AEROSPACE REPORT NO.
ATR-74(7349)-1

Advanced Space Program Studies

Overall Executive Summary

DRA

Prepared by
ADVANCED MISSION ANALYSIS DIRECTORATE
Advanced Orbital Systems Division

30 September 1974

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

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ADVANCED SPACE PROGRAM STUDIES
OVERALL EXECUTIVE SUMMARY

Prepared

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1. INTRODUCTION

This report is an Overall Executive Summary of work accomplished from 1 September 1973 through 31 August 1974 on the three Advanced Space Program Studies covered by NASA Contract NASW-2575. Table 1-1 lists the studies, their funding, and The Aerospace Corporation MTS deliveries.

Table 1-1. Advanced Space Program Studies

Study	Title	Funding	MTS Man Months
2.1	Operations Analysis	\$362,500[1]	72.5
2.2	Shuttle User Analysis	\$520,000[2]	91.0
2.3	Systems Cost/Performance Analysis	\$325,000	72.7

[1] Includes \$12,500 transferred from Study 2.2.

[2] Includes \$25,000 allocated to special study on "NASA Long Range Planning" and \$20,000 for additional BRAVO analyses on alternate ways to operate the EOS with the Shuttle. This latter study was initiated 30 August 1974 in support of GSFC and will be reported to NASA sepaately upon completion.

The objective of these studies was to provide NASA with advanced planning analyses which relate integrated space program goals and options to credible technical capabilities, applications potential, and funding resources. Both NASA and DOD requirements and plans were to be considered in these analyses. The DOD planning related to the Advanced Space Program Studies was primarily in the areas of interim upper stage planning and on-orbit payload servicing. In addition, the NASA Long Range Planning Study, initiated on 1 July as a special study task of Study 2.2, is examining potential military, as well as civilian, advanced mission concepts in the context of mission models as reported in ATR-74(7344)-1.

Although all elements of the NASA space program were included in the Statement of Work, the studies concentrated on upper stage options for the Space Transportation System (STS) based on payload considerations, space servicing and standardization of payloads, payload operations, STS economic analyses related to user charges and new space applications, and a significant extension of the payload cost/performance model initiated in FY 73. In general, all of the basic FY 74 activities were included in the FY 73 effort but were examined in much greater detail in FY 74; the NASA Long Range Planning Study was a new start.

The three studies performed this year were selected to provide NASA with additional planning data on lower cost space operations in the Shuttle era in the areas of:

1. Operational approaches leading to lower space program costs through more efficient utilization of the STS by payloads, primarily through payload modularization and standardization. These payload design concepts, in turn, indicated the economic desirability of space servicing NASA payloads with the STS.

2. Economic analyses of the STS related to: (a) charge policies to be applied by NASA to the user, and (b) new uses of space which would be competitive with terrestrial systems because of the lower operating costs of the STS and the ability of the STS to achieve high systems availability.

3. Cost analyses to develop a more accurate method of relating payload costs to payload performance characteristics. The method being analyzed considers payloads at the assembly level rather than at the subsystem level used in previous costing approaches. It also uses catalog item data, where possible, rather than cost estimating relationships based primarily on subsystem weight.

Data developed on the three studies were used to the maximum possible extent on the other studies. Thus, Study 2.2 was able to take advantage of the modularized payload data developed in Study 2.1 as inputs for the standardization task (Task 3) of Study 2.2.

On an interagency level, the DORCA program developed in FY 73 Study 2.5 continued to be used by SAMSO to perform payload capture analyses for the DOD upper stage utility assessment. It is intended that the capability to cost out payloads using the Systems Cost/Performance Model of Study 2.3 be transferred to SAMSO, once the utility of the Model has been adequately demonstrated. It should be noted, however, that cost/performance data derived from DOD payloads now comprise a major portion of the data base for the Cost/Performance Model.

As a result of the work accomplished during FY 74 on Contract NASW-2575, it will be possible to use information developed on most of the FY 74 studies for wider ranging but related studies in FY 75. Study 2.1, which will be investigating man's role in space operations in FY 75, will be able to use the information developed in FY 74 on automated space servicing of payloads as a point of departure. Since Study 2.2 will be examining a completely new area next year, it will be unable to use most of the data developed in FY 74. Study 2.3 will be aimed primarily at getting an updated computer program of the Systems Cost/Performance Model into operation at MSFC. FY 75 Study 2.4 will be a new study on the impact of payload subsystem standardization for the Low Cost Payloads Office (KC) at NASA Headquarters. Study 2.5 will be a direct continuation of the effort initiated on 1 July 1974 on NASA Long Range Planning.

2. STUDY TEAM

Table 2-1 lists The Aerospace Corporation and NASA study directors for the three studies performed under Contract NASW-2575 as well as the NASA review team members who helped guide these studies.

Table 2-1. Study Management

Study	Study Managers		Review Members
	Aerospace	NASA	
2.1	R. Wolfe	HQ/V. Huff	MSFC/J. Steincamp
2.2	E. Pritchard	HQ/W. Moore	MSFC/J. Turner
2.2.2	E. Pritchard	GSFC/Cepollina	
2.2.3.4	I. Bekey	HQ/R. Freitag	HQ/F. Roberts
2.3	B. Campbell	HQ/R. Carley MSFC/R. Kramer	MSFC/O. Green B. Shelton J. Steincamp M. Teal M. Vanhook

3. REPORTS ISSUED

The results of the Studies performed under Contract NASW-2575 are documented in the following reports.

