.005-.006	--
- Stereo[b]		0	.02-.024	--
- Left/right wrist[b]		0	.005-.006	--
- Data readout (force, torque, position, etc.)[b]		0	.005-.006	--
Video switcher	1 (+1 backup)	0	.05-.06	.05-.06
Communication	5 systems	.25-.3	.25-.3	1.25-1.5
- FTS telemetry (200-meter range)		--	--	--
- Inter-workstation voice[a,b]		0	.05-.3	.25-.3
- Ground voice[a,b]		0	.05-.06	.25-.3
- Workstation-to-EVA voice[a,b]		0	.05-.06	.25-.3
- FTS automated voice control[a,b]		0	.05-.06	.25-.3
Keyboard entry system	2 (+2 backup)	0	.02-.024	.08-.1
Force reflecting handcontrollers (left/right)[b]	2 sets	1.2-1.4	.3-.36	.6-.72
Dedicated handcontroller processors[b]	4 (+4 bkup)	1.0-1.2	.1-.12	.8-1.0
Workstation executive processor (integrating)b	2	.5-.6	.1-.12	.8-1.0
Shared memory interface for teleop. handoff[b]	1 (+1 backup)	.2-.24	.05-.06	.1-.12
Voice input (helmet/head mounted)[b]	2	0	.05-.06	.1-.12
System executive processor (integrating)[a,b]	1 (+1 backup)	.5-.6	.1-.12	.2-.24
AI planner processor (integrating)[a]	1 (+1 bkup)	18.0-19.0	.5-.6	1.0-1.2
Run-time control processor (integrating)[a,b]	1 (+1 bkup)	1.6-1.9	.1-.12	.2-.24
Manipulator control processor (integrating)[a,b]	1 (+1 bkup)	1.8-2.16	.1-.12	.2-.24
Sensing and perception processor (integrating)[a,b]	1 (+1 bkup)	1.8-2.16	.1-.12	.2-.24
Workstation hardware mount structure[b]	1	.8-1.0	.3-.36	.3-.36
FTS Software Delineation/Complexity (KDSI[c] range)		--	--	--
FTS dedicated servo control processors	N/A	--	--	--
- Manipulators/simple (25 KDSI)		.94-1.1		
- Cameras/simple (2 KDSI)		.06-.07		
- Lighting/simple (2 KDSI)		.06-.07		
- Temperature control/simple (5-10 KDSI)		.26-.31		
- Power control/simple (5-10 KDSI)		.45-.54		
- Housing control/simple (2 KDSI)		.06-.07		
- Memory (10 MB)		--	.6-.72	--
Subtotal		29.5-32.2	3.1-3.8	6.9-9.2

[a] Industry estimates
[b] JPL estimates
[c] KDSI refers to thousands of delivered source code instructions

Table 6-1. FTS Reference System Hardware Components and Costs (continued)

Component	Quantity	Development Cost $M	Flight Unit Cost $M	Spares Cost $M
FTS workstation dedicated/integrating processors[b]	N/A			
- Handcontrollers/medium (50 KDSI)		2.05-2.46	--	--
- Workstation executive/large (150 KDSI)		3.91-4.69	--	--
- System executive/large (150 KDSI)		7.00-8.4	--	--
- AI planner/very large (250 KDSI)		1.0-1.2	--	--
- Run-time control/very large (300 KDSI)		15.22-16.32	--	--
- Manipulator control/large (150 KDSI)		7.00-8.4	--	--
- Sensing and perception/large (200 KDSI)		9.67-11.6	--	--
- Memory (100 MB)[a]		--	.6-.72	--
Subtotal		45.85-53.1	.6-.72	--
Grand Total		160.5-176.8	69.9-77.6	93.1-112
Total FTS Cost Estimate (excluding spares plus systems integration cost = $46.8M - 50.8M)		$277 - 304M		

[a] Industry estimates
[b] JPL estimates

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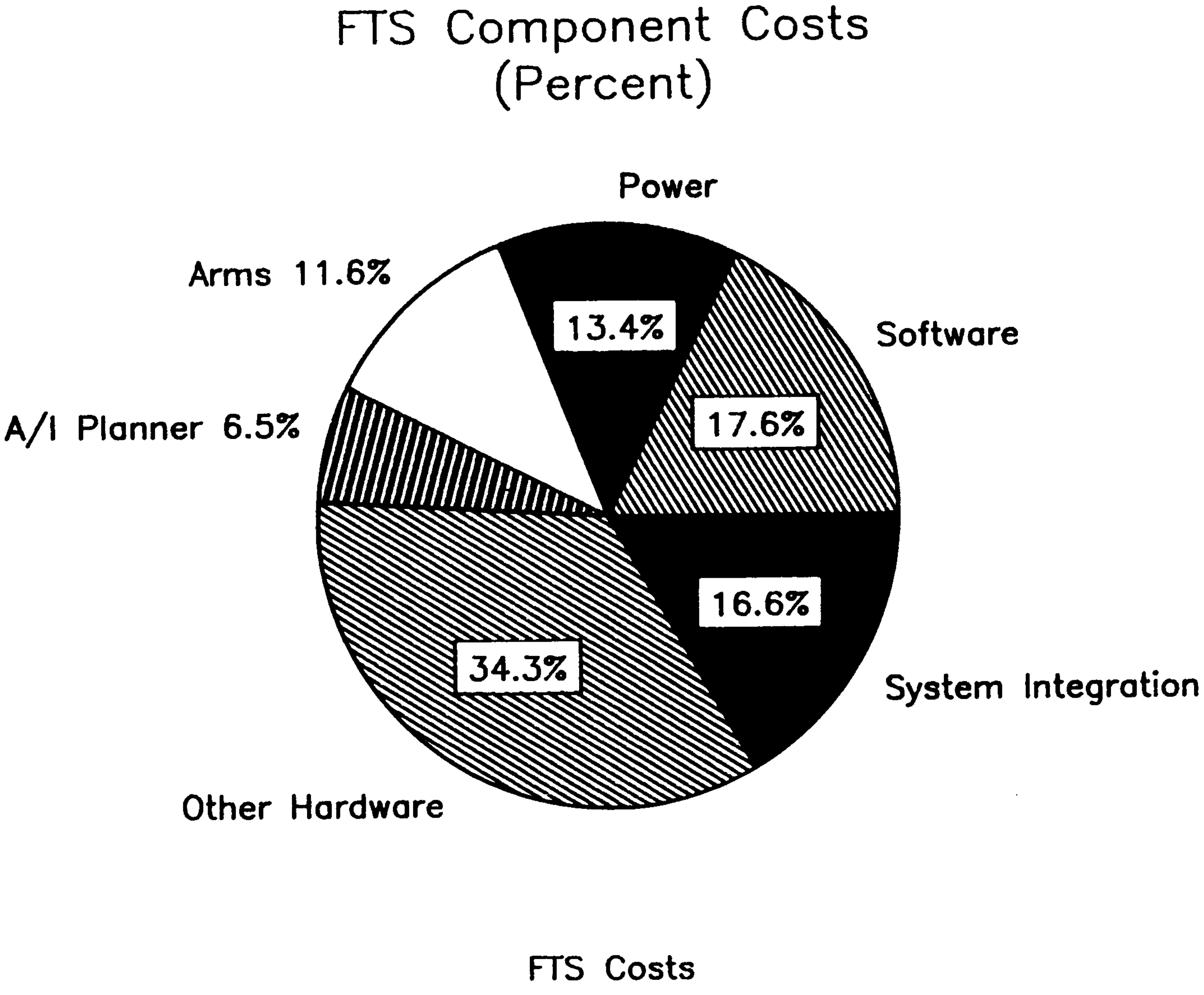

Figure 6-1. Distribution of FTS Reference System Costs

SECTION VII

ECONOMIC EVALUATION

There are benefits and costs associated with the EVA-Only and EVA+FTS cases for Space Station assembly, maintenance, and servicing. These benefits and costs provide information for policymaking regarding the possible use of an FTS for assembly, maintenance, and servicing tasks from FEL through IOC. The objective of this analysis is to evaluate the EVA-Only and EVA+FTS cases to illustrate the procedures of the methodology and to investigate the feasibility of the cases.

A. APPROACH

Estimates are derived for the operating costs incurred from the assembly, maintenance, and servicing tasks for the Space Station using the EVA-Only and EVA+FTS cases. The difference in savings of operating costs of both cases is discounted over the time period from FEL to the end of IOC, summed, and compared with the discounted investment cost of the FTS. The elements of this procedure are illustrated in Figure 7-1 and defined below.

(1) FTS DDT&E Hardware Cost:

The development cost of the FTS includes the design, development, testing, and engineering cost. This cost is estimated using industrial robot component costs, FTS integration cost, and timing of the FTS development.

(2) FTS Software Cost:

Estimated using the COCOMO1 (Reference 21) knowledge base software program. Represents an approximation of software cost required to operate the system.

(3) FTS DDT&E Cost:

Total of (1) hardware DDT&E costs, and (2) software DDT&E costs.

(4) FTS Investment Cost:

The sum of the DDT&E, flight hardware, integration, testing, software, and delivery costs of the FTS.

(5) FTS Flight Unit Cost (FLT):

The Flight Unit Cost of the FTS is the cost to fabricate and test the actual unit to be used in space.

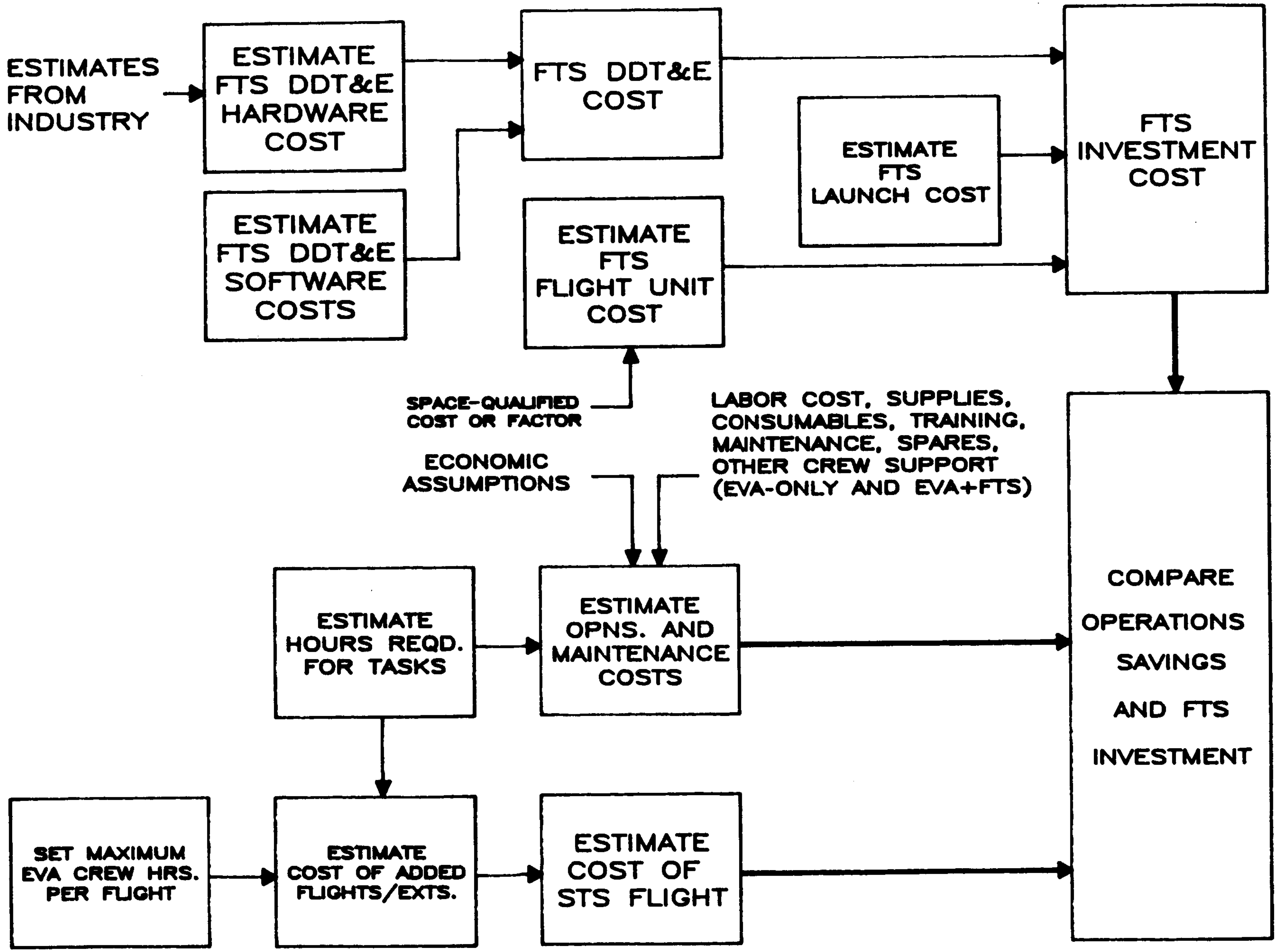

Figure 7-1. Economic Evaluation Procedure

(6) FTS Delivery Cost:

The cost incurred to transport the FTS to the launch site and deliver it to orbit. This does not include the development or flight unit cost of the FTS.

(7) Compare Operations Savings and FTS Investment:

The savings in operations and maintenance cost as a result of using FTS is compared with additional investment for FTS; the difference is the net cost or benefit for a given FTS configuration.

(8) Number of Hours Required To Complete the Tasks:

The number of hours required to do the work. Obtained by identifying the tasks to be accomplished, estimating the task timelines, and estimating and using the performance ratios of FTS to EVA.

(9) Operations and Maintenance (O&M) Cost:

O&M cost includes supplies, consumables, labor, spares, training, utilities, and other crew support costs such as tethers, handholds, foot restraints, extra lights, and extra cameras.

(10) STS Transportation Costs:

The cost incurred for assembly, maintenance, and servicing tasks for extended stay or any additional flights.

(11) Maximum EVA Crew Hours per Flight:

This is the maximum number of hours per flight the EVA crew is allowed to work.

(12) Cost of Extra STS Flights:

This is the transportation cost incurred for any additional flights required to complete EVA tasks.

