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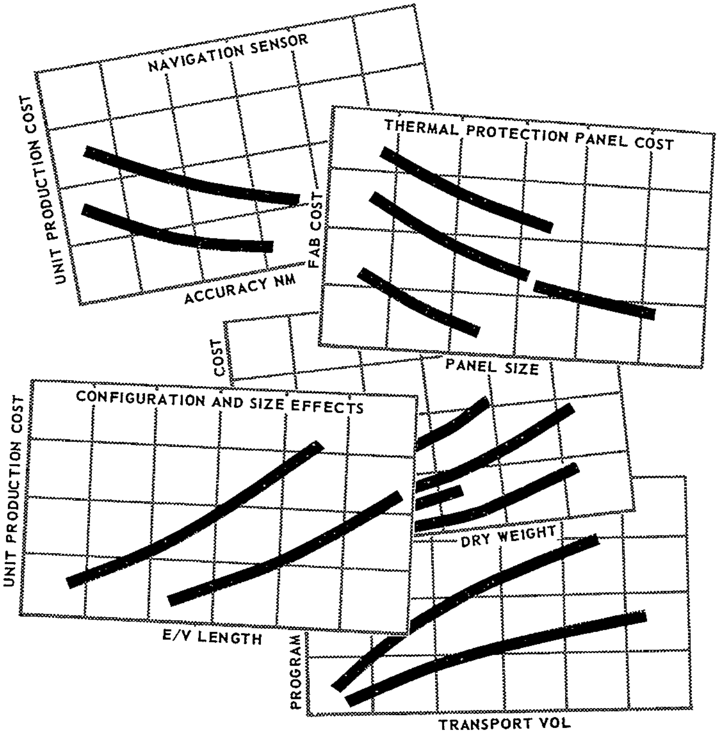
REPORT MDC E0005

OPTIMIZED COST/PERFORMANCE DESIGN METHODOLOGY



VOLUME III CONCEPT ANALYSIS AND MODEL DEVELOPMENT

BOOK 1 CONCEPT ANALYSIS

CONTRACT NAS 2-5022

MCDONNELL DOUGLAS CORPORATION

SERIAL NO. 91

REPORT MDC E0005

1 SEPTEMBER 1969

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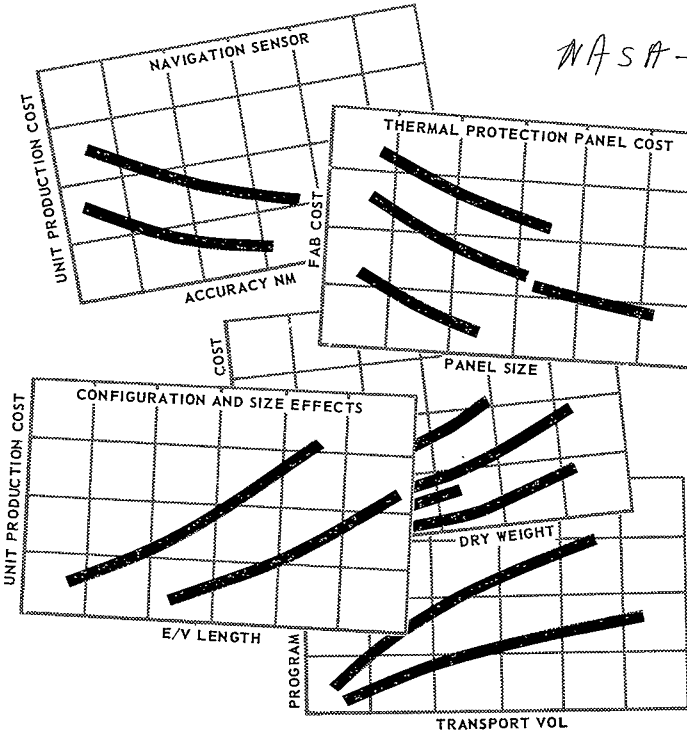

VOLUME III CONCEPT ANALYSIS AND MODEL DEVELOPMENT

BOOK 1 CONCEPT ANALYSIS

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FOREWORD

This report is submitted to NASA, the Mission Analysis Division of OART, as part of the final reporting on Contract NAS 2-5022, Optimized Cost/Performance Design Methodology of Orbital Transportation Systems. This twelve month study was initiated in July 1968 and was performed in two general phases: a data review and analysis phase and a system evaluation phase. The reporting of the study is organized in three volumes but includes several books in Volumes 2 and 3. Volume 1 is a short summary of the complete study, Volume 2 covers the phase 1 data review and analysis, and Volume 3 covers the phase 2 system evaluation. The Study Manager was L. M. McKay; the major Task Leaders were P. T. Gentle, V. E. Henderson, L. E. Smith, and A. D. Trautman. The NASA Technical Monitor was C. D. Havill.

McDonnell Douglas gratefully acknowledges the support and cooperation of many companies which supplied information to the study. A list of the companies and their area of contribution is included in Volume II, Book 1, Appendix A.

ABSTRACT

The broad objectives of this study were to gather historical cost and performance data, organize and analyze the data so that cost estimating relationships could be developed, and evaluate several system concepts for space logistics support.

The primary source of historical cost data was the Gemini and Saturn Programs and cost estimating relationships draw extensively on this experience. A range of reuse concepts were evaluated and optimum (least cost) concepts defined for a variety of program options. These include variations in such things as crew size, cargo capacity, program requirements, etc. for either ballistic or lifting body (M2-F2) entry vehicles.

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ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

1. INTRODUCTION - The Optimized Cost/Performance Design Methodology study seeks to provide a method of using cost as a basic design parameter in identifying and defining more economical space transportation systems. This study was performed in six tasks as shown in Figure 1-1. Task 1 involved developing the cost data, organizing the data by categories, and developing cost estimating relationships. Tasks 2 and 3 developed the requirements and the physical and functional characteristics of the alternate spacecraft subsystems and operations. An analytical cost model was formulated in Task 4. Task 5 developed the logic, data, and methods for systematically varying the design and operational specifications of each vehicle configuration. Using the data and tools developed in the other tasks, Task 6 determined the economically optimum design and operational philosophies; sensitivities to program size, launch rate, payload size; and the problem area and technology limitations.

The work performed in Task 6 is reported here. The objectives of this task were to:

1. Synthesize systems for cost analysis using the alternate parameters defined in Tasks 2 and 3.
2. Compare and evaluate the synthesized systems to optimize the spacecraft and operations.
3. Determine sensitivity of program costs as program parameters are varied.

The data resulting from the evaluation performed in this task are based on the analysis of historical programs and thus, reflect the development and operational philosophies employed on these programs. However, the data obtained from the cost model is broken down in sufficient detail that the analyst has complete visibility of how the costs accrue and can apply his own adjustments to reflect a cost reduction philosophy.

STUDY TASK FLOW

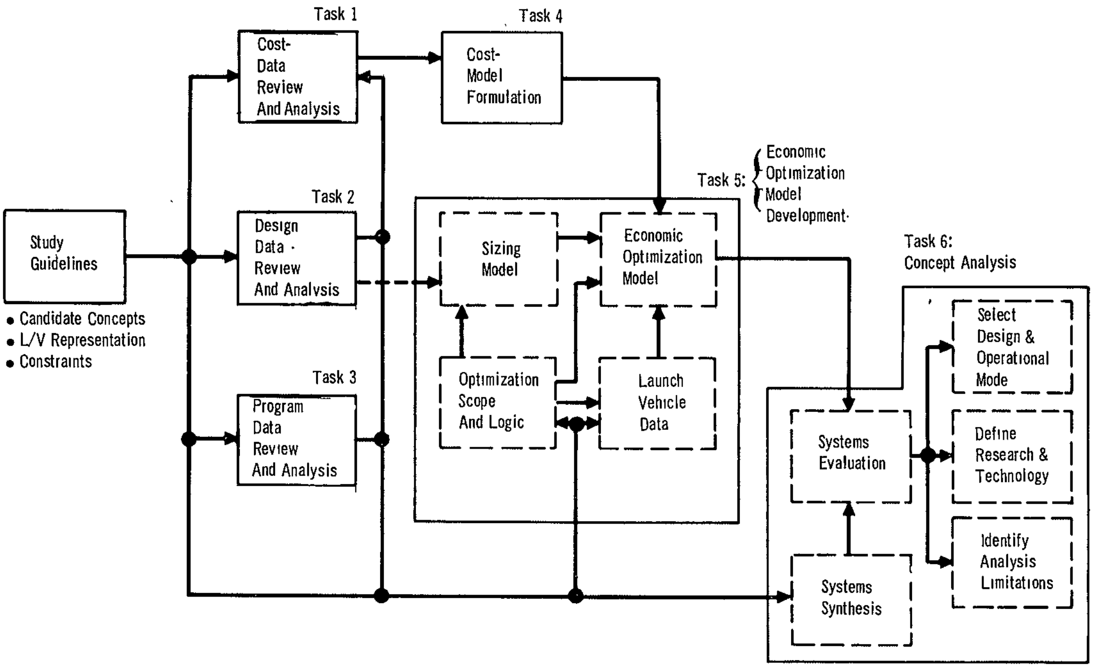


Figure 1–1

2. SUMMARY - The Task 6 effort, Concept Evaluation, of the Optimized Cost/Performance Design Methodology study, has synthesized logistics systems for the resupply of an orbiting space station analyzed these systems and on the basis of total program cost, optimized certain parameters and determined sensitivity to other parameters, defined critical problems and identified uncertainties and the analysis limitations.

Using the alternates defined in Tasks 2 and 3, systems for resupply of an orbiting space station in a 300 na.mi. orbit were synthesized. These systems included both ballistic and lifting body (M2-F2) entry vehicles with reuse concepts ranging from completely expendable to completely reusable vehicles. These systems were analyzed using the Economic Optimization Model developed in Task 5 to determine the effect of various system parameters on total program cost for a fixed program size. Cargo weight per launch and certain operational modes were optimized. Sensitivity of program cost to other operational modes, crew size, cargo density, number of launches, subsystem elements, return time, orbit inclination and number of landing sites were also evaluated.

The system analysis produced much additional data, some of which was assembled and presented in this book. This includes sensitivity of development cost to spacecraft dry weight; program and operations cost to number of launches; program cost to annual cargo volume; and, spacecraft development cost to spacecraft dry weight. Special attention is called to the fact that the cargo weight (discretionary payload) was used in deriving the $/lb data presented in Section 5.2.

The data resulting from this study are based on analysis of historical programs and reflect the development and operational philosophies which were employed in these programs. Many suggestions are currently being made as to ways to effect cost reductions; most of these are valid suggestions and will have a significant affect on cost if they are implemented. Furthermore, it is recognized that the cost of space transportation must be reduced in order to have a viable program. However, no data are available to use as a basis for projecting the effect of these suggestions and it is not clear which cost reduction approaches will be used. Therefore, it was felt to be more meaningful to provide the advanced planner with a consistent set of comparative data based on historical facts than to include estimates which cannot be substantiated and which vary between any two individuals. The data from the cost model is broken down in

sufficient detail that the analyst has complete visibility of how the costs accrue and can apply his own adjustments to reflect a cost reduction philosophy.

GROUND RULES AND ASSUMPTIONS

3. GROUND RULES AND ASSUMPTIONS - The study ground rules and assumptions listed below are those that have an effect on the costs shown in this book.

1. The size of the re-entry spacecraft will be varied over the range of crew sizes from two to twelve men and over the range of return cargo capacity of 200 to 2000 lb occupying from 100 to 400 cu ft.
2. Cargo space, either integral with the entry vehicle or in an expendable cargo module, will be provided for delivered cargo over the range of 20,000 lb to 200,000 lb with density variations between 5 and 10 lb/cu ft.
3. Boost capability will be provided from both ETR and WTR into a 100 na. mi. orbit for inclinations of 50 deg, 70 deg, and polar. An orbital propulsive capability will also be provided to accelerate into a rendezvous orbit of 300 na. mi. altitude with a maximum plane change of 1 deg, to dock, and to initiate recovery.
4. During orbital storage, all spacecraft subsystems will be in a quiescent state with all support requirements being supplied by the space station.
5. The cargo will not require any support from any vehicle subsystems other than provisions for mounting and retention.
6. In assigning the reliability budget, it will be assumed that the probability of mission success for the spacecraft and the upper stage shall be 0.95.
7. The launch vehicle diameter will be infinitely variable with no upper limit within the range of spacecraft sizes being investigated.
8. Historical Gemini and Saturn S-IVB data can be used as a basis for estimating future spacecraft programs.
9. The actual Gemini and Saturn S-IVB development history can be used to formulate realistic development plans for new spacecraft systems.
10. The Saturn S-IVB development history is representative of the development required for a spacecraft having integral upper stage propulsion.
11. The nominal wait time in orbit prior to return will be a maximum of 24 hours.
12. The exact composition of any given subsystem has little effect upon the total development time for qualification of all subsystems.

13. The historical development schedule of the J-2 engine is representative of an integral upper stage propulsion system engine schedule.
14. Vertical or horizontal land landing technology is developed by other preceeding programs.
15. The development program is defined to include the first five flights - unmanned and manned combined.
16. The lateral range (or cross-range) capability (-3σ) of the ballistic vehicle will be 150 na. mi, and of the M2-F2, 600 na. mi.
17. Recovery sites will be existing sites within the continental U.S. unless a new, ideally located site is specified.
18. The following mid-calendar 1969 labor rates which include direct labor, overhead, G. & A. & overtime premium (but exclude fee) shall be employed in translating man-hour estimates into cost.

	In-Plant	Remote Site
Engineering and Testing	\$20.00/hr	\$20.00/hr
Production (including planning and quality assurance)	\$11.80/hr	\$13.00/hr
Tooling	\$13.40/hr	
Remote Site Composite Rate		\$16.00/hr

19. All other program costs shall be adjusted to mid-calendar 1969 dollars using a 5% annually compounded factor.
20. A 10% fee is to be used at the program phase level.
21. A 1963 technological base shall be assumed for both the Gemini and Saturn S-IVB programs.
22. The total program cost includes the NASA cost for program management, the prime contractors cost of managing the project segments and the contractors fee.
23. The launch rate is a constant number per year over the life of the program with no buildup in rate in the early portion of the program.
24. The development and operational philosophies are based on those of historical programs.

4. SYSTEM SYNTHESIS - Before system evaluation can take place, the systems must be synthesized. This requires definition of all the elements of the system: the program parameters, the operational modes, the space vehicle configuration, and the spacecraft subsystems. Each element must have one or more values or configurations. Once these have been defined they must be combined in a logical manner to give systems that, when evaluated, gives the results needed to meet the objectives of the evaluation.

4.1 System Alternates - All of the system elements, their range or alternates, are defined in Volume II of this report. They are repeated here for the readers convenience in Tables 4-1 through 4-3. Table 4-1 shows the nominal value and the range for each of the program elements. These establish a range of vehicle sizes, launch rates, and propulsion requirements. Table 4-2 lists the alternates for the operational modes. These range from Gemini state-of-the-art to post Apollo. Table 4-3 shows all the vehicle parameters including spacecraft configuration, subsystem definitions, and launch vehicle configuration. The alternates range from completely expendable to completely reusable vehicles, modular to integral configurations, present to advanced subsystem technology, and simple to complex subsystems.

Since this study emphasized the space craft with the launch vehicle treated parametrically, the definition of the spacecraft is more complex. There are two expendable two stage launch vehicles for those spacecraft without integral upper stage propulsion; two expendable and one reusable single stage launch vehicles for those spacecraft with integral upper stage propulsion.

4.2 Synthesis of Systems - With all the variables given above literally millions of systems could be defined, each different from all the others in some way. Table 4-4 lists all the systems that were synthesized. These combinations of alternates for the system elements were selected to show trends as these elements are changed. These systems show the effect on program costs of vehicle configuration, reuse concept, cargo weight per launch, total cargo to orbit, number of launches, crew size, and cargo density. The effects of orbit inclination, return time and number of landing sites on total program costs are also shown. Various operational concepts as well as the effects of subsystem technology can be evaluated.

TABLE 4-1

SYSTEM ALTERNATES

Program Parameters

PARAMETER	NOMINAL VALUE	RANGE OR ALTERNATE
Length	10 Years	5-10 Years
Total Cargo Delivered	2,500,000 lb.	2.5 to 30 million lb.
Orbit Inclination	50° from ETR	70° from ETR
		90° from WTR
Crew Size	9	2 to 12
Orbit Stay Time	1 Day	1 to 90 Days
Cargo Weight/Launch	20,000 Lb.	20000 to 200000 lb.
Return Time	24 Hours	2 to 24 Hours
Cargo Density	$10\#/ft^3$	$5\#/ft^3$

TABLE 4-2

SYSTEM ALTERNATES

Operational Parameters

PARAMETER	ALTERNATES	ALTERNATE NUMBER	VEHICLE APPLICABILITY
Launch Operations	Buildup & Checkout at Launch Site	1	All
	Integrated Checkout at Pad	2	All
AGE Approach	Semi-Automatic	1	All
	On-board Cehckout	2	B,C,D,E,F
Refurbishment Philosophy	Scheduled Maintenance & Testing (W/Hot Firings)	1	D,E,F
	Scheduled Maintenance & Testing (W/O Hot Firings)	2	B,C,D,E,F
	Limited Scheduled Maintenance	3	B,C,D,E,F
Refurbishment Site	Factory	1	B,C,D,E,F
	New Site	2	B,C,D,E,F
Recovery Mode	Land	1	All
	Water	2	IA
Recovery Site	Two New Sites	1	All
	Two Existing Sites	2	All
	Three Existing Sites	3	All
	Four Existing Sites	4	All
Transportation Mode	Water	1	All
	Land	2	A,B,C
	Air	3	A,B,C

TABLE 4–3

SYSTEM ALTERNATES
VEHICLE PARAMETERS

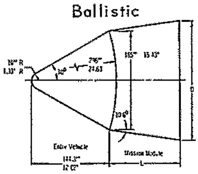
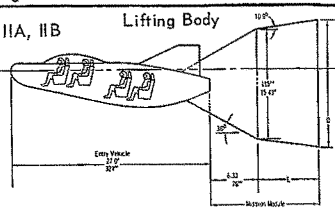
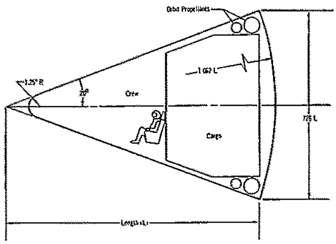
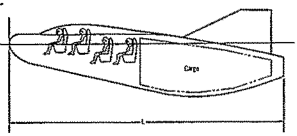
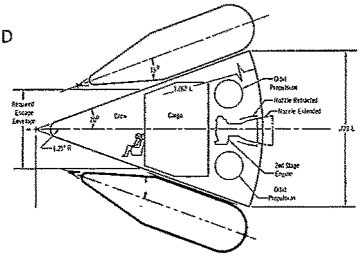
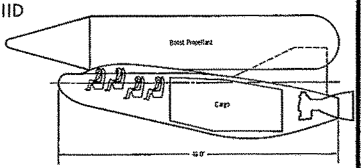
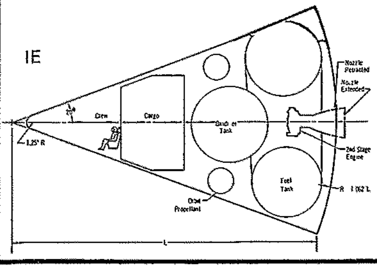
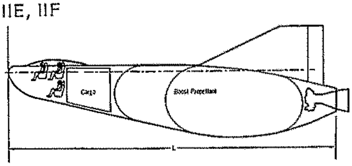
Reuse Category	Aerodynamic Configuration: Ballistic	Aerodynamic Configuration: Lifting Body
Modular Expendable and Reusable EV	IA IB 	IIA, IIB 
Integral Cargo and Propulsion	IC 	IIC 
Integral Propulsion Hardware with Expendable Tanks	ID 	IID 
Integral Upper Stage Boost (Expendable and Reusable 1st Stage)	IE 	IIE, IIF 

TABLE 4-3 (Continued)

SYSTEM ALTERNATES

Vehicle Parameters (Continued)

ALTERNATES		VEHICLE APPLICABILITY
SPACECRAFT SUBSYSTEMS STRUCTURE		
Methods of Construction	Materials	
Single Skin with Frames	*Aluminum	
*Sheet Stringer With Frames	Magnesium	
	Titanium	
Single Skin Corrugations With Frames	Steel	All
THERMAL PROTECTION		
Max. Allow. Temp. °F (See Note 1.)	Inner Shell Cooling	
400	*Passive	
1200	Passive/Active	All
1600		
2400		
*3100		
3500		

* Indicates Baseline

NOTE 1: Each temperature represents the upper operating limit for a particular material. All external surfaces that exceed the specified temperature use ablative panels for thermal protection. The remainder of the surfaces use all the lower temperature materials in the areas where there temperature limits are not exceeded. See Vol. II Book 1 for definition of materials.