ATR-74(7341)-1	Description of the Attitude Control, Guidance and Navigation Space Replaceable Units for Automated Space Servicing of Selected NASA Missions	5 April 1974
ATR-74(7341)-2	Operations Analysis (Study 2.1) Program SEPSIM (Solar Electric Propulsion Stage Simulation)	28 June 1974
ATR-74(7341)-3	Operations Analysis (Study 2.1) Payload Designs for Space Servicing	30 June 1974
ATR-74(7341)-4	Operations Analysis (Study 2.1) Shuttle Upper Stage Software Requirements	15 July 1974
ATR-74(7341)-5	Operations Analysis (Study 2.1) Contingency Analysis	15 July 1974
ATR-74(7341)-6	Operations Analysis (Study 2.1) Program Manual and Users Guide for the LOVES Computer Code	30 September 1974
ATR-74(7341)-7	Operations Analysis (Study 2.1) Program Listing for the LOVES Computer Code	30 September 1974
ATR-74(7341)-8	Operations Analysis (Study 2.1) Final Report Volume I - Executive Summary Volume II - Space Servicing Tradeoffs	30 September 1974
ATR-74(7342)-1	Shuttle User Analysis (Study 2.2) Final Report Volume I - Executive Summary Volume II - User Charge Analysis Part 1 - Summary Part 2 - The Analysis Part 3 - Tabulated Results	30 September 1974

ATR-74(7342)-1	Shuttle User Analysis (Study 2.2) Final Report Volume III - Business Risk and Value of Operations in Space (BRAVO) Part 1 - BRAVO Summary Part 2 - BRAVO Manual Part 3 - BRAVO Worksheets Part 4 - BRAVO Computer Program and Reference Data	30 September 1974
	Part 5 - Analysis of GSFC Earth Observation Satellite (EOS) System Mission Model	30 December 1974
	Volume IV - Standardized Subsystem Modules	30 September 1974
ATR-74(7343)-1	Systems Cost/Performance Analysis (Study 2.3) Final Report Volume I - Executive Summary Volume II - Systems Cost/Performance Model Volume II, Appendix A - Data Base Volume III - Program Manual and Users Guide	27 September 1974
ATR-74(7344)-1	Long Range Planning Study Volume I - Progress Report Volume II - Study Plan	19 September 1974
ATR-74(7449)-1	Advanced Space Program Studies, Overall Executive Summary	30 September 1974

The following addendum contains supplementary reliability data the payloads studied in Study 2.1.

ATR 74(7341)-3 ADD.	30 September 1974

4. OPERATIONS ANALYSIS
(STUDY 2.1)

4.1 INTRODUCTION

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 in 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, 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 other 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?

4.2 STUDY APPROACH

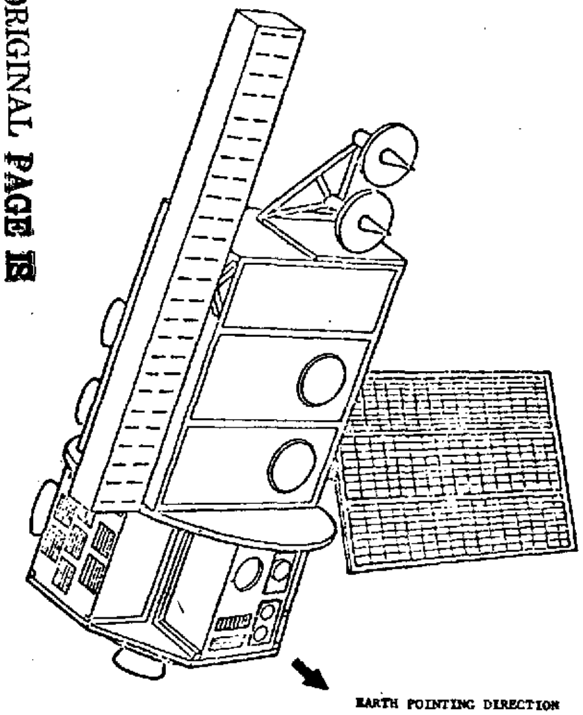
The study effort was divided into several subtasks, all associated with developing data for subsequent tradeoff analyses. The most important of these was the development of a space serviceable payload data base. Information from several detailed payload redesign efforts was employed together with the 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 ATR-74(7341)-3. 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. Five subsystem categories were selected: Attitude and Velocity Control, Guidance and Navigation, Telemetry and Command, Data Processing, 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 as desired.

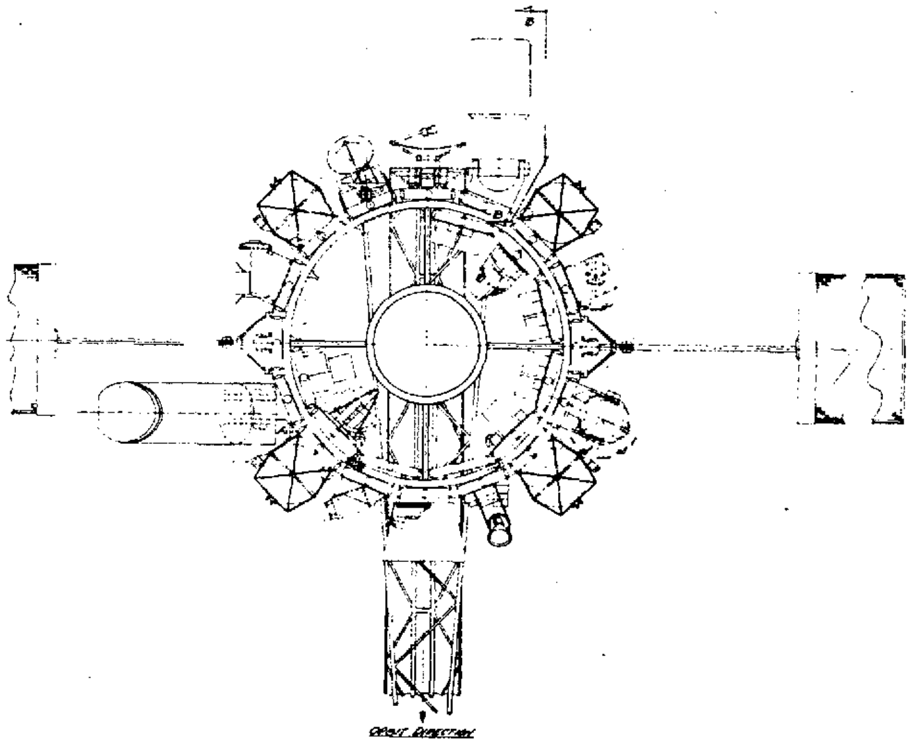
This information was then used to reconfigure an example satellite for space servicing. The selected design was the NASA Earth Observatory Satellite (EOS). The baseline definition is shown along with its reconfigured version in Figure 4-1. The mission equipment modules are principally located around the periphery of the ring frame to allow for future growth of equipment. Subsystem modules, where the size can be 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 30 to 40 percent.

