AEROSPACE REPORT NO.
ATR-74(7341)-8 VOL I

Operations Analysis (Study 2.1) Final Report

Volume I: Executive Summary

DRA

Prepared by ADVANCED MISSION ANALYSIS DIRECTORATE
Advanced Orbital Systems Division

21 February 1975

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

Contract No. NASW-2575

Systems Engineering Operations

THE AEROSPACE CORPORATION

(NASA-CR-143354) OPERATIONS ANALYSIS (STUDY 2.1). VOLUME 1: EXECUTIVE SUMMARY Final Report (Aerospace Corp., El Segundo, Calif.) 32 p HC $3.75 CSCL 22B

N75-30233

Unclas
G3/18 17759

Aerospace Report No.
ATR-74(7341)-8 Vol I

OPERATIONS ANALYSIS (STUDY 2.1) FINAL REPORT

Volume I: Executive Summary

Prepared by

R R Wolfe

R. R. Wolfe
NASA Study 2.1 Director
Advanced Mission Analysis
Directorate

Approved

R. H. Herndon

R. H. Herndon, Group Director
Advanced Mission Analysis
Directorate
Advanced Orbital Systems Division

CONTENTS

1.	INTRODUCTION AND SUMMARY		1
	1.1	Space Servicing Concepts	1
	1.2	Payload/Tug Software Cost Estimates	2
2.	SPACE SERVICING CONCEPTS		3
	2.1	General	3
	2.2	Payload Reconfiguration for Space Servicing	4
	2.3	Space Servicing Tradeoffs	9
	2.4	Conclusions	18
	2.5	Recommendations	18
3.	PAYLOAD/TUG SOFTWARE COST ESTIMATE		19
	3.1	Software Requirements	19
	3.2	Summary and Conclusions	23
4.	STUDY CONCLUSIONS		25
5.	REFERENCES		26

PRECEDING PAGE BLANK NOT FILMED

FIGURES

1. Modified EOS Payload Reconfiguration 5
2. TT&C Block Diagram (Example). 7
3. Reliability Block Diagram for TTC-4 SRU 8
4. Space Serviceable Payload Definition 10
5. Simulation Results 12
6. Impact of Boiloff on Centaur Capability 15
7. Software Cost Estimating Relationship 22

TABLES

1. Telemetry, Tracking, and Command Requirements (Example 7
2. SRU Component Characteristics (TTC-4) 8
3. Simulation Results 12
4. Software Cost Summary 22

1. INTRODUCTION AND SUMMARY

Study 2.1, Operations Analysis, addressed two major subjects related to future STS operations concepts. The majority of effort was directed at assessing the benefits of automated space servicing concepts as related to improvements in payload procurement and Shuttle utilization. The second subject was directed at understanding Shuttle upper stage software development and recurring costs relative to total program projections.

1.1 SPACE SERVICING CONCEPTS

Space servicing of automated payloads has the potential to reduce future space program costs and provide a great deal of flexibility relative to conducting mission operations. The subject is addressed in this effort by examining the broad spectrum of payload applications with the belief that shared logistic operations will be a major contributor to reduction of future program costs. However, there are certain requirements for support of payload operations, such as availability of the payload, that may place demands upon the Shuttle fleet. Because future projections of the NASA Mission Model are only representative of the payload traffic, it is important to recognize that it is the general character of operations that is significant rather than service to any single payload program.

Space servicing, as employed for this Study, implies an ability to extend the life of a given payload by replacing modular increments rather than a complete payload. In so doing, the total weight to orbit can be reduced; also, the feasibility of sharing flight operations moves closer to reality, both of which contribute to reduced operating costs. However, failure patterns over such a broad spectrum of payloads will inherently be random and this random nature may place demands for servicing at a time when the Shuttle is occupied with other commitments, such as sorties. So it is important to see if savings can be realized without undue penalty to either the payload community or the Shuttle community.

To assess space servicing, it was necessary to develop an entirely new data base of payload definitions. Weight and reliability characteristics are the principal features required. In addition, it was necessary to develop a computer simulation program to represent the various elements of each payload and simulate the random pattern of failure events. Although the total model is considered, emphasis has been placed on servicing payloads in geostationary orbit. The results indicate that a substantial cost benefit can be realized sufficient to compensate for DDT&E costs associated with the payload and service mechanism design efforts as well as the associated servicing operation.

1.2 PAYLOAD/TUG SOFTWARE COST ESTIMATES

Software costs were addressed because very little firm data exist. Speculation of software costs for the upper stage, especially if servicing is employed, has provided a broad band of cost estimates. Consequently, the effort here was devoted to developing an understanding of the driving factors affecting software costs and then developing sufficient data to allow a valid estimate of upper stage or Tug costs that may be incurred in the future.

The results of this effort indicate that existing Cost Estimating Relationships (CERs) are insufficient in the present form but can provide a basis of understanding. Modifying factors were developed based upon such historical data as Apollo, Titan IIIC, and Centaur programs and applied to airborne, ground support, and mission control center software costs. It is estimated that software development costs for the Shuttle upper stage including multiple rendezvous, docking, and servicing functions should not exceed an initial cost of $21 million, with a recurring cost of $2.5 million annually.

2. SPACE SERVICING CONCEPTS

2.1 GENERAL

Study 2.1, Operations Analysis, had as its principal objective the investigation of new operational concepts for the Shuttle era. Attention was directed primarily at space servicing of automated payload programs and the impact this could have on upper stage designs and overall resources utilization. Although this is not an economics study, cost benefits resulting from space servicing can be determined in a gross sense so that the concept can be pursued further within NASA, or included in detail design studies with other contractors.

To perform this study it was necessary to develop an entirely new data base and analysis technique. Candidate payloads were selected from the October 1973 NASA Mission Model of Automated Payload Opportunities and reconfigured for space servicing. This design process resulted in a set of standard space replaceable units (SRUs) which serve as the building blocks of each serviceable payload. Mission equipment for each candidate payload was also reconfigured for space servicing.