TABLE 4-3 (Continued)

SYSTEM ALTERNATES

Vehicle Parameters (Continued)

ALTERNATES			VEHICLE APPLICABILITY
UPPER STAGE BOOST			
Propellant	Engine Design		
*O_2/H_2	*Bell		I/D,E and
F_2/H_2	Bell		II/D,E,F
Flox/CH_4	Bell		
Nto/A-50	Bell		
ORBIT MANEUVER			
System - Function	Propellant	Engine Groups	
A - All Functions	NTO/MMH	Single	I/A,B
△2 A - All Functions	NTO/MMH	Dual	All
A - Docking/AC B - Ascent/Phasing/Deorbit	NTO/MMH O_2/H_2	Single Single	I/A,B II/A,B
A - Docking/AC B - Descent/Phasing/Deorbit	NTO/MMH O_2/H_2	Dual Single	All
* A - Ascent/Docking/Phasing/AC B - Deorbit	NTO/MMH Solid	Single Single	I/A, B II/A, B
A - Ascent/Docking/Phasing/AC B - Deorbit	NTO/MMH Solid	Dual Single	All
A - Docking/AC B - Ascent/Phasing C - Deorbit	NTO/MMH O_2/H_2 Solid	Single Single Single	I/A, B II/A, B

△2 Baseline for C,D,E&F

TABLE 4-3 (Continued)

SYSTEM ALTERNATES

Vehicle Parameters (Continued)

ALTERNATES			VEHICLE APPLICABILITY
ORBIT MANEUVER (Continued)			
System - Function	Propellant	Engine Groups	
A - Docking/AC	NTO/MMH	Dual	All
B - Ascent/Phasing	O_2/H_2	Single	
C - Deorbit	Solid	Single	
ELECTRICAL POWER			
Ascent and Phasing Power	Re-entry Power		
* Batteries in MM	Batteries in EV		IA, IIA
* Fuel Cells and Batteries in EV, Reactant Supply in MM	Batteries in EV		IB, IIB
* Fuel Cells, Batteries and Reactant Supply in EV	Batteries in EV		IC thru IF IIC thru IIF
Batteries in EV	Batteries in EV		IA (Land Landing) IB thru IF IIA thru IIF
Fuel Cells and Reactant in MM	Batteries in EV		IA, IB IIA, IIB
HYDRAULIC SYSTEM POWER SOURCE			
Batteries			IIA, B
* Turbine			IIA, B,C,D,E,F
ENVIRONMENTAL CONTROL			
5 psi O_2 atmosphere - gaseous storage; Water boiler and LiOH in EV; Primary O_2			IA, IB, IIA, IIB
*5 psi O_2 atmosphere-gaseous storage; Water boiler and LiOH			IC, ID, IE, IF IIC, IID, IIE, IIF

TABLE 4-3 (Continued)

SYSTEM ALTERNATES

Vehicle Parameters (Continued)

ALTERNATES	VEHICLE APPLICABILITY
ENVIRONMENTAL CONTROL (Continued)	
5 psi O_2 atmosphere-cryo storage; Water boiler and LiOH	IC, ID, IE, IF IIC, IID, IIE, IIF
5 psi O_2 atmosphere-gaseous storage; Water boiler and LiOH in EV; Primary O_2 and H_2O in MM	IA, IB, IIA, IIB
5 psi O_2 atmosphere-cryo storage; Water Boiler and LiOH in EV; Primary O_2 and H_2O in MM	IA, IB, IIA, IIB
5 psi atmosphere-cryo storage; Water boiler, LiOH and primary O_2 in EV; Radiator and H_2O in MM	IB, IIB
GUIDANCE AND CONTROL	
* Single IMU, Computer, FCS (GC-1)	IA (Water Landing)
* Gimballed and Strap-down IMU (GC-2) Dual Computers, Single FCS	IC
* Gimballed and Strap-down IMU (GC-3) Dual Computers, Redundant FCS	IA (Land Landing), IB, IIA, IIB and IIC
* 2 Gimballed and 1 Strap-down (GC-4) IMU, Dual Computers, Redundant FCS	ID, IE, IF, IID, IIE, IIF
Advanced Concept of GC-1	IA (Water Landing)
Advanced Concept of GC-2	IC
Advanced Concept of GC-3	IA (Land Landing), IB, IIA, IIB and IIC
Advanced Concept of GC-4	ID, IE, IF, IID, IIE, IIF

TABLE 4-3 (Continued)

SYSTEM ALTERNATES

Vehicle Parameters (Continued)

ALTERNATES	VEHICLE APPLICABILITY
TELECOMMUNICATIONS	
Separate Systems (Gemini Type Concept) (TC-1)	
* Unified S-Band System (Apollo Type (TC-2) Concept)	
Unified S-Band System with Integral (TC-3)	
Rendezvous Ranging Capability	All
Same as TC-2 but with the use of Advanced Circuit Techniques	
Same as TC-3 but with the use of Advanced Circuit Techniques	
LAUNCH VEHICLE TYPE	
* 0 & 1st, 156 in. solid; 2nd, LOX/H_2	IA, B, C, IIA, B, C
1st, LOX/RP; 2nd, LOX/H_2	IA, B, C, IIA, B, C
* 260 in. solid	ID, E, IID, E
Saturn S1-C	ID, E, IID, E (Single Point)
* Reusable first stage	IIF

TABLE 4-4

SYSTEMS SYNTHESIZED FOR ECONOMIC ANALYSIS

PARAMETERS	ALTERNATES										
Spacecraft Configuration	IA	IB	IC	ID	IE	IIA	IIB	IIC	IID	IIE	IIF
Program Length	10 Years										
Total Cargo Delivered (Millions of Lbs.)	2.5	2.5 5 10 20 30	2.5	2.5	2.5	2.5	2.5 5 10 20 30	2.5 5 10 20 30	2.5	2.5 5.0 10 20 30	2.5
Orbit Inclination	50	50 70 90	50	50	50 70 90	50	50 70 90	50	50	50 70 90	50
Crew Size	9	2 6 9 12	9	9	2 6 9 12	9	2 6 9 12	9	9	2 6 9 12	9
Orbit Stay Time	1 Day										
Cargo Weight per Launch	Several Discrete Values Between 20,000 and 200,000 Lbs.										
Return Time (Hours)	24	2 6 24	24	24	2 6 24	24	2 6 24	24	24	2 6 24	24
Cargo Density (Lb/Cu.Ft.)	10	5 10	10	10	5 10	10	5 10	10	10	5 10	10
Operational Modes	All Applicable Alternates ⚠1										
Subsystem Alternates	Selected Applicable Alternates ⚠1										

⚠1 Except for ID and IID which used the baselines.

5. SYSTEM EVALUATION - System evaluation used the cost model developed in Task 5 to investigate the trends of program cost as the system elements are varied according to the system syntheses described in section 4.2. The initial evaluation was in the form of optimization of some of the parameters. Using these optimized parameters, the other parameters were varied to determine the sensitivity of the program cost to these parameters.

The program costs shown in the following figures, unless specified otherwise, are the total program costs which include the contractors fee, the prime contractors cost of managing the project segments and the NASA cost of managing the total program.

5.1 Total Program Cost Development - The parameters that were optimized as the first step in the system evaluation were the cargo weight per launch and the operational modes. The cargo weight per launch was done first, followed by optimization of the operational modes using the optimized cargo weights. These studies used baseline subsystems and operational modes and were done for all vehicle configurations except for the ID and IID (which were evaluated for only the 20,000 lbs of cargo size). The program parameters were the nominal values as specified in Table 4-1.

5.1.1 Optimization of Cargo Weight per Launch - Using the baseline program, subsystem and operational mode parameters, the cargo weight per launch was varied to determine the effect on total program cost. As shown in Figure 5-1 and 5-2 for the ballistic and lifting body vehicles, all vehicles exhibited a characteristic curve that gives a minimum program cost within the range of cargo weights of interest.

Figures 5-1 and 5-2 are based on a fixed program where 250,000 lb of cargo are delivered to orbit each year for 10 years. As a result the number of vehicles varies from 135 and 10 for the expendable and reusable configurations respectively at 20,000 lb cargo capacity to 28 and 3 at 100,000 lb cargo capacity. Thus, as the cargo weight per launch is increased and fewer flights are required to support the fixed program, the benefits from learning decreases. Some results for larger programs are discussed in section 5.2.2, showing the effect of fixed launch rates (variable total cargo delivered).

Launch vehicle costs account for from 36% to 50% of the total program costs for vehicles of 20,000 lb cargo capacity and from 55% to 60% for vehicles of 100,000 lb cargo capacity for those configurations with a separate launch vehicle. For the ballistic vehicle with integral upper stage boost and expendable first stage (IE), the launch vehicle costs range from 32% to 38% of total program costs; for the lifting body vehicle (IIE), this percentage is about 28%. For the lifting body vehicle with the reusable first stage, the launch vehicle costs range from 42% to 52% over the cargo range of 20,000 lb to 50,000 lbs. In general, the percentage is slightly higher for the ballistic vehicles reflecting their lower cost.

The sum of the fee and management costs for the spacecraft and launch vehicle range from 17% to 22% of total program cost over the range of cargo capacity from 20,000 lb to 100,000 lb. The fee and management cost percentage is relatively independent of spacecraft configuration and reuse category.

The land landing version of the expendable vehicles is more expensive than the water landing version because of the more sophisticated guidance required to effect a land landing and because of the gliding type parachute used for a horizontal landing. The expendable vehicles optimize at a higher cargo weight as would be expected because of the payoff in the investment cost with fewer vehicles.

The relative costs of the concepts as shown in figures 5-1 and 5-2 are primarily the result of three interacting factors: the vehicle size, the operations philosophy, and the launch vehicle cost. The IC curve diverges from the IB curve as the cargo weight per launch increases because, for a given cargo weight, the IC is always heavier as a result of the additional heat protection with the accompanying increase in propulsion requirements. This, in turn, requires a larger, more expensive booster, which, combined with the increase in refurbishment cost because of the larger spacecraft size, more than offsets the savings in investment of the cargo/propulsion module. The size of the IIE configurations, figure 5-2, is so large that besides a significant penalty for the expendable launch vehicle, the investment costs actually exceed the investment costs for the B configuration for this size program. It should be pointed out that the IIE configuration is not the most efficient vehicle for an upper stage and therefore, presents an overly pessimistic picture from what might be achieved. Some of the vehicle design characteristics are shown in section 5.1.3.

EFFECT OF CARGO WEIGHT PER LAUNCH ON TOTAL PROGRAM COST
BALLISTIC VEHICLES

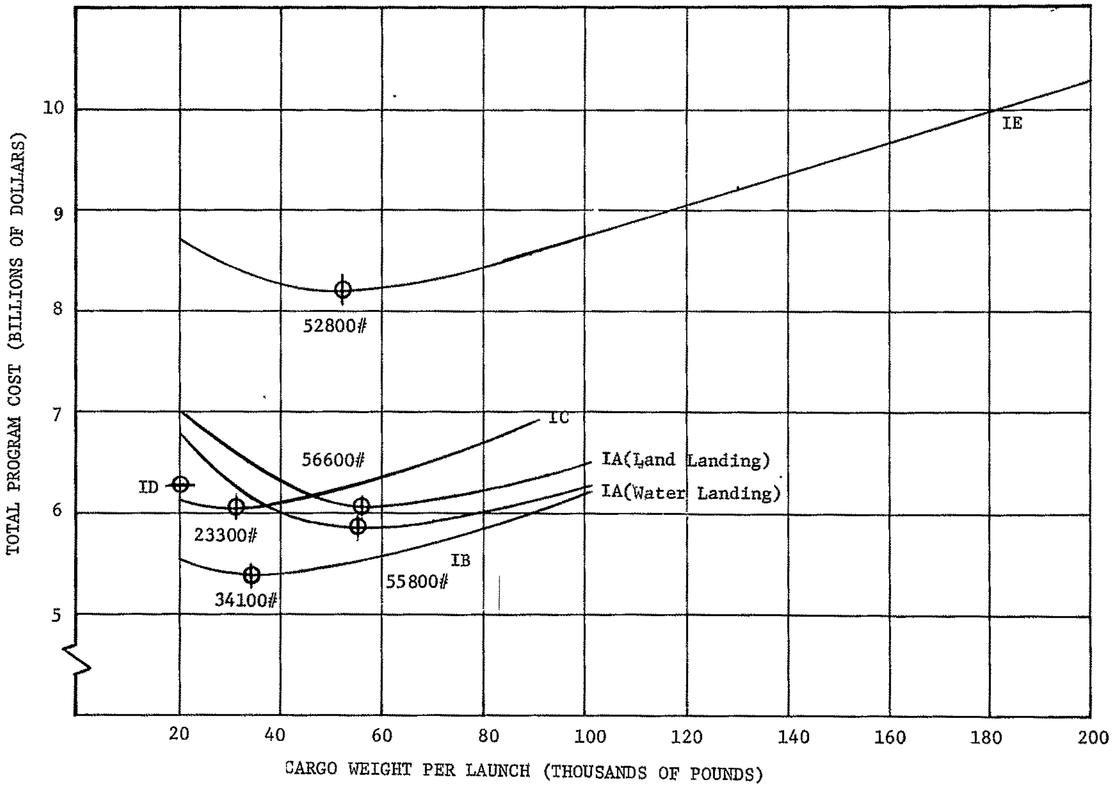
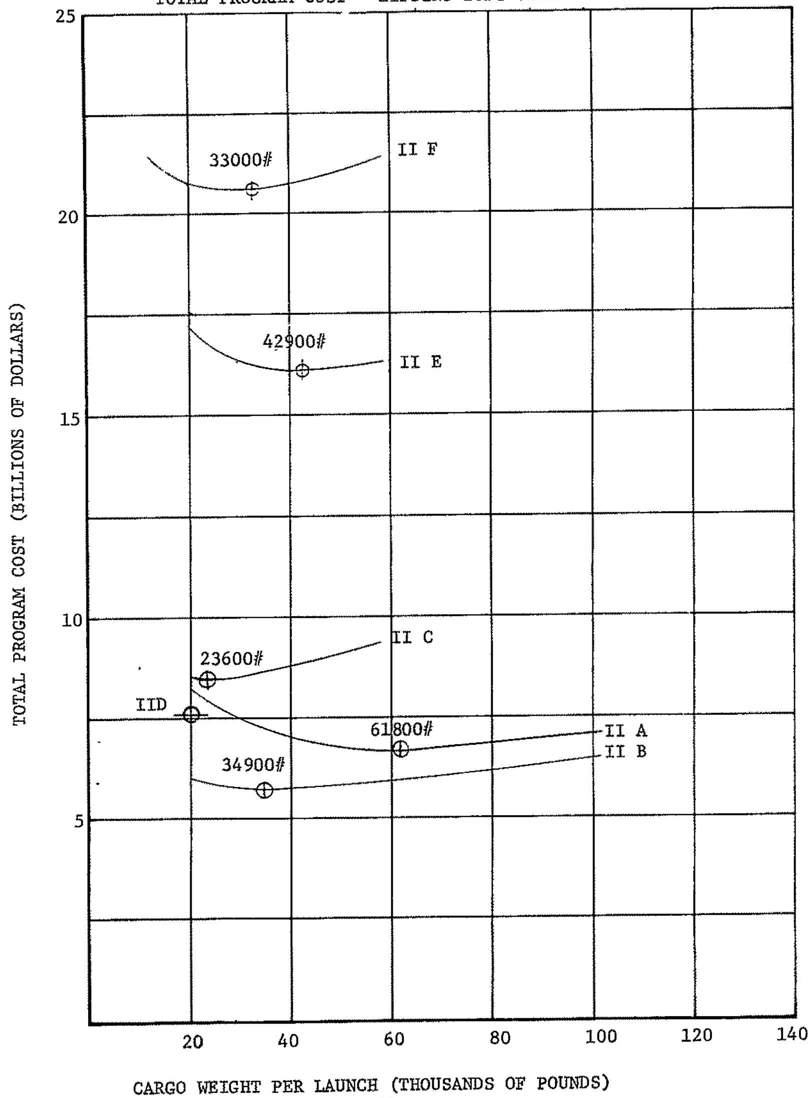


FIGURE 5-1

FIGURE 5-2

EFFECT OF CARGO WEIGHT PER LAUNCH ON
TOTAL PROGRAM COST - LIFTING BODY VEHICLES



To see the effect of the operations philosophy, a comparison can be made between the IB and IE configurations (Figure 5-1). If the operations costs are assumed to be zero for both configurations (an assumption not far different from current thinking), the B has a cost of about $3.5B and the E about $4.5B at the optimum size cargo (excluding management and fee). The E configuration has a higher RDT&E cost but a lower investment cost than the B and would show a savings for a larger program.

One of the constraints affecting the total program cost for the E configuration is simply the turn around time. These vehicles are so large that in some cases, the time for recertification exceeds the minimum time between launches for a fixed launch rate program. Therefore inventory requirements are high simply because of the pipeline. Some consideration should be given to a program requirement which would build, as learning decreased the turn around time.