Another subtask effort addressed the cost of implementing software for upper stage space servicing operations. The fundamental question involved the additional complexity associated with automated rendezvous, docking, reinitialization and transfer to another position in orbit for further servicing. The approach taken for this task was to develop software requirements for space servicing of automated payloads in conjunction with a costing technique that could be related to the requirement set. This effort covered all phases of software development and recurring operations except crew training and simulation. Manned interactive support was assumed for only contingency situations and visual inspection of the payload.

The results of this subtask have been published in two Aerospace reports, ATR-74(7341)-4 and ATR-74(7341)-5. In summary, including such factors as integration, design complexity, etc., it was determined that those functions required for space servicing increased the software costs by less than 10 percent. The total DDT&E cost for spaceborne, ground checkout, and flight support (MCC) operations should not exceed $20 million. Space Servicing would add another $2 million to this value. Recurring costs should not exceed $2.5 million per year for all functions. These costs are estimated to be between 5 and 10 percent of the upper stage development costs.



CURRENT
CONFIGURATION



MODIFIED FOR AUTOMATED
SPACE SERVICING

Figure 4-1. Modified EOS Payload Reconfiguration

4.3 SPACE SERVICING TRADEOFFS

The fundamental tradeoff which was performed addressed the cost of space servicing of automated payloads versus expendable and ground refurbishable payload design concepts. In addition, various upper stages were considered to determine if space servicing is sensitive to the selection of an upper stage. Upper stage candidates employed in this study were the Titan IIIC Transtage, the Transtage with a kick motor, a 28-foot large tank Centaur, the full capability Tug and a Centaur/SEPS (Solar Electric Propulsion Stage) combination.

The results presented here have been limited to geosynchronous orbit payloads. Further effort is required to place the remaining orbits of interest in proper perspective. There are 23 different payload programs scheduled for geosynchronous orbit in the time period of 1980 through 1990 (11 years). Sixty-one percent are COMSAT-type programs, 30 percent are earth observations, and 9 percent are Explorer-type programs. The total number of operational payloads in geosynchronous 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 geosynchronous 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 4-2 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 six 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 is also shown indicating 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.

Of the total payloads deployed during this time period, 32 were space serviceable. Nine of these payloads had failures of non-replaceable units, thereby forcing a total payload replacement for continued operations. 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 is therefore estimated to be approximately 51 payloads. In addition, during this same time period, approximately 14 expendable payloads (not suitable for space servicing) were deployed, providing a total payload procurement of 65 payloads to fulfill the geosynchronous operations objectives of the October 1973 Mission Model. If space servicing were not employed, a total procurement of 98 expendable payloads would be required to provide the same level of support to operational programs.

These results are summarized in Table 4-1 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 ten million dollars. However, in certain cases, it was necessary to expend the upper stage resulting in additional procurement costs.

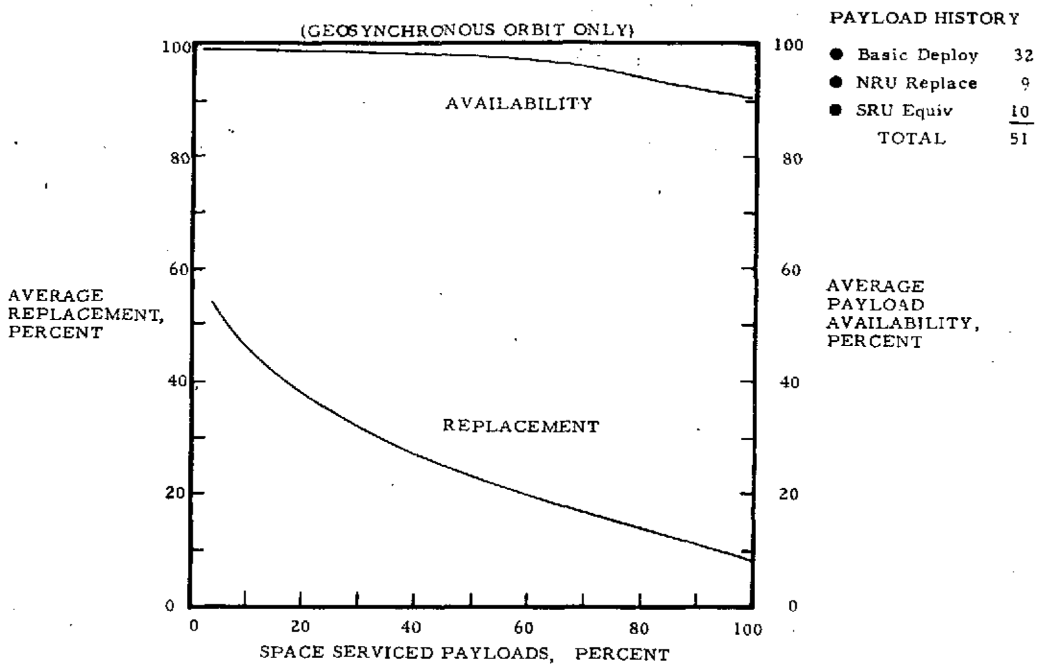


Figure 4-2 - Simulation Results

Table 4-1 - 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

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 costs but forcing the purchase of an extra 35 upper stages at approximately \$5 million each. As a result, the overall return after eleven 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.

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 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 equatorial orbit, based on the reference mission model, it would appear that a large tank Centaur is adequate.