B. ECONOMIC EVALUATION METHODOLOGY

This subsection describes the definitions and derivation of the Net Savings (NS) equation used to compare the O&M savings of an FTS Reference System with its investment cost.

The basic relationship is given by the following:

Net Savings accrued by the FTS

= O&M cost savings - the FTS investment cost or

- (Total O&M expenditures for the EVA-Only case

  minus

  Total O&M expenditures for the EVA+FTS case)

  minus

  The FTS investment cost.

If the net savings relationship is positive (greater than zero), then a net savings is achieved. If negative, then a net loss is incurred because the investment cost is more than the savings achieved. The derivation of these component costs is described below. The investment cost is described first because of its simplicity, followed by the operations and maintenance elements. The final equations used are presented at the end of the subsection.

The capital expenditures for the FTS (the investment costs) are estimated and compared with the operating cost savings resulting from the use of an FTS. There are two components to the net savings relation that have different time frames and discounting factors: (1) an investment period of seven years while the FTS is being developed, and (2) an operation period while the FTS is on-orbit over the 30-flight time period. The FTS investment cost calculations are discounted over the first time frame. The operations costs are discounted over the flight intervals relative to FEL (Flight 1) and then discounted from FEL back to 1987 dollars. Because different time periods and discount rates are used, separate discounting calculations are performed. The diagram below shows the two different time scales.

```
        FTS Investment         |--------------|
(8 investments:  0 to 7)       0   1   2 ...  n

        Assembly phase
        Operations (N=30                      |--------------|
        Flight Intervals)
                                              0   1   ...    N
                                             FEL            IOC
```

1. <u>FTS Investment Cost--Capital Expenditures</u>

Capital investment (CI) expenditures for the FTS include all expenses incurred for developing, fabricating, testing, and flight-qualifying the FTS unit.

The present value of the capital expenditures is given by

$$CI_{pv} = \sum_{t=0}^{n} (DDTE_t + FLT_t + L_c) \left(\frac{1+g_c}{1+k_1}\right)^t \qquad \text{Eq 1}$$

where

CI_{pv} is the present value of all capital expenditures on the FTS, expressed in 1987 dollars (1987 $).

$DDTE_t$ is the capital expenditure for FTS Design, Development, Testing, and Evaluation (1987 $) during the t-th year after 1987.

FLT_t is the capital expenditure for the Flight Hardware Unit (1987 $) during the t-th year after 1987.

DC_t is the capital expenditure for delivering and transporting the FTS to the launch site, preparing for launch, and delivering the unit to orbit (1987 $). This cost does not include the STS cost, but rather the FTS payload delivery cost per pound.

g_c is the real escalation rate for capital expenditures (annual).

k_1 is the real cost of capital (annual).

n is the number of years required to develop, test, and flight-qualify the FTS unit.

The result of computing CI_{pv} is the total cost of the FTS investment. The next step is to derive the O&M expenditures for the two cases examined--the EVA-Only case and EVA+FTS case.

2. Operations and Maintenance Expenditures

For accounting purposes, O&M costs are treated separately. The present value of O&M expenditures is given by

$$TOTALO\&M_{pv} = OPS_{pv} + MC_{pv} \qquad \text{Eq 2}$$

where

$TOTALO\&M_{pv}$ is the total present value of the O&M expenditures for a given case (EVA-Only or EVA+FTS).

OPS_{pv} is the present value of operations expenditures for a given case.

MC_{pv} is the present value of maintenance expenditures for a given case.

The present value (1987 $) of the operating cost is given by

$$OPS_{pv} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} OPS_t \left(\frac{1+g_{ops}}{1+k}\right)^t \qquad \text{Eq 3}$$

where

OPS_{pv} is the present value of operating expenditures.

OPS_t is the operating cost (1987 $) during the t-th year.

g_{ops} is the real escalation rate of operating expenditures between flights (periodic).

N is the time period from FEL to end of PMC.

k_1 is the real cost of capital (annual).

k is the real cost of capital between flights (periodic).

n is the number of years required to develop, test, and flight-qualify the FTS unit.

Note that although OPS is indexed by year, prior to FEL, years are used, while after FEL, the time interval is based on the periodic length of time between STS flights. These periodic time intervals will vary according to the number of flights per year.

The maintenance cost includes expenses for scheduled and unscheduled maintenance and repair work done during the assembly phase. The present value of maintenance cost is given by

$$MC_{pv} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} MC_t \left(\frac{1+g_{mc}}{1+k}\right)^t \qquad \text{Eq 4}$$

where

MC_{pv} is the present value of the maintenance cost, expressed in 1987 dollars.

MC_t is the maintenance cost (1987 $) incurred during the t-th year.

g_{mc} is the real escalation rate for maintenance expenses between flights (periodic)

k_1, n, k and N are as defined earlier.

The total O&M cost for the EVA-Only and EVA+FTS cases becomes:

$$TOTALO\&M_{pv}^{EVA\text{-}Only} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} OPS_t^{EVA\text{-}Only} \left(\frac{1+g_{ops}}{1+k}\right)^t + \sum_{t=1}^{N} MC_t^{EVA\text{-}Only} \left(\frac{1+g_{mc}}{1+k}\right)^t$$

Eq 5

and

$$TOTALO\&M_{pv}^{EVA+FTS} = \left(\frac{1+g_c}{1+k}\right)^n \sum_{t=1}^{N} OPS_t^{EVA\&FTS} \left(\frac{1+g_{ops}}{1+k}\right)^t + \sum_{t=1}^{N} MC_t^{EVA\&FTS} \left(\frac{1+g_{mc}}{1+k}\right)^t$$

Eq 6

As discussed earlier, the use of the FTS is cost-effective if the present value of O&M cost savings (i.e., TOTALO&M for EVA-Only minus TOTALO&M for EVA+FTS costs) exceeds or equals the present value of the investment in the FTS. Thus, the FTS is cost-effective if

$$TOTALO\&M_{pv}^{EVA\text{-}Only} - TOTALO\&M_{pv}^{EVA+FTS} - CI_{pv} \geq 0 \qquad \text{Eq 7}$$

O&M costs for the EVA+FTS case consist of EVA labor cost, IVA labor cost, supplies, consumables, training, spares, other support costs, FTS operating cost, and additional STS costs for any additional flights or extended stay. An additional STS flight may be necessary to accomplish an EVA task before PMC when crew-EVA is STS-based and there are EVA and IVA time limits (e.g., a maximum of 24 hours of work per flight). The operating costs for each time period (flight interval) can be further defined as:

$$OPS_t = C_l^{EVA}(t)+C_l^{IVA}(t)+C_{spl}(t)+C_c(t)+C_{trn}(t)+C_s(t)+C_{ocs}(t)+C_{ops}^{FTS}(t)+C_{STS}(t)+C_m^{FTS}(t)$$

Eq 8

where

$C_l^{EVA}(t)$ is the EVA labor cost (1987 $).

$C_l^{IVA}(t)$ is the IVA labor cost (1987 $).

$C_{spl}(t)$ is the cost of supplies (1987 $).

$C_c(t)$ is the cost of consumables (1987 $).

$C_{trn}(t)$ is the cost (1987 $) of training the FTS operator. Training for EVA and IVA operations is assumed to be the same for both cases.

$C_s(t)$ is the cost (1987 $) of spares for the FTS. Spares for EVA and IVA operations are assumed to be the same.

$C_{ocs}(t)$ is the cost (1987 $) of other crew support equipment.

$C_{ops}^{FTS}(t)$ is the cost of operating the FTS (1987 $).

$C_{STS}(t)$ is the cost of the STS for extended stay or additional flights (1987 \$).

$C_m^{FTS}(t)$ is the maintenance cost for the FTS (1987 \$).

The above values are estimated in further detail using the following:

$$C_1^{EVA}(t) = C^{EVA} \times H^{EVA}(t) \qquad \text{Eq 9}$$

where

C^{EVA} is the EVA labor rate (1987 \$/hour).

$H^{EVA}(t)$ is the total EVA hours (hours) for flight interval t.

$$C_1^{IVA}(t) = C^{IVA} \times H^{IVA}(t) \qquad \text{Eq 10}$$

where

C^{IVA} is the IVA labor rate (1987 \$/hour).

$H^{IVA}(t)$ is the total IVA hours (hours) for flight interval t.

$$C_{spl}^{EVA} = H^{EVA}(t) \times C_{spl}^{EVA} \qquad \text{Eq 11}$$

where

C_{spl}^{EVA} is the supplies cost per hour (1987 \$/hour).

$$C_c(t) = H^{EVA}(t) \times C_c^{EVA} \qquad \text{Eq 12}$$

where

C_c^{EVA} is the consumables cost per hour (1987 \$/hour).

$$C_{ocs}(t) = H^{EVA}(t) \times C_{ocs}^{EVA} \qquad \text{Eq 13}$$

where

C_{ocs}^{EVA} is the cost of other support equipment per hour (1987 \$/hour).

$$C_{ops}^{FTS}(t) = H^{FTS}(t) \times C_{oph}^{FTS} \qquad \text{Eq 14}$$

where

$H^{FTS}(t)$ is the hours the FTS is operating on tasks (hours).

C_{oph}^{FTS} is the cost to operate FTS per hour (1987 \$/hour).

Letting $C = C^{EVA} + C_{spl}^{EVA} + C_{c}^{EVA} + C_{ocs}^{EVA}$

and substituting Equations (9)-(14) in Equation (8), the O&M cost for the EVA+FTS case is:

$$OPS_t = C \cdot H^{EVA}(t) + C^{IVA} H^{IVA}(t) + C_{trn} + C_s + C_{sts} + C_{oph}^{FTS} H^{FTS}(t) + C_m^{FTS} \qquad \text{Eq 15}$$

The total hours of operation (both EVA-Only and EVA+FTS) consist of hours for assembly, maintenance, and servicing and are divided into two components--the hours for EVA and the hours of FTS operation (if present).

Thus

$$H^{EVA}(t) = h_a^{EVA}(t) + h_m^{EVA}(t) + h_s^{EVA}(t)$$

where

H^{EVA} is the crew-EVA hours.

$h_a^{EVA}(t)$ is the assembly hours (hours) for flight interval t.

$h_m^{EVA}(t)$ is the maintenance hours (hours) for flight interval t.

$h_s^{EVA}(t)$ is the servicing hours (hours) for flight interval t.

and

$$H^{FTS}(t) = h_a^{FTS}(t) + h_m^{FTS}(t) + h_s^{FTS}(t)$$

where

$H^{FTS}(t)$ is the hours of FTS operation.

$h_a^{FTS}(t)$ is the FTS operating hours spent on assembly (hours).

$h_m^{FTS}(t)$ is the FTS operating hours spent on maintenance (hours).

$h_s^{FTS}(t)$ is the FTS operating hours spent on servicing (hours).

In a similar manner, the IVA time is defined as

$$H^{IVA}(t) = h_a^{IVA} + h_m^{IVA}(t) + h_s^{IVA}(t)$$

where

$H^{IVA}(t)$ is the IVA hours for the given case (EVA-Only or EVA+FTS).

$h_a^{IVA}(t)$ is the hours for crew-IVA assembly hours for the given case.

$h_m^{IVA}(t)$ is the hours for crew-IVA maintenance hours for the given case.

$h_s^{IVA}(t)$ is the hours for crew-IVA servicing hours for the given case.

Equation (15) can now be written as:

$$OPS_t = C\ h_a^{EVA}(t) + h_m^{EVA}(t) + h_s^{EVA}(t) + C^{IVA}\ h_a^{IVA}(t) + h_m^{IVA}(t) + h_s^{IVA}(t)$$
$$+ C_{trn} + C_s + C_{STS} + C^{FTS}\ h_a^{FTS}(t) + h_m^{FTS}(t) + h_s^{FTS}(t) + C_m^{FTS} \qquad \text{Eq 16}$$

For the EVA + FTS case, the present value of O&M costs is obtained by substituting Equation (16) in Equation (6):

$$TOTALO\&M_{pv}^{EVA+FTS} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\left(h_a^{EVA}(t) + h_s^{EVA}(t)\right) + C^{IVA}\left(h_a^{IVA}(t) + h_s^{IVA}(t)\right) \right.$$
$$\left. + C_{trn} + C_s + C_{STS} + C^{FTS}\left(h_a^{FTS}(t) + h_s^{FTS}(t)\right)\right] \left(\frac{1+g_{ops}}{1+k}\right)^t$$
$$+ \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[Ch_m^{EVA}(t) + C^{IVA}\ h_m^{IVA}(t) + C^{FTS}\ h_m^{FTS}(t) \right.$$
$$\left. + C_m^{FTS}\right] \left(\frac{1+g_{mc}}{1+k}\right)^t \qquad \text{Eq 17}$$

For the EVA-Only case, the present value of O&M cost is simply Equation (17) without the FTS-related terms, using the different values for the EVA and IVA hours.

$$\mathrm{TOTALO\&M}_{pv}^{EVA\text{-}Only} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\left(h_a^{EVA}(t) + h_s^{EVA}(t)\right) + C^{IVA}\left(h_a^{IVA}(t) + h_s^{IVA}(t)\right)\right.$$

$$\left. + C_{trn} + C_s + C_{STS}\right]\left(\frac{1+g_{ops}}{1+k}\right)^t$$

$$+ \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\, h_m^{EVA}(t) + C^{IVA}\, h_m^{IVA}(t)\right]\left(\frac{1+g_{mc}}{1+k}\right)^t \qquad \text{Eq 18}$$

The key equations are summarized in Figure 7-2. The procedure involves subtracting Equations (17) from Equation (18) and then subtracting the FTS investment cost, Equation (1). If the result is positive, a net savings indicates the FTS is cost-effective (Equation (7)).

C. ASSUMPTIONS

A number of assumptions were made in each of four categories: Economic assumptions, operational assumptions, performance assumptions, and data estimates. The assumptions and data estimates are listed below with a brief rationale.

<u>Economic Assumptions Based On:</u>

(1) Lifetime begins with FTS development and extends through Flight 30. The purpose here was to examine only the assembly phase.

(2) Real cost of capital: 10% per year. This is the discount rate suggested by the Office of Management and Budget (OMB) for use to evaluate Government projects (Reference 22). A lower value of 6% was examined during the sensitivity analysis.