A complex computer simulation program was developed to support the analysis of space servicing. This statistical program employs Monte Carlo techniques to establish failure events which then require servicing by the Space Shuttle with an upper stage to put the payloads back into an operating condition. Various upper stage configurations can be employed in the analysis. The computer program has been implemented for NASA use at the NASA Computation Facility, Slidell, Louisiana.

Although space servicing of automated payloads appears to be attractive for individual programs, in the past it has not been shown that its application in a broad sense would be beneficial. Since servicing operations are random in nature, they may place severe demands on the logistic fleet which could otherwise be occupied by operations such as Sorties. Consequently, the total mission model must be considered and the following questions assessed:

1. Can the total number of flights be reduced by space servicing of payloads?
2. Can the total payload procurement be reduced?
3. Are the benefits sufficient to justify the DDT&E costs and the risk associated with developing a new concept?

2.2 PAYLOAD RECONFIGURATION FOR SPACE SERVICING

This portion of study effort was divided into several subtasks, all associated with developing data and performing subsequent tradeoff analyses. The most important of these was the development of a space serviceable payload data base. Information from several detailed payload redesign efforts was employed together with the results of this study to provide a composite of subsystem and mission equipment weights, volumes, and reliabilities. This new data base has been issued as an Aerospace report (Ref. 1). A summary of the content is provided below.

The subsystem requirements for 42 payload programs were evaluated to establish the range over which any set of standard equipment would have to perform. Four subsystem categories were selected: Attitude and Velocity Control, Guidance and Navigation, Telemetry and Command, and Electrical Power. Certain high reliability components were incorporated with the basic structure of each payload to form a non-replaceable unit (NRU). This was the framework within which the space replaceable units (SRUs) could be inserted and removed as required for servicing. Mission equipments were also placed upon SRU baseplates to be replaced either because of failures or for equipment improvement.

This information was then used to reconfigure an example satellite for space servicing. The selected design was the NASA Earth Observatory Satellite (EOS). The baseline definition is shown along with its reconfigured version in Figure 1. The mission equipment modules are principally located around the periphery of the ring frame to allow for future growth of equipment. Subsystem modules, where the size can be

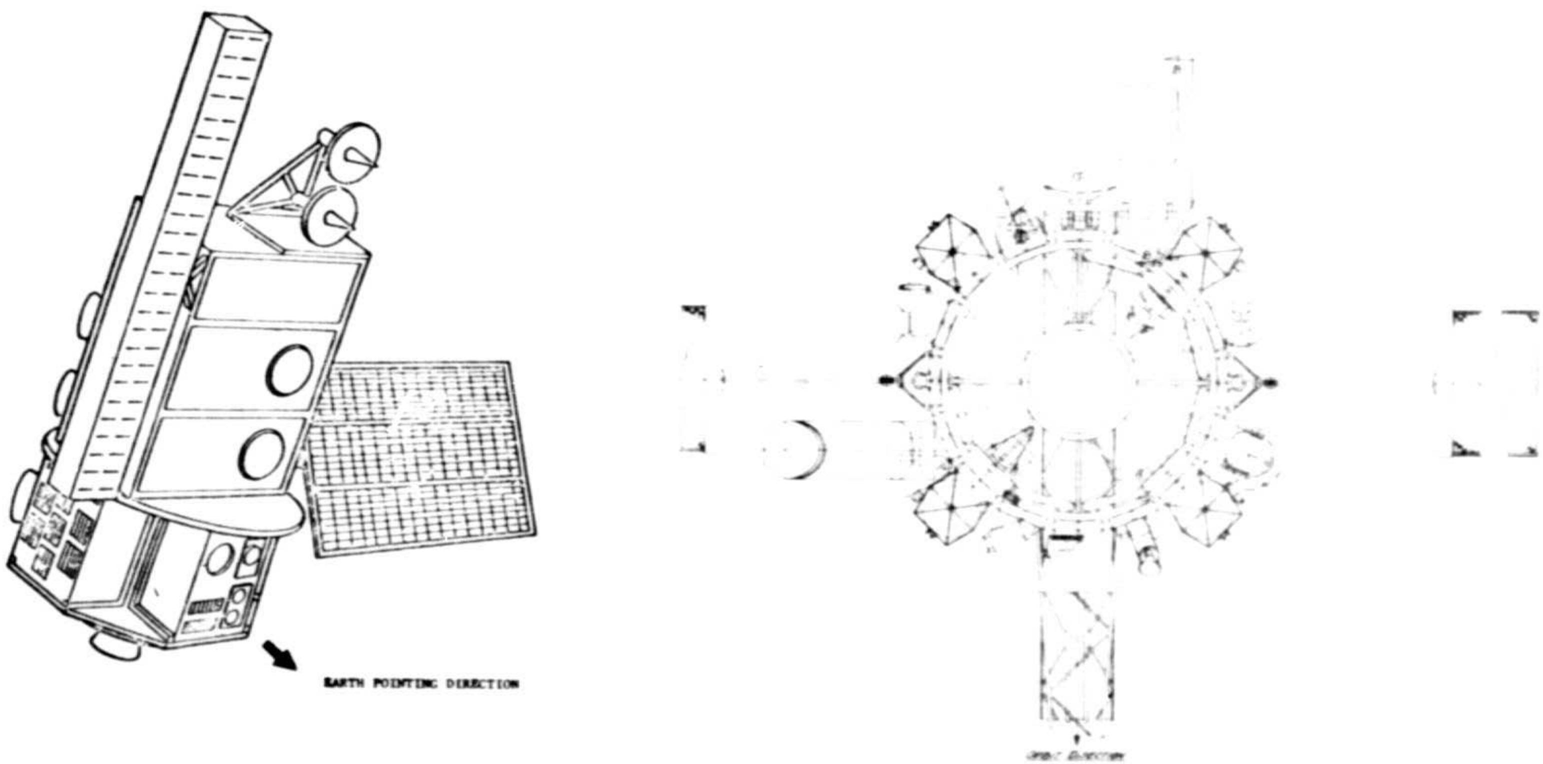


Figure 1. Modified EOS Payload Reconfiguration

controlled, are located inside the ring frame. This general configuration was then employed for the remaining space serviceable payload candidates. In all, 29 different designs were developed to satisfy the 42 payload programs. Thirty-four different subsystem SRUs were required along with 104 mission equipment modules. In general, the weight growth for payloads over 1000 kg (current design) was 10 to 30 percent.