The total program cost was determined for the tip tank versions of both configurations (ID & IID) at a single cargo weight per launch. These points are shown on Figures 5-1 and 5-2. A comparison with the integral cargo/orbit propulsion versions (IC and IIC) reveals that in one case the tip tank version has a higher and in the other a lower total program cost. However, in both cases the spacecraft costs are higher for the tip tank configuration because the spacecraft is slightly larger to contain the propulsion hardware and because of the addition of the tip tanks. The total program costs reveal the effect of launch vehicle costs which decrease since only a single stage is required.

5.1.2 Optimization of Operational Modes - For this portion of the study, alternates for operational phases for the spacecraft portion of the program were defined. The differences between some of the alternates affect only one part of the program and therefore there is no optimization between them, only a sensitivity to the change. These are in the area of launch operations, refurbishment site, refurbishment philosophy, and number of recovery sites. In the discussions that follow, it is less cumbersome not to differentiate between the optimizations and the sensitivities, therefore all will be referred to as optimizations.

The operational alternates can be optimized independent of the rest of the system parameters and independent of each other. The only alternate that affects vehicle size is the AGE alternate using on-board checkout. The addition of the on-board checkout system increases the vehicle weight slightly but not enough to affect the optimization of the other parameters. The only alternate that is affected is the transportation mode. For a given cargo size, the vehicle size does not change enough with the addition of on-board checkout equipment that the size limits set for land and air transportation are likely to be exceeded unless the vehicle size is very close to the limit.

As in the cargo weight per launch optimization, this optimization was done for a fixed program of 250,000 lbs of cargo to orbit each year for ten years. For larger programs, the results in some areas might be slightly different than shown here; this affect was not examined.

In this optimization, the total program cost when using baseline modes was determined and compared to the program cost when using the alternate modes which were changed one at a time. The alternate that gives the lowest program cost is then considered the optimum for that vehicle under investigation. The results of this optimization are shown in Figures 5-3 thru 5-11. The alternates are designated by number as defined in Table 4-2.

The only alternate modes that are applicable to the expendable ballistic vehicle (IA) are in the area of launch operations, transportation, recovery mode, and recovery sites. The results of the optimization of the operational mode alternates for the IA vehicle are shown on Figure 5-3. Total program cost is less when using integrated checkout (Launch operations = 2) because of the reduction of labor costs in both launch operations and launch area support. For the land landing version, increasing the number of landing sites over two does not decrease spacecraft size or weight since only two sites are required within the United States with a 24 hour return time (the ballistic vehicles carry enough propulsion in case one of the two sites is closed due to weather, a landing can be made at the other site). Therefore, increasing the number of sites only increases the cost of site activation, modification, and labor. Obviously, the building of new sites is more expensive than the use of existing sites. Transportation by land (Transportation = 2) is slightly less expensive than by either water or air but the difference is so slight that total program cost would not be used as a factor in the final choice of transportation mode. As shown also on Figure 5-1, water recovery is less expensive than land recovery.

In addition to the alternates for the IA vehicle, the modular ballistic with reusable entry vehicle (IB) has operational alternates in the areas of refurbishment philosophy, refurbishment sites, and AGE. The comparison of these alternates is shown on Figure 5-4. The comments above concerning the results for the IA apply here for the common areas. Since the entry vehicles do not have a cruise capability, the launch site was not considered as a landing site or as a refurbishment site. Therefore, there is a larger difference in transportation costs because of the transportation from the landing site to the refurbishment site, and from the refurbishment site back to the launch site. The use of on-board checkout (AGE=2) reduces checkout time and therefore turn around time but not enough in this program to offset the added spacecraft weight and the resulting added booster costs. The use of a new refurbishment site (Refurb. site = 2) shows the cost of adding a new site and the additional AGE at this site. The limited maintenance alternate (Refurb. Philosophy = 3) reduces both labor costs and the recertification flow time, both of which tend to reduce total program costs. Both alternates, limited maintenance and scheduled maintenance with testing (Refurb. Philosophy = 2) assume that all ablative exterior surface panels are replaced during each recertification and that all radiative exterior panels are inspected and 20% are replaced during each recertification. With the baseline program total cargo used for this optimization, only the savings in labor costs was realized. The total calendar time for first unit recertification was reduced to 62% but because of the small program, this was not enough to reduce the number of vehicles in the inventory.

The comparison of the operational alternates for the ballistic entry vehicle with integral cargo and orbit propulsion (IC) is shown in Figure 5-5 and for the ballistic entry vehicle with integral upper stage boost (IE) is shown in Figure 5-6. The trends are identical with those for the IB shown on Figure 5-4 and the comments for the IB apply. A twelve foot diameter and 60 foot length were established as upper limits in size for transportation by land based on allowable truck lengths and clearances. Likewise, a limit of 25 feet in diameter and 70 feet in length were established as upper limits for air transportation. Land transportation (Transportation = 2) is not an applicable mode for the IC vehicle because it exceeds the 12 foot maximum diameter. Neither land nor air (Transportation = 3) are applicable for the IE because of size. The use of engine hot firing tests with scheduled maintenance (Refurb. Philosophy = 1) with the IE configuration increases AGE costs, subsystem test costs and recertification flow time.

The results of the comparison of the operational alternates for the lifting body vehicles are shown on Figures 5-7 thru 5-11. The trends are, in general, the same as for the ballistic vehicles discussed above. The only change in

FIGURE 5-3

Comparison of Operational Alternates - IA

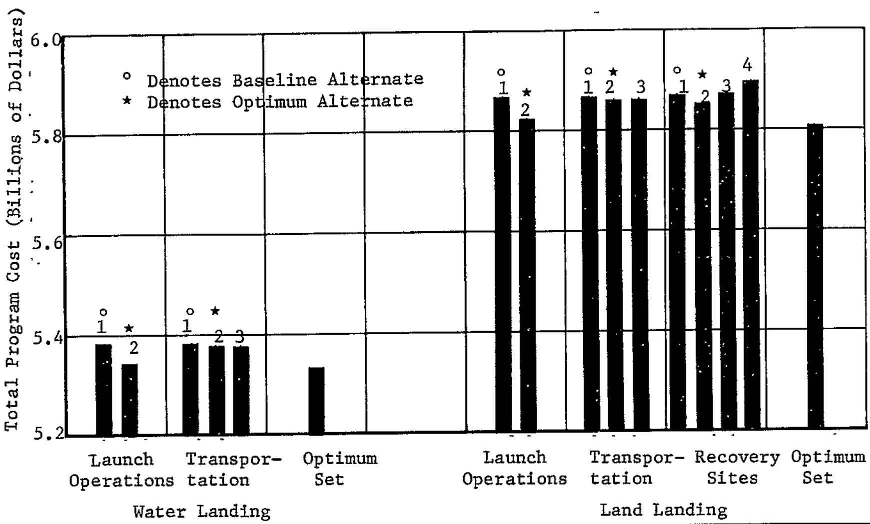


FIGURE 5-4

Comparison of Operational Alternates - IB

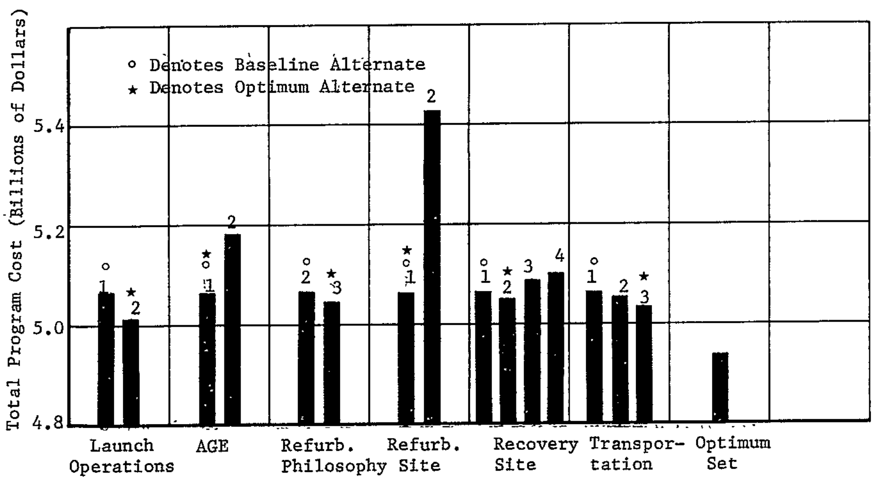


FIGURE 5-5

Comparison of Operational Alternates - IC

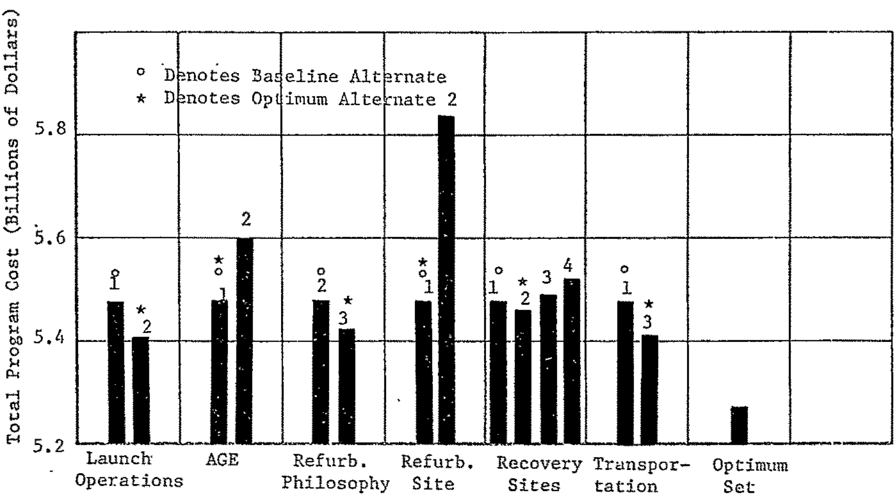


FIGURE 5-6

Comparison of Operational (Alternates - IE)

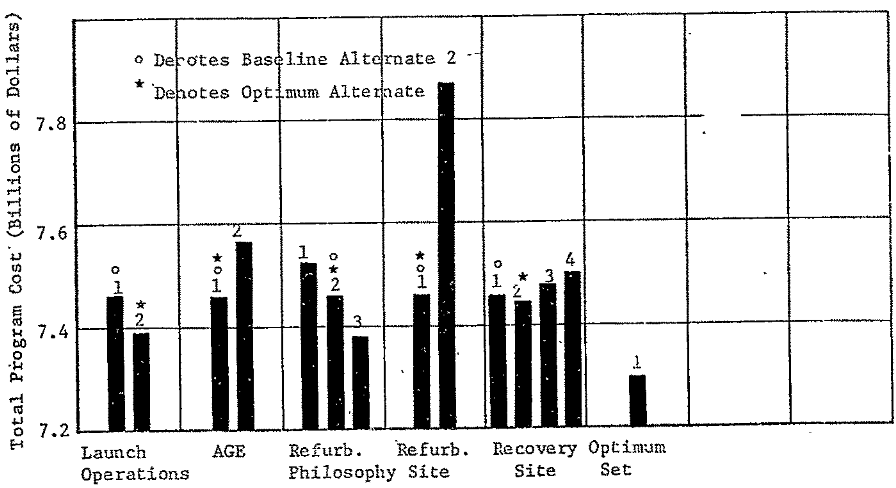


FIGURE 5-7

Comparison of Operational Alternates - IIA

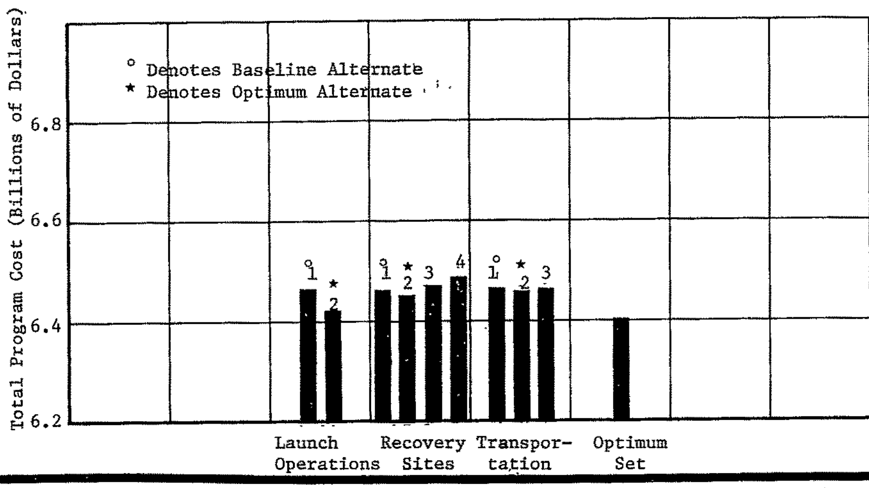


FIGURE 5-8

Comparison of Operational Alternates - IIB

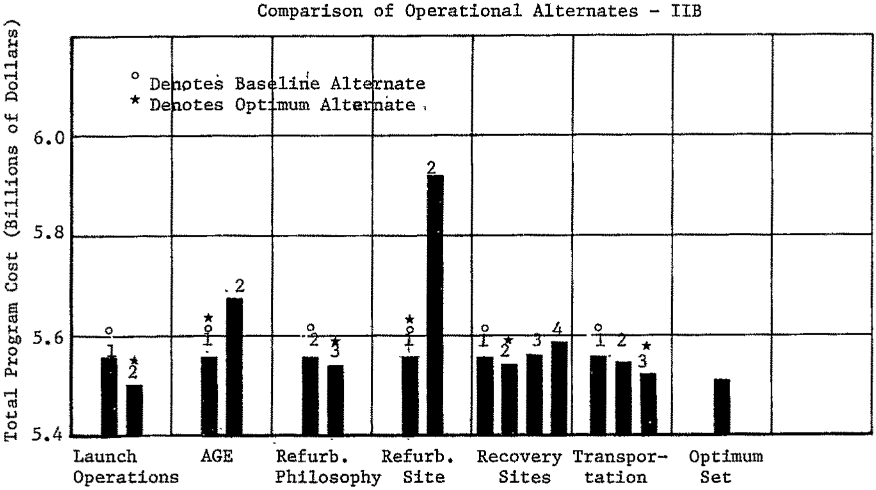


FIGURE 5-9

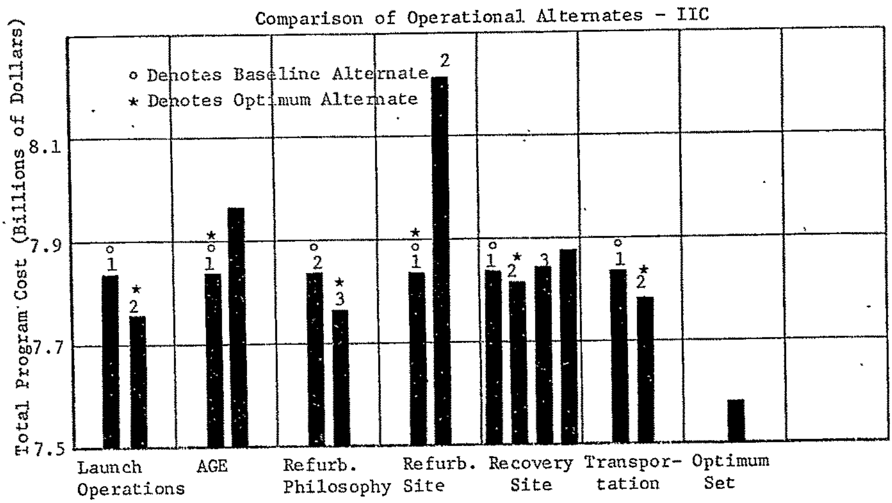


FIGURE 5-10

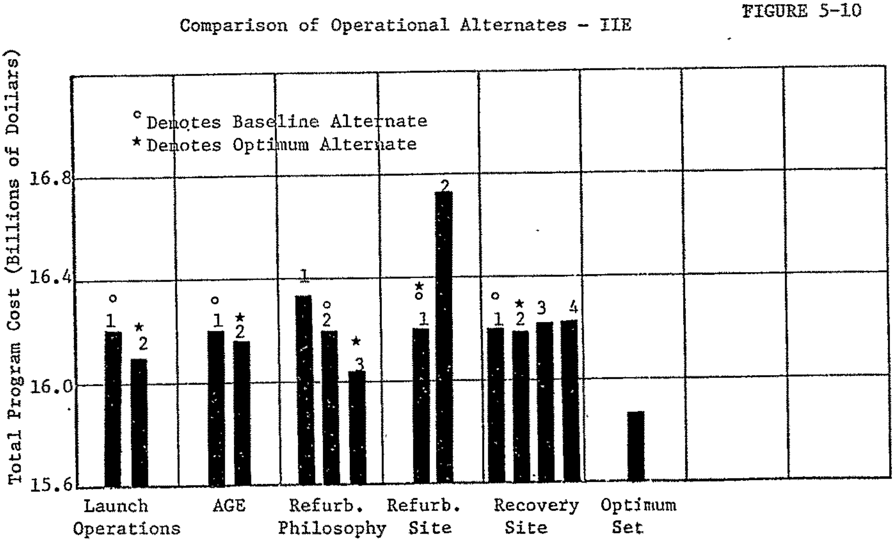
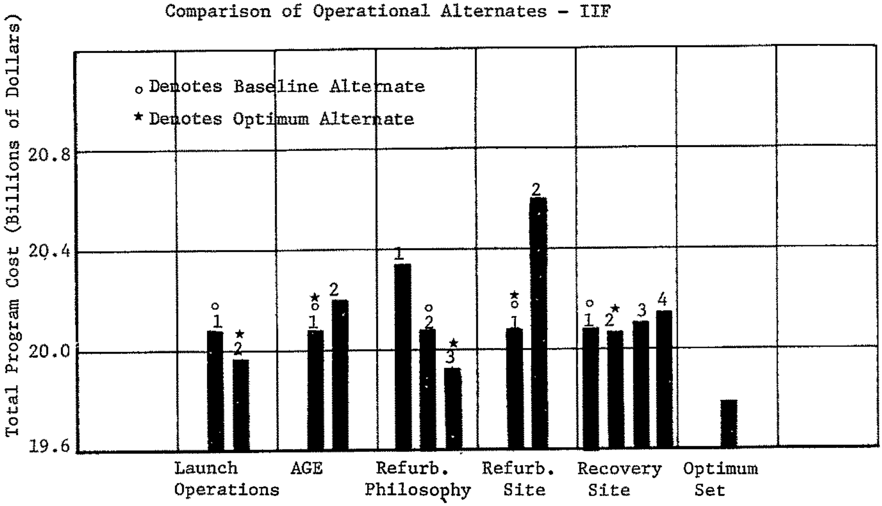


FIGURE 5-11

Comparison of Operational Alternates - IIF



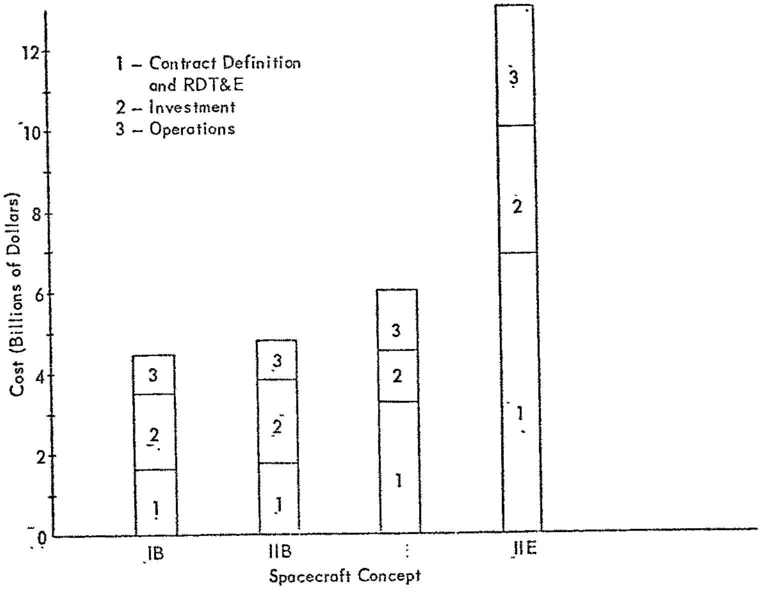
trend is for the use of on-board checkout (AGE=2) with the IIE. The use of on-board checkout reduces the calendar time required for recertification enough that one less vehicle is required.