(3) Real periodic (flight-interval) discount rate: 1.3%. This is based on the assumption that there will be an average of 7.5 flights per year (i.e., 30 flights/4 years = 7.5 flights per year; then 10% per year/7.5 flights per year = 1.33% per flight [interval]).

(4) It is assumed that no significant changes in the rates of change of capital, operating, and maintenance expenditures will occur during the time period of study. Thus, $g_c = g_{ops} = g_{mc} = 0$.

$$\text{Net Savings} = \text{TOTALO\&M}_{pv}^{\text{EVA-Only}} - \text{TOTALO\&M}_{pv}^{\text{EVA+FTS}} - CI_{pv} \geq 0$$

where

$$CI_{pv} = \sum_{t=0}^{n} (DDTE_t + FLT_t + L_c) \left(\frac{1+g_c}{1+k_1}\right)^t$$

$$\text{TOTALO\&M}_{pv}^{\text{EVA+FTS}} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\left(h_a^{EVA}(t) + h_s^{EVA}(t)\right) + C^{IVA}\left(h_a^{IVA}(t) + h_s^{IVA}(t)\right) \right.$$

$$\left. + C_{trn} + C_s + C_{STS} + C^{FTS}\left(h_a^{FTS}(t) + h_s^{FTS}(t)\right)\right] \left(\frac{1+g_{ops}}{1+k}\right)^t$$

$$+ \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[Ch_m^{EVA}(t) + C^{IVA}\, h_m^{IVA}(t) + C^{FTS}\, h_m^{FTS}(t) \right.$$

$$\left. + C_m^{FTS} \right] \left(\frac{1+g_{mc}}{1+k}\right)^t$$

$$\text{TOTALO\&M}_{pv}^{\text{EVA-Only}} = \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\left(h_a^{EVA}(t) + h_s^{EVA}(t)\right) + C^{IVA}\left(h_a^{IVA}(t) + h_s^{IVA}(t)\right) \right.$$

$$\left. + C_{trn} + C_s + C_{STS} \right] \left(\frac{1+g_{ops}}{1+k}\right)^t + \left(\frac{1+g_c}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\, h_m^{EVA}(t) \right.$$

$$\left. + C^{IVA}\, h_m^{IVA}(t) \right] \left(\frac{1+g_{mc}}{1+k}\right)^t$$

Figure 7-2. General Cost Equations for the EVA-Only versus EVA+FTS Cases (see text for definitions)

The operational and performance assumptions are related to the performance of EVA:

Operational and Performance Assumptions Based on:

(1) FTS available 24 hours per day subject to power supply constraints. This is based on the premise that the FTS is a machine capable of working at all times.

(2) FTS operator hours of productive work per day: 8 hours (maximum). It is assumed that the IVA operator works regular normal hours in a pressurized environment.

(3) Maximum EVA hours per flight: 24 hours up to PMC. As needed between PMC and IOC. This is stipulated by CETF.

Finally, a number of assumptions were required to obtain estimates for major cost elements of the analysis:

Data Assumptions Based On:

(1) STS flight charge: $105M-178M; Baseline = $137M.

(2) EVA operating cost per hour: $25,000-45,000; Baseline = $35,133 (Reference 23).

(3) IVA operating cost per hour: Baseline = $11,018 (Reference 23).

(4) Crew training: $307,000 per flight (Reference 24).

(5) FTS development cost (study baseline): $192.6M-$210M (from Section VI).

(6) FTS flight unit cost (study baseline): $84.5M - $94.3M (from Section VI).

(7) Total FTS budget: $232.2M.

(8) FTS operating cost per year (includes ground support and refurbishment costs): $10-15M (Reference 25). Used $12.5M/year.

(9) Maintenance hours on FTS: 2% of available FTS operating hour. This estimate was obtained from a telerobot manufacturer.

(10) FTS delivery cost to orbit: $3,600 per lb (Reference 26).

(11) FTS weight: Approximately 4,100 lbs (study estimate by authors).

(12) FTS spares cost: $3,100 per flight (JPL estimate of total spares).

D. APPLICATION TO EVA-ONLY AND EVA+FTS CASES

For the EVA+FTS case, the present value of O&M cost as given in Equation (18) with g_c, g_{mc}, g_{ops} set to zero is:

$$\text{TOTALO\&M}_{pv}^{EVA\&FTS} =$$

$$\left(\frac{1}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C \left(h_a^{EVA}(t) + h_m^{EVA}(t) + h_s^{EVA}(t)\right) + C_a^{IVA}(t) \left(h_a^{IVA}(t) + h_m^{IVA}(t) + h_s^{IVA}(t)\right) \right.$$

$$\left. + C_{trn} + C_s + C_{STS} + C^{FTS} \left(h_a^{FTS}(t) + h_m^{FTS}(t) + h_s^{FTS}(t)\right) + C_m^{FTS} \right] \left(\frac{1}{1+k}\right)^t$$

From the data above,

EVA operating cost/hour	C	= \$35,133/hour
IVA operating cost/hour	C^{IVA}	= \$11,018/hour
Cost of training of IVA crew/flight	C_{trn}	= \$307,000
Cost of spares for FTS	C_s	= \$3,100
FTS operating cost/hour	C^{FTS}	= \$1,427/hour (includes ground operations)
Maintenance labor cost on FTS/hour		\$35,133/hour
Annual discount rate	k_1	= 0.10
Average discount rate between flights (periodic rate)	k	= 0.0133 (10%/7.5 flights per year)
FTS investment period	n	= 7 years (8 investments: 0 to 7)
Period from FEL to IOC	N	= 30 flights

Mixed manifesting indicates that extra shuttle flights must be added to meet the estimated EVA requirements and that the extra EVA time allowed by the additional flights can be remanifested to some extent on later flights.

Substituting these values in the above, we get

$$\text{TOTALO\&M}_{pv} = \left(\frac{1}{1.1}\right)^7 \sum_{t=1}^{30} \left[35{,}133 \left(h_a^{EVA} + h_m^{EVA} + h_s^{EVA}\right) + 11{,}018 \left(h_a^{IVA} + h_m^{IVA} + h_s^{IVA}\right) + \right.$$

$$\left. 307{,}000 + 3{,}100 + 137M + 1{,}427 \left(h_a^{FTS} + h_m^{FTS} + h_s^{FTS}\right) + 35{,}133 \times C_m^{FTS} \right] \left(\frac{1}{1.013}\right)^t$$

The remaining values for the hours in the above equation are taken from Table 5-6.

When the low-range EVA hour and low-range investment values are used in the above equation, the result is:

$$\mathrm{TOTALO\&M}_{pv}^{EVA\&FTS} = \$125.1M$$

For the EVA-Only case, the present value of O&M cost as given in Equation (17) is

$$\mathrm{TOTALO\&M}_{pv}^{EVA\text{-}Only} = \left(\frac{1}{1+k_1}\right)^n \sum_{t=1}^{N} \left[C\left(h_a^{EVA} + h_m^{EVA} + h_s^{EVA}\right) + C^{IVA}\left(h_a^{IVA} + h_m^{IVA} + h_s^{IVA}\right) + C_{trn} + C_s + C_{STS}\right]\left(\frac{1}{1+k}\right)^t$$

When the low-range EVA hour and low-range investment values are used in the equation, the result is:

$$\mathrm{TOTALO\&M}_{pv}^{EVA\text{-}Only} = \$396.5M$$

Thus the savings in O&M cost resulting from the use of FTS is

$$\mathrm{TOTALO\&M}_{pv}^{EVA\text{-}Only} - \mathrm{TOTALO\&M}_{pv}^{EVA\&FTS} = \$271.4M$$

To complete the net savings, Equation (7) is used with the computed value of the FTS investment cost, again using the low-range value for the FTS investment cost:

$$\begin{aligned} \text{Net Savings} &= \mathrm{TOTALO\&M}_{pv}^{EVA\text{-}Only} - \mathrm{TOTALO\&M}_{pv}^{EVA+FTS} - CI_{pv} \\ &= (396.5 - 125.1) - 241.1 \\ &= \$30.3M \text{ (the FTS is cost-effective for this case)} \end{aligned}$$

The above result represents one example calculation using the previous cost and benefit equations. The next section provides the complete results of the cost and sensitivity analysis.

SECTION VIII

RESULTS

This section summarizes the results of the study divided into two categories. The first category presents the baseline results of the technical analysis of the assembly phase, including the FTS Reference System and the estimates of EVA and IVA. The second category focuses on the economic analysis and the sensitivity analysis of significant parameters affecting the net savings calculation.

A. BASELINE RESULTS

A methodology (Figures 1-1, 3-1, 7-1) was developed to better understand the possible role an FTS might play during the assembly phase of Space Station construction using the CETF model (30 flights). A comparison was made between two cases: an EVA-Only case (no FTS) and an EVA+FTS case, in which an FTS would be available to assist during the assembly phase. The methodology required development of (1) the FTS Reference System and its cost estimates, (2) development of an operationally feasible task set and assessment of EVA and IVA for the assembly tasks, maintenance tasks, and attached payloads by flight interval for the CETF 30-flight period, and (3) a cost model to compare the savings in operations costs against the required FTS investment cost. The results of each of these elements is described below.

B. FTS REFERENCE SYSTEM

An FTS Reference System was synthesized using the CETF assembly sequence and related information to produce a technically feasible task set to which FTS functions could be matched. A technology assessment of candidate FTS telerobot functions was performed to assess technology configurations with reasonable technical and performance risks available by FEL. The CETF functions were matched with FTS functions to synthesize the FTS Reference System used in the study. The FTS Reference System defined by this study was most suitable for performing:

(1) Truss assembly tasks.
(2) Limited ORU replacement tasks.
(3) Deployment of special equipment.
(4) Pallet handling, loading, and unloading tasks.

A component parts list was prepared for the FTS Reference System and cost estimates were developed using a bottom-up approach. Estimates of costs were obtained from NASA, JPL, and industry sources. The total estimated cost of the FTS Reference System ranged from $277 to 304 million (1987 dollars). The distribution of costs for the FTS is shown in Figure 6-1 (does not include spares costs).

C. OPERATIONALLY FEASIBLE TASK SET

At the same time that the FTS Reference System was developed, a set of technically feasible tasks was specified that the FTS could perform. A set of operational constraints were defined that consisted of EVA and IVA budget constraints (particularly during the period FEL to PMC) as well as proximity operations rules. The operational constraints were applied to produce an operationally feasible task set--a set of tasks performable by the FTS Reference System and allowable within the constraints. These tasks were combined with the remaining non-FTS-related tasks to produce a list of tasks in the areas of assembly, maintenance, and attached-payload servicing. Polar platforms, logistics, and satellite servicing were examined but not included in the final results.

In order to illustrate the methodology, estimates of EVA and IVA were made for two cases: an EVA-Only case (FTS during the assembly phase) and an EVA+FTS case, in which an FTS could be used to displace critical EVA resources on operationally feasible tasks. These estimates were made by flight interval, assuming a four-year, 30-flight assembly phase with 5, 8, 8, and 9 flights per year. Because of uncertainties in the estimation process, ranges were used to bound the process. As a result, the EVA and IVA estimates were presented as either a low-range or high-range value. For example, the total EVA and IVA estimates for the study are:

	EVA	IVA
EVA-Only Case	1,572-1,671	1,002-1,054
EVA+FTS Case	1,187-1,258	1,066-1,613
EVA/IVA Savings	385-413	< 64-559 >

The primary difficulty arises when more EVA is needed than is available, and this is most apparent during the period FEL to PMC, when all EVA is Shuttle-based. Figures 5-1 and 5-2 illustrate this problem for the low-range EVA estimates. There are a number of early flights that exceed the EVA constraint of 24 hours per flight. After PMC, although the budget line is exceeded for two flight intervals, it is anticipated that the excess EVA could be "spread" out over subsequent intervals, since there is additional flexibility in the PMC mode.

Another key result is illustrated in Figures 5-3 through 5-10, which display the distributions of EVA for both cases. Maintenance is more pronounced than originally thought, and it is generally insensitive to the case and uncertainties in the EVA estimates. Although the original focus was on assembly activities, more attention to scheduled and unscheduled maintenance activities may be required.

D. ECONOMIC ANALYSIS

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. The model used was:

Net Savings Due to FTS =

(Operations and Maintenance Cost of EVA-Only Case)

\-

(Operations and Maintenance Cost of EVA+FTS Case)

\- Investment Cost of the FTS.

If the net savings is positive, the FTS Reference System is cost-effective; otherwise it is not (the cost of building it exceeds any savings it might generate).

The results indicate that the key trade-off is between the cost of the FTS itself 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. These added flights can be very expensive and are a major factor in the cost-effectiveness of the FTS. Figure 8-1 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; however, a range of price curves is presented to provide a generalized result. Note also that the FTS cost ranges from a low $232M (Reference 26) to $340M (Reference 27). These endpoints were selected merely to limit the scope of the trade-off region. The area in the center of the region bounds the feasible region using the FTS Reference System costs developed in Section VI. 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 it 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.

Note the term "Mixed Manifesting" on Figure 8-1. 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 next case--flexible manifesting. The flexible manifesting case assumes that it is very 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.