A sample of this technique is illustrated in Table 1. The telemetry tracking and command (TT&C) requirements for various sets of payloads under consideration were summarized as shown in this example. These requirements were then transferred into a set of subsystem block diagrams as shown in Figure 2, each diagram satisfying a specific set of the payload requirements. This then defines the design elements of one of the TT&C space replaceable units (SRU).

Each block diagram is further broken into specific components, necessary to meet specific payload requirements, such as transmitter frequency and power levels, type of receiver, etc. A typical component list for TT&C-4 is shown in Table 2, listing the number of components required and their associated failure rates. It is now possible to make use of the reliability block diagram shown in Figure 3 to develop the associated reliability characteristics. This diagram reflects both active and standby forms of redundancy for various components. Payload requirements dictate a mission life of no less than three years. The derived SRU would therefore have a reliability at that design life of 0.883. The associated Weibull parameters express the shape of the reliability curve and serve as input discriptors for the simulation program. This particular SRU (TT&C-4) was assigned to three different payloads. In all, 10 different SRUs were required with three variants (tape recorder options) to satisfy the complete spectrum of payloads considered.

The remaining subsystems were treated in a similar manner resulting in 11 different attitude and velocity control subsystems (AVCS),

Table 1. Telemetry, Tracking, and Command Requirements (Example)

PAYLOAD CODE	ALTITUDE (nmi)	INCLINATION	ORIENTATION	DATA RATE (bps)	STORATE (bits)	COMPRESSION	COMMAND RATE (bps)
EOP-7	108/CIRC	90°	EARTH	1,000	9×10^5	NO	1,000
NND-1	SYNC	0°	EARTH	1,024	NONE	NO	50
NND-2A	SYNC	0°	EARTH	512	NONE	NO	1,000
NND-2B	SYNC	0°	EARTH	1,024	NONE	NO	50
NND-2D	SYNC	0°	EARTH	1,000	NONE	NO	1,000
NND-3	SYNC	0°	EARTH	600	NONE	NO	1,000
NND-4	SYNC	0°	EARTH	512	NONE	NO	1,000
NND-5	SYNC	0°	EARTH	[illegible],000	NONE	NO	50
NND-6	SYN[illegible]	0°	EARTH	6,400/ 1,000	NONE	NO	1,000

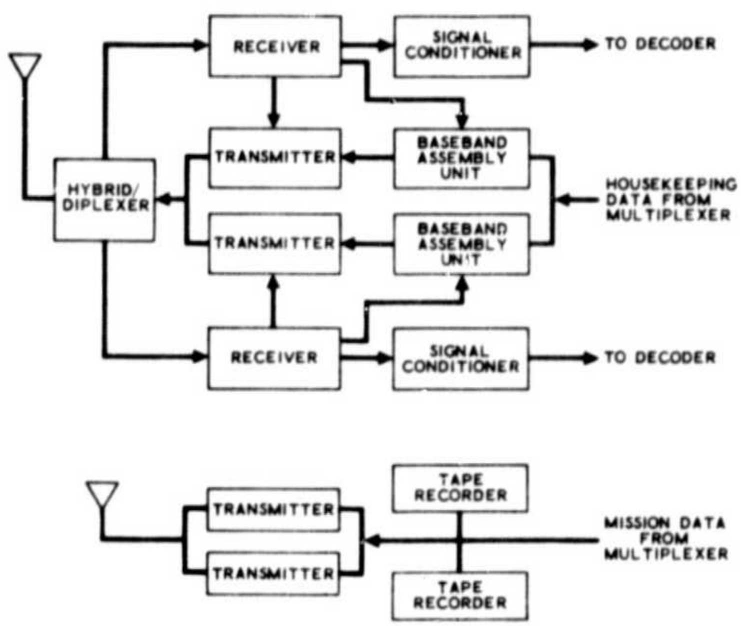
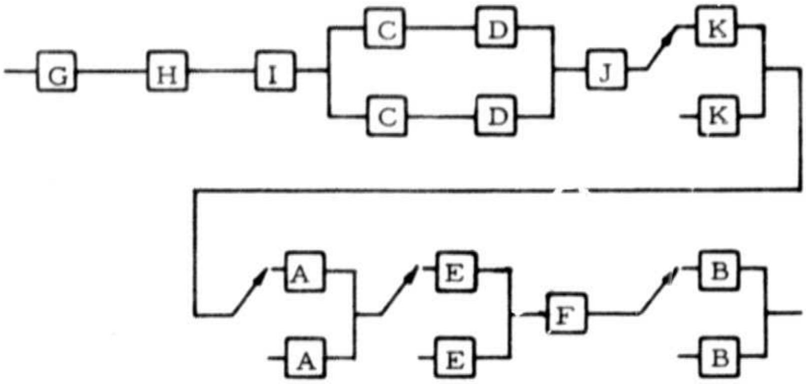


Figure 2, TT&C Block Diagram (Example)

Table 2. SRU Component Characteristics (TTC-4)

Telemetry, Tracking & Command TTC-4	A	Transmitter (S-band 8 W)	2	2	4	8000
	B	Transmitter (S-band 40 W)	2	8	16	12,000
	C	Receiver (S-band)	2	4	8	4000
	D	Signal Condition	2	2	4	2500
	E	Baseband Assembly	2	1	2	1500
	F	Dish Antenna (S-band, 1 1/2')	1	1	1	25
	G	Omni Antenna (S-band)	1	1	1	100
	H	Diplexer	1	1	1	150
	I	Hybrid	1	1	1	50
	J	Power Conditioing	1	1	2	500
	K	Data Processing Units	2	13.6	27.2	5500
		Cabling	AR	5	5	
		Connectors	AR	2	2	
		Environmental Protection	AR	5	5	
		Structure	AR	17	17	
		TOTAL			96.2	



Module Design Life 3 yrs

Reliability at Design Life 0.883

Weibull Parameters

α = 12.67 yrs

β = 1.512

Figure 3. Reliability Block Diagram for TTC-4 SRU

and 2 guidance and navigation subsystems (G&N), and 7 Electrical Power Subsystem modules which could be replaced on orbit. Base plates and power supplies were added to each SRU design and weight and reliability estimates were developed as described above. Mission equipment modules were developed in essentially the same manner to arrive at a total inventory of SRUs and NRUs to be used to compose each space serviceable payload.