5.1.3 Additional Visibility Studies - In addition to the optimization studies, the data generated were broken down in different ways to give additional visibility. This included breaking down costs by program phase, by cost category, and by subsystem. Some of these data are presented in the following paragraphs.

In Figures 5-12 thru 5-14, the costs associated with the modular reusable entry vehicle and the integral upper stage concepts are shown broken down in several ways. These are the costs associated with the optimum cargo size and therefore have differing quantities of vehicles. Table 5-1 shows for each vehicle the cargo size and quantity of vehicles required for the investment phase. For all the vehicles, there are 5 entry vehicles and 5 launch vehicles required for the development phase. Basic cost as used in those figures indicates that the costs shown do not include the contractors fee or the management costs.

FIGURE 5-12

BASIC SPACECRAFT AND LAUNCH VEHICLE COST BY PROGRAM PHASE



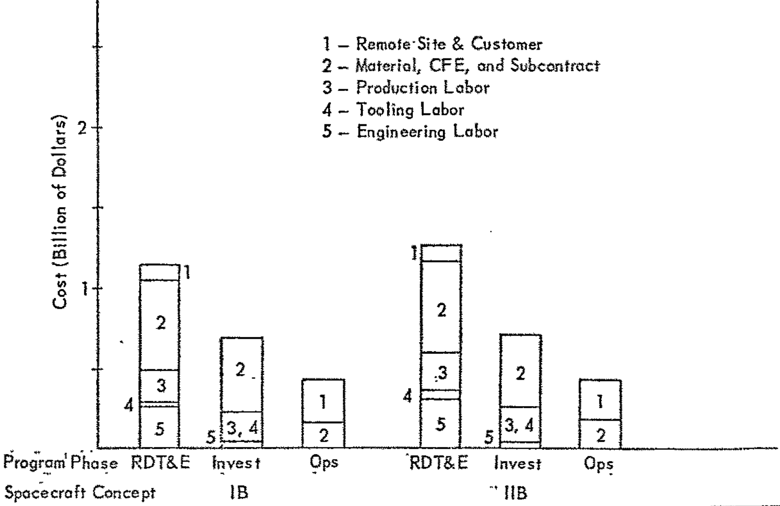
The basic spacecraft plus launch vehicle costs broken down by program phase is shown on Figure 5-12. As would be expected, the investment cost is a smaller percentage of the total for the reusable upper stage vehicle and drops from about 40% to about 20%. Likewise, the operations costs for the integral vehicles is a larger percentage because the vehicles are larger and require more refurbishment under the study ground rules.

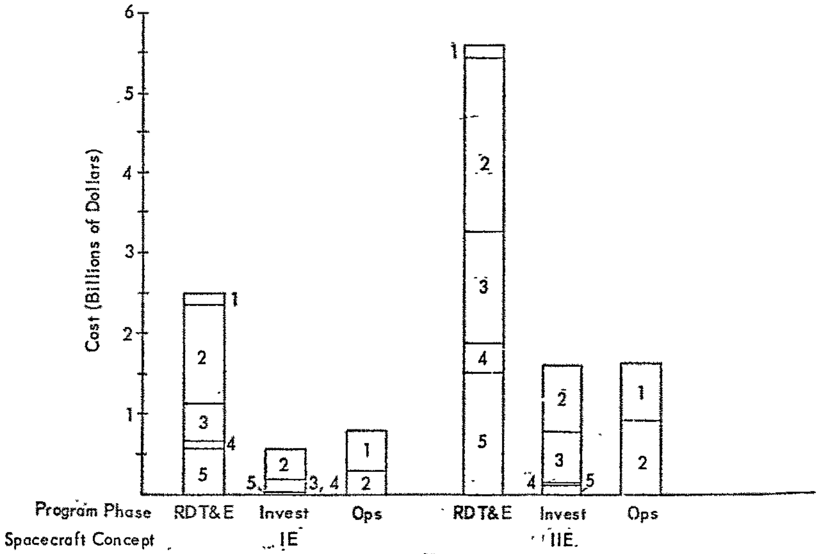
Figure 5-13 further breaks down the costs within each mission phase by cost category. It should be noted that this figure shows basic spacecraft costs only and does not include the launch vehicle. The contribution to the total cost by each cost category is not greatly affected either by configuration or by reuse concept.

The spacecraft subsystem costs broken down by program phase is shown on Figure 5-14. For the modular vehicles, both the entry vehicle and mission module costs are included. The avionics and ECS are nearly fixed cost regardless of configuration or reuse concept; the avionics because it is largely dependent

BASIC SPACECRAFT COST BY PROGRAM PHASE AND COST CATEGORY

FIGURE 5-13





upon mission and the ECS because of its dependence upon crew size. The thermostructure costs vary both with configuration and reuse category; with configuration because of the efficiency of the shape and with reuse category because of vehicle size.

Several approaches to relating costs to vehicle parameters are shown in Figures 5-15 thru 5-17. In Figure 5-15 the development cost is broken out of the total program cost to increase visibility. This figure shows that development costs per pound of dry weight are closely related to dry weight. All of the plotted points fall on the same curve regardless of degree of reusability and hypersonic L/D. The development costs were more closely related to dry weight than any other parameter that could be found. For example, total development costs were plotted against wetted area (Figure 5-16) and the trend shown is that development cost increases with both increased reusability and increased size.

A comparison of RDT&E costs for seven different configurations (including Gemini) is presented in Figure 5-17. The total basic spacecraft RDT&E cost appears to be determinable from the dry weight. The correlation is quite high.

The variation of basic spacecraft parameters (wetted area, unit weights, spacecraft length, and payload size) with dry weight are presented in Figures 5-18 through 5-20.

5.2 Sensitivity Studies - The OCPDM computer program is designed so that changes in subsystems may be evaluated systematically. Any change in a subsystem weight or volume results in resizing, reweighing and recosting all components of the spacecraft including the booster. Therefore, the total impact of a design change on total program cost can be determined. Also, the reasons for the changes in cost can be determined.

The following paragraphs present the sensitivity of total program cost to subsystem design and operational changes.

5.2.1 Return Time, Number of Landing Sites and Orbit Inclination - The cross-range requirement for an entry vehicle is determined by the required return time, number of landing sites, and the orbit inclination. The minimum cost is obtained when the cross-range can be obtained purely from aerodynamic lift without the use of propulsion. This is shown in Figures 5-21 through 5-32.

SUBSYSTEM COSTS BY PROGRAM PHASE FIGURE 5-14

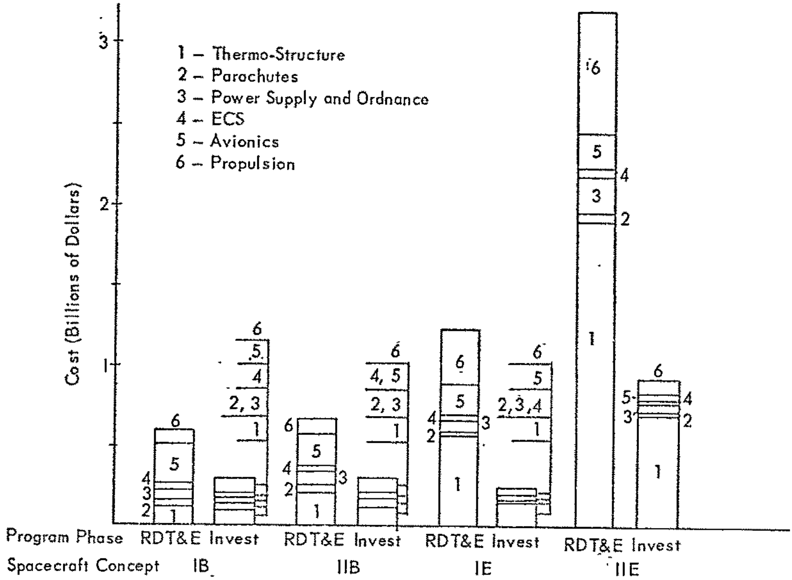


TABLE 5-1

Vehicle Quantities

Vehicle	Cargo Wt/Launch	Quantity Entry Vehicle	Quantity Launch Vehicle
IB	34100#	6	81
IIB	34900#	6	81
IE	52800#	5	53
IIE	42900#	7	64

FIGURE 5-15

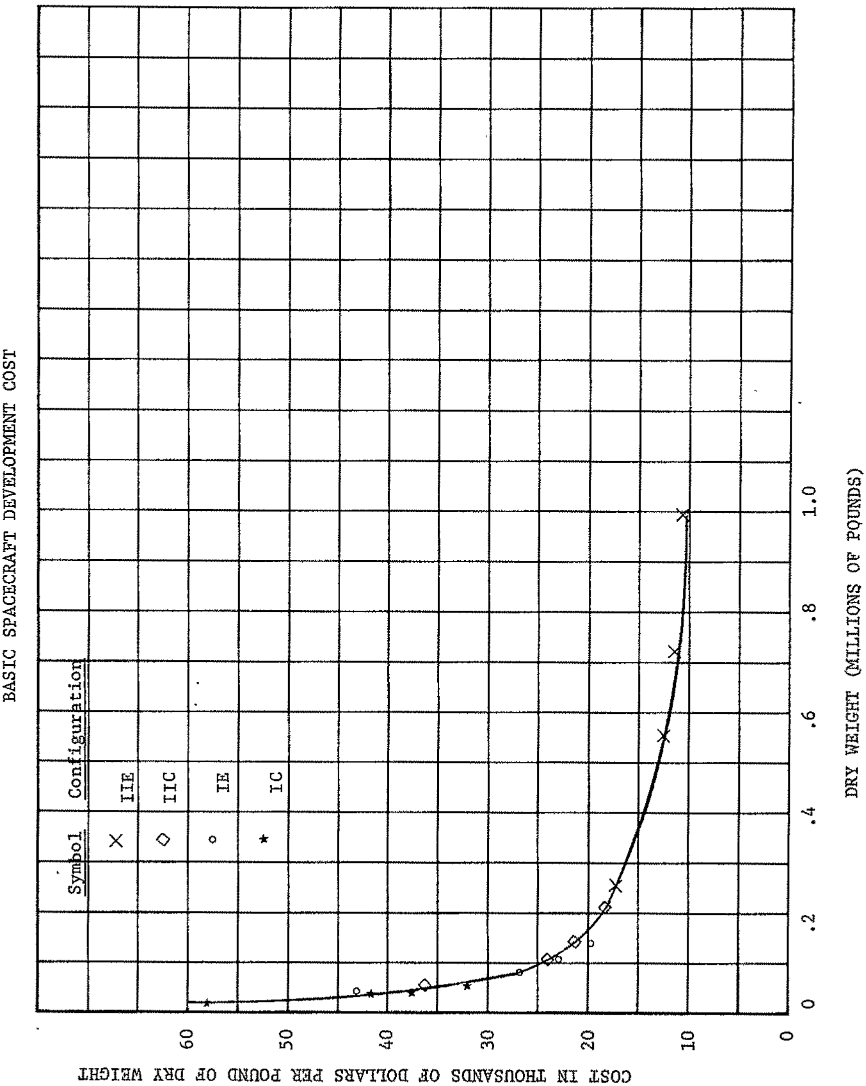

BASIC SPACECRAFT DEVELOPMENT COST
Symbol
Configuration
IIE
IIC
IE
IC
0
.2
.4
.6
.8
1.0
DRY WEIGHT (MILLIONS OF POUNDS)
60
50
40
30
20
10
0
COST IN THOUSANDS OF DOLLARS PER POUND OF DRY WEIGHT

FIGURE 5-16

Variation of Spacecraft Development Cost With Wetted Area

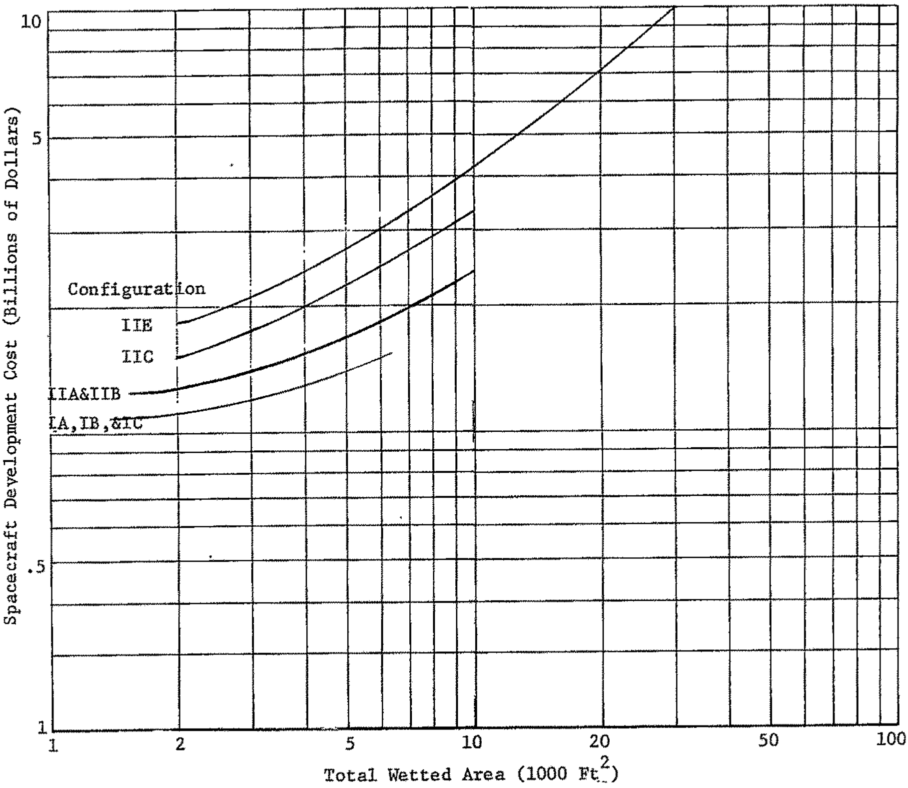


FIGURE 5-17

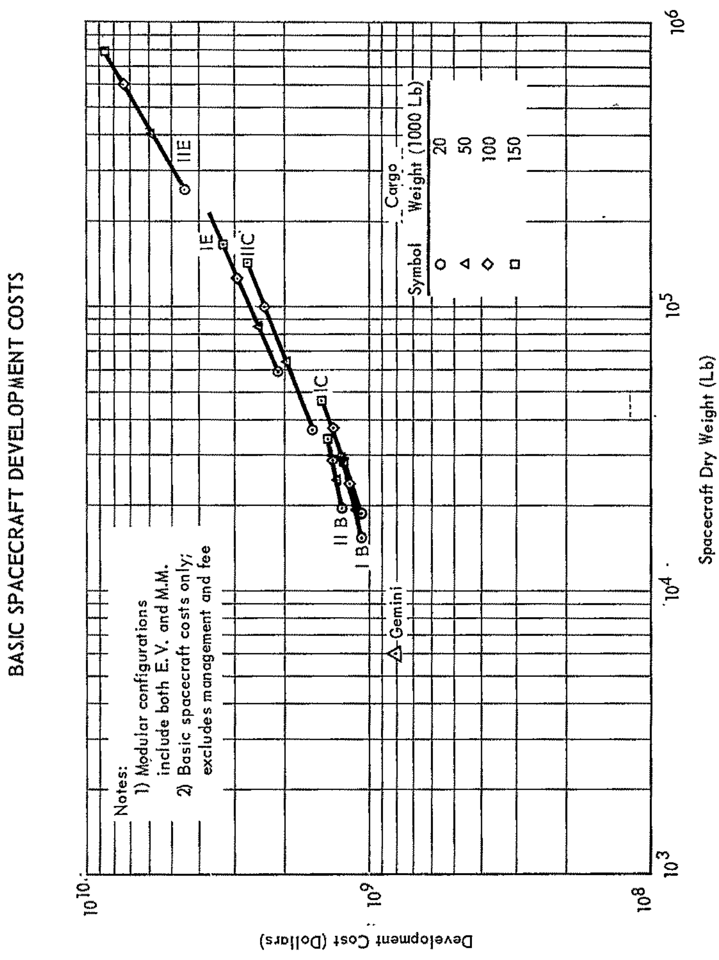

BASIC SPACECRAFT DEVELOPMENT COSTS
Notes:
1) Modular configurations include both E.V. and M.M.
2) Basic spacecraft costs only; excludes management and fee
Symbol
Cargo Weight (1000 Lb)
20
50
100
150
IIE
IE
IIC
IC
II B
I B
Gemini
10^{10}
10^9
10^8
10^3
10^4
10^5
10^6
Development Cost (Dollars)
Spacecraft Dry Weight (Lb)