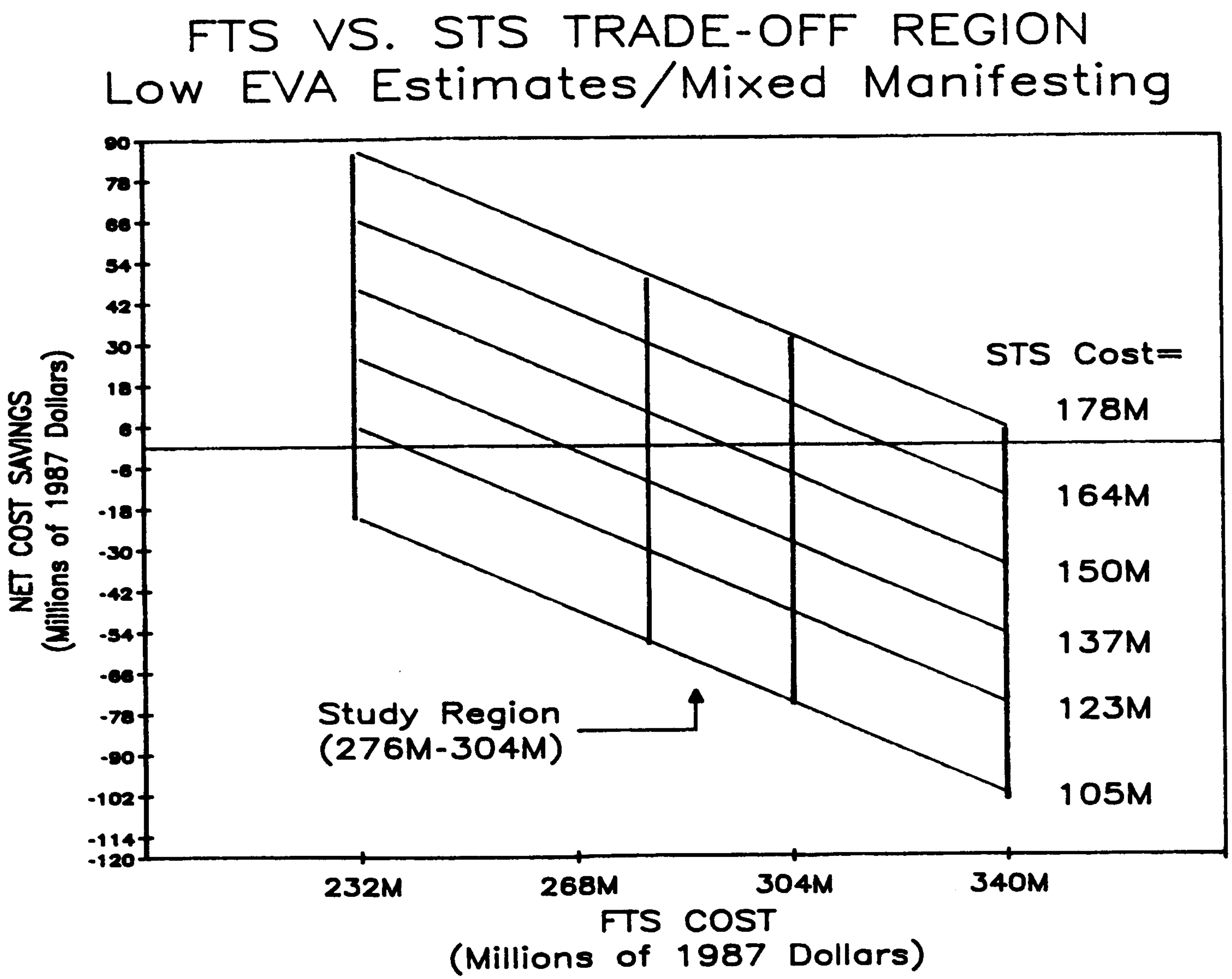

Figure 8-1. FTS versus STS Trade-Off Region--Low EVA Values

In terms of sensitivity, note that if the scenario is moved toward the flexible manifesting assumption, the trade-off region moves down (towards 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 delivery cost and the effects of discounting.

The region in Figure 8-1 is for the low-range EVA values. If the high-range EVA values are used, the region moves down significantly (Figure 8-2). Similarly, as the estimated cost of the FTS increases, cost-effectiveness drops (the region shifts downward) and the slope changes to -0.82 (FTS cost-effectiveness is more sensitive to STS cost) (see Figure 8-3).

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, using $45K, $35K, and $25K per hour, are displayed in Figure 8-4. 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.

The discount rate used in the above results is the OMB value of 10% used for cost-benefit analysis on government projects (Reference 22). The effect of varying the discount rate was also examined, using a 6% rate (Figure 8-5). The effect is to move the trade-off region up significantly. This simply indicates that a lower discount rate more appropriate to evaluating aerospace projects would have a significant impact on improving the cost-effectiveness of the FTS.