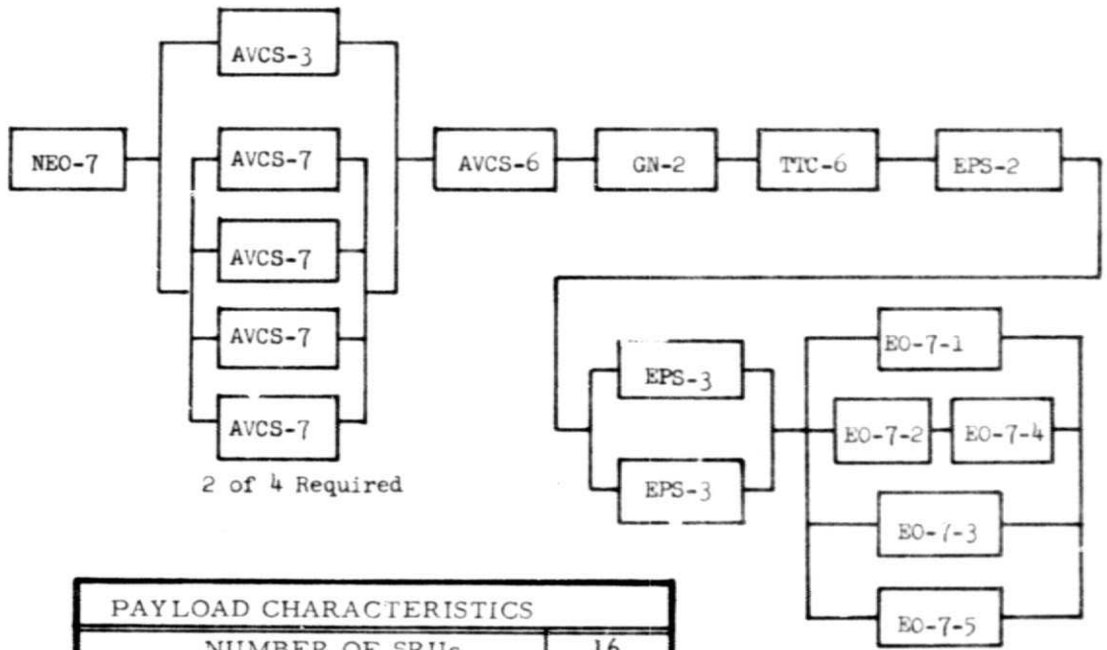
An example of this process is shown in Figure 4. This shows the reliability block diagram of the payload and specifies its pertinent characteristics. This process was performed for each of the 29 different payload designs to be used in subsequent tradeoffs.

It is important to note the various levels of redundancy assumed because the simulation process must reflect this in responding to failure conditions. If for example two of four AVCS-7 SRUs (reaction control units) are required to maintain stabilization of the payload, it would not be necessary to demand an immediate servicing operation if one SRU failed. If a second unit failed, however, a servicing flight would be required because any subsequent failure would be interpreted as loss of the payload. These are arbitrary ground rules but are easily changed in the simulation process. The significant point is, however, that each payload has unique characteristics which create different requirements for servicing, even though standard modules are employed. This approach should be representative of the operational process which would exist if space servicing is incorporated on a broad applications basis.

2.3 SPACE SERVICING TRADEOFFS

The fundamental tradeoff addressed the relative cost of space servicing of automated payloads versus expendable payload design concepts. In addition, various upper stages were considered to determine the sensitivity of space servicing benefits to the selection of an upper stage. Upper stage candidates employed in this study were the modified Titan IIIC Transtage, the Transtage with a kick motor, a 28-foot large-tank Centaur, the full capability Tug, and a

EO-7 Synchronous Meteorological Satellite



PAYLOAD CHARACTERISTICS	
NUMBER OF SRUs	16
DESIGN LIFE (YRS)	5
RELIABILITY @ D. L.	0.169
WEIGHT - DRY (Kg)	1519.8
PROP (Kg)	62
TOTAL (Kg)	1581.8

Figure 4. Space Serviceable Payload Definition

Centaur/SEPS (Solar Electric Propulsion Stage) combination.

The results presented here have been limited to geostationary orbit payloads. Further effort is required to place the remaining orbits of interest in proper perspective. There are 16 different payload programs scheduled for geostationary orbit in the time period of 1980 through 1990 (11 years). Approximately 60 percent are COMSAT-type programs, 30 percent are earth observations, and 10 percent are Explorer-type programs. The total number of operational payloads in geostationary orbit at any given time ranges between 30 and 40.

The servicing process consists of recording when a failure event occurs in each payload deployed to geostationary orbit. The replacement SRU is then placed in a loading queue to await delivery to the payload of interest. As other failures occur, the process of loading is continued. When a full load, compatible with the Shuttle and the upper stage under investigation is achieved, the combined load is delivered to orbit. The payloads are then placed in an operational state to await the next failure event. This procedure is repeated through a Monte Carlo process to arrive at a statistical distribution of SRU replacements and logistic vehicle operations. Cost estimates can then be implied by equivalent payload procurement and vehicle launch costs.

The results of this simulation effort are shown in Figure 5 indicating the degree to which each payload is serviced over the time period of interest (1980 - 1990). This curve shows that each space serviceable payload required at least a 6 percent replacement of equipment, and that 20 percent of the payloads required, on the average, a replacement of approximately 40 percent of their equipment. The results are related to the NASA full capability Tug but only slight changes occur when other upper stages are employed. The average payload availability shown indicates that, in general, a value above 95 percent is readily achievable without the use of orbital spares or dedicated logistic operations. An in-depth analysis is required if availabilities above 99 percent are desired, as is the case with commercial communication satellites.