FIGURE 5-18

M_2F_2 Dry Weight Vs. Wetted Area

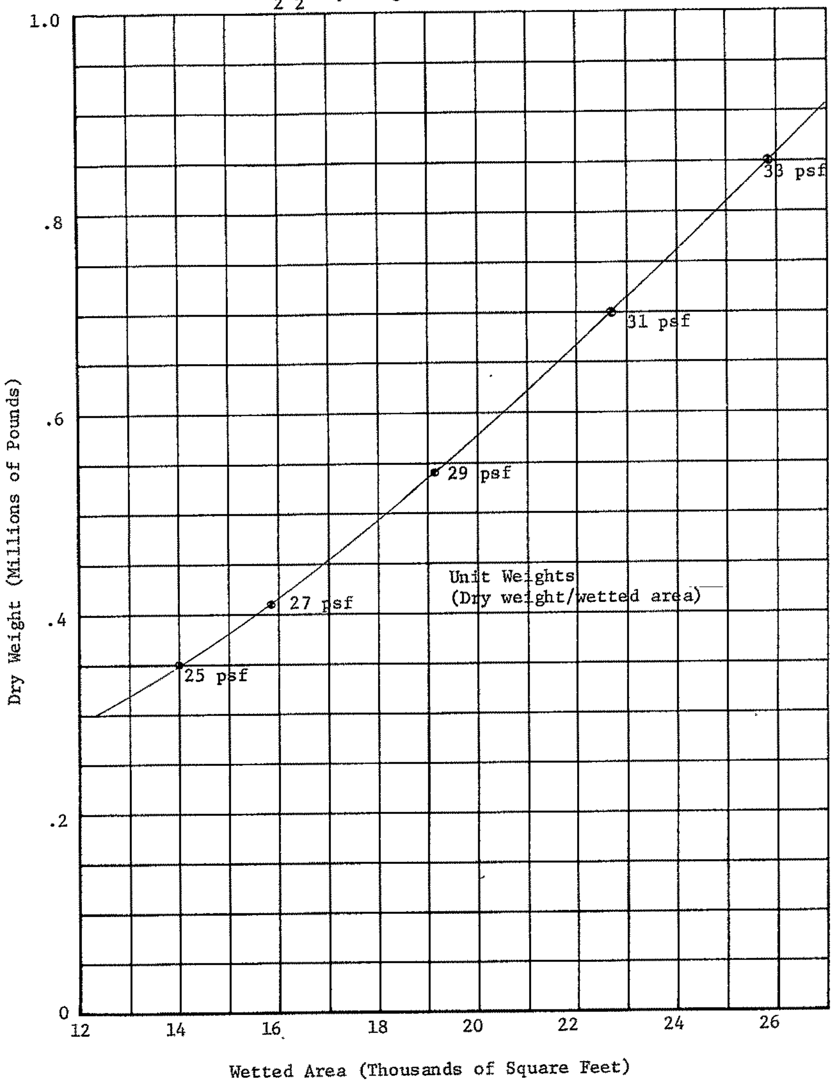
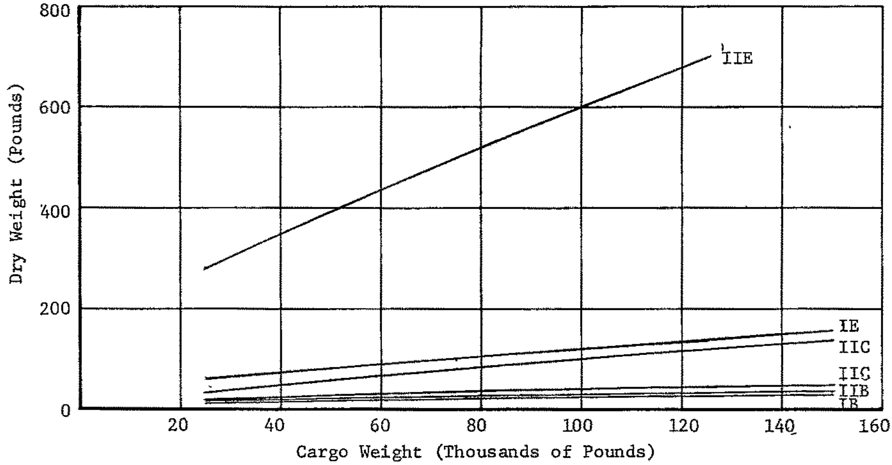


FIGURE 5-19

Spacecraft Dry Weight Variation With Payload



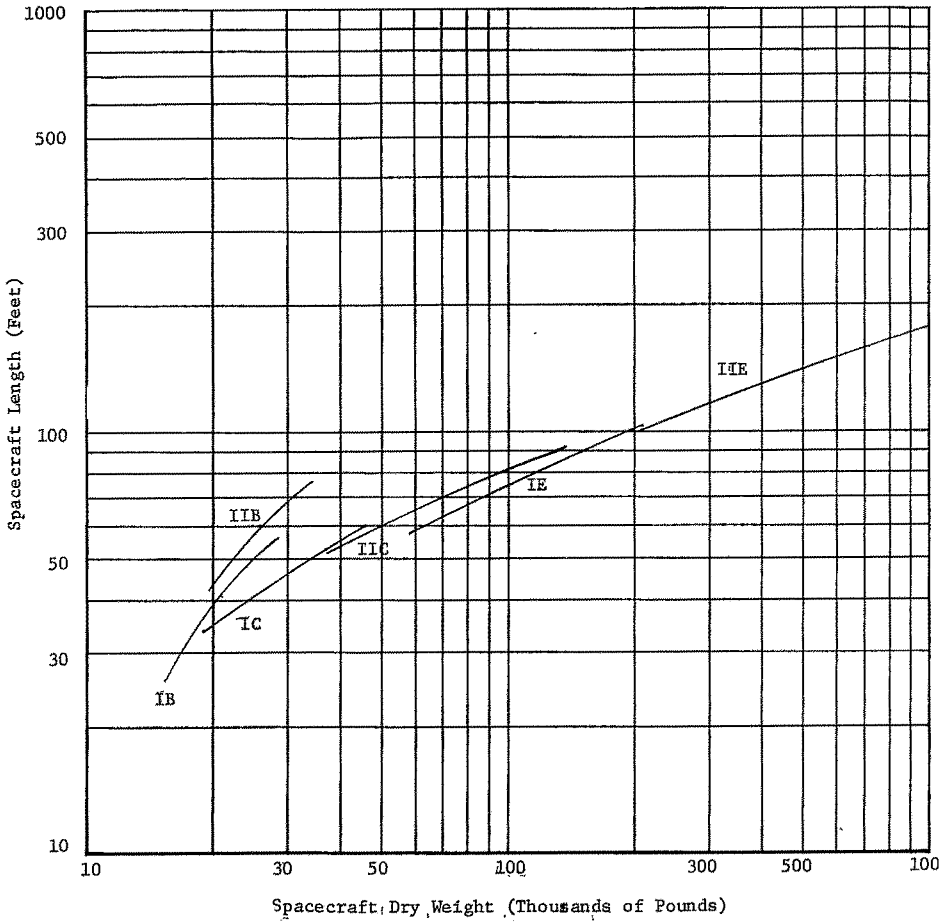
In this analysis the landing sites are equally spaced at 50 degrees north latitude. Therefore, increasing the number of sites from two to four cuts the cross-range requirement in half. The cost of maintaining a site for the modular vehicles runs from 10 to 20 million dollars per year. The total program cost of increasing the hypersonic L/D from .35 to 1.1 was 500 million (Figure 5-21 versus Figure 5-24). Reducing the cross-range requirement by adding sites is more economical than increasing the hypersonic L/D.

The cost of maintaining a landing site for the E configuration runs from 20 to 200 million dollars per year, and the cost increment between the IE and the IIE is 9 billion dollars. This, too, indicates the relatively low cost of maintaining landing sites.

However, if the cross-range can be obtained with aerodynamic lift there is no cost saving in increasing the allowable return time, and increasing the number of sites merely increases the cost of maintaining the sites with no compensating cost saving. In this case the fewer the number of sites the better

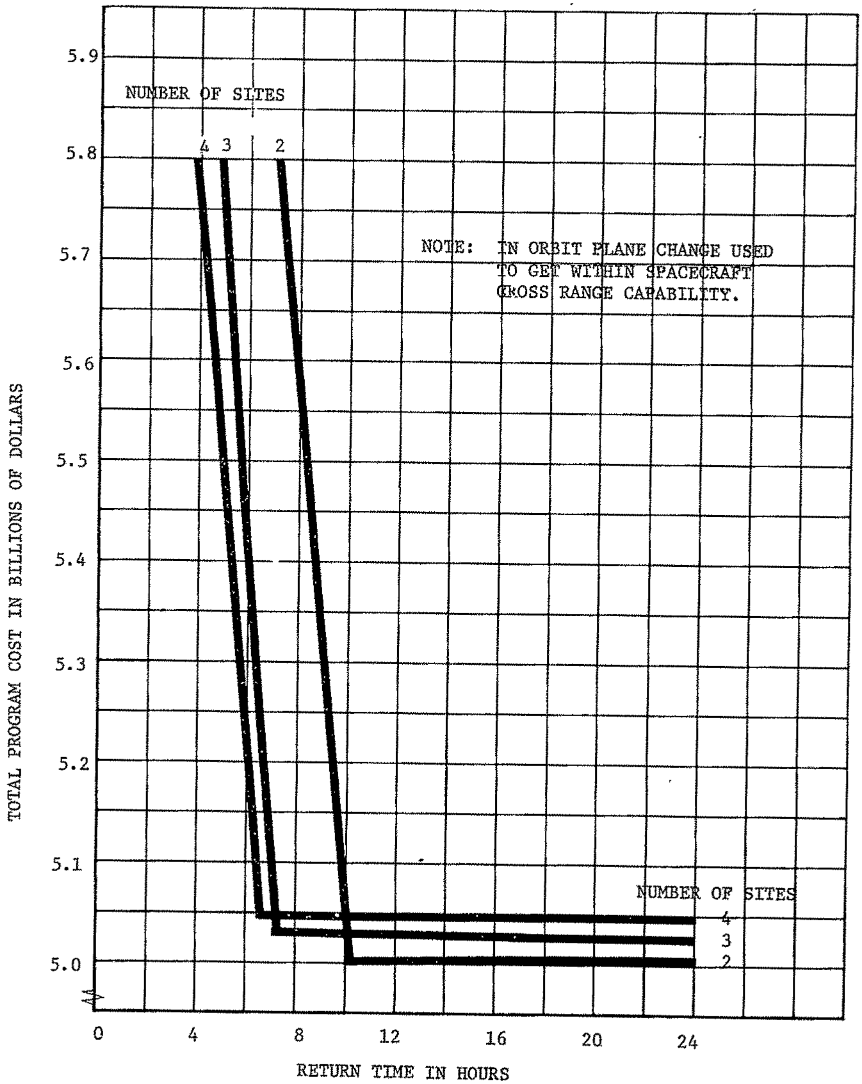
FIGURE 5-20

Spacecraft Dry Weight Variation with Spacecraft Length



IB COST VS. RETURN TIME AND NUMBER OF SITES
50° ORBIT INCLINATION
LANDING SITES AT 50° LATITUDE

FIGURE 5-21



IB COST VS. RETURN TIME AND NUMBER OF SITES

FIGURE 5-22

70° ORBIT INCLINATION

LANDING SITES AT 50° LATITUDE

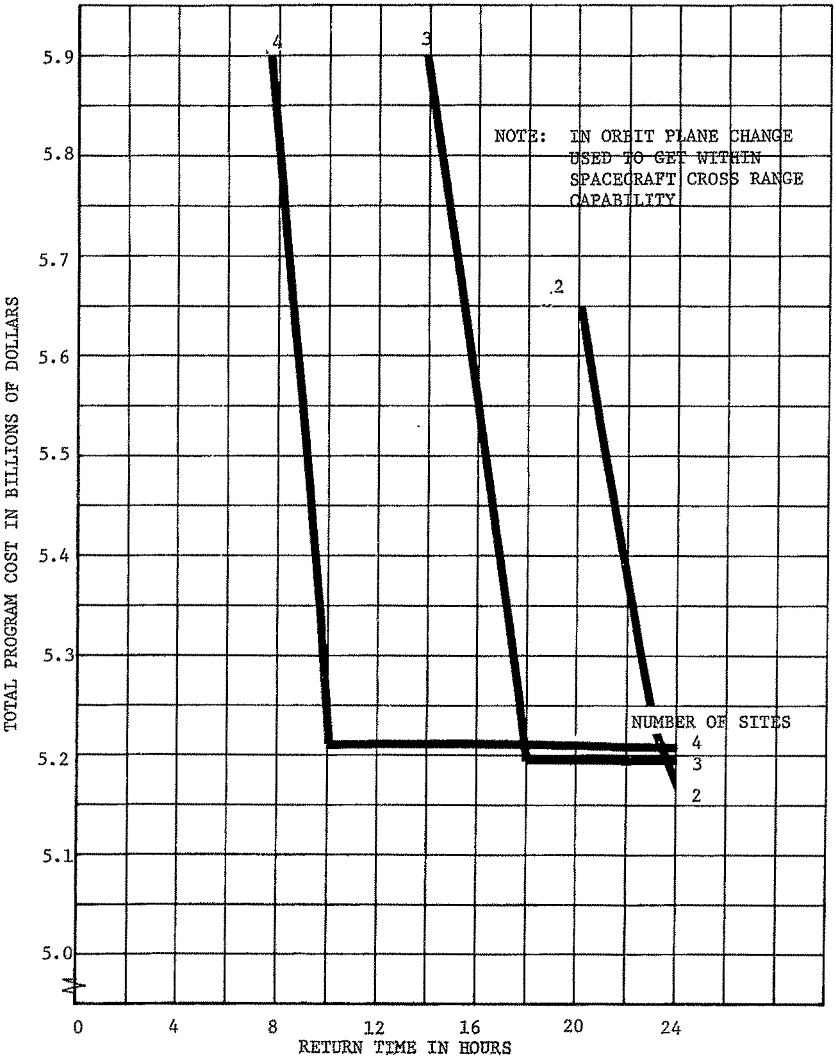


FIGURE 5-23

IB COST VS. RETURN TIME AND NUMBER OF SITES

90° ORBIT INCLINATION

LANDING SITES AT 50° LATITUDE

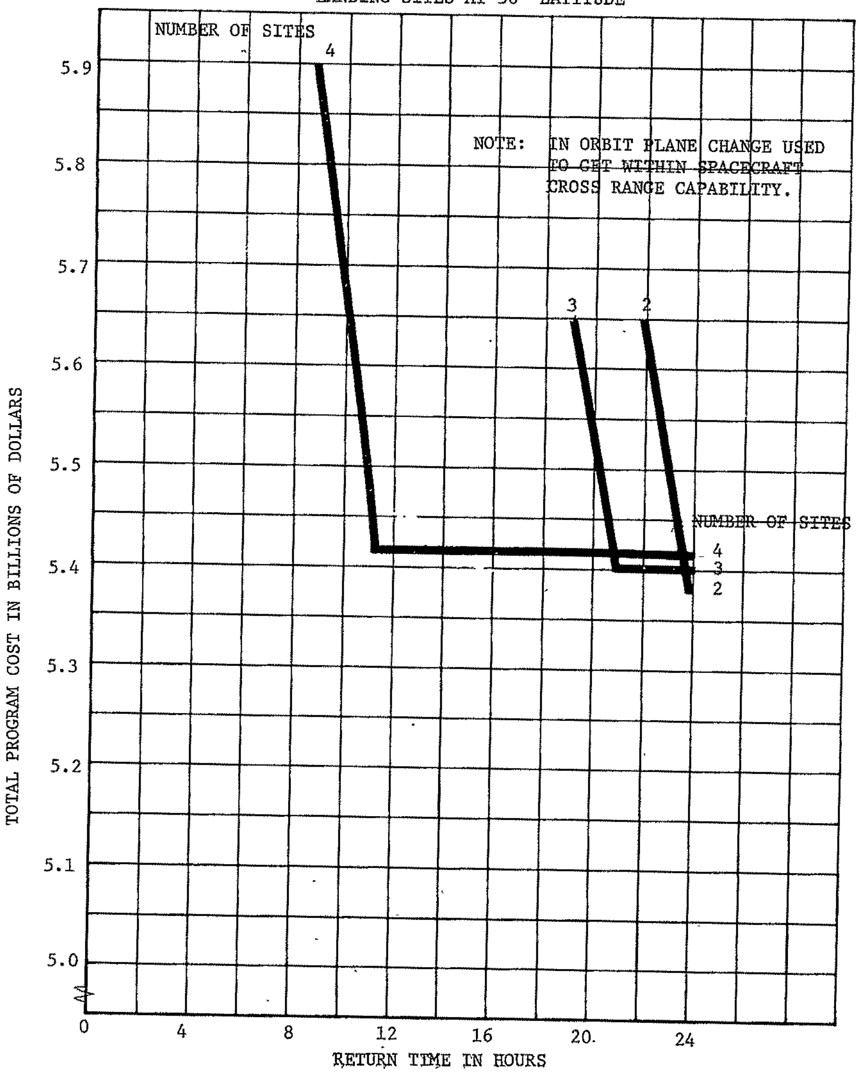
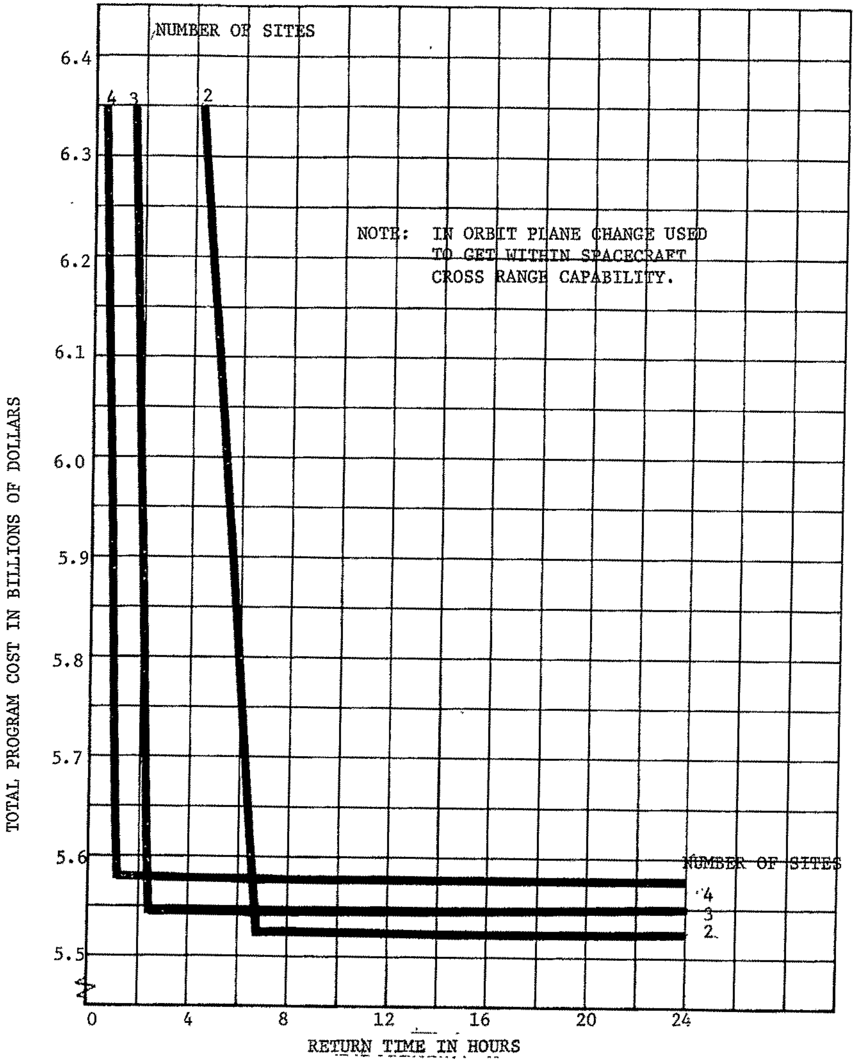


FIGURE 5-24

IIB COST VS. RETURN TIME AND NUMBER OF SITES

50° ORBIT INCLINATION

LANDING SITES AT 50° LATITUDE



As mentioned in section 5.1, no atmospheric cruise capability is assumed and therefore, once the cross-range requirement cannot be met purely by aerodynamic lift the costs increase quite rapidly. Adding sites at this point is beneficial.