Continuing with the results presented in Table 4-1, 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. If the Centaur boiloff rate and other losses could be reduced by the addition of insulation and by engineering modifications to reduce thermal leakage paths, its orbital performance could be improved sufficiently 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 4-3. 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 reduced boiloff is less than $10 million, it appears to be a worthwhile investment.

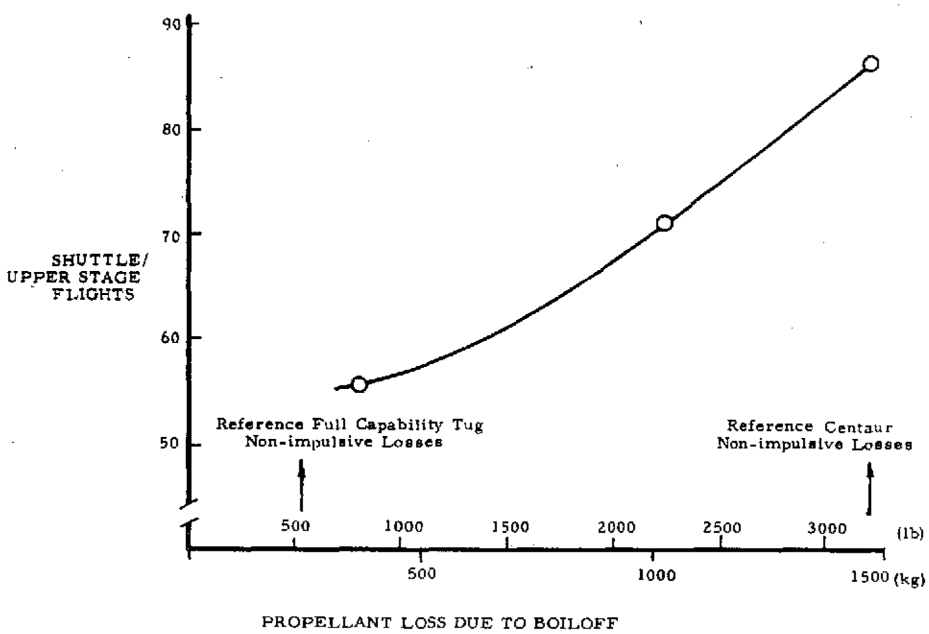


Figure 4-3. Impact of Boiloff on Centaur Capability

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 so sensitive to inert weight and orbital life.

It can be seen from Table 4-1 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 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 ten to twenty 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 life time 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 geosynchronous operation. 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 transfers 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 geosynchronous orbit is quite competitive with the full capability Tug, in the order of two to three days. As shown in Table 4-1, 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 $100-150 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 get definitive results.

4.4 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 geosynchronous 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.

4.5 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 had been 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.

5. SHUTTLE USER ANALYSIS
(STUDY 2.2)

The Shuttle User Analysis consists of the following three tasks:

1. STS User Charge Analysis
2. Business Risk and Value of Operations in Space (BRAVO)
3. Standardized Subsystem Module Analysis.

The STS User Charge Analysis considered the many possible approaches to charging the payloads transported by the Space Shuttle and upper stages. The Business Risk and Value of Operations in Space (BRAVO) Analysis was concerned with the development and testing of sophisticated techniques to rapidly determine the relative cost effectiveness of potential future space systems. The Standardized Subsystem Module Analysis task developed techniques and data which will generally predict the effects on payload characteristics and costs of standardizing subsystem modules. Each of these three studies is described below.

5.1 STS USER CHARGE ANALYSIS

5.1.1 Objective

The objective of this study was to generate alternative STS flight charge approaches which would provide a basis for determining a NASA STS flight charge policy.

5.1.2 Approach

It is expected that STS flight modes will be so different from current flight modes that the present charging policies may need modifications; for example, multiple payloads and payloads returned to earth will be common with the STS. Therefore, methods of pro-rating transportation costs to each of the multiple payloads and charging for payload return must be established.

This study is a continuation of a low-level effort initiated in FY 73. The FY 73 study brought the user charge problem into focus and described many of the issues involved, based on testing STS charge options numerically against evaluative criteria. The analyses of FY 73, based on one or two typical flights, were expanded in FY 74 to initially include analyses of an entire year's STS flights and then, in the final testing of desirable charge approaches, the 12 years of STS flights as shown in the October 1973 NASA mission model.

The FY 74 approach carried out the analysis in the following four steps. First, criteria for the evaluation of the alternative flight charge approaches were generated and then NASA approval was obtained for these criteria. Next, some 260 alternative flight charge approaches were defined. Payload transportation charges were calculated for 80 of these 260 charge approaches. The resulting charges were then evaluated against the following criteria and candidate flight charge approaches were recommended to NASA.

1. The charges should recover at least the total costs of Shuttle flights in the October 1973 mission model.
2. The charge policy should contain incentives for payload effects implementation. Returned payload charges should be competitive with the cost of new payloads.
3. The policy should provide incentives for STS operations with high load factors.
4. The selection of the policy should be insensitive to mission model changes.
5. Charges for the individual users who share a flight should be a fair share of the total costs.
6. Charge rates should be competitive with expendable launch vehicles.
7. The charge policy should be simple to administer.

Contact was made with several tariff organizations to obtain information on their approaches to charges for transportation and their recommendations for STS transportation charges. Among the organizations contacted were Interstate Commerce Commission, Air Transport Association, Military Airlift Command, Continental Airlines, and Western Motor Traffic Bureau. It was found that tariffs have historically evolved in response to anti-trust laws. The commercial charges are determined by carrier/user negotiation with cognizant agency approval. The Military Airlift Command (MAC) operates with an industrial fund provided by appropriation. Charges generally vary according to cargo weight and distance carried.

After the technical work was completed on the User Charge Analysis, additional technical assistance was given to NASA Headquarters and NASA JSC for the purpose of supporting Headquarter's briefings and the initiation of a JSC user charge study.