Table 3. Simulation Results

	OPTIONS			OPERATIONS			APPROXIMATE BENEFITS *				
	STAGE	EXP	REC	SPACE SERV	FLTS	PL PROC	Δ FLTS	Δ PLS	Δ STGs	Δ SEPS	Δ COST $M
B. L.	TRANS/KICK		✓	No	83	96	-	-	19/83**	-	0
MOD/NEW DEV.	TRANSTAGE	✓		No	54	99	29	-3	54	-	93
	CENTAUR		✓	No	64	98	19	-2	-	-	273
	FULL CAP. TUG		✓	No	61	99	22	-3	-	-	293
	CENTAUR		✓	Yes	86	63	-3	33	23	-	219***
	FULL CAP TUG		✓	Yes	54	64	29	32	2	-	693
SEPS †	CENTAUR/SEPS		✓	Yes	37	63	46	33	-	3	833
	FCT/SEPS		✓	Yes	36	64	47	32	-	2	853

* Benefits to be Applied Against
  - DDT&E - Payloads and Stages
  - Recurring Refurbishment Costs
  - Additional Mission Ops. Support

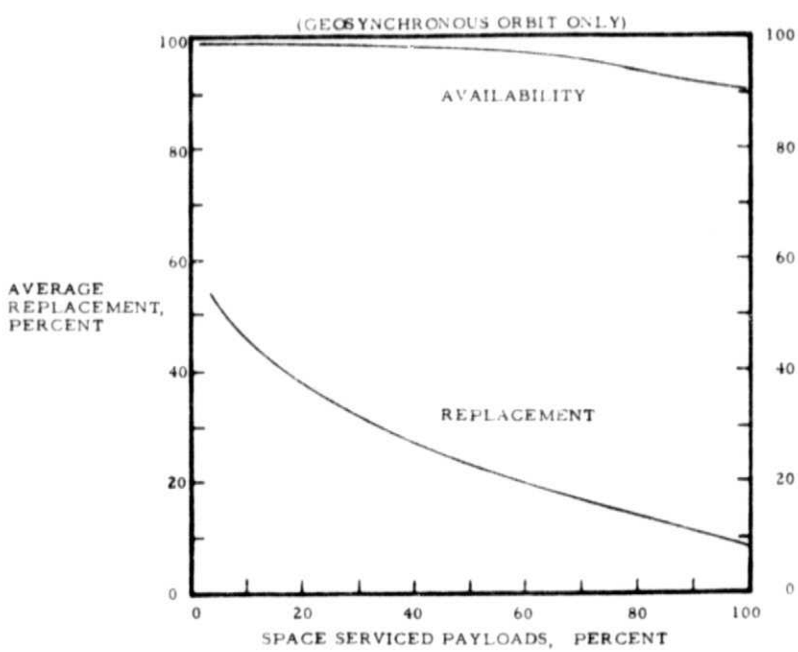
** Nineteen Transtages expended

*** Function of propellant boiloff. See page 4-8 for discussion

† SEPS data extracted from manual calculations

Reference Cost Data

Shuttle/Tug Flt	$10.0 M
Transtage	5.0 M
Kick Motor	0.1 M
Centaur	8.0 M
Full Cap. Tug	10.0 M
SEPS Stage	20.0 M
Avg. Payload Cost	10.0 M



PAYLOAD HISTORY

● Basic Deploy	32
● NRU Replace	9
● SRU Equiv	10
TOTAL	51

Figure 5. Simulation Results

ORIGINAL PAGE IS OF POOR QUALITY

During this time period, 32 space serviceable payloads were deployed to establish operational systems in geostationary orbit. Nine of these payloads had failures of non-replaceable units, thereby forcing a total payload replacement to maintain continuity of the programs. In addition, on the average, over 145 space replaceable units (SRUs) were replaced, representing an equivalent payload procurement of 10 additional payloads. The total procurement of space serviceable payloads for geostationary orbit is therefore estimated to be approximately 51 payloads. In addition, during this same time period, approximately 13 expendable payloads (not suitable for space servicing) were deployed, providing a total payload procurement of 64 payloads to fulfill the geostationary operational objectives of the October 1973 Mission Model. If space servicing were not employed, a total procurement of 96 expendable payloads (with equivalent reliabilities) would be required to provide the same level of support to operational programs. This represents, conservatively, a 30% improvement in payload procurement costs.

These results are summarized in Table 3* for various upper stage configurations. The baseline case is taken as the Transtage/kick motor operation which recovers the Transtage, but employs expendable payload designs. The required number of flights is reduced as the performance capability of the selected upper stage is increased. In performing the analysis, a reduction of one Shuttle flight was assumed to provide a savings in cost of operations of $10 million. However, in certain cases, it was necessary to expend the upper stage, resulting in additional procurement costs. For example, if the Transtage were expended to deploy payloads, the total number of flights would be reduced from 83 to 54 (35%), saving approximately $290 million in flight operations' costs

---

*These results have been extended to additional modes of space servicing with improved loading criteria, as documented in an Aerospace report (Ref. 2).

but forcing the purchase of an extra 35 upper stages at approximately $5 million each. As a result, the overall return after 11 years of operation still favors expending the Transtage over the baseline mode by as much as $93 million. This reflects the fact that even though the baseline mode of operations normally recovers the Transtage, on the average it was necessary to expend 19 stages, in addition to the kick motors, because payload weights were sufficiently high that stage recovery could not be achieved.

Again, for expendable payload operations, a large tank, 28-ft long Centaur has sufficient performance to deploy all the payloads in the mission model without the need to expend any of the Centaurs. A further, although small, reduction in the number of Shuttle flights results from the use of the full capability Tug, again without expending any propulsive stages. The return on investment over the 11-year period is essentially the same for both vehicles, although the DDT&E is considerably greater for the Tug. It is possible that other high energy missions, such as planetary, may require the higher performance of the full capability Tug. However, for expendable payload operations in synchronous equitorial orbit, based on the reference mission model, it would appear that a large-tank Centaur is adequate.

Continuing with the results presented in Table 3, it can be seen that space servicing offers significant cost benefits over expendable payload operations.