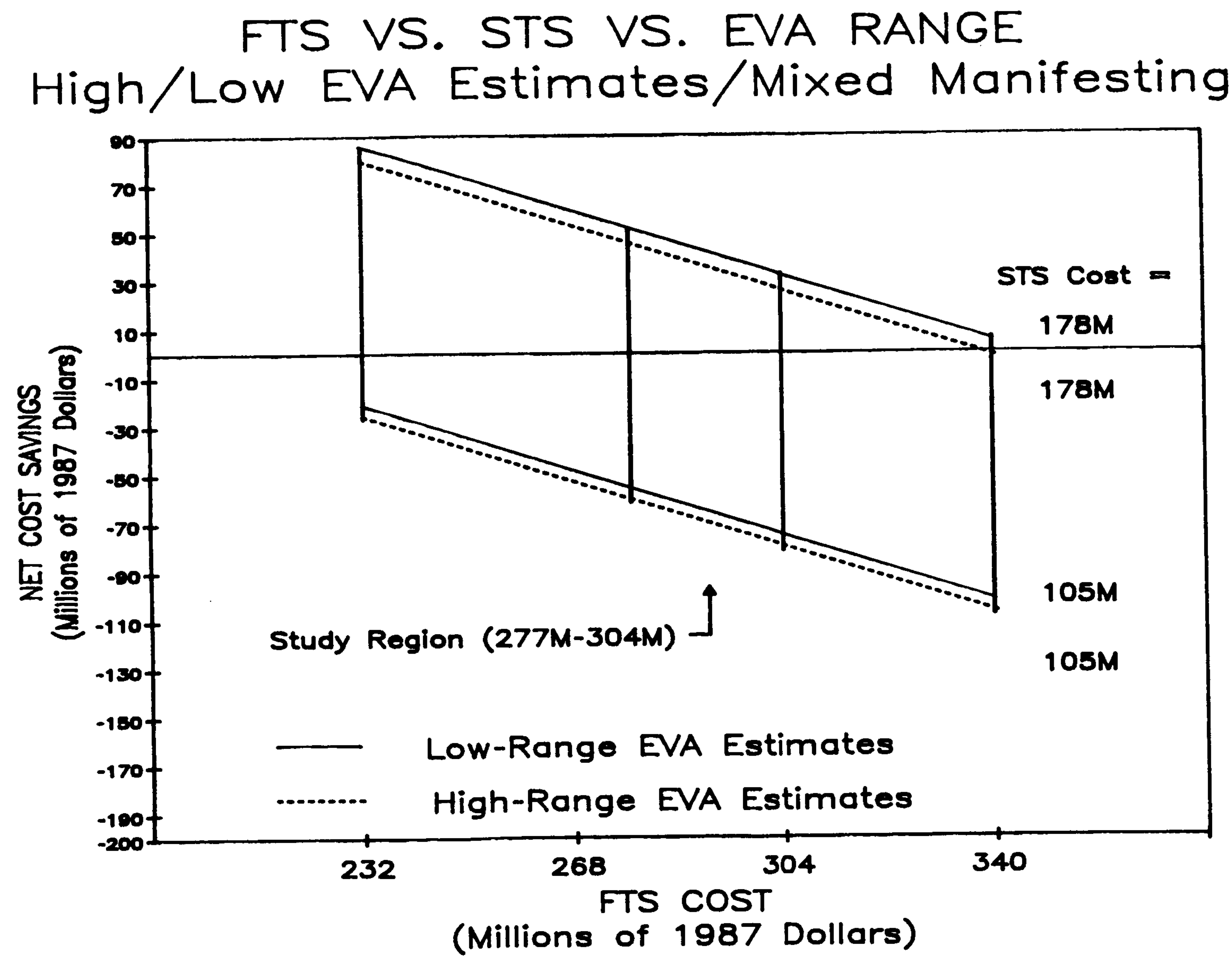

Figure 8-2. FTS versus STS Trade-Off Region--High EVA Values

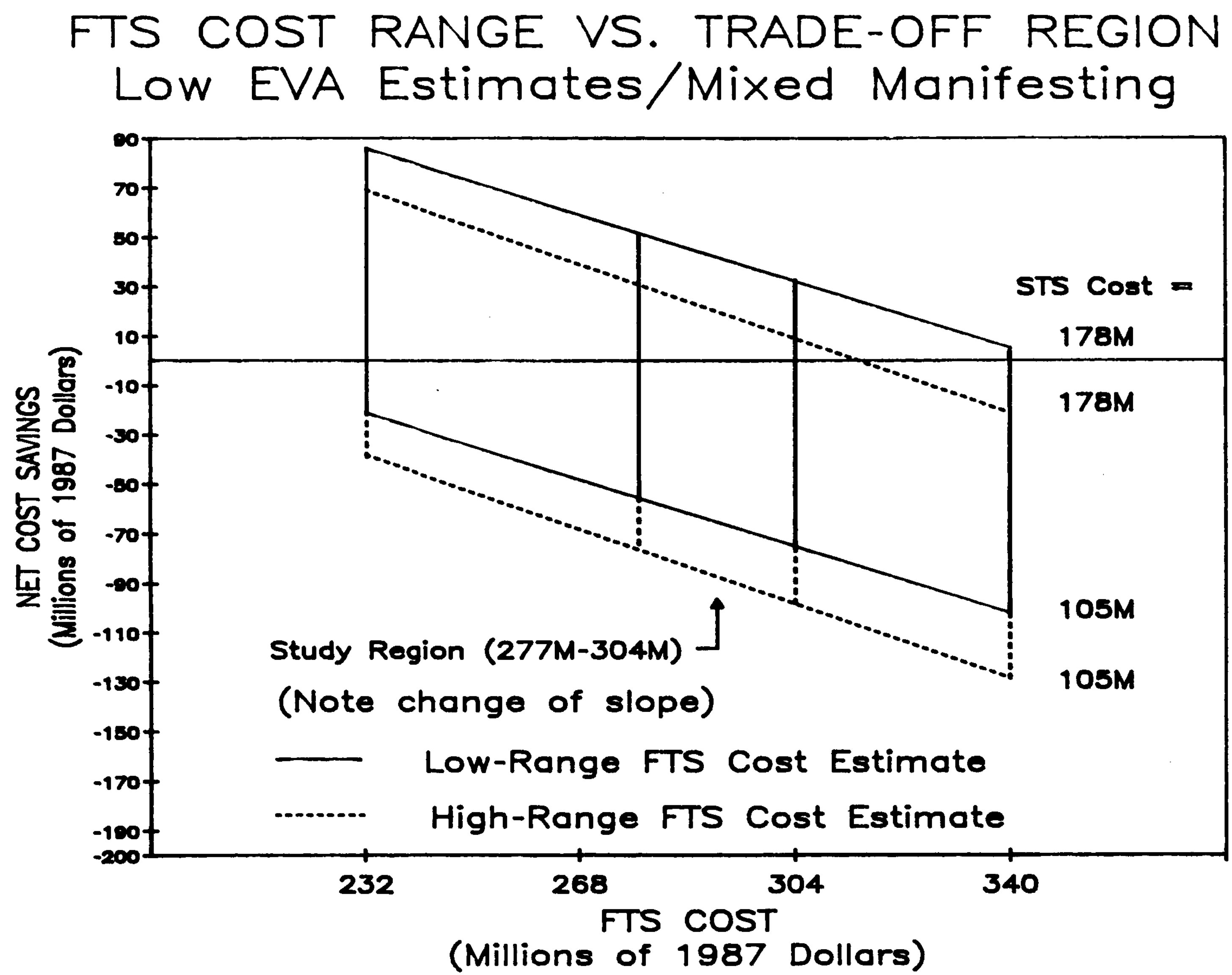

Figure 8-3. High-Range versus Low-Range FTS Cost

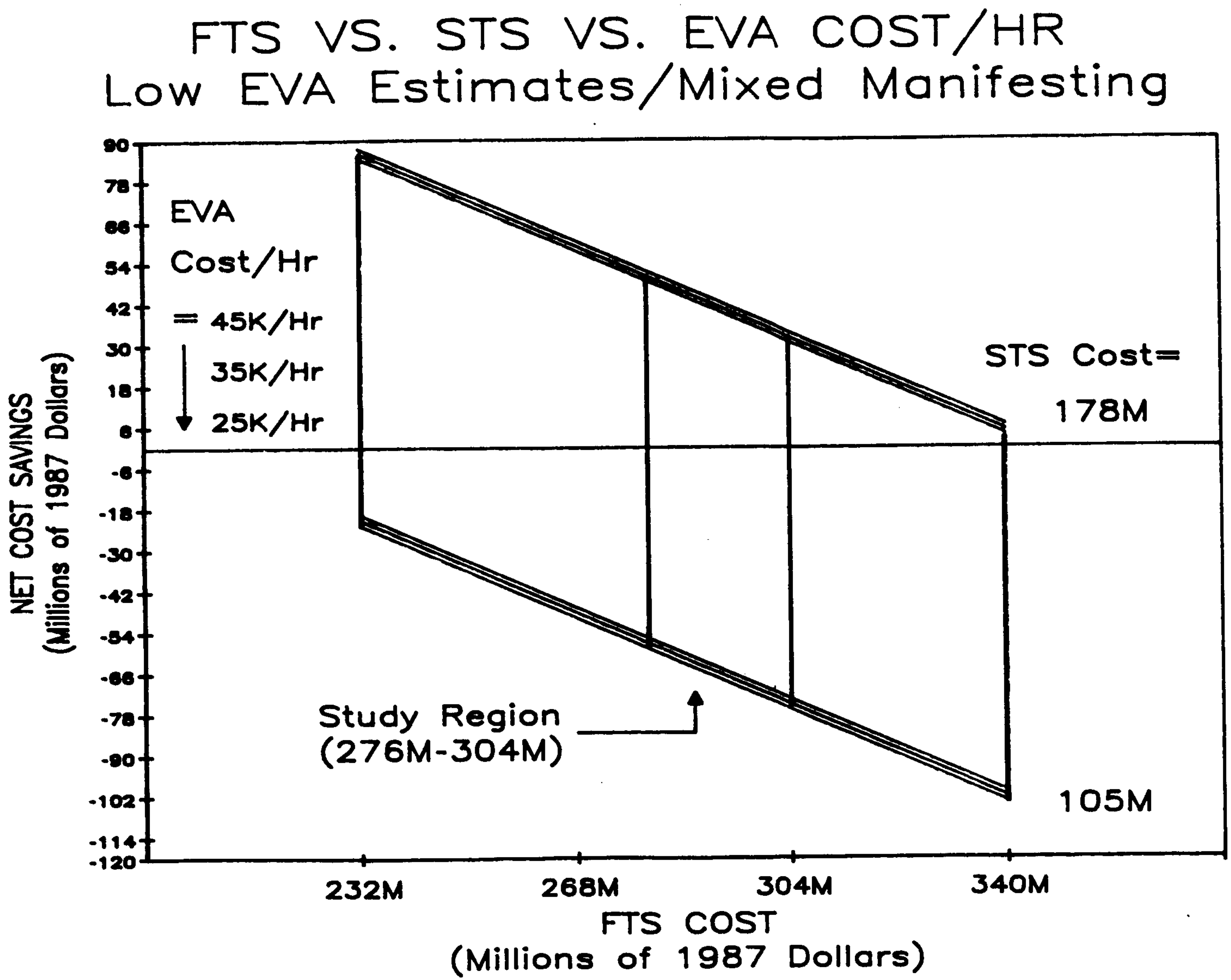

Figure 8-4. FTS Cost versus STS Cost versus EVA Cost Per Hour

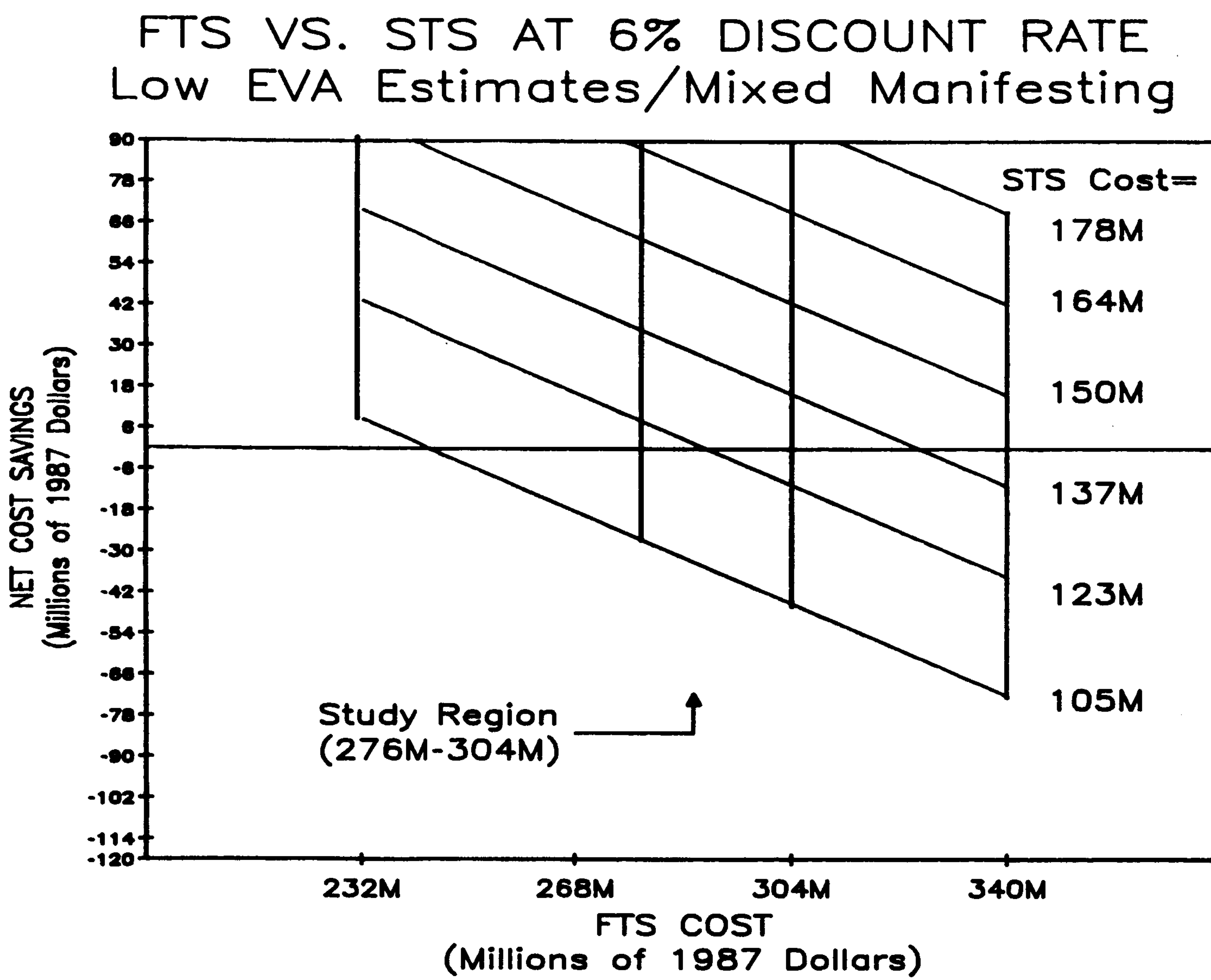

Figure 8-5. FTS versus STS Cost Trade-Off Region for a 6% Discount Rate

SECTION IX

DISCUSSION AND CONCLUSIONS

A. DISCUSSION

To place the results of the study in context with the Space Station Program, two issues should be considered:

(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 as illustrated in Section III 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 A&R technology development since both terrestrial spin-off and Station benefits can accrue from the 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 would still hold for the combined Phase I and Phase II design, current interest is focused on Phase I, so 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 based on 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 (325-344 EVA hours). However, this is conjecture at this point and could 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, it has 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 (References 28, 29). Although the division is between an applications-oriented FTS and a demonstration-oriented one, 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 which 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 then 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 EVA-equivalence--the issue of whether 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. For example, the requirement that any task performed by the FTS must be designed such that it can be accomplished by EVA astronauts equipped with tools (Reference 30). 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 of many possible ones. 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 here was to identify the components that ought to be examined when comparing FTS options. Nonetheless, a number of observations were made.

B. OPERATIONALLY FEASIBLE TASK SET

Definition of the operationally feasible tasks requires an extensive amount of detailed EVA task data. While the assembly sequence data tends to be the most widely published, it is still sparse and incomplete, requiring extensive assumptions about the objects to be handled, the activities to be performed, and physical locations and envelopes. As noted in Reference 31, there is a need to make Station documentation with the latest updates widely available in a common format. While estimates made in the present study were carefully made, the basic inputs are still subject to question due to a lack of clarity and uniformity of some of the inputs. An assembly sequence database containing the latest assembly sequence, task definitions, manifests, and timing would be useful for all Station design participants. There are numerous activities dependent on the assembly sequence for their own planning that would benefit from such a database (the Satellite Servicing Facility [SURFAC], Mobile Servicing Centre, the Orbital Maneuvering Vehicle, the polar platforms and payloads, the attached payloads, and the present FTS study, to name a few). If such a database were available, it might be possible to rule out (or include) more tasks based on the proximity operations constraints.

One such example are the attached-payload inputs derived from the modified MRDB--many of the attached payloads that survived the initial sorting criteria suffered from missing data. Those cases had to be eliminated from the computed averages. The concept of an MRDB is a good one and should be continued with the addition of a data quality review system. Many of the inputs in the MRDB (as noted in the documentation) are simply for illustrative purposes. This leads to a situation in which EVA and IVA are added without rationale or basis. It would be useful if no attached payload were allowed in the MRDB unless it had a reviewed plan for the use of Station resources.

There is also a lack of clarity in the expected EVA/IVA requirements for maintenance. Prior to the PMC the STS provides on-orbit repair for high-criticality items, placing severe constraints on EVA. There are alternative maintenance strategies to using FTS that could be examined, including deployable trusses and built-in redundant in-line (cold) spares for high-failure-rate EVA-accessible parts. Thus, trade-offs could be made between EVA-performed and FTS-performed repairs and increased redundancy. Safety and redundancy benefits due to the use of an FTS for repair of high-criticality items were not examined in detail.

The CETF option was to increase the Mean Time Between Failure (MTBF) to 5 years (43,800 hours), but a number of ORUs already show MTBFs of 50-100K hours. However, some items (e.g., truss members) will have an actual MTBF of far less because of induced failures--something that cannot be mitigated by design. A more detailed understanding of the scheduled and unscheduled maintenance tasks is needed.

The polar platform data were one of the few areas containing the information needed, but it is not clear what role polar platforms will play within the assembly phase time frame. A more crucial issue would be whether the feasibility of using an FTS for polar platform servicing is justified given the high cost of a second FTS. At face value it does not appear justified within the assembly phase. However, the extremely high costs of performing EVA on the polar platform due to the high transport costs may be an indication that EVA, FTS, and STS costs and their relationships should be examined differently for polar platforms. This is a topic for future study.

Finally, the logistics component needs to be examined. The effect of not including logistics in the present study is to undervalue the FTS, since it could be useful for "pick and place" transfer activities, holding large objects, and providing additional video and lighting during transfers. In general, it is assumed that most of the logistics transfers will be performed by an RMS or the MSC; however, there are some tasks (yet to be well-defined) for which an FTS might be useful. Again, such a study must be deferred until further data become available.

This raises the issues of work allocation. In a multiple robot environment (FTS, MSC, RMS, SURFAC, etc.), in which more than one robot might be involved cooperatively, how should tasks be allocated? There will be additional proximity operations rules required for such an environment, but there may be significant benefits. For example, if the MSC unloads an STS logistics module, additional berthing clearances might be achieved via handoff of the module from the RMS to the MSC, resulting in a large extension of the total reach envelope between the RMS and MSC.

Another area for further investigation involves co-EVA, or cooperative EVA, in which an EVA crew member is working in parallel with an FTS. More study needs to be done to identify the kinds of co-EVA tasks and the potential benefits of such tasks.

C. FTS REFERENCE SYSTEM

For many of the reasons cited above, the FTS specification also could be improved. There are a number of technical issues that could be explored given more data.

With additional data on the estimated costs of deployable trusses, the trade-off between erectable and deployable trusses could also be examined to determine if the cost of deployables does in fact outweigh the added STS flights and/or investment cost.

FTS mobility could make a significant difference in the results that state that the momentum management requirements of the MSC constrain the MSC movement. The dynamic disturbance budget limits the center of gravity shift to eight feet, which appears acceptable except when large masses are being handled (Reference 32). A larger functional reach envelope could be traded against the FTS mobility. When mobility is required to enable task performance, the methodology presented here could also be used to compare rail-mounted systems with the envelope of a transportable RMS. The difference in potential EVA savings between the practical mobility options of EVA-carried, transportable-RMS-mounted, and rail-mounted or MSC-mounted alternatives could also be compared. A free-flying capability would undoubtedly be useful, but probably not acceptable operationally.

In-situ satellite servicing by an OMV Smart Front-End is a primary factor for telerobotic technology. Potentially hundreds of millions of dollars could be saved in transfer propellant costs alone (Reference 33). This is a post-IOC trade-study topic that should be accounted for in OMV cost-benefit studies.

Also not examined here is the issue of the similarity and therefore potential competition between the MRS in the SURFAC and the FTS applications.

This study did not address potential safety and redundancy benefits of the FTS for critical tasks. However, these benefits could be significant and, even in a high-cost situation, be required for safety reasons. Reducing EVA exposure time is always desirable, but there are specific kinds of tasks for which safety is a key issue (such as handling propellants). This introduces a factor which is difficult (if not impossible) to quantify in cost terms. Methods are available for performing trade-offs between cost and non-cost attributes that allow the usage of difficult-to-quantify variables like safety, spin-off potential, and programmatic risk (References 34, 35). Such methods can be used at the task level to screen out tasks with safety implications or at the system level to rank alternative FTS configurations with different levels of safety.

A key issue is the technical risk of building even a partially autonomous FTS at FEL or IOC. There are no current working examples of fully integrated telerobots that perform vision, tracking, planning, and handling functions as integrated units. The potential for some of the short-term technologies must be reviewed carefully before committing to or relying on the advertised capabilities. A strong benefit of autonomous operation is the potential to reduce Station IVA for supervisory tasks and thus improve FTS value and productivity. However, these benefits must be examined in the light of their technical complexity against performing the functions telerobotically from the ground.

The analysis highlights a difference between the kinds of tasks in which the FTS can achieve large benefits and originally held views of large-benefits tasks. The present FTS Baseline Configuration Document places an emphasis on servicing stating, "At the time of Space Station FEL the FTS shall have a capability, at a minimum, ORU changeout and the mating, demating of thermal utility connections" (Reference 36). However, the results of Section III indicate large benefits for truss assembly. The proportion of time spent on truss assembly needs to be compared with the proportion of time spent on ORU changeout to ascertain whether there are other, more appropriate tasks on which the FTS should be focused. Another area for study is inspection tasks--in some cases, inspection tasks require 90% of crew task time versus 10% for actually performing a repair (Reference 12). These differences will also impact any pre-FEL flight demonstrations.

D. ECONOMIC ANALYSIS

The cost estimates of the FTS Reference System are uncertain due to large uncertainties in a number of areas. As mentioned above, no large integrated telerobotic system such as the FTS has been built yet for space applications. The RMS is the closest comparison, but the scope of its technology integration issues is much smaller than that for the FTS. Therefore, the cost factor (20%) used to estimate the systems integration cost may be too low. While it would be easy to vary this value, there is little information on which to base another value at this time. This is also true for the AI planner, arms, and software costs.

One of the big areas of uncertainty is software cost. The cost of software is a function of its size and complexity. Uncertainty stems from the validation and evaluation of systems in the context of unexpected events and their uncertainties. For example, in robot control, 90% of the computer code is written to deal only with the unplanned events. The added uncertainties of operating in the space environment complicate the software systems engineering process.

Many of the estimates for the FTS component costs were educated guesses on the part of cost analysts at NASA/JPL and within the specific industries. The range estimates help to bound the uncertainties, but they by no means define the true uncertainties.

E. OPEN TOPICS AND RECOMMENDATIONS FOR FUTURE WORK

As described in the preceding sections, there are numerous areas for further study.