Adding sites is beneficial for a three hour return time since a hypersonic L/D of 1.1 will not give sufficient cross-range and additional propulsion is required. Therefore, in all twelve figures the order for three hours return time is just the reverse of that at twenty four hours.

The data presented in Figures 5-21 through 5-32 can be summarized as follows:

1. Increasing orbit inclination increases the total program cost because a larger booster is required. A 90 degree orbit costs 300 to 500 million more than a 50 degree orbit.
2. A greater cross-range is required for landing from the higher orbit inclinations (70 degrees and 90 degrees) than from a 50 degree orbit inclination. Therefore, the optimum number of landing sites is greater than for a 50 degree orbit.
3. The minimum cost is obtained by having just enough aerodynamic lift to meet the cross-range requirement.
4. The least expensive way to meet the cross-range requirement is to add sites if there is a cross-range deficiency.
5. The next best way (from a cost basis) to meet the cross-range requirement is to increase the hypersonic L/D.
6. The least efficient way to meet the cross-range requirement is to add ΔV capability. The curves are very steep in the region where cross-range is obtained propulsively.

5.2.2 Annual Cargo Volume and Cargo Density - The total program cost variation with payload size and annual cargo volume is presented in Figures 5-33 through 5-39. These curves indicate that:

1. The optimum payload size increases as the annual cargo volume increases.
2. There is greater penalty for undersizing the payload than in oversizing the payload.
3. A 50,000 pound payload will result in a total program cost which is near the minimum regardless of the annual cargo volume, hypersonic L/D, and reusability.