5.1.3 Results and Conclusions

Some of the criteria were satisfied for nearly all charge approaches. Costs were recovered satisfactorily by forcing the revenue to be equal to the costs. With one exception, the charge approaches selected for analysis are rated as relatively simple to administer. Many of the simpler charge approaches, based on weight, volume, or length of payload, failed to account for changes in launch vehicle capability with altitude and inclination, and therefore were unsatisfactory relative to the fair share criterion. Charging payloads in proportion to the propellant used proved to be a complex, multipath computation and did not rate well relative to simplicity of administration. It was shown that the transportation of the upper stage by the Shuttle should be charged to the payloads using an upper stage. Recovery of transportation costs for each flight was the lowest risk approach relative to recovering costs but the payload transportation costs could not be predicted satisfactorily on this basis.

Payload volume is important for STS charges when considering multiple payloads. The cube rule approach was found to be best in accounting for payload volume. (The cube rule states that a payload shall be charged by weight or volume, depending on which is more critical relative to the launch vehicle constraints.) The implementation is explained in the User Charge Analysis volume of the final report for Study 2.2.

A composite charge approach combining a unit, or minimum, charge with a charge proportional to payload load factor proved to be the most satisfactory relative to the seven criteria. The composite approach rated high against the criteria when discounts were given for payloads sharing the flight leg and payloads returning to earth. The discount for flight leg sharing tends to encourage multiple payloads; thus, multiple payloads are needed to maintain a high load factor for the STS, particularly on ascent flights. The discount for payload return charges tends to encourage payload return for reuse, thus increasing the STS load factor on the return flight leg.

It is recommended that the composite charge approach be studied in more detail by NASA. Factors that should be considered in such a study are contained in the final report.

5.2 BUSINESS RISK AND VALUE OF OPERATIONS IN SPACE (BRAVO)

5.2.1 Objective

The objective of the BRAVO effort was to develop, document, and test a tool for the analysis of potential space users' problems.

5.2.2 Approach

The BRAVO tool provides a means for rapidly analyzing an advanced space application such as communications, space-generated power, and earth observations to assess its cost effectiveness. A direct comparison is made between space and terrestrial systems accomplishing the same function at equal risk in the Shuttle era. Because it was designed to stimulate potential users of space in the Shuttle era into examining space-based versions of their applications, it normally uses Shuttle launch vehicle cost and performance data and was not intended to provide a means of evaluating alternative future launch vehicles. The work accomplished during FY 74 is an extension of the BRAVO effort reported last year. The BRAVO analysis capability has been expanded, and additional test cases have been completed for the Solar Cell Power Satellite, a DOD communications satellite system (DSCS-II), and the GSFC Earth Observation Satellite. The BRAVO results are being compared with contractor study results on these space systems.

The end result of a BRAVO analysis is illustrated in Figure 5-1. The economic advantages or disadvantages can be measured in many ways at the end of an analysis. The cumulative cash flow over the period of installing and operating a particular system to meet an expected demand measures the return to the user on his investment in terms of cumulative cash and also shows the peak deficit cash flow encountered. Cash flow can be presented in either constant dollars or current (inflated) dollars. Both are usually of interest.

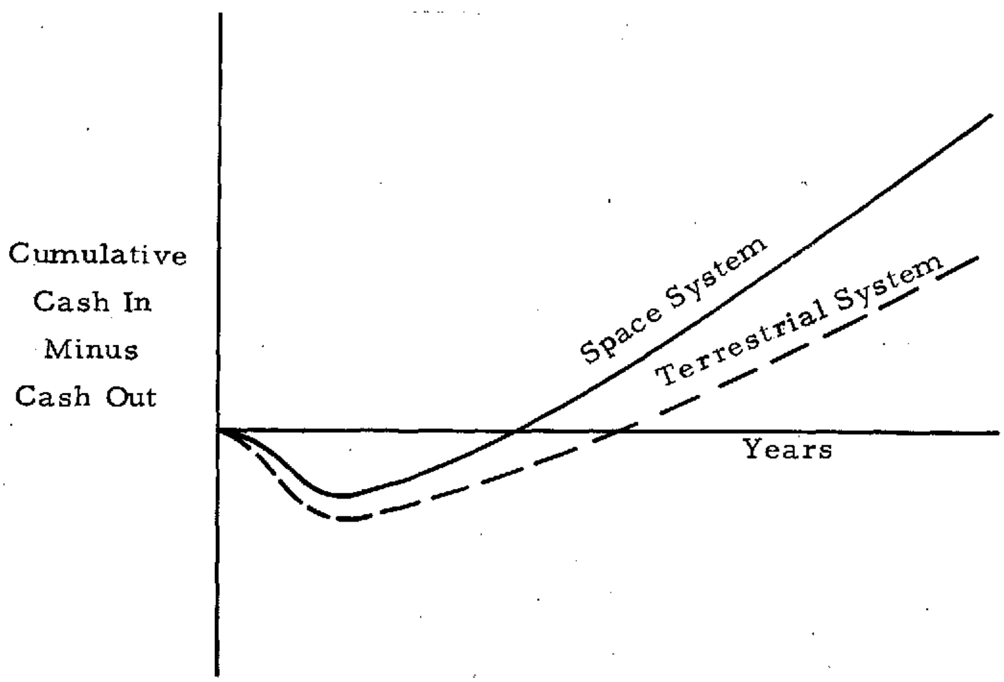


Figure 5-1. Cash Flow at Equal Demand, Equal Revenue and Equal Risk

5.2.3 Results and Conclusions

In FY 74 the BRAVO capability for analysis of earth observations was expanded. The techniques for mission equipment selection in the space system analyses and the terrestrial system analyses were improved in the earth observation area. The capability to analyze on-orbit service was added to BRAVO. Major changes were made to satellite synthesis, STS accommodation and traffic analysis, and space system risk and optimization analysis in the space system analysis in order to analyze satellite design and operation in an on-orbit service mode. The cost-effectiveness analysis techniques were improved. Economic scenarios and predictions for long-term projects have been put on a firm basis, utilizing work accomplished on a subcontract to ECON, Inc. The techniques for economic analysis were computerized.