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 any redefinition and reestimation of EVA/IVA times. If the same FTS Reference System was used, the entire study could be updated. If a different FTS configuration was used, a new cost estimate would be required, as well as new EVA/IVA estimates for the 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 Monte Carlo simulation to generate a cumulative probability distribution for net savings or O&M cost. Then, as assumptions regarding elements of the problem (e.g., 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 because of 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.

A related allocation problem that requires further understanding is the allocation of work among and between multiple robots (FTS, RMS, MSC, SURFAC, etc.) 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.

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.

F. CONCLUSIONS

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.

(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) 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 the 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, unloading tasks.

   The potential exists for transferring some on-orbit tasks to ground operations, so long as appropriate technology and human engineering constraints are considered.

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

(11) Improved and more detailed data are needed on task descriptions, timelines, manifests, etc., updated quarterly or semiannually and available, for example, via telemail.

(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 which 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 (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. The 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. ATAC and SSP work package contractors have been remarkably consistent in their conclusions regarding which tasks are 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 the use of an FTS, on the grounds that on-orbit assembly by telerobotic devices has 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. This maximizing of the 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.

SECTION X

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APPENDIX A

GLOSSARY AND ACRONYMS

GLOSSARY OF TERMS

Assembly Phase - The CETF assembly period from FEL to IOC (Flights 1-30).

Assembly Phase EVA Tasks - The set of all tasks located outside of pressurized volume during the period from FEL to IOC that nominally are performed by EVA crew. Both STS- and SS-based crew tasks are included.

Critical Evaluation Task Force (CETF) - The Critical Review Team with members from all areas of space station development that met during August 1986 to reexamine the entire Space Station design. The result of the activity was a reconfigurement station concept and a revised set of assumptions. (Note: The CETF design was later revised into a Phase I and Phase II configuration.)

EVA+FTS Case - The CETF assembly phase with an FTS Reference System to displace EVA time.

EVA-Only Case - The CETF assembly phase with no FTS to perform EVA tasks.

First Element Launch (FEL) - The first Station-assembly STS flight.

FTS Reference System - An FTS configuration synthesized for the study by matching FEL technologies with required assembly-phase functions.

Initial Operational Configuration (IOC) - Space Station assembly completed at the end of Flight 30.

KDSI - Thousands of delivered source-coded instructions. Used for estimating software development costs.

Maintenance - Tasks performed on core Station hardware/software.

Net Savings (NS) - The difference between the savings in operations and maintenance costs due to the FTS minus the FTS investment cost. If this value is positive, the FTS is cost-effective.

Operational Constraints - These constraints are on actual EVA/IVA operations regarding time limitations, physical envelopes, and proximity operations.

Operationally Feasible Task Set - The subset of assembly-phase EVA tasks that are not only technically capable of being performed by an FTS, but also meet the constraints of crew EVA and IVA budgets and proximity operations rules. For example, a technically feasible task on flight 1 that an FTS would perform in 50 IVA hours would not be operationally feasible because there are only 30 hours of IVA available.

Operations and Maintenance (O&M) Cost - The cost of operations and maintenance during the assembly phase. The O&M cost is fundamental to the net savings equation because the focus is on the O&M cost savings. All elements of the initial cost are the same in both the EVA-Only and EVA+FTS case and thus subtract to zero.

Performance (Time) Ratio (PR) - The ratio of the time to perform a task using a machine versus the time to perform the same task using a human. PR = IVA (machine)/EVA (human). A PR of 1.0 indicates a task can be performed in the same amount of time by man or machine.

Proximity Operations Rules - Restrictions placed on crew and equipment (FTS) (physical envelopes) during on-orbit operations.

Servicing - Tasks performed on user or customer hardware/software such as payloads and satellites.

Task - An activity to be performed in the space environment.

Technically Feasible Task Set - The subset of assembly-phase EVA tasks that are technically capable of being performed by an FTS based on technologies forecast to be available for an operational system by FEL.

ACRONYMS

A&R	Automation and Robotics
ACA	Attitude Control Assembly
AI	Artificial Intelligence
ATAC	Advanced Technology Advisory Committee
CER	Cost Estimating Relationships
CERV	Crew Emergency Rescue Vehicle
CETR	Critical Evaluation Task Force
CI	Capital Investment
CMG	Control Moment Gyro
DC	Direct Current
DDT&E	Design, Development, Testing, and Engineering
DMS	Data Management System
ELV	Expendable Launch Vehicle
EMU	Extravehicular Mobility Unit

ESA	European Space Agency
EVA	Extra-Vehicular Activity
FLT	Flight Hardware Unit
FSE	Flight Support Equipment
FTS	Flight Telerobotic Servicer
GN&C	Guidance, Navigation, and Control
HAB	Habitation (module)
IOC	Initial Operating Capacity
IVA	Intravehicular activity
JEM	Japanese Module
JSC	Johnson Space Center
McDAC	McDonnell Douglas Astronautics Co.
MRDB	Mission Requirements Data Base
MRDB*	JPL's modification of the MRDB
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Centre
MSS	Mobile Servicing System
MTBF	Mean Time Between Failure
NS	Net Savings
O&M	Operations and Maintenance
OMB	Office of Management and Budget
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replaceable Unit
PDRD	Program Design and Requirements Document
PMC	Permanently Manned Configuration
PMDS	Power Management and Distribution System
PV	Photovoltaic

R&R	Repair and Replace
RCS	Reaction Control System
RFP	Request for Proposal
RMS	Remote Manipulator System
SD	Solar Dynamic (power system)
SF	Servicing Facility
SIA	Service Interface Adaptor
SPDM	Special-Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System (same as RMS)
SS	Space Station
SSE	Space Support Equipment
SSP	Space Station Program
STS	Space Transportation System
SURFAC	Satellite Servicing Facility
TCS	Thermal Control System
THURIS	The Human Role in Space

APPENDIX B

FTS HARDWARE/SOFTWARE COMPONENTS

Table B-1. FTS Hardware/Software Component Breakdown

Component	Quantity
FTS Hardware-	
Manipulator arms (7 DOF)	4 (see Fig. 3-2)
FTS main shell or housing	1
- contains radiation/SEU shielding	
- contains adaptors for manipulator attachment	4
- contains adaptors for power interface	3
- contains self-aligning adaptor for RMS	1
- contains adaptor for antennae (telemetry)	1
- contains adaptors for peripheral cameras	2
- contains adaptors for proximity sensors	4-6
- contains adaptor for main lighitng fixture	1
- contains temp. control medium (heat fins/pipes)	2 sets
Dedicated arm/end-effector servo microprocessors	4 (+4 backup)
Dedicated camera servo microprocessors	4 (+4 backup)
Dedicated lighting servo microprocessors	2 (+2 backup)
Dedicated temp. control microprocessors	2 (+2 backup)
Dedicated power distribution/monitoring processor	1 (+1 backup)
NiH_2 storage batteries (4 hrs. of service)	6-10 kW total
Power conditioning (switching, routing, etc.)	1 set
Servos/actuators	
- FTS base pivot	1
- Manipulators (included in complete arm assembly)	-
- Temperature control	2 sets
- Camera control (wrist, lower arm, and periph.)	5 (+5 backup)
- Lighting control (lower arm and housing)	2 (+2 backup)
Sensors/encoders	
- Proximity (end-effec., wrist, elbow housing)	16-18 (+18)
- Joint position/orientation (included in arm assy)	-
- Main housing orientation	1 (+1 backup)
- Position (peripheral cameras, main lighting)	6 (+6 backup)
- Velocity (included in arm assembly)	-
- Lighting level (lower arm, main housing)	6 (+6 backup)
- Temperature (main housing internal)	4 (+4 backup)
- Power level	1 (+1 backup)
- Force/torque (at each end-effector)	2 (+2 backup)
Movable FTS support platform/adaptor	1 or 2
- with power adaptors built-in	
- with expandable adaptors to fit in EVA handholds	
I/O Telemetry	
- Antennae	1
- Receiver/transmitter	2
- Signal conditioning	2
- Signal distribution circuitry (integrated circuit)	-
Short term archival memory (ROM)	1 for each MP

Table B-1. FTS Hardware/Software Component Breakdown (continued)

Component	Quantity
End-effectors (task-tailored, nondexterous)	assume 4 sets
- Basic grasping	
- Inspecting/testing	
Tools (tailored)	assume 4 sets
- Latch removal	
- Bolt removal	
- Screw removal	
- Inspection probe	
- Object accommodation (capturing/controlling)	
FTS workstation hardware-monitors	5 (+2 backup)
- Left peripheral camera	
- Right peripheral camera	
- Stereo	
- Left/right wrist	
- Data readout (force, torque, position, etc.)	
Video switcher	1 (+1 backup)
Communication	5 systems
- FTS telemetry (200-meter range)	
- Inter-workstation voice	
- Ground voice	
- Workstation-to-EVA voice	
- FTS automated voice control	
Keyboard entry system	2 (+2 backup)
Force reflecting handcontrollers (left/right)	2 sets
Dedicated handcontroller processors	4 (+4 backup)
Workstation executive processor (integrating)	2
Shared memory interface for teleop handoff	1 (+1 backup)
Voice input (helmet/head mounted)	2
System executive processor (integrating)	1 (+1 backup)
AI planner processor (integrating)	1 (+1 backup)
Run-time control processor (integrating)	1 (+1 backup)
Manipulator control processor (integrating)	1 (+1 backup)
Sensing and perception processor (integrating)	1 (+1 backup)
Workstation hardware mount structure	1
FTS Software Delineation/Complexity (KDSI range)	see Reference 21
FTS dedicated servo control processors	
- Manipulators/simple (25 KDSI)	
- Cameras/simple (2 KDSI)	
- Lighting/simple (2 KDSI)	
- Temperature control/simple (5-10 KDSI)	
- Power control/simple (5-10 KDSI)	
- Housing control/simple (2 KDSI)	
- Memory (1 MB)	

Table B-1. FTS Hardware/Software Component Breakdown (continued)

Component	Quantity
FTS workstation dedicated/integrating processors	
- Handcontrollers/medium (50 KDSI)	
- Workstation exec/large (150 KDSI)	
- System exec/large (150 KDSI)	
- AI planner/very large (250 KDSI)	
- Run-time control/very large (300 KDSI)	
- Manipulator control/large (150 KDSI)	
- Sensing and perception/large (200 KDSI)	
- Memory (10 MB)	

Note: The above software complexity ratings and KDSI (thousands of lines of delivered source instructions) were extrapolated based on examining the present JPL testbed breadboard software designs, and on considering other design factors such as built-in error flags, error recovery, and task growth which might tend to increase the breadboard KDSI level; the above ratings do not reflect the maximum software complexity that might be required for post IOC FTS functions.

APPENDIX C

MODIFIED ASSEMBLY SEQUENCE TASK ESTIMATES FOR EVA+FTS CASE

Table C-1. Performance Time Ratios (IVA/EVA) for Assembly Phase Tasks

	Task Activity	IVA/EVA
1.	Adjust/align elements (minimum)	2.2
2.	Connect/disconnect electrical interface	5.75
3.	Connect/disconnect fluid interface	2.1
4.	Deploy/retract appendage (solar array)	0.75
5.	Detect change in state/condition	0.62
6.	Gather/replace tools/support equipment	2.2
7.	Inspect/observe	1.0
8.	Position module (e.g., PV module, RCS module)	2.1
9.	Precision manipulation of objects	N/A
10.	Problem solving/data analysis	0.9
11.	Release/secure mechanical interface	1.4
12.	Remove module	3.0
13.	Remove/replace cover (hard or flexible)	2.0
14.	Replace/clean surface coatings	1.0
15.	Replenish materials	1.0
16.	Transport load	1 for large object 5 for small object

Note: Due to a lack of operationally feasible tasks that require precision manipulation that <u>is</u> anticipated for a near-term FTS, no estimate of this value was made.

Table C-2. Modified CETF Reference Assembly Sequences by Flight (Source: Reference 7)

ASSEMBLY	PR	EVA-Only		EVA+FTS	
		EVA_o	IVA_o	EVA_F	IVA_F
Flight #1					
Remove pallet and place in cradle	1-3	.72	.36	0	.36-1.1
Erect workstation	1-2.2	.3-.7	.16-.35	0	.7
Deploy truss SSE/construction matls.	.75-2.2	3.5	1.75	0	1.31-3.85
Assemble 10 truss bays	1-2.2	7.9	3.95	0	3.95-8.69
Install utility trays	1-6	7.9	3.95	7.9	3.95
Make electrical connections	1-6	3.6	1.8	3.6	1.8
Security truss FSE to truss section	1.4-2.2	1.2	0.6	1.2	0.6
Grasp alpha joint and position	1-2.2	.27-.6	.14-.3	0	0.6
Attach alpha joint	1-1.4	2.4	1.2	2.4	1.2
Grasp PVB module/radiator & position	2.2	.27	.14	0	.6
Attach PV module/radiator	1.4-2.2	3.6	1.8	3.6	1.8
Grasp RCS module/antenna & position	2.2	.27	.14	0	.6
Attach RCS module/antenna	1.4-2.2	1.2	.6	1.2	.6
Grasp stinger/ACA-GN&C unit; position	1.4	.43	.21	0	.6
Attach ACA-GN&C unit	2.1-2.2	1.2	.6	1.2	.6
Grasp aft node and position	1.4	.43	.21	0	.6
Attach aft node	2.2	2.4	1.2	2.4	1.2

Detail (grapple, maneuver, position for attachment, attach/install):

- Alpha joint
- RCS pods
- PV solar array and gimbal
    - Attach umbilical for deployment
    - Deploy solar array
    - PV equipment section
    - Batteries
    - PMDS
    - Thermal control
- PV radiator fins
- ACA
- Node #1
- Utility tray
- S-band antenna
- Stinger truss/resistojets
- Truss workstation
- Truss member boxes
- Truss structure struts-connect
- RCS tank farm
- DC power utility distribution center
- Load management system
- Electrolysis unit