FIGURE 5-25

IIB COST VS. RETURN TIME AND NUMBER OF SITES

70° ORBIT INCLINATION

LANDING SITES AT 50° LATITUDE

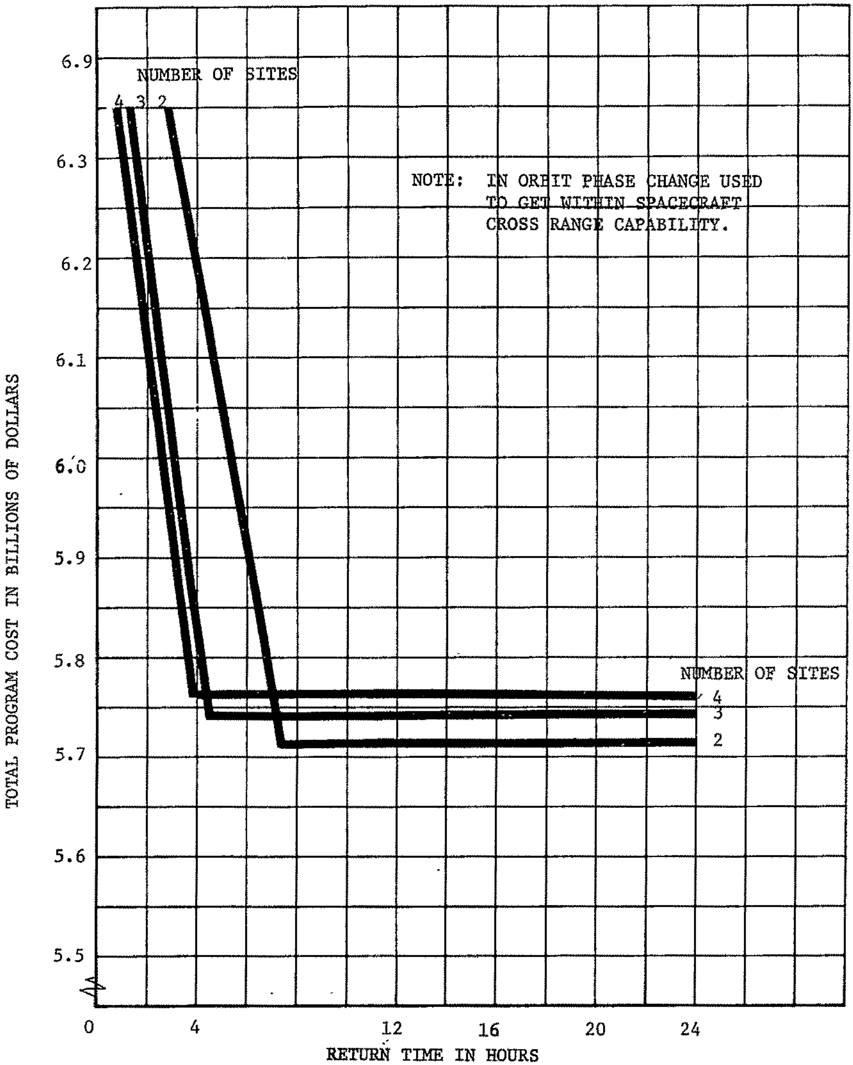


FIGURE 5-26

IIB COST VS. RETURN TIME AND NUMBER OF SITES

90° ORBIT INCLINATION

LANDING SITES AT 50° LATITUDE

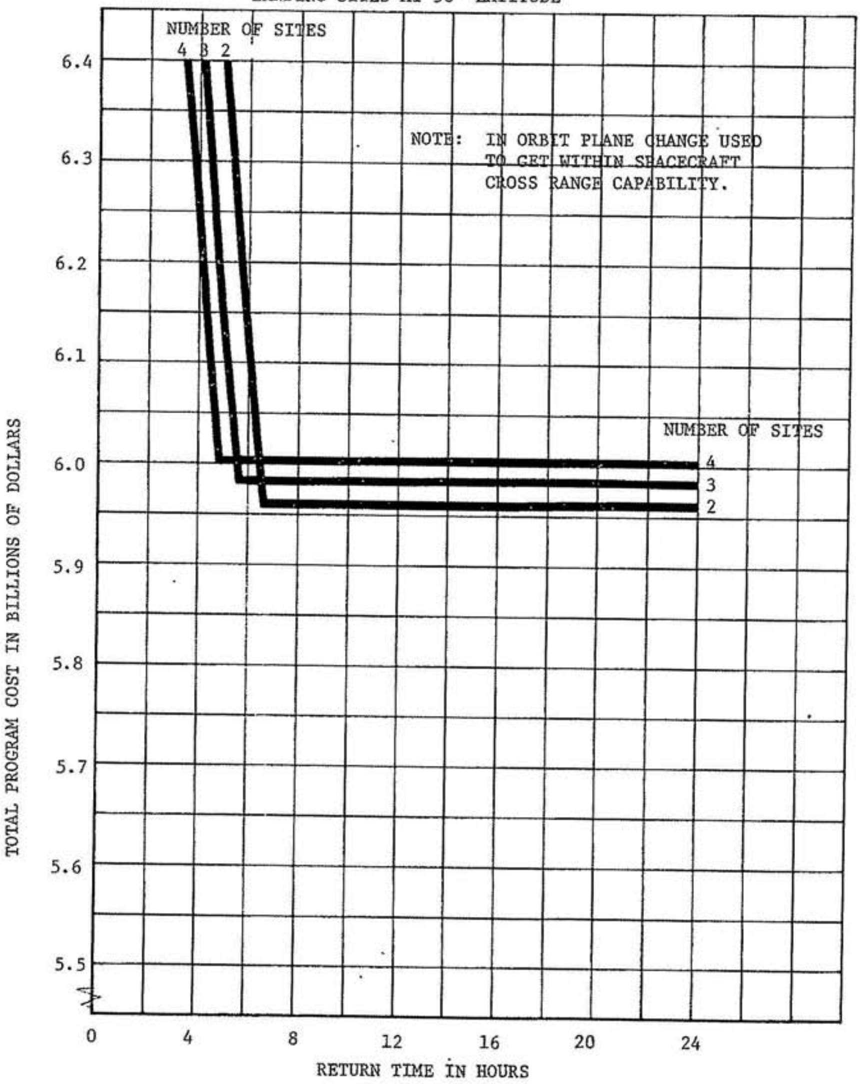


FIGURE 5-27

IE COST VS. RETURN TIME AND NUMBER OF SITES
50° ORBIT INCLINATION
LANDING SITE AT 50° LATITUDE

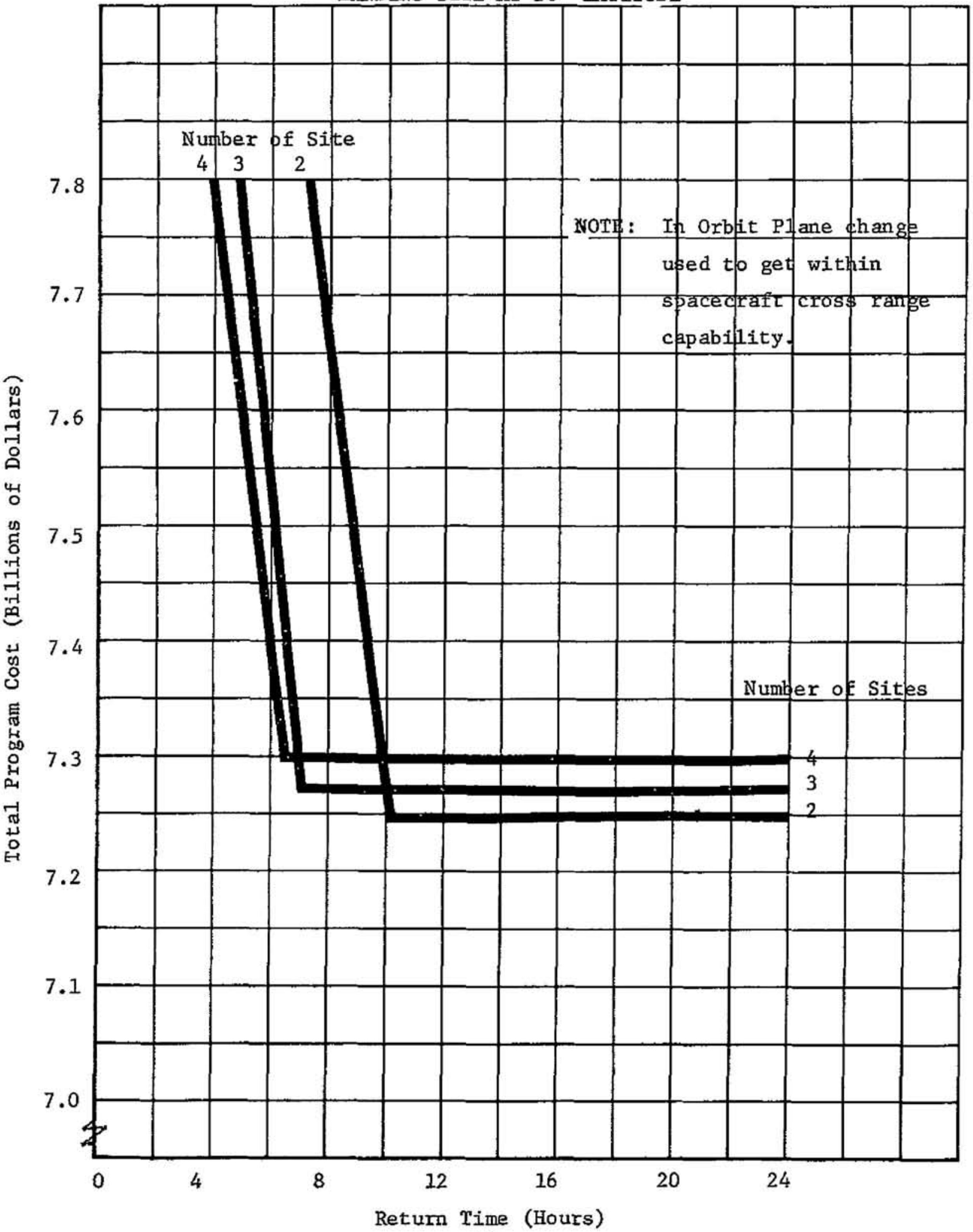


FIGURE 5-28

IE COST VS. RETURN TIME AND NUMBER OF FLIGHTS
70° ORBIT INCLINATION
LANDING SITE AT 50° INCLINATION

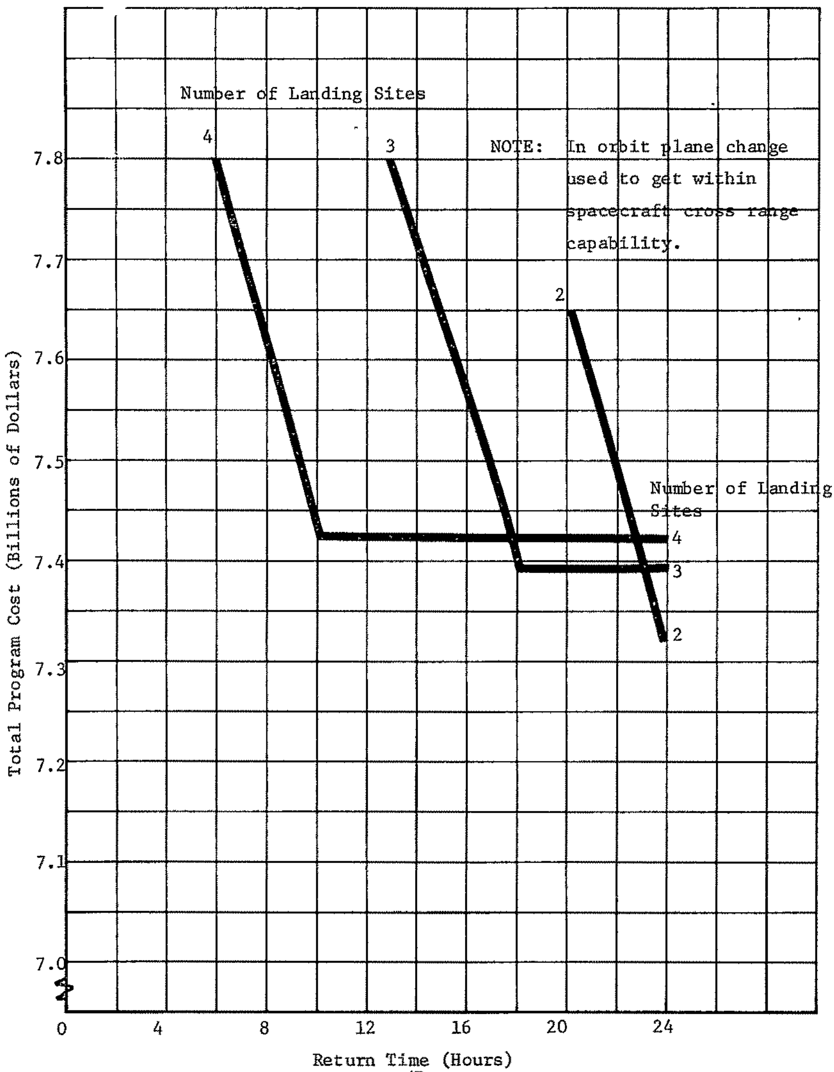


FIGURE 5-29

IE COST VS. RETURN TIME AND NUMBER OF FLIGHTS
90° ORBIT INCLINATION
LANDING SITE AT 50° INCLINATION

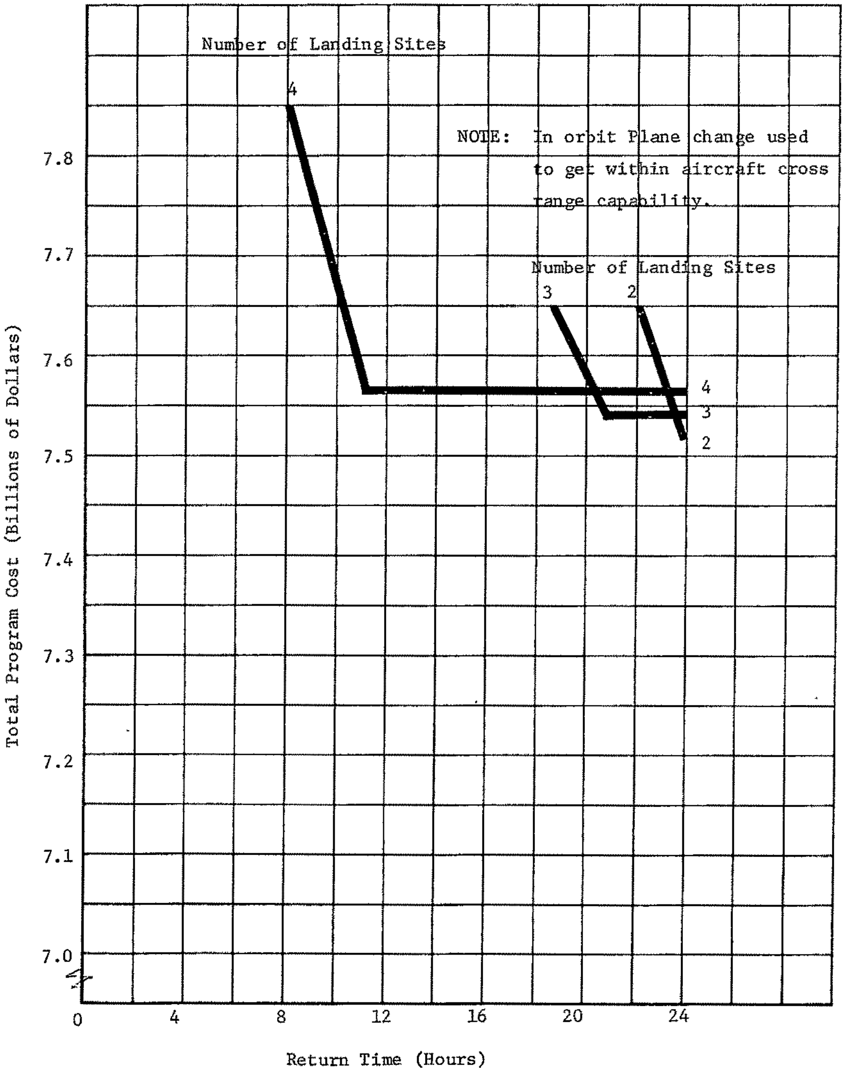


FIGURE 5-30

IIE COST VS RETURN TIME AND NUMBER OF SITES
50° ORBIT INCLINATION
LANDING SITE AT 50° LATITUDE

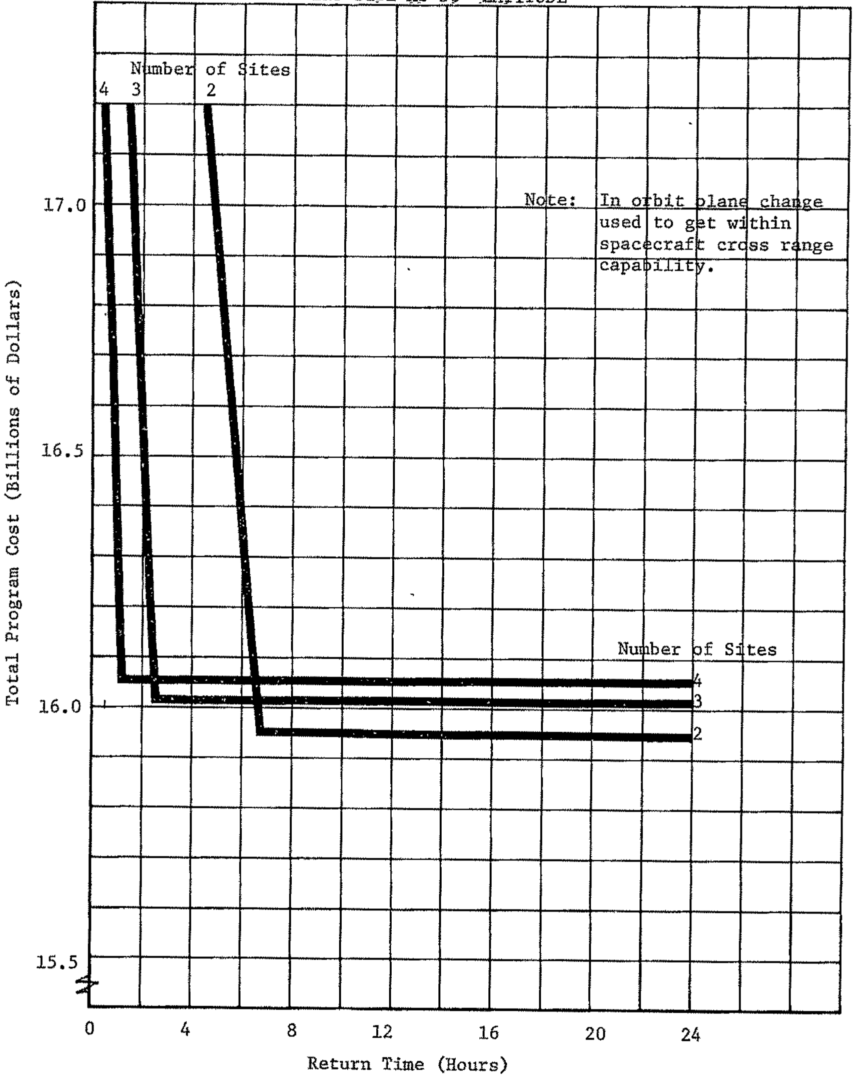


FIGURE 5-31

IIE COST VS. RETURN TIME AND NUMBER OF SITES
70° ORBIT INCLINATION
LANDING SITE AT 50° LATITUDE

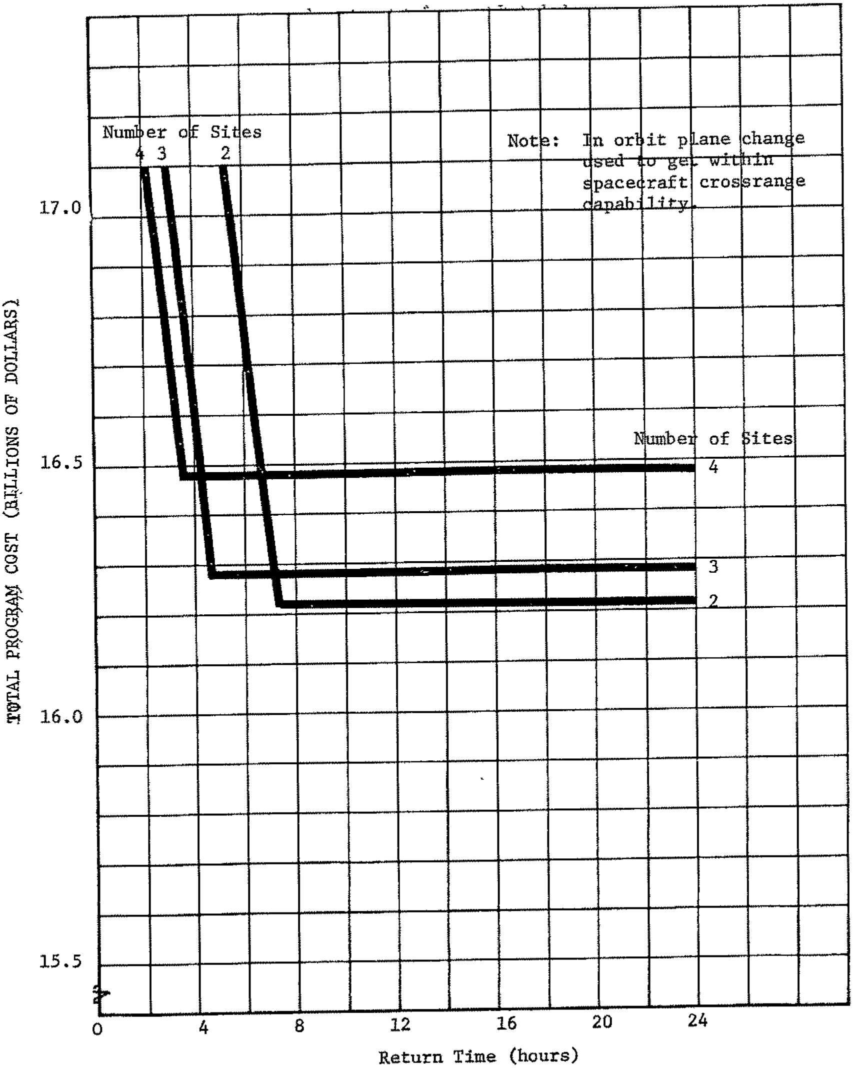
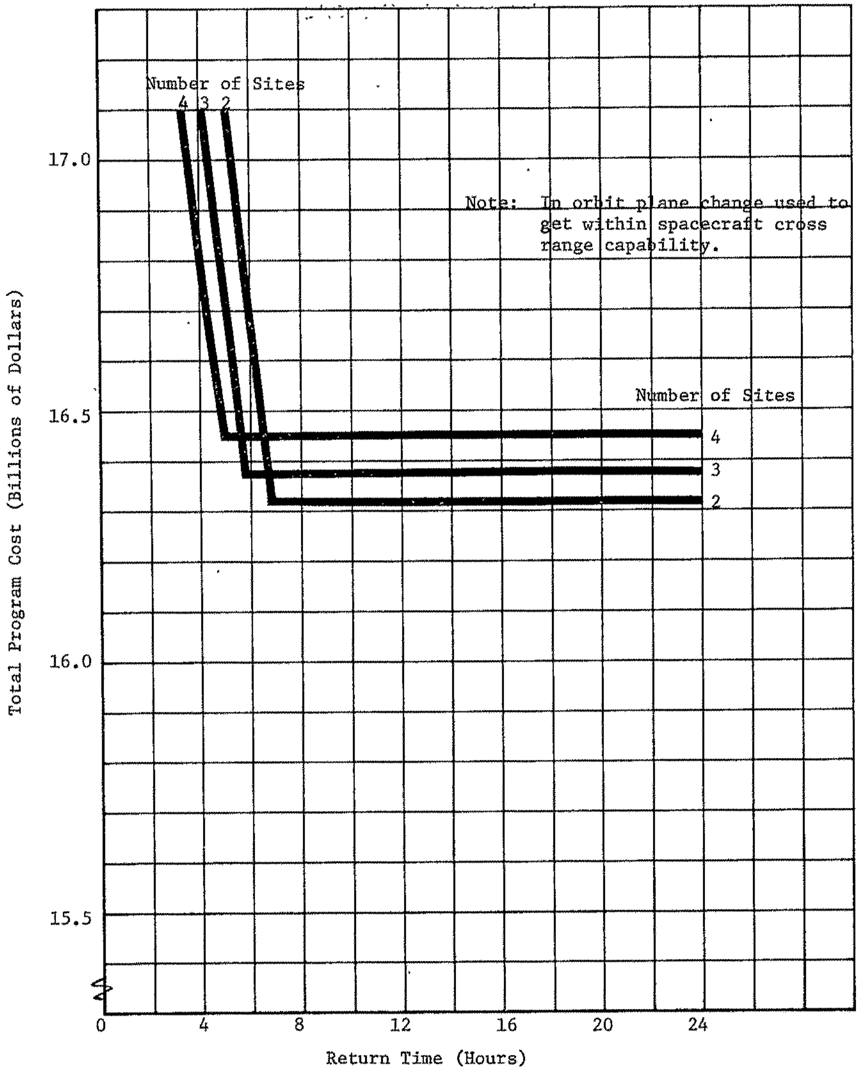
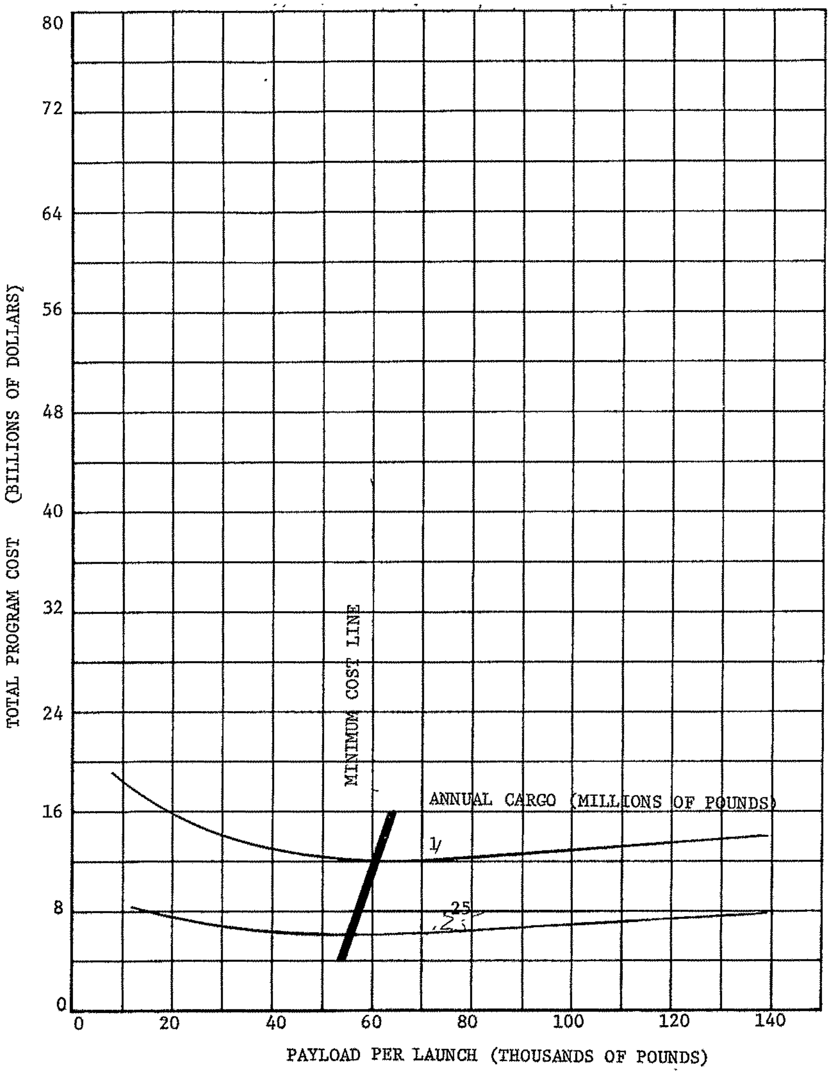


FIGURE 5-32

IIE COST VS RETURN TIME AND NUMBER OF
90° ORBIT INCLINATION
LANDING SITE AT 50° LATITUDE



IA(L) COST VARIATIONS WITH ANNUAL CARGO RATES FIGURE 5-33



IB COST VARIATION WITH ANNUAL CARGO RATES FIGURE 5-34

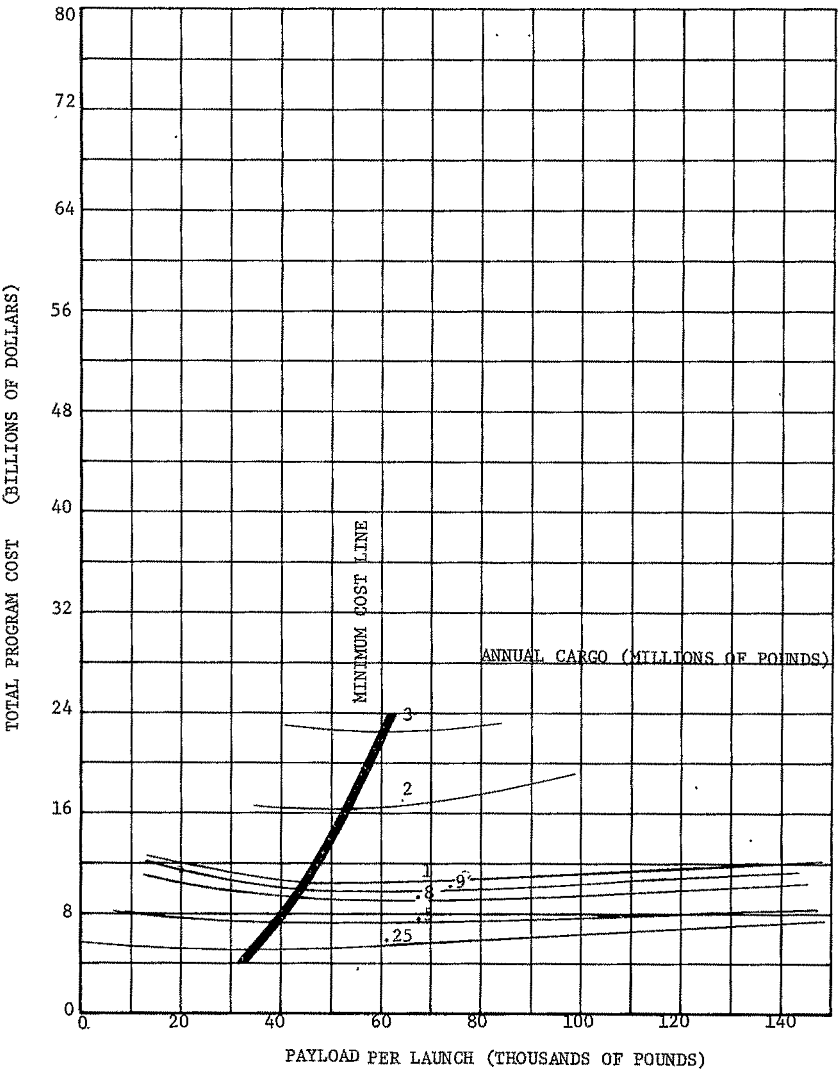
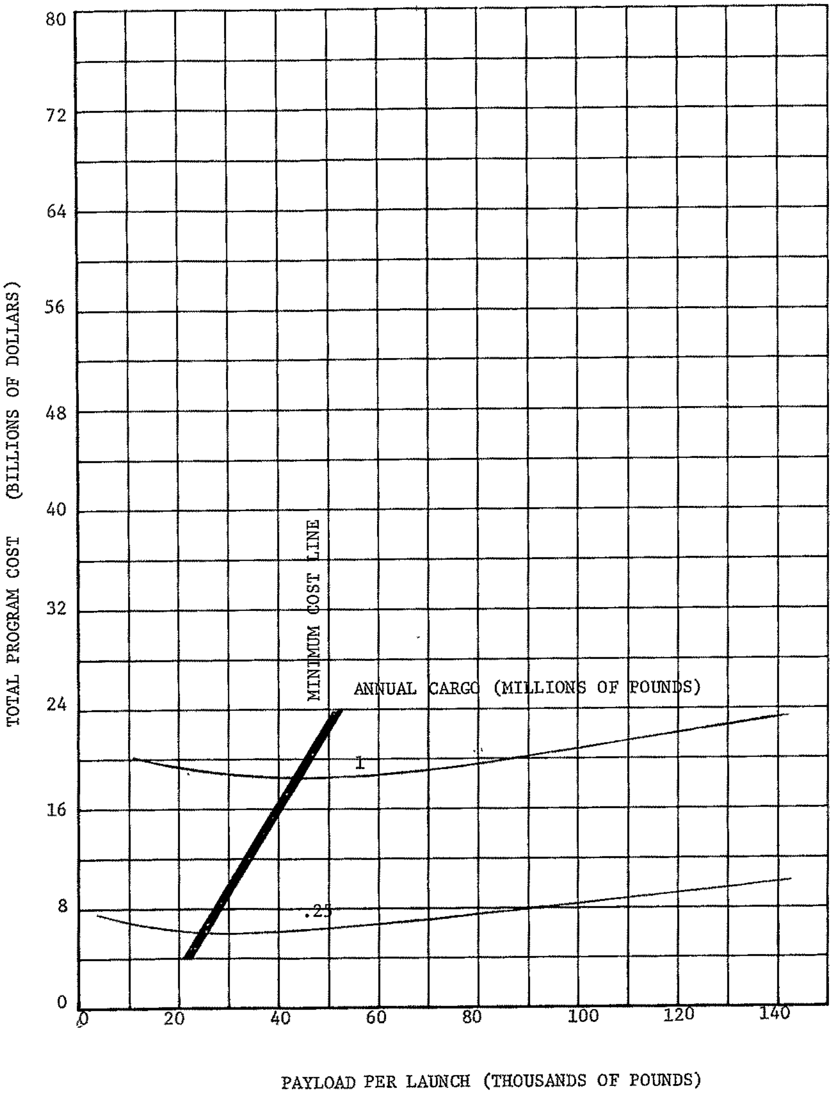
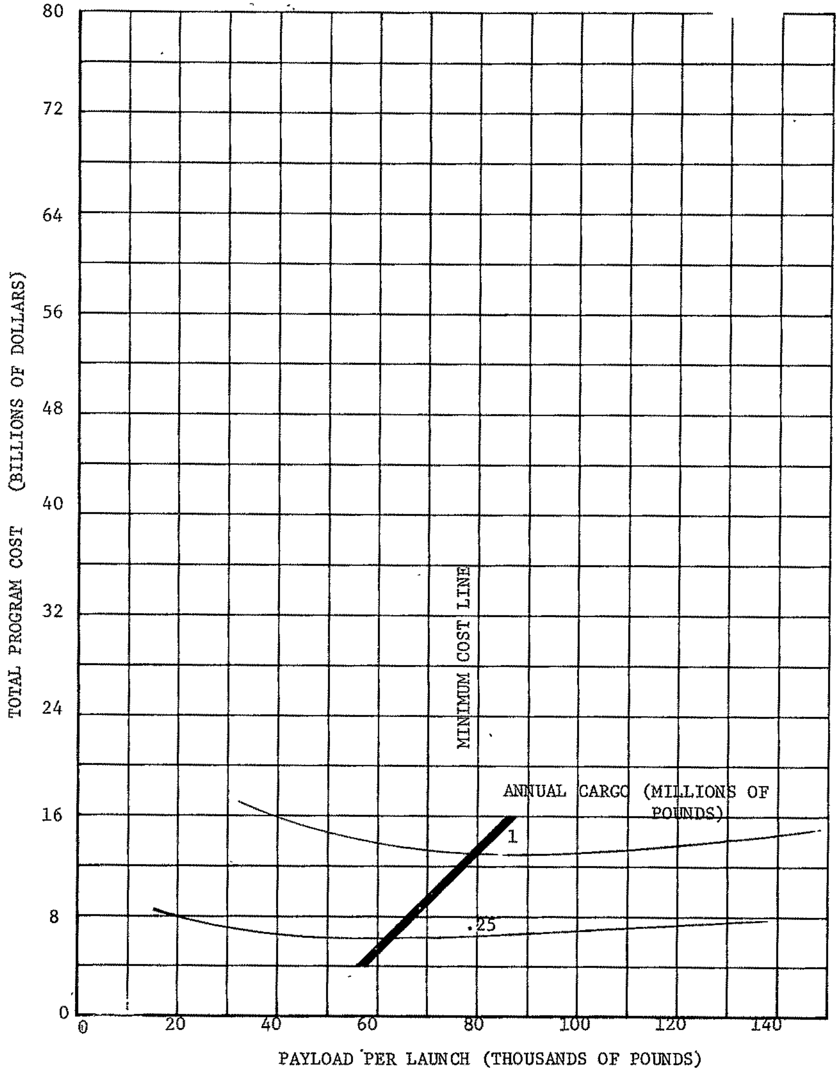