The testing of the BRAVO capability continued. The cost effectiveness analysis was completed for a power generating satellite using solar cells (A.D. Little concept). The Solar Cell Power Satellite analysis tended to validate BRAVO, since the results compared well with the NASA-sponsored study by A.D. Little and Associates. This favorable comparison of BRAVO and contractors' results was similar to the results of the first BRAVO test case run in FY 73 on the Intelsats of the 1980's, in which the BRAVO results were in general agreement with Comsat Corporation data, as reported last year in the Study 2.4 final report.

An additional set of BRAVO analyses was initiated on 30 August to provide NASA with data on alternate ways to use the Shuttle/Earth Observation Satellite (EOS), thereby assisting NASA in selecting the best way to operate the EOS with the Shuttle. This analysis will be reported in ATR-74 (7342)-1, Volume III, Part 5, upon completion.

The BRAVO tool provides NASA with a powerful and rapid means of accomplishing space system economic analyses by comparing space systems and terrestrial systems capable of performing the same user task.

5.2.4 Recommendations for Future Work

It is recommended that NASA set up a BRAVO analysis capability in-house with enough independence so that unbiased, auditable analyses can be accomplished.

5.3 STANDARDIZED SUBSYSTEM MODULE STUDY

5.3.1 Objective

The objective of this study was to provide NASA/MSFC with the capability to perform capture/cost analyses of payloads constructed from standardized modules.

5.3.2 Approach

The definition of STS payloads for MSFC capture and cost analysis, using The Aerospace Corporation capability transferred to MSFC in FY 73, is currently limited to the following types of payloads: current design expendable, current design reusable, low-cost expendable, and low-cost reusable. The need to analyze standardized module payloads as a potential type of payload for the STS has been recognized for some time, but funding to do this analysis was not available until this year.

An initial set of standardized module designs was obtained from Study 2.1 in March of 1974. The characteristics of these modules were reviewed and the number of different modules reduced in order to obtain cost reductions by increasing the number of applications of each module. The study developed key characteristics which would be used to determine the applicability of each module to new satellites. Four reference satellites were then synthesized using the standardized modules to obtain the design characteristics required for each satellite. The four reference satellites were the Synchronous Equatorial Orbiter (SEO), the Orbiting Astronomical Observatory (OAO), the Earth Observation Satellite (EOS), and the Domestic Communications Satellite. The baselines for the reference satellites were the same baselines which were used in the Lockheed Low Cost Satellite Study.

Cost estimates and weight estimates were then made on the four reference satellites and weight and cost factors estimated for each. These weight and cost factors were put into a form in which they could be applied routinely as a part of the automated capture/cost analysis techniques at MSFC.

5.3.3 Results and Conclusions

The gross weights of the standardized subsystem configurations of three of the four reference satellites (OAO is the exception) fall between those of the current design modified for reuse and the "low-cost" configurations. Modularization and overkill due to standardization generally cause increased weight, but there are cases in which the weight actually decreases.

Using standardized modules, satellites designed for servicing on orbit can be configured in different ways to be compatible with the mission equipment. This flexibility provides independence from the service unit configuration selection. One configuration has all the modules facing in one direction, allowing the mission equipment to be mounted on the sides and opposite face. If the modules face out on the four sides, the mission equipment can be mounted on the top and/or bottom faces. A third configuration has modules mounted on a ring structure.

5.3.4 Recommendations for Future Work

It is recommended that NASA sponsor the development of a generalized capability to analyze the application of standardized hardware to future spacecraft. This should result in a computerized approach to building up satellites from standardized hardware--either components and assemblies, or modularized subsystems.

6. SYSTEMS COST/PERFORMANCE ANALYSIS (STUDY 2.3)

As the space program matures into an applications industry, greater emphasis will be placed on improving the ability to predict the effect of program requirements on cost and schedules. Cost estimating techniques that give greater insight earlier in the program cycle are required. As a step in this direction, this study was initiated to identify and quantify the interrelationships between and within the performance, safety, cost, and schedule parameters for unmanned, automated payload programs. These data would then be used in support of the overall NASA effort to generate program models and methodology which would provide the needed insight into the effect of changes in specific functional requirements (performance and safety) on the total vehicle program (cost and schedule).

This year's study had three objectives. The first objective was to refine and improve the cost/performance methodology which was developed during the preceding fiscal year's study. The second study objective was to then apply the cost/performance methodology to the following vehicle subsystems: Stabilization and Control, Auxiliary Propulsion, Communications, Data Processing and Instrumentation, Electrical Power, Thermal Control, and Structure. The product of this effort was the Systems Cost/Performance Model. The third objective was to implement the Systems Cost/Performance Model as a digital computer program which could operate on the MSFC Univac 1108 with only minor modifications necessitated by differences between the Aerospace CDC 7600 and the MSFC Univac 1108. The resulting program would be used to perform initial program planning, cost/performance tradeoffs, and sensitivity analyses and could be used for mission model and advanced payload studies.

6.1 APPROACH

One of the first tasks was to determine the functions performed by each subsystem and by specific hardware types within each subsystem.

Interfaces between subsystems determined some of the functions to be performed. The definition of functions had to be complete, since subsystem designs are generally related directly to the functions they are required to perform.

Block diagrams, consisting of equipment types used in each configuration and illustrating the functions performed by the equipment, were developed for all generally used subsystem configurations. Since there may be an infinite number of block diagram variations, block diagrams were established that were valid for most designs.