The Centaur stage used in this space servicing analysis is based on the current design and incurs a loss of 1454 kg (3200 lb) when used in a seven-day mission. This penalty is very severe and results in a high flight rate even though the number of procured payloads is reduced. It also requires the expenditure of a significant number of stages to accommodate the increased payload weights associated with space servicing. However, the boiloff rate and other losses of the Centaur must be reduced before its orbital performance could be sufficiently improved to make it a viable candidate for space servicing. A reduction of 454 kg in the boiloff would reduce the Shuttle flight rate as shown in Figure 6. Although this boiloff rate is still considerably higher than for the Tug, it would result in a cost saving of approximately $150 million due to the reduction in Shuttle flights. Since the estimated DDT&E cost to achieve this level of boiloff is less than $10 million, it appears to be a worthwhile investment.

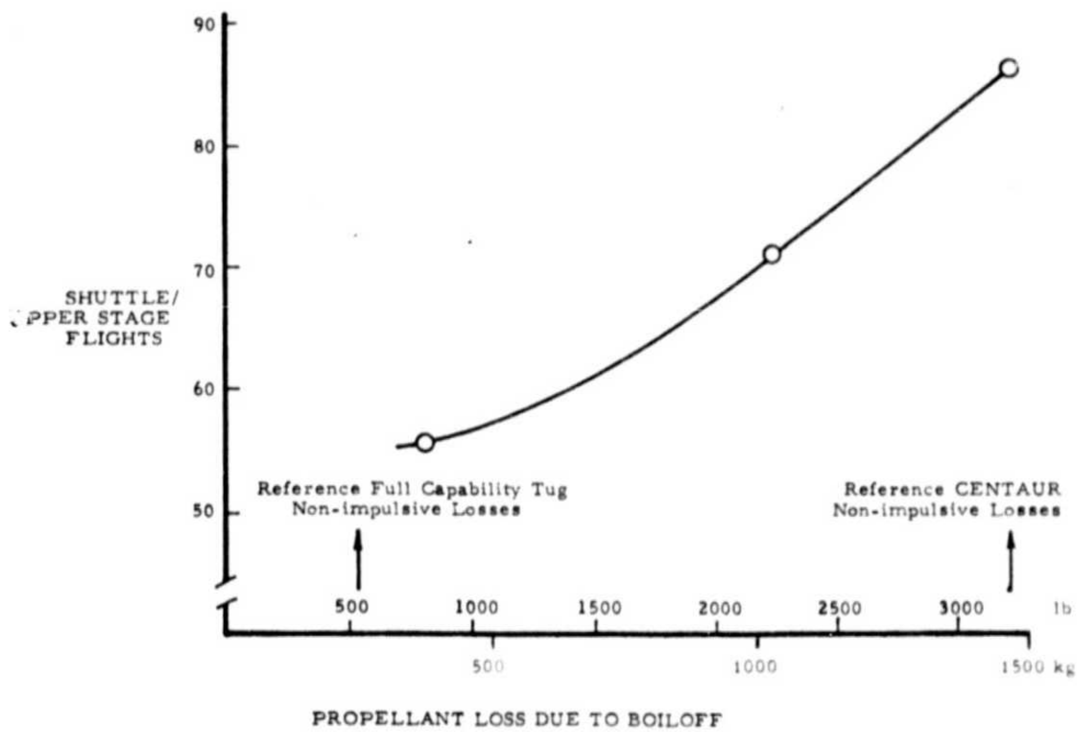


Figure 5. Impact of Boiloff on Centaur Capability

It is recommended that a thorough review of the Centaur design be performed, preferably by the manufacturer, to assess its potential capability (and associated costs) for space servicing, since the Centaur results are very sensitive to inert weight and orbital life.

It can also be seen from Table 3 that the full capability Tug, which is being designed to perform a seven-day orbital mission, can substantially reduce the Shuttle flight rate, leading to a return on investment of approximately $700 million over the baseline case for the 11-year period.

This significant cost saving is considered to be conservative for several reasons. First, flight costs will probably be closer to $12 million per flight because of the additional upper stage functions. Second, an average payload will probably cost more than $10 million. While communication satellites currently cost approximately $7 million, other operational and scientific payloads, which are highly complex, are expected to cost over $40 million each. Finally, no effort was made to optimize the flight operations; as a result, payloads were serviced as failures occurred without exercising priorities, leading to relatively poor upper stage load factors of only 65 percent.

Although further improvement could be achieved by additional analysis, it is obvious that space servicing can offer a substantial payoff in a relatively short period of time. An initial DDT&E investment of over $100 million to achieve space serviceable payload configurations would be returned in five to six years. Since a return on investments of this magnitude generally requires 10 to 20 years, the cost benefits cannot be ignored. Moreover, the average time for advancing technologies to create a new generation of payload configurations has been found to be approximately six years; thus, a given payload program can upgrade its payload configuration and realize a return from space servicing within the first generation of the program plan.

A further point of importance is the flexibility of design and operation that space servicing offers. Improvements in mission equipment can be incorporated as they become available, rather than requiring a new payload design. If a given program drops behind schedule or cost overruns are imminent because of a single equipment item, the requirements can be relaxed to meet the initial deployment schedule knowing that an improved version of the equipment can be installed on-orbit at a later date. Since the subsequent equipment replacement would only bear a fraction of the flight cost, as compared to a total payload replacement, it may be possible to reduce the total runout costs while at the same time meeting the initial flight schedule.

An alternative to increased orbital lifetime for the Centaur is to couple its operation with that of a space-based Solar Electric Propulsion Stage (SEPS). Although a complete analysis could not be performed, it is possible to extrapolate previous manual calculations to this mission model. In this mode, the Centaur performs two functions: direct payload deployment of all payloads (including SRUs) not requiring a SEPS, and supply of payloads to the SEPS when the Centaur performance will not allow geostationary operations. In this way, payloads requiring immediate servicing could be accommodated by the Centaur, whereas heavy payloads exceeding the Centaur capability would employ a SEPS, making it unnecessary to expend any Centaurs. The SEPS, after receiving payloads and SRUs from a single Centaur flight, then will transfer from position to position to service numerous payloads in orbit. Initial deployment and retrieval of the SEPS is performed by the Centaur.