FIGURE 5-35

IC COST VARIATION WITH ANNUAL CARGO RATES

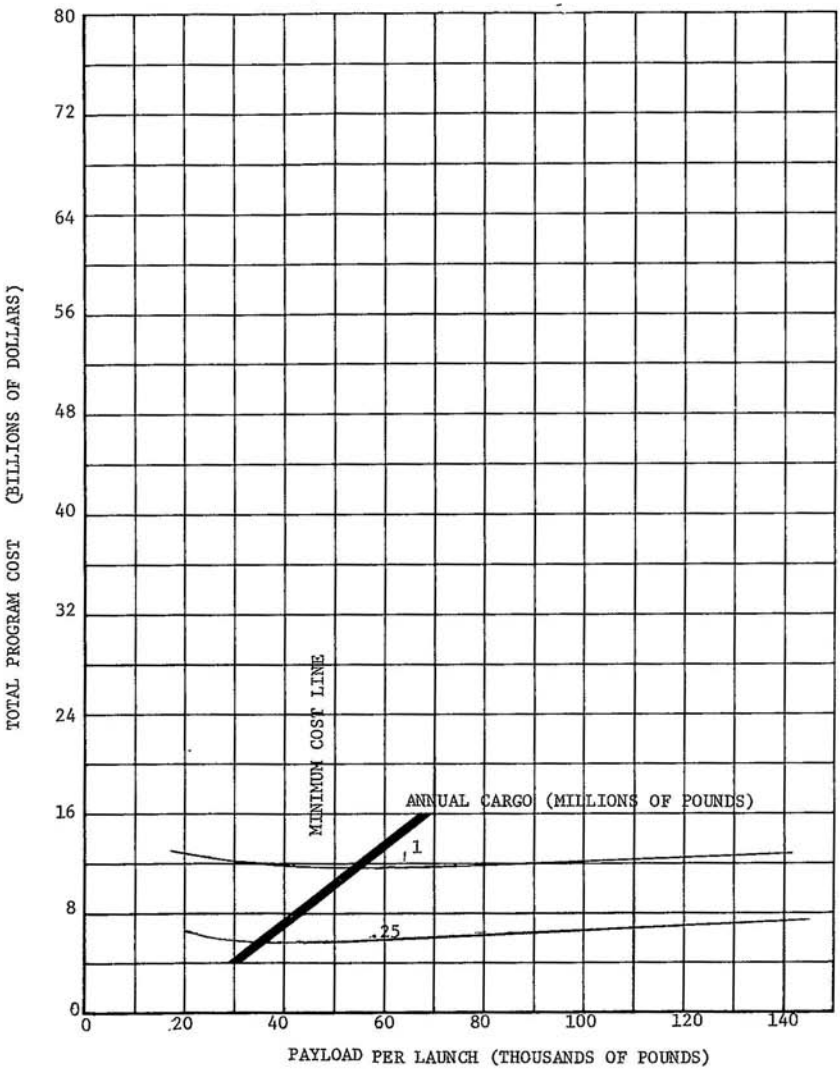


IIA COST VARIATIONS WITH ANNUAL CARGO RATES FIGURE 5-36



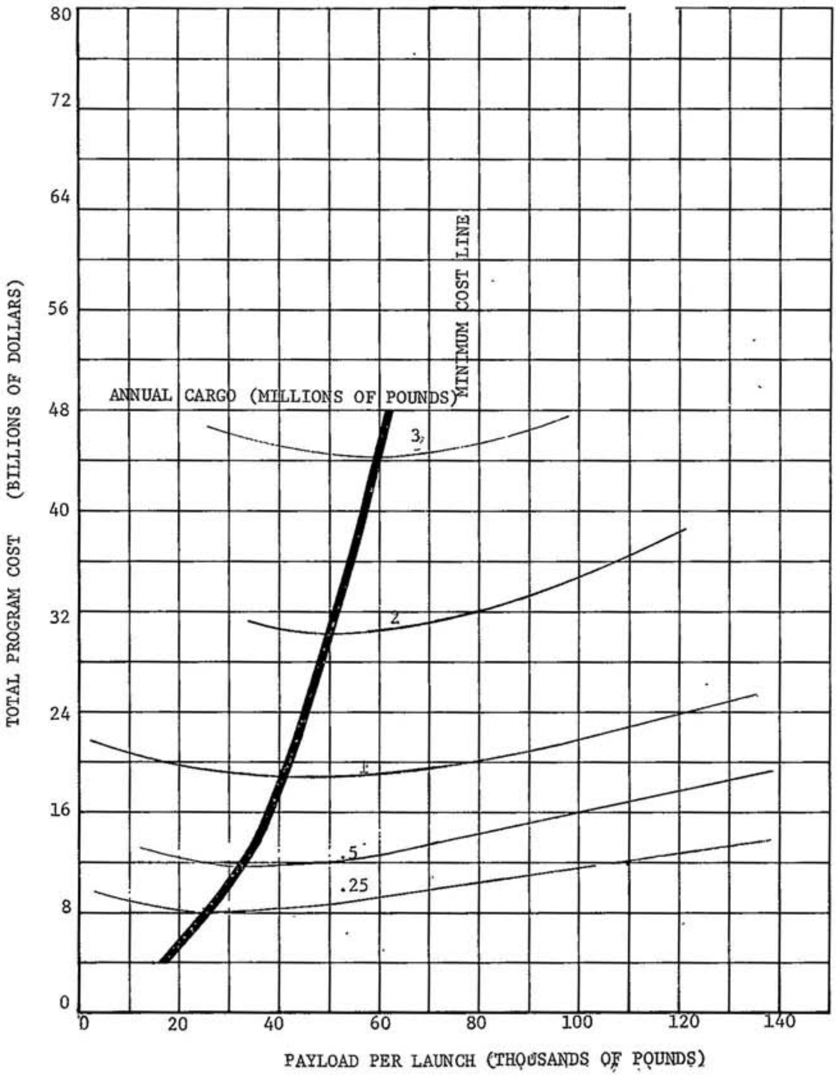
IIB COST VARIATIONS WITH ANNUAL CARGO RATES

FIGURE 5-37



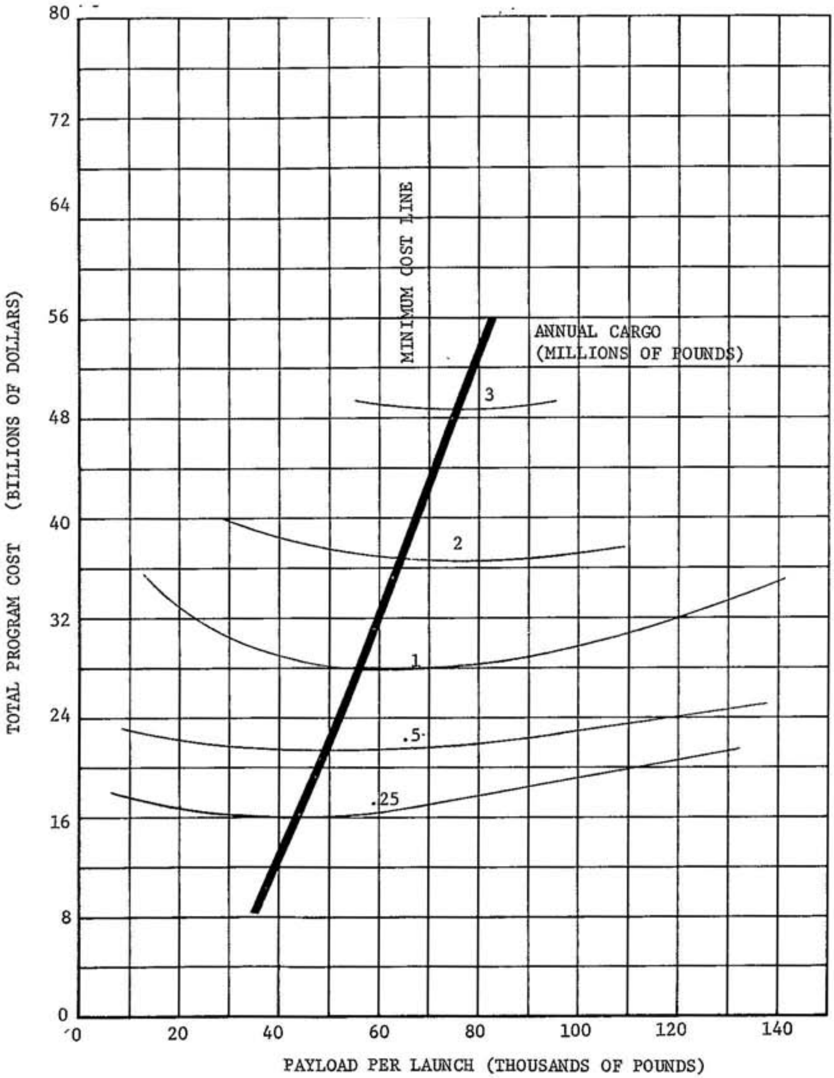
IIC COST VARIATION WITH ANNUAL CARGO RATES

FIGURE 5-38



IIE COST VARIATION WITH ANNUAL CARGO RATES

FIGURE 5-39



4. A fourfold increase in annual cargo only doubles the cost.

The way total program cost varies with number of flights is presented in Figures 5-40 through 5-43 and summarized in Figure 5-44. In the summary figure the payload was held constant at 50,000 pounds. The interesting feature in Figure 5-44 is that the curves seem to diverge with increasing number of flights. The cost per pound of payload delivered in orbit is actually decreasing with increasing number of flights, but it is decreasing at a decreasing rate.

These curves indicate that the more reusable the spacecraft becomes the more expensive it becomes. As mentioned in section 5-1, this is the result of three interactions: the vehicle size, the operation philosophy, and the launch vehicle cost. The vehicle size characteristics were shown previously; figures 5-45 through 5-48 provide additional insight into the other factors.

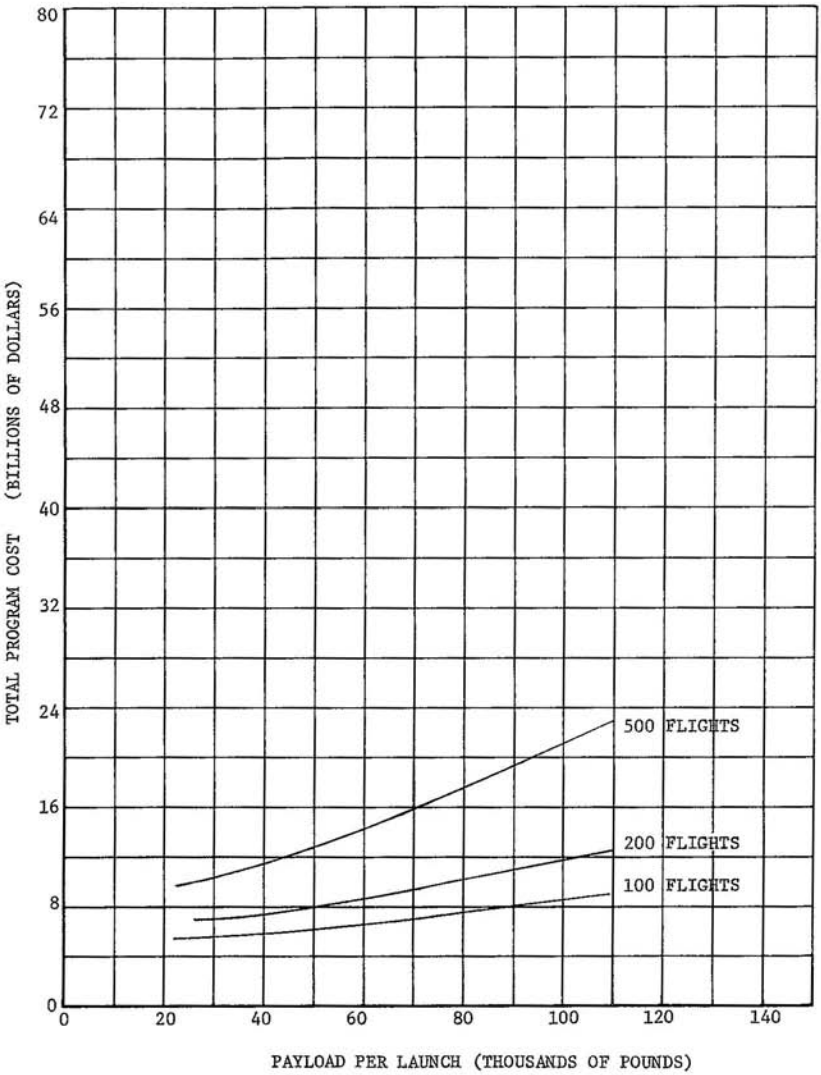
These figures show that launch vehicle investment is a major part of the recurring cost. The launch vehicle investment cost for 100 flights is $460M, $520M, $100 M, and $520M for the IB, IIB, IIC, and IIE configurations. A fully reusable launch vehicle would put the booster in the same catagory as the spacecraft. In this case these investment costs could be eliminated which would significantly reduce the recurring costs since it is assumed that the five flight test boosters would serve the operational program.

The fee plus management costs are also shown to run from 10 to 23 percent of the recurring cost and is another factor which inflates the recurring costs. In summary, Figures 5-40 through 5-48 indicate that:

1. The largest contributor to toal program cost is launch vehicle investment which was only studied parametrically. The object of the study was to investigate spacecraft cost.
2. Total fee and management cost exceed spacecraft operations costs.
3. The cost per pound declines steadily as the number of flights increase.
4. Spacecraft operational costs increase as more of the hardware is recovered (progressing from B to C to E configuration) but this is due to the ground rules of the study. A reverse trend could be obtained from a less conservative or more aircraft type philosophy.

The penalty for undersizing the payload is shown quite clearly in Figures 5-49 through 5-52. The curves are steep for small paylods but are fairly flat at the large payloads. These curves are summarized in Figures 5-53 and 5-44.

IIB COST VARIATIONS WITH NUMBER OF FLIGHTS FIGURE 5-40



IB COST VARIATIONS WITH NUMBER OF FLIGHTS — FIGURE 5-41

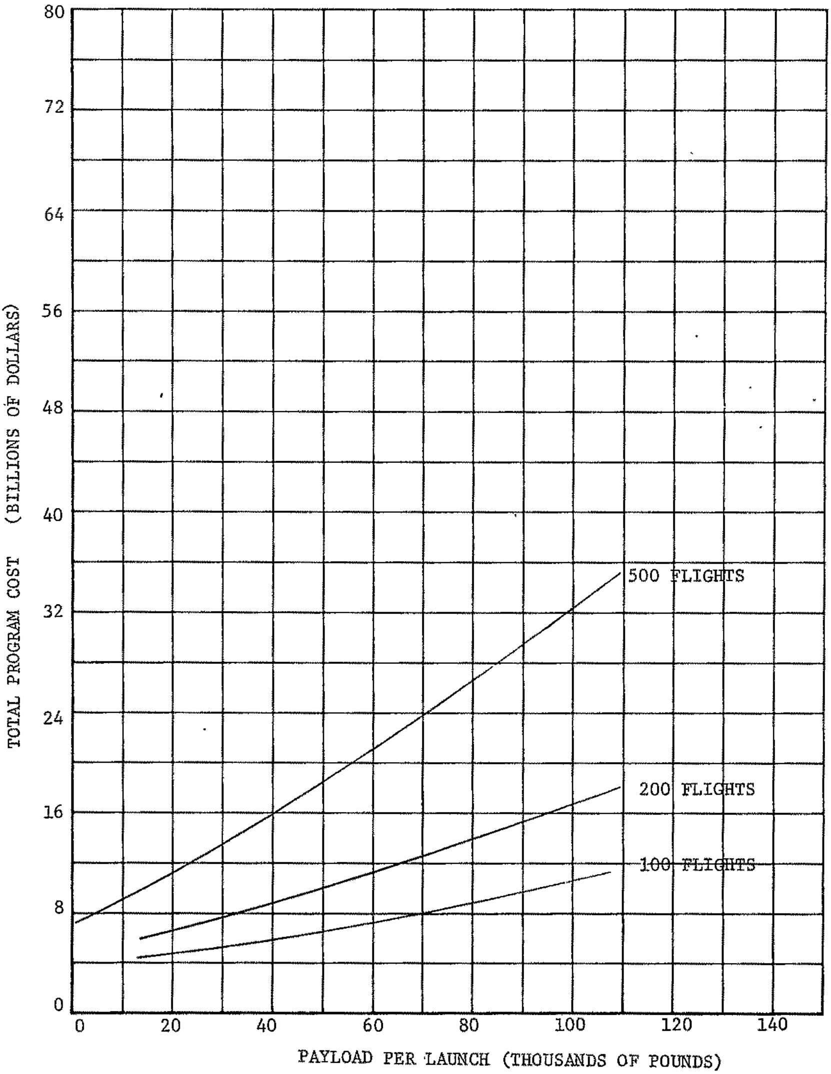


FIGURE 5-42

IIC COST VARIATIONS WITH NUMBER OF FLIGHTS