A design algorithm was developed which selected preconfigured subsystem designs satisfying the input requirements. This implies that, as part of the vehicle design algorithm, a complete set of alternative designs has been established from which to choose. Having selected an acceptable design, the hardware required to implement the design is selected from available off-the-shelf hardware listed in the data base. Obviously, the model must be capable of differentiating between hardware components of the same type and determining which hardware component has the characteristics to satisfy all of the requirements. To have a workable algorithm, the input data required to select a design and size the necessary equipment were established. These data, which are familiar to the payload designers (i.e., orbit altitude, pointing accuracy, satellite lifetime, reliability, etc.) are inputted and then processed to select specific system designs. The input data include subsystem performance requirements, interface requirements, and other data necessary to make design decisions.

A data base consisting of off-the-shelf hardware was established using data for each hardware component. The data for each component contains sufficient information to allow the equipment selection algorithm to select specific pieces of equipment and to provide the necessary output data. Cost data were based on seven specific satellite programs.

The Systems Cost/Performance Model was implemented as a digital computer program. The program was written in the language of

Fortran IV, as adapted to the CDC 7600 computer and the Univac 1108 computer. The program includes the Systems Cost/Performance Model and the related data base.

Two forms of model checkout were performed. The first was a set of computer runs to ensure that both the logic and arithmetic models were accurate and complete and that all submodels were interfacing properly. The second set of computer runs was limited to a few special runs, selected for the purpose of comparing the Systems Cost/Performance Model against other existing models and actual payload programs.

6.2 DISCUSSION

The user of the Cost/Performance Model (as currently programmed) must supply certain program data which would normally include the payload performance requirements as well as general information necessary to select a payload design. The technical portion of the model consists of a two-step process: the first step is to select subsystem configurations which are acceptable to the user, and the second step is to select equipment from a data base to mechanize the subsystem configuration. The reliability portion of the model adds redundancy to the design so that the reliability requirements are met. The resulting output of the technical model is a number of payload designs which meet or exceed the input requirements and which are specified at the component (assembly) level in the subsystems. The cost and schedule to design, build, and operate each payload design are estimated by summing up the individual cost and schedule allocations based on each end item assembly specified as part of the particular design.

The model selects equipment for a specific design in one of three ways:

a. Most equipment is selected from the data base on the basis of technical performance.

b. Some equipment which cannot be differentiated on the basis of technical performance is simply called up from the data base on a first-called basis in order to provide a complete design description.

c. Certain equipment is not amenable to cataloging in the data base. This equipment is identified and specific parameters are determined. Examples include the wiring harness and the Thermal Control Subsystem components.

As a result of satisfying the input performance requirements, a finite number of designs are established by the Cost/Performance Model. The calculated reliability of each particular design is evaluated against the requirement provided as the model input. If it does not meet the specified reliability level, a search for the least reliable element is initiated. Upon identification, it is paralleled by an identical unit, and the system reliability is recalculated. The evaluation and paralleling process continues until the reliability exceeds the specified requirement.

The Cost Model consists of cost equations which process cost information associated with each subsystem component. This costing technique requires each component to have cost information stored in the data base. The Cost Model adds up the cost information for every piece of equipment (component) selected from the data base. Cost Estimating Relationships (CERs) are used to estimate the costs for six components which were not amenable to cataloging.

The non-recurring cost for each component takes into account redundancy and inflation. The average recurring cost for each equipment component is adjusted to account for labor, materials, redundancy, and inflation. If more than one unit is to be built, a learning curve is used to account for reduced unit cost as additional quantities are built. The total non-recurring cost is the sum of the non-recurring costs for all of the system components. Total recurring cost is a function of the equipment quantities and the appropriate average recurring costs. The total spacecraft cost is obtained by summing the total recurring and non-recurring costs and then adding in the mission equipment cost and contractor's profit.

In general, the estimates of the schedule lead times are functions of the hardware selected by the Cost/Performance Model. The schedule lead times are estimated in a manner similar to that used by the Cost Model. The justification for such an approach lies in the fact that specific equipment components provide an indication of the complexity of the system and, hence, a measure of the time required to complete the activities associated with the system.

6.3 RESULTS

The major accomplishment of this study was the successful development of a Systems Cost/Performance Model which has the capability to synthesize automated, unmanned spacecraft configurations based on the system requirements and a list of equipments at the assembly level. In addition, the Model estimates cost and development schedule data for each of the configurations selected. The Model was programmed for operation on a digital computer, successfully checked out at The Aerospace Corporation, and put into an operational status where it was then used to make several sample calculations on both CDC 7600 and IBM 360 computers. The program, however, is not yet operational at MSFC.

Sample runs were made for several performance and safety requirements for one operational Air Force satellite program and for baseline configurations of the NASA ERTS-A and OSO-I satellites. Table 6-1 compares actual stabilization and control (S&C) subsystem weights for one of these satellites with weights from a design generated by the Model from component (assembly) data in the data base. Table 6-2 presents a comparison of the cost estimates for this satellite generated by the Systems Cost/Performance Model and by conventional subsystem CERs. The actual total program costs were approximately 18 percent lower than those computed by the Cost/Performance Model. The cost estimates produced by conventional subsystem CERs agreed more closely with the actual costs than those generated by the Model because the curves for the CERs passed through the actual data points for the example Air Force satellite. In general, the current computer program gives high cost values for spin-stabilized satellites and low values for three-axis stabilized satellites with the cost data in the computer program. Improved

Table 6-1. Example Satellite S&C Weight Comparison

Equipment Type	Wt in lb.	
	Selected by Cost/Perf. Model	Actual Satellite Equipment
Despin Mechanical Assembly	21.8	21.6
Despin Electronics Assembly	8.5	8.3
Valve Driver Assembly	4.2	1.4
Sun Sensor Assembly	11.2	2.8
Nutation Damper	4.0	4.0
Gimbal Electronics Assembly	6.2	6.2
Control Timing Assembly	7.4	7.3
Bi-Axial Drive Assembly	14.3	14.3
Earth Sensor Assembly	7.3	4.1
S&C Power Converter	5.1	None used

Table 6-2. Total Satellite Cost Estimate Comparisons
(Thousands of Dollars)

	Cost/Performance Model	Subsystem* CERs
DDT&E	(60, 359)	(61, 610)
Spacecraft	28, 059	29, 310
Mission Equipment	32, 300	32, 300
Investment	(61, 571)	(49, 610)
Spacecraft	41, 531	29, 570
Mission Equipment	20, 040	20, 040
Operations	(2, 366)	(4, 540)
Contractor Fee	(5, 037)	(4, 439)
Total	(129, 333)	(120, 199)

* The subsystem level cost estimates were generated by the current payload cost estimating model, PALCM.

cost data were developed late in the study to reduce these variations but were not included in the computer program delivered to NASA because of insufficient time to perform the reprogramming. It is planned to accomplish this reprogramming early in the FY 75 study.