	PR	EVA_o	IVA_o	EVA_F	IVA_F
Subtotal		37.2-37.9	18.8-19.2	23.5	21.1-29.1

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only		EVA+FTS	
		EVA_o	IVA_o	EVA_F	IVA_F
Flight #2					
Remove pallet and place in cradle	1-3	.72	.36	0	.4-1.1
Erect workstation	1-2.2	.3-.7	.16-.35	0	.7
Deploy truss SSE/construction matls.	.75-2.2	3.5	1.75	0	1.31-3.85
Assemble 10 truss bays	1-2.2	7.9	3.95	0	3.95-8.69
Install utility trays	1-6	7.9	3.95	7.9	3.95
Make electrical connections	1-6	3.6	1.8	3.6	1.8
Security truss FSE to truss section	1.4-2.2	1.2	0.6	1.2	0.6
Grasp alpha joint and position	1-2.2	.27-.6	.14-.3	0	0.6
Attach alpha joint	1-1.4	2.4	1.2	2.4	1.2
Grasp PVB module/radiator & position	2.2	.27	.14	0	.6
Attach PV module/radiator	1.4-2.2	3.6	1.8	3.6	1.8
Grasp RCS module/antenna & position	2.2	.27	.14	0	.6
Attach RCS module/antenna	1.4-2.2	1.2	.6	1.2	.6
Grasp stinger/ACA-GN&C unit; position	1.4	.43	.21	0	.6
Attach ACA-GN&C unit	2.1-2.2	1.2	.6	1.2	.6
Grasp aft node and position	1.4	.43	.21	0	.6
Attach aft node	2.2	2.4	1.2	2.4	1.2

Detail (grapple, maneuver, position for attachment, attach/install):
- Alpha joint
- RCS pallet
- PV solar array and gimbal
  - Attach umbilical for deployment
  - Deploy solar array
- PV equipment section
  - Batteries
  - PMDS
  - Thermal control
- PV radiator fins
- GN&C pallet
- Node #2
- Utility tray
- CMG pallet
- Truss member boxes
- Truss structure struts-connect
- UDCs
- Docking port
- Reattach FL 1 to orbiter

Subtotal		37.2-37.9	18.8-19.2	23.5	21.1-29.1

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA_o	EVA-Only IVA_o	EVA+FTS EVA_F	EVA+FTS IVA_F
Flight #3					
Summary:					
Install two TCS radiators					
Remove pallet and place in cradle	1-3	.72	.36	0	.36-1.08
Erect workstation	1-1.2	.32-.7	.16-.35	0	.7
Deploy SSE/construction materials	.75-2.2	2.9	1.45	0	1.1-3.2
Grasp radiators and position	2.2	.27	.14	0	.6
Attach two radiators	1.5 -2.2	4.8	2.4	4.8	2.4
SSRMS/docking adaptors					
Grasp docking adaptors and position	2.2	.27	.14	0	.6
Attach docking adaptors	1.4-2.2	1.2	.6	1.2	.6
Airlock					
Grasp airlock and position	2.2	.27	.14	0	.6
Attach airlock	1.4-2.2	1.2	.6	1.2	.6
Make electrical connections	1-6	.1	.05	.1	.05
Antenna					
Grasp antenna and position	2.2	.27	.14	0	.6
Attach antenna	1.4-2.2	1.2	.6	1.2	.6
Install RCS tankage					
Grasp RCS tank and position	2.2	.27	.14	0	.6
Install RCS tankage	1.4-2.2	1.2	.6	1.2	.6
Grasp SSRMS and position	2.2	.27	.14	0	.6
Attach SSRMS	1.4-2.2	3.2	1.6	3.2	1.6
Detail:					
Reattach FL 2 orbiter					
MSC phase 1					
Main radiators					
Airlock #1					
Ku-band antenna					
RCS tankage					
Payloads					
Total Without Payloads		18.8-19.1	9.41-9.60	13.2	12.36-15.18
Total		24.8-25.1	12.41-12.60	19.2	15.35-18.18

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA$_O$	EVA-Only IVA$_O$	EVA+FTS EVA$_F$	EVA+FTS IVA$_F$
Flight #4					
Summary:					
Install airlock					
Remove pallet and place in cradle	1-3	.72	.36	0	.36-1.08
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy truss SSE/construc. matls.	.75-2.2	2.9	1.45	0	1.08-3.19
Grasp airlock and position	2.2	.27	.14	0	.6
Attach airlock	1.4-2.2	1.2	.6	1.2	.6
Install utility trays	1-6	.7	.35	.7	.35
Make electrical connections	1-6	.4	.2	.4	.2
Bolt down airlock from inside	1.4-2.2	10.7	5.35	10.7	5.35
Grasp CERV and position	2.2	.27	.14	0	.6
Install CERV	1.4-2.2	2.4	1.2	2.4	1.2
Detail:					
Reattach SS to orbiter					
SSRMS					
Airlock #2					
RCS tankage					
Main radiators					
Payloads/SIA					
Berthing/CMGs					
Fluid module/NO kit					
Subtotal		19.88-20.26	9.95-10.14	15.4	11.04 13.87

Flight #5

POLAR PLATFORM LAUNCH; NO SS INVOLVEMENT.

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA_o	EVA-Only IVA_o	EVA+FTS EVA_F	EVA+FTS IVA_F
Flight #6					
Summary:					
U.S. Lab Module					
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy special grapple/ berthing fixtures	.75-2.2	.32-.93	.16-.47	0	.7
Grasp lab module position	1.4-2.2	.27-.43	.14-.21	0	.6
-IVA teleops. support provided for coarse/fine positioning:					
Attach lab module	1-6	4.8	2.4	4.8	2.4
Bolt down lab module from inside	1-6	10.6	5.3	10.6	5.3
Detail:					
Reattach SS to orbiter					
Lab module					
Utilities connect to modules					
Attach hardware					
Subtotal		16.31-17.46	8.16-8.73	15.4	9.7
Flight #7					
Summary:					
U.S. Lab Module outfitting					
Remove lab module outfitting pallet	1-3	.72	.36	0	.36-1.08
Transfer/install 13 racks of user equipment	2.2-3	7.2	3.6	7.2	3.6
Detail:					
Reattach SS to orbiter					
Module off-loads					
Subtotal		7.92	3.96	7.2	3.96-4.68

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA_o	EVA-Only IVA_o	EVA+FTS EVA_F	EVA+FTS IVA_F
Flight #8					
Summary:					
U.S. Hab. Module					
Erect workstation	1-2.2	.7	.35	.7	.35
Deploy special grapple/ berthing fixtures	.75-2.2	.27-.8	.14-.4	0	.6
Grasp hab. module and position	1.4-2.2	.27-.43	.14-.21	0	.6
Attach hab. module	1-6	4.8	2.4	4.8	2.4
Bolt down hab. module from inside	1.4-2.2	16.6	8.3	16.6	8.3
Detail:					
Reattach SS to orbiter					
Hab. module					
Utilities connect to module					
Attach hardware + SSRMS					
Truss bay (optional)					
Subtotal		22.64-22.33	11.33-11.66	22.1	12.25
Flight #9					
POLAR PLATFORM LAUNCH; NO SS INVOLVEMENT					

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only		EVA+FTS	
		EVA_o	IVA_o	EVA_F	IVA_F
Flight #10					
Summary:					
Install two nodes					
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy special grapple/ berthing fixtures	.75-2.2	.27-.8	.14-.4	0	.6
Grasp node #1 and position	2.2	.27	.14	0	.6
Install node #1	1.4-2.2	2.4	1.2	2.4	1.2
Grasp node #2 and position	2.2	.27	.14	0	.6
Install node #2	1.4-2.2	2.4	1.2	2.4	1.2
Bolt down node(s) from inside		TBD			
Install cupola					
Grasp cupola and position	2.2	.27	.14	0	.6
Install cupola	1.4-2.2	2.4	1.2	2.4	1.2
Bolt down cupola from inside	1.4-2.2	3-6	1.5-3	3-6	1.5-3
Install utility trays	1-6	.7	.35	.7	.35
Make electrical connections	1-6	.4	.2	.4	.2
Detail:					
Reattach SS to orbiter					
Node #3					
Node #4					
Cupola #1					
Cupola #2					
Phase 1 MMD					
Subtotal		12.7-16.6	6.4-8.3	11.3-14.3	8.8-10.3

Flight #11 - Permanently Manned Configuration (PMC)

ASSEMBLY

DELIVER FIRST STATION CREW OF 4 WITH LOGISTICS. NO ASSEMBLY. FROM THIS FLIGHT ON, EVA WILL BE PRIMARILY STATION-BASED.

NOTE: LOGISTICS FLIGHT COULD MEAN TRANSFER OF SUPPLIES FROM STS TO SS BY IVA OR AUTONOMOUSLY

Detail:

Reattach SS to orbiter

Log module

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA_O	EVA-Only IVA_O	EVA+FTS EVA_F	EVA+FTS IVA_F
Flight #12					
Summary:					
Assemble, deploy truss flight					
Support equipment					
Remove pallet and place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy truss SSE/const. matls.	.75-2.2	3.5	1.75	0	1.31-3.85
Assemble 10 truss bays	1-2.2	7.9	3.95	0	3.95-8.7
Install utility trays (two trays/bay; util. preinstalled in trays; trays are self-aligning and one bay in length)	1-6	7.9	3.95	7.9	3.95
Make electrical connections	1-6	3.6	1.8	3.6	1.8
Secure truss FSE to assembled truss section	1.4-2.2	1.2	.6	1.2	.6
Install two (2) solar dynamic power modules					
Grasp solar dynamics module #1 and position	2.1	.29	.14	0	.6
Attach module #1	1.4-2.2	26.4	13.2	26.4	13.2
Attach utility trays	1-6	1.7	.85	1.7	.85
Make electric and fluid line connections	1-6	.7	.35	.7	.35
Grasp solar dynamics module #2 and position	2.1	.29	.14	0	.6
Attach module #2	1.4-2.2	26.4	13.2	26.4	13.2
Attach utility trays	1-6	1.7	.85	1.7	.85
Make electric and fluid line connections	1-6	.7	.35	.7	.35
Deliver SS EMUs					
Grasp EMUs	2.2	.5-1.5	.3-.8	.5-1.5	.3-.8
Transfer from STS bay to TBD	1.4-2.2	.5-1	.3-.5	.5-1	.3-.5
Detail:					
Reattach SS to orbiter					
Port and starboard solar dynamic beta gimbal					
Port and starboard solar dynamic PCU/heat receiver and radiator					
Port outboard truss					
Starboard outboard truss					
Utilities					
MSC POA					
Subtotal		82.8-83.7	41.9-42.3	70.8-71.3	43.0-51.2

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only		EVA+FTS	
		EVA_O	IVA_O	EVA_F	IVA_F
Flight #13					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					
Flight #14					
Summary:					
Install JEM					
Remove JEM pallet & place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy special grapple/berthing fixtures	.75-2.2	.27-.8	.14-.4	0	.6
Grasp JEM module and position	2.2	.27	.14	0	.6
Attach JEM module	1.4-2.2	4.8	2.4	4.8	2.4
Bolt down JEM module	1.4-2.2	3-6	1.5-3	3-6	1.5-3
Install JEM exposed facility No. 1					
Grasp JEM exposed facility No. 1 and position	2.2	.27	.14	0	.6
Attach JEM exposed facility No. 1	1.4-2.2	3.6	1.8	3.6	1.8
Bolt down JEM exposed facility No. 1	1.4-2.2	3-6	1.5-3	3-6	1.5-3
Make electrical connections	1-6	.4	.2	.4	.2
Detail:					
Reattached SS to orbiter JEM module and exposed facility					
Subtotal		13.6-17.5	6.8-8.8	11.8-14.8	8.8-11.0
Flight #15					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA$_O$	EVA-Only IVA$_O$	EVA+FTS EVA$_F$	EVA+FTS IVA$_F$
Flight #16					
Summary:					
Install ESA module after solar array					
Remove pallet and place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy special grapple/berthing fixtures	.75-2.2	.27-.8	.14-.4	0	.6
Grasp lab module and position	2.2	.27	.14	0	.6
Attach ESA module	1.4-2.2	4.8	2.4	4.8	2.4
Bolt down ESA module	1.4-2.2	3-6	1.5-3	3-6	1.5-3
Deliver two additional crew					
Detail:					
Reattach SS to orbiter					
ESA module					
Subtotal		9.4-13.3	4.7-6.6	7.8-10.8	7.2-8.4
Flight #17					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					
Flight #18					
Summary:					
Install servicing facility					
Remove pallet and place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.37-.7	.16-.35	0	.7
Deploy SF components	.75-2.2	3.5	1.75	0	1.31-3.85
Assemble/utilities	1-6	39.7	19.85	39.7	19.85
Install TBD additional attached payloads					
Detail:					
Reattach SS to orbiter					
SPDM					
Service facility phase 1					
Payloads/SIA?					
Subtotal		44.22-44.6	22.11-22.3	39.7	22.21-25.45

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA_o	EVA-Only IVA_o	EVA+FTS EVA_F	EVA+FTS IVA_F
Flight #19					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					
Flight #20					
Summary:					
Outfit servicing facility					
Remove SF pallet & place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Unload outfitting components	1.4-2.2	1.59-2.5	.80-1.25	0	3.5
Outfit SF	1.4-2.2	39.7	19.85	39.7	19.85
Deploy special grapple/berthing fixtures	.75-2.2	.32-.93	.16-.47	0	.7
Grapple log module and position	2.2	.27	.14	0	.6
Attach log module	1.4-2.2	4.8	2.4	4.8	2.4
Bolt down module from inside	1.4-2.2	306	1.5-3	3-6	1.5-3
Detail:					
Reattach SS to orbiter					
Service facility phase 2					
Module off-load					
Subtotal		50.7-55.6	25.4-27.8	47.5-50.5	29.6-31.8
Flight #21					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only		EVA+FTS	
		EVA_O	IVA_O	EVA_F	IVA_F
Flight #22					
Summary:					
Install JEM exposed facility No. 2					
Remove JEM pallet & place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy special grapple/berthing fixtures	.75-2.2	.32-.93	.16-.47	0	.7
Grasp JEM facility and position	2.2	.27	.14	0	.6
Attach JEM facility No. 2	1-6	3.6	1.8	3.6	1.8
Install European logistics module					
Grasp logistics module and position	2.2	.27	.14	0	.6
Install log module	1-6	4.8	2.4	4.8	2.4
Bolt down European logistics module	1.4-2.2	3-6	1.5-3	3-6	1.5-3
Detail:					
Reattach SS to orbiter					
JEM log module					
JEM exposed facility #2					
Subtotal		13.3-17.3	6.7-8.7	11.4-14.4	8.6-10.9
Flight #23					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA_o	EVA-Only IVA_o	EVA+FTS EVA_F	EVA+FTS IVA_F
Flight #24					
Summary:					
Install and mate MSC transporter					
Remove MSC pallet and place in cradle	1-3	.7	.35	0	.35-1.05
Erect work station	1-2.2	.32-.7	.16-.35	0	.7
Deploy SSE/materials	.75-2.2	3.5	1.75	0	1.31-3.85
Grasp MSC transporter/position	1-5	.12-.6	.1-.3	0	.6
Install MSC transporter	1-6	5.8	2.9	5.8	2.9
Grasp manipulator/position	2.2	.27	.14	0	.6
Install MSC	1-6	2.6	1.3	2.6	1.3
Detail:					
Reattach SS to orbiter					
MSC phase 2/transporter					
Subtotal		13.31-14.17	6.7-7.09	8.4	7.76-11.0
Flight #25					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					
Flight #26					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					
Flight #27					
NO ASSEMBLY EVA; LOGISTICS FLIGHT					