The reference SEPS is a 25 kW configuration with approximately 1360 kg (3000 lb) of mercury propellant, achieving a specific impulse of 3000 seconds. Although deployment and retrieval operations may require 20 to 30 days, the servicing time in geostationary orbit is quite competitive with the full capability Tug, in the order or two to three days. As shown in Table 3, the cost benefits exceed $800 million over the baseline reference case. In this case, the Centaur is quite competitive with the full capability Tug because orbital lifetime is not a problem. The additional $100 million to $150 million savings should be sufficient to cover adaptation of the SEPS to space servicing, assuming that the SEPS is developed for planetary operations. In fact, the benefits are such that it may be possible to compensate for the total SEPS development cost, although further optimization would be required to obtain definitive results.

2.4 CONCLUSIONS

Although a great deal of analysis is still needed, it is apparent from the results developed in this study that space servicing should be pursued, especially for geostationary orbits. The potential benefits in terms of costs, flexibility for equipment changes, and increased reliability of operations more than compensate for the payload weight increase and the associated investment required to develop this operational concept. However, it may be difficult to convince the payload users to take this step due to a concern over the risk of developing the concept. Therefore, the following recommendations are submitted.

2.5 RECOMMENDATIONS

One alternative is to initiate a pilot program prior to Shuttle IOC to demonstrate the operational technique. It may be possible, using the USAF Space Technology Program (STP), to develop a simple payload experiment program that can be deployed with a replacement SRU after sufficient information is accumulated from the initial experiment. The service unit could be derived from several options, using existing equipments or prototype development items to maintain a low cost operation. Experience with the servicing unit should be beneficial also because it will aid in developing requirements and components for future upper stage operations, especially for rendezvous and docking operations.

The advantage of this pilot program lies in focusing attention on a new concept which must involve the payload user from the start. This involvement should enhance standardization of subsystems by emphasizing interface relationships and design guidelines.

While a pilot program will not completely overcome the payload developer's reluctance to take the first step toward space servicing because of uncertainty in the development risk, it should move the process much closer to reality.

3. PAYLOAD/TUG SOFTWARE COST ESTIMATES

3.1 SOFTWARE REQUIREMENTS

In addition to the space servicing efforts discussed in Section 2, a functional analysis of upper stage operations was performed to establish the overall software requirements. For the purpose of this effort, the MSFC full capability cryogenic Tug was assumed to be the upper stage; however, the results are not particularly sensitive to the vehicle itself. Tug operations include the space flight and servicing functions as well as ground checkout and mission control center support. The functional analysis was based upon Titan IIIC experience for deployment of expendable payloads.

In parallel with the software requirements development, a survey of software costs was performed. This involved contacting several software and computer development firms to determine their procedures for estimating software costs. This also served to point out the major factors influencing software costs over and above the basic programming effort. The results of this effort are documented in an Aerospace Technical Report (Ref 3). A summary is provided below.

From the functional analysis it was determined that the spaceborne software would require approximately 30,000 words of instructions to perform space servicing. An additional 2,000 words would be required for the service unit sequencer. These functions include orbital transfer, navigation updates, rendezvous and docking, and other support functions.

Ground checkout software functions were estimated to require over 1 million words of instructions for Tug preparations. The service unit would require an additional 100,000 words. This estimate assumes that the overall ground support operations are managed by a large computer complex similar to the Launch Processing System currently envisioned for the Kennedy Space Center. As such, many peripheral functions would be required in support of the Shuttle and could be shared by the upper stage with no impact.

A similar approach was assumed for the Mission Control Center (MCC) functions. The MCC is required to support Shuttle operations, including all telemetry conditioning, tracking and navigation updates, display formatting, and command uplink capability. As such the additional support required for the upper stage and servicing functions is estimated to have a minimal impact on the flight support functions. For this reason, it was estimated that approximately 30,000 words of instruction would be required plus an additional 5,000 words to support the service unit.

In developing these estimates, serious consideration was given to two other points which bear on the software requirements. One is that all payload checkout operations are performed by the payload user, not by the Tug or service unit. The service unit exchanges space replaceable units (SRUs) and verifies proper insertion, but that is the extent of the service operation. This is particularly significant when considering the wide variety of payloads to be serviced. To expect one universal checkout system to exist on the service unit is unrealistic. The second point concerns Tug/service unit and payload responses to contingencies and the possible need for manned interactive support. A brief contingency analysis was performed (Ref 4), which indicates that a visual check of the payload configuration prior to docking is necessary to assure a clear path of approach. Consequently, the above software estimates are based upon automated servicing operations with a command override capability from MCC to support a stand-off and inspection maneuver before and after servicing.

The impact of the above software requirements cannot be assessed without some basis for estimating future software costs. Software costing has always been elusive and difficult to predict for several reasons. In surveying various contractor efforts, the one point that continually arose was the lack of firm software requirements. This tends to negate any software cost estimating relationships (CERs). Although actual software costs may exist, it is difficult to relate these costs to an original set of requirements. The approach taken, therefore, was to establish a basic cost estimate related to the words of instruction and then use modifiers to adjust this cost based upon empirical judgment factors.

The results of the survey are shown in Figure 7. Various programs are shown relative to the number of words in machine language versus the man months of effort to develop, code, and check out the program. It should be recognized that in several cases the points shown do not represent total program efforts, but only a portion for which data could be found. This is sufficient for developing the relationship shown. It should also be noted that a band for the updated Titan IIIC airborne computer is provided. This band reflects the fact that although a fixed word count exists there are several contractors involved and therefore the actual cost, including integration, may be double that derived from the curve. This point is discussed next.

Five factors were considered as modifiers of the basic relationship shown in Figure 7. They are computer capacity, program complexity, prior experience, coding language, and level of integration effort required. When taken together, these factors, based upon a manpower cost of $4000 per man month, increase the basic spaceborne software cost from $3.93 million to $9.91 million, a factor of approximately 250 percent.

Similar approaches were taken for ground checkout and flight support hardware. Basic cost ratios range from $200 per word for spaceborne systems to $7 per word for ground and flight support. Adjusting these values for the five factors mentioned above provides the overall results shown in Table 4. The total developmental cost for a Shuttle upper stage is estimated to be approximately $21 million. Of this, less than 10% would result from the additional functions related to space servicing. In addition, it is estimated, based upon Titan IIIC, Agena, and Centaur experience, that yearly recurring costs would be approximately $2.5 million per year.