At the same time, the model provides insight into the effect of other variables on payload cost. Figure 6-1 presents the satellite cost estimates generated by the Model as a function of payload reliability. The cost estimates are relatively insensitive to changes in payload reliability at low levels due to the inherent reliability of a single string system. However, attempts to increase reliability substantially cause costs to turn upward, reflecting the diminishing returns and increasing costs of adding redundancy. Further increase of the payload reliability is inappropriate due to the fixed mission equipment reliability. The model is simply pointing out that either of two approaches are necessary to increase reliability further: (a) make the mission equipment more reliable, or (b) change the entire payload design to a more reliable, but less redundant, concept. The cost curves generated by the Model provide more insight than the current CER approaches, which are restricted to straight-line approximations about the nominal value.

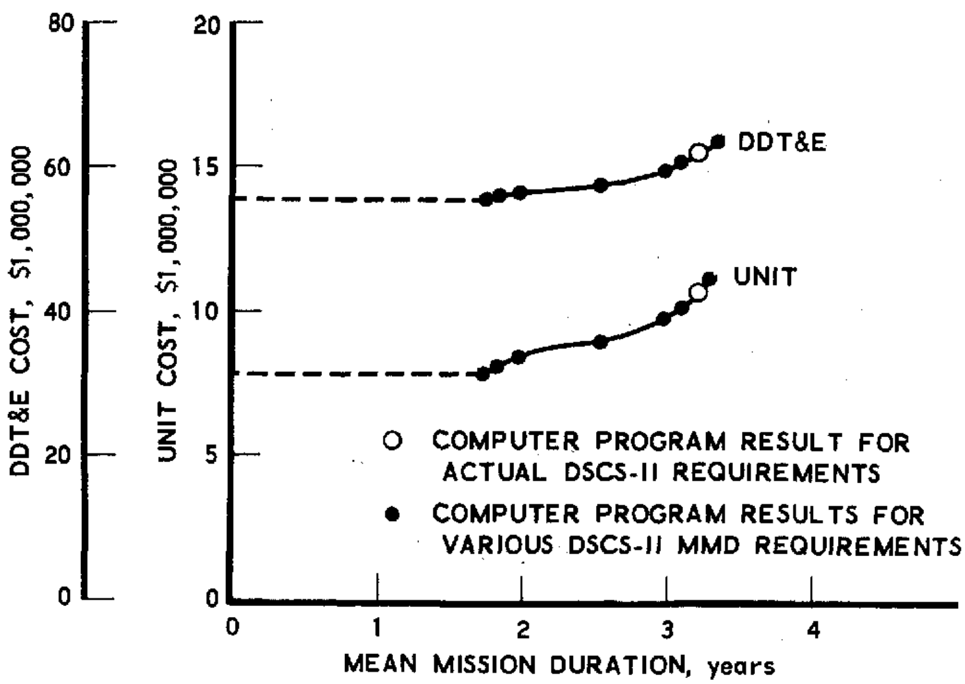


Figure 6-1. Cost Versus Extended Life

6.4 CONCLUSIONS

In general, the Cost/Performance Model as programmed equals the performance of "top-down" models. The Model uses a "bottom-up" approach, and, therefore designs the payload at the assembly level. Greater accuracy is achieved by the very nature of the more detailed design. This accuracy will be reflected in the cost and schedule model estimates. A second attribute of the Cost/Performance Model is the completeness of the design specified. Pieces of equipment are not forgotten, and redundancy is automatically included in the specified design. In addition, the impact of all subsystem interfaces and interactions is properly modeled. The net result is a payload design which is as accurate and complete as from a pre-Phase A study and which is available to the Cost/Performance Computer Program user almost immediately.

Because of the detailed nature of the Model, the potential uses of the System Cost/Performance Model exceed those for "top-down" models. The following uses of the model are suggested:

a. Establish specific payload designs and the related costs and schedule to meet given requirements.
b. Determine the sensitivity of payload design, costs, and schedules to changes in requirements.
c. Perform trade studies to identify optimal designs.
d. Identify low cost designs using a data base consisting of standardized off-the-shelf equipment.
e. Perform modularity studies by modifying the Model to assign equipment to modules.

The Model should become a more and more useful tool in terms of preliminary program planning and in actual program management as it becomes more fully developed and as the data base is expanded to include more equipments.

The current Cost/Performance Model is restricted to modeling unmanned, automated payloads in earth orbit. More importantly, the current Model is constrained in the range of payload designs it can generate by the limited number of equipments in the data base. Accuracy of the spacecraft cost estimates is limited by the relatively small amount of cost data which could be reduced and processed as part of this year's effort to support the data base cost entries.

Even with these limitations, the computerized Cost/Performance Model provides the user with a relatively complete satellite design (excluding mission equipment) together with appropriate programmatic data in a running time of less than two minutes. Development of the design and programmatic data would require considerable effort if it were to be performed manually.

6.5 RECOMMENDATIONS

It is recommended that further effort be directed towards eliminating the deficiencies listed in the previous section.

In addition, the Cost/Performance Model should be operated to the maximum extent possible to determine its overall utility to assess new program activities. This latter recommendation is especially important if the strengths and weaknesses of the Model are to be objectively evaluated.

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