Table C-2. Modified CETF Reference Assembly Sequences by Flight (continued)

ASSEMBLY	PR	EVA-Only EVA$_o$	IVA$_o$	EVA+FTS EVA$_F$	IVA$_F$
Flight #28					
Summary:					
Assemble, deploy truss flight support equipment					
Remove pallet and place in cradle	1-3	.7	.35	0	.35-1.05
Erect workstation	1-2.2	.32-.7	.16-.35	0	.7
Deploy SSE/construction materials	.75-2.2	3.5	1.75	0	1.31-3.85
Erect 56 truss bays	1-2.2	112	56	0	56-123.2
Install utility trays	1-6	39.2	19.6	39.2	19.6
Make electrical connections	1-6	16.8	8.4	16.8	8.4
Secure FSE to assembled truss sect.	1.4-2.2	1.2	.6	1.2	.6
Detail:					
Reattach SS to orbiter					
Upper port keel					
Lower port keel					
Upper starboard keel					
Lower starboard keel					
Relocate RCS module					
Install RCS module					
Subtotal		173.7-174	86.86-	57.2	86.96-157.4

Flight #29

NO ASSEMBLY EVA; LOGISTICS FLIGHT

Flight #30

Summary:

Install attached payloads (assumes usage of MRS and MSC) NO ASSEMBLY EVA

Detail:
- Reattach SS to orbiter
- Service facility phase 3
- Payload/SIA (see above)
- Phase 2 MMD

APPENDIX D

SUPPORTING DATA FOR ATTACHED PAYLOAD CALCULATIONS

Table D-1. Attached-Payload Setup Tasks

		EVA-Only Case		EVA+FTS Case	
		EVA_O	IVA_O	EVA_F	EVA_F
Flight #3 (year 1)					
Install attached payloads					
Grasp payload interface adaptor	#1	.2		.1	
Attach payload interface adaptor	#1	.2		.1	
Grasp system interface adaptor	#1	.2		.2	
Attach system interface adaptor	#1	.2		.2	
Grasp attached payload	#1	.3		.2	
Install attached payload	#1	1.4	4.2	1.2	4.2
Grasp payload interface adaptor	#2	.2		.1	
Attach payload interface adaptor	#2	.2		.1	
Grasp system interface adaptor	#2	.2		.2	
Attach system interface adaptor	#2	.2		.2	
Grasp attached payload	#2	.3		.2	
Install attached payload	#2	1.4	4.2	1.2	4.2
Grasp payload interface adaptor	#3	.2		.1	
Attach payload interface adaptor	#3	.2		.1	
Grasp system interface adaptor	#3	.2		.2	
Attach system interface adaptor	#3	.2		.2	
Grasp attached payload	#3	.3		.2	
Install attached payload	#3	1.4	4.2	1.2	4.2
Total:		7.5	12.6	6.0	12.6

Table D-1. Attached Payload Setup Tasks (continued)

	EVA-Only Case		EVA+FTS Case	
	EVA_O	IVA_O	EVA_F	EVA_F
Flight #18 (year 2)				
Install attached payloads				
Grasp payload interface adaptor #1	.7		.5	
Attach payload interface adaptor #1	1.5		1.0	
Grasp system interface adaptor #1	.7		.5	
Attach system interface adaptor #1	1.5		1.0	
Grasp attached payload #1	1.0		.8	
Install attached payload #1	5.4	25.3	4.8	25.3
Grasp payload interface adaptor #2	.7		.5	
Attach payload interface adaptor #2	1.5		1.0	
Grasp system interface adaptor #2	.7		.5	
Attach system interface adaptor #2	1.5		1.0	
Grasp attached payload #2	1.0		.8	
Install attached payload #2	5.4	25.3	4.8	25.3
Grasp payload interface adaptor #3	.7		.5	
Attach payload interface adaptor #3	1.5		1.0	
Grasp system interface adaptor #3	.7		.5	
Attach system interface adaptor #3	1.5		1.0	
Grasp attached payload #3	1.0		.8	
Install attached payload #3	5.4	25.3	4.8	25.3
Grasp payload interface adaptor #4	.7		.5	
Attach payload interface adaptor #4	1.5		1.0	
Grasp system interface adaptor #4	.7		.5	
Attach system interface adaptor #4	1.5		1.0	
Grasp attached payload #4	1.0		.8	
Install attached payload #4	5.4	25.3	4.8	25.3
Grasp payload interface adaptor #5	.7		.5	
Attach payload interface adaptor #5	1.5		1.0	
Grasp system interface adaptor #5	.7		.5	
Attach system interface adaptor #5	1.5		1.0	
Grasp attached payload #5	1.0		.8	
Install attached payload #5	5.4	25.3	4.8	25.3
Total:	54.0	126.5	43.0	126.5

Table D-1. Attached Payload Setup Tasks (continued)

		EVA-Only Case		EVA+FTS Case	
		EVA_o	IVA_o	EVA_F	EVA_F
Flight #30 (year 4-5)					
Install attached payloads (assumes usage of MRS and MSC)					
Grasp payload interface adaptor	#1	0.0		1.0	
Attach payload interface adaptor	#1	0.0		1.0	
Grasp system interface adaptor	#1	0.0		.8	
Attach system interface adaptor	#1	0.0		1.0	
Grasp attached payload	#1	0.0		.8	
Install attached payload	#1	0.0	7.3	4.8	7.3
Grasp payload interface adaptor	#2	0.0		1.0	
Attach payload interface adaptor	#2	0.0		1.0	
Grasp system interface adaptor	#2	0.0		.8	
Attach system interface adaptor	#2	0.0		1.0	
Grasp attached payload	#2	0.0		.8	
Install attached payload	#2	0.0	7.3	4.8	7.3
Grasp payload interface adaptor	#3	0.0		1.0	
Attach payload interface adaptor	#3	0.0		1.0	
Grasp system interface adaptor	#3	0.0		.8	
Attach system interface adaptor	#3	0.0		1.0	
Grasp attached payload	#3	0.0		.8	
Install attached payload	#3	0.0	7.3	4.8	7.3
Grasp payload interface adaptor	#4	0.0		1.0	
Attach payload interface adaptor	#4	0.0		1.0	
Grasp system interface adaptor	#4	0.0		.8	
Attach system interface adaptor	#4	0.0		1.0	
Grasp attached payload	#4	0.0		.8	
Install attached payload	#4	0.0	7.3	4.8	7.3
Grasp payload interface adaptor	#5	0.0		1.0	
Attach payload interface adaptor	#5	0.0		1.0	
Grasp system interface adaptor	#5	0.0		.8	
Attach system interface adaptor	#5	0.0		1.0	
Grasp attached payload	#5	0.0		.8	
Install attached payload	#5	0.0	7.3	4.8	7.3
Total:		0.0	36.5	6.0	12.6

Table D-2. Attached-Payload Setup EVA/IVA Time Derivation

Flight	EVA-Only Case		EVA+FTS Case	
	EVA_O	IVA_O	EVA_F	IVA_F
<u>Flight 3</u>				
Raw data	3.0-7.5[a]	1.5-12.6[b]	1.3-6.0	1.2-3.0[a]
Performance ratio form	EVA_R = 2.4-6.0	IVA_{FS} = 0.0	EVA_A = 0.6-1.5	
Final Values:	3.0-7.5	1.5- 3.8	2.4-6.0	1.6-6.8
<u>Flight 18</u>				
Raw data	54.0[c]	27.0-126.5[a]	43.2	21.6-115.1[a]
Performance ratio form	EVA_R = 43.2	IVA_{FS} = 0.0	EVA_A = 10.8	
Final Values:	54.0	27.0	43.2	29.2-48.6
<u>Flight 30</u>				
Raw data	0.0[c]	36.5[c]	0.0[d]	36.5
Performance ratio form	EVA_R = 0.0	IVA_{FS} = 0.0	EVA_A = 0.0	
Final Values:	0.0	36.5	0.0	36.5

a Source: For x-y, 1st value, x, from CETF, 2nd value, y, from modified MRDB (Reference 19).

b Source: 1st value from CETF/2.0, 2nd value from modified MRDB (Reference 19).

c Source: Reference 19.

d Assumes low EVA servicing requirements and emphasis on use of RMS, MSC, and FTS after Flight 24.

Table D-3. Attached-Payload Servicing Raw Data (work-hours per week)

Flight	EVA-Only Case		EVA+FTS Case	
	EVA_O	IVA_O	EVA_F	IVA_F
3	0.0	0.0	0.0	0.0
18	1.4[a]	1.1[a]	1.1[b]	0.8[b]
30	1.0[a]	4.4[a]	0.8[b]	0.0[c]

[a] Source: modified MRDB (Reference 19).

[b] Source: modified MRDB (Reference 19) x 0.8.

[c] Assumes low EVA servicing requirements and emphasis on use of RMS, MSC, and FTS after Flight 24.

Table D-4. Attached-Payloads Servicing Data by Flight (service work-hours per week)[a]

Flight		EVA-Only		EVA+FTS (EVA * 0.8)	
		EVA_O	IVA_O	EVA_F	IVA_F
1-2		0	0	0	0
3		2.4-3.6	4-6	1.9-2.9	3.2-4.8
4		6.4-9.6	20-30	5.1-7.7	16-24
5	Polar Platform				
6		0	20-30	0	20-30
7	Outfitting				
8		1.6-2.4	20-30	1.3-1.9	16-24
9	Polar Platform				
10		1.6-2.4	20-30	1.3-1.9	16-24
11	Logistics				
12		1.6-2.4	48-72	1.3-1.9	38.4-86.4
13	Logistics				
14		1.6-2.4	48-72	1.3-1.9	38.4-86.4
15	Logistics				
16		1.6-2.4	48-72	1.3-1.9	38.4-86.4
17	Logistics				
18		1.1-2.4[b]	96-144	1.3-1.9	76.8-172.8
19	Logistics				
20		1.1-2.4	96-144	1.3-1.9	76.8-172.8
21	Logistics				
22		1.1-2.4	96-144	1.3-1.9	76.8-172.8
23	Logistics				
24		1.1-2.4	182.4-273.6	1.3-1.9	145.9-328.3
25	Logistics				
26	Polar Platform				
27	Logistics				
28		1.1-2.4	182.4-273.6	1.3-1.9	145.7-328.3
29	Logistics				
30		.8-2.4	182.4-273.6	.6-1.9	145.9-328.3

[a] All estimates ± 20%; Flights 3-17 are CETF budgets.

[b] Flights 18-30 are MRDB (Reference 19) + CETF, e.g., from Table 5-6, Flight 18: 1.4 to 2 -> 1.4(± 0.8) to 2.0(± 0.8) = [1.1, 2.4].

Table D-5. Conversion of EVA+FTS Estimates for Attached-Payload Servicing Time by Flight Period to Service Work-Hours Per Week[a]

		EVA-Only Case		EVA+FTS Case	
Flight[b]		EVA_O	IVA_O	EVA_F	IVA_F
3	Input	EVA_R = 1.9-2.9		IVA_{FS} = 0	EVA_A = .5-.7
	Result	2.4-3.6	1.2-1.8	1.9-2.9	1.3-3.2
4	Input	EVA_R = 5.1-7.7		IVA_{FS} = 0	EVA_A = 1.3-1.9
	Result	6.4-9.6	3.2-4.8	5.1-7.7	3.5-8.6
6	Input	0	0	0	0
	Result	0	0	0	0
8	Input	EVA_R = 1.3-1.9		IVA_A = .3-.5	
	Result	1.67-2.4	0.8-1.2	1.3-1.9	0.9-2.2
10	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .3- .5
	Result	1.6-2.4	0.8-1.2	1.3-1.9	0.9-2.2
12	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .3- .5
	Result	1.6-2.4	0.8-1.2	1.3-1.9	0.9-2.2
14	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .3- .5
	Result	1.6-2.4	0.8-1.2	1.3-1.9	0.9-2.2
16	Input	EVA_4 = 1.3-1.9		IVA_{FS} = 0	EVA_A = .3- .5
	Result	1.6-2.4	0.8-1.2	1.3-1.9	0.9-2.2
18	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .2- .5
	Result	1.5-2.4	0.8-1.2	1.3-1.9	0.8-2.2
20	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .2- .5
	Result	1.5-2.4	0.8-1.2	1.3-1.9	0.8-2.2
22	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .2- .5
	Result	1.5-2.4	0.8-1.2	1.3-1.9	0.8-2.2
24	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .2- .5
	Result	1.5-2.4	0.8-1.2	1.3-1.9	0.8-2.2
28	Input	EVA_R = 1.3-1.9		IVA_{FS} = 0	EVA_A = .2- .5
	Result	1.5-2.4	0.8-1.2	1.3-1.9	0.8-2.2
30	Input	EVA_R = .6-1.9		IVA_{FS} = 0	EVA_A = .2- .5
	Result	0.8-2.4	0.4-1.2	0.6-1.9	0.4-2.2

[a] [Min(actual,calculated), max(actual,calculated)] values used for range throughout. Performance ratio range of 1.4 to 5.0 used.

[b] Assembly flights only.

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15. Supplementary Notes

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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