Table 4. Software Cost Summary

TYPE	DDT&E $M		*RECURRING $M/YR	
	TUG	SERV	TUG	SERV
SPACEBORNE	8.98	0.93	1.00	0.10
GROUND SUPPORT	10.00	1.00	1.00	0.10
FLIGHT SUPPORT	0.30	0.05	0.10**	0.05**
TOTAL	19.28	1.98	2.10	0.25
	$21.26		$2.35/YR	

*ESTIMATED FROM T-III AND SCF EXPERIENCE

**ESTIMATED THRESHOLD VALUES

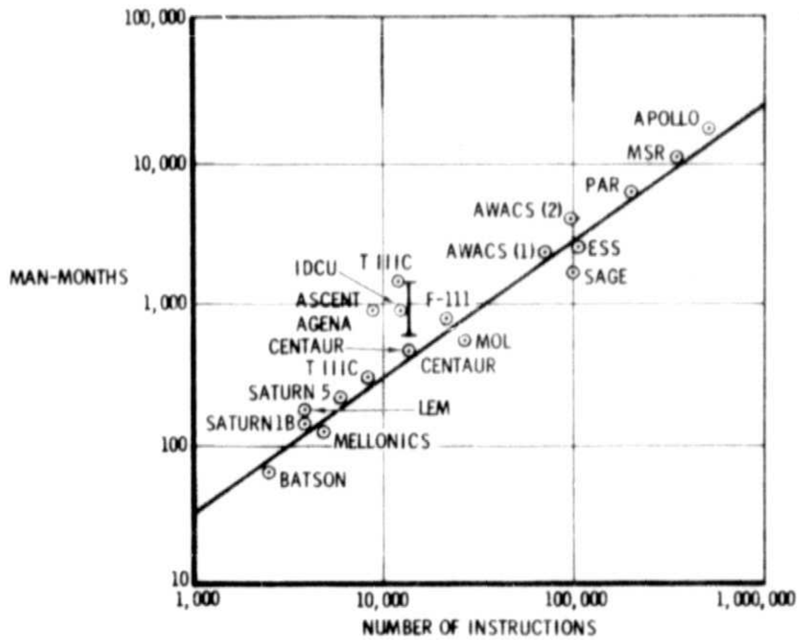


Figure 7. Software Cost Estimating Relationship

3.2 SUMMARY AND CONCLUSIONS

In summary, the following conclusions are drawn:

a. Manned interactive support is required for stand-off and inspection operations prior to and after space servicing.

b. The majority of upper stage and service unit functions can be readily automated without a serious impact on the software costs.

c. Total software costs for the upper stage program should not exceed approximately $21 million, of which less than 10 percent would be due to servicing operations. This total represents only 5 percent or less of the overall upper stage development costs, which is considered to be very realistic.

d. Recurring software costs, including program improvements, generation of new coefficients and preflight verifications efforts should not exceed $2.5 million per year based upon an estimated flight rate of 10 flights per year.

e. The lack of a firm software specification and the overall integration of the software effort will probably be the major factors involved in software costs and should be tightly controlled from the outset of program initiation.

f. New techniques need to be developed to reduce future software costs, such as structured programming or standardization of software modules. NASA GSFC has been investigating these techniques in an effort to keep spiraling costs in check. This type of work should be encouraged.

4. STUDY CONCLUSIONS

The principal conclusion to be drawn from this Study effort is that space servicing, especially in geostationary orbit, is substantially more attractive as an operational concept than continued use of expendable payload designs. The potential savings in payload procurement and logistics cost over an 11-year period should be more than sufficient to compensate for associated DDT&E costs. In addition, the capability to modify the mission equipment as new designs evolve offers unparalleled flexibility for performing scientific programs at substantial savings.

This effort has been restricted in depth but the general character of future operations can be assessed. For example, the random demands for servicing do not appear to place any severe demands on fleet size. The overall flight rate is in fact reduced substantially, while still maintaining a relatively high payload availability. The average down time, when a critical failure occurs, should not exceed 60 days on the average. Also, it can be expected that, on the average, 25 percent of the modules within a given satellite will require replacement to satisfy the requirements of the reference NASA Mission Model.

The results further indicate that study activities should be directed toward space based servicing operations in geostationary orbit. Consequently, although further analysis is needed, it is very apparent that this concept should not be precluded when considering development of a servicing capability.

Finally, a recommendation is made to initiate a low cost pilot flight test program to demonstrate automated space servicing to the payload community. The objectives of such a test are to develop confidence in the concept, demonstrate that the associated technical risk is minimal, and to show that operational procedures are adequate to support this concept. Further work is planned on this subject in the next Study effort to be initiated in September 1974.

It has also been shown that software costs associated with the upper stage for rendezvous, docking, servicing, or retrieval operations do not impose a substantial cost burden on the Tug development. The costs are not expected to exceed $21 million for development with a recurring annual cost not to exceed $2.5 million. The impact of servicing is predicted to be relatively minor, less than 10 percent of the total software costs. Consequently, there is no reason to suspect that software development represents a severe risk to the Tug development or to space servicing operations.

REFERENCES

1. M. G. Wolfe, OPERATIONS ANALYSIS (STUDY 2.1) Payload Designs for Space Servicing (with Addendum), ATR-74(7341)-3, The Aerospace Corporation, El Segundo, Calif. (30 June 1974).

2. Space Servicing Pilot Program Study, ATR-75(7361)-1, The Aerospace Corporation, El Segundo, Calif. (30 January 1975).

3. OPERATIONS ANALYSIS (STUDY 2.1) Shuttle Upper Stage Software Requirements, ATR-74(7341)-4, The Aerospace Corporation, El Segundo, Calif. (15 July 1974).

4. OPERATIONS ANALYSIS (STUDY 2.1) Contingency Analysis, ATR-74(7341)-5, The Aerospace Corporation, El Segundo, Calif. (15 July 1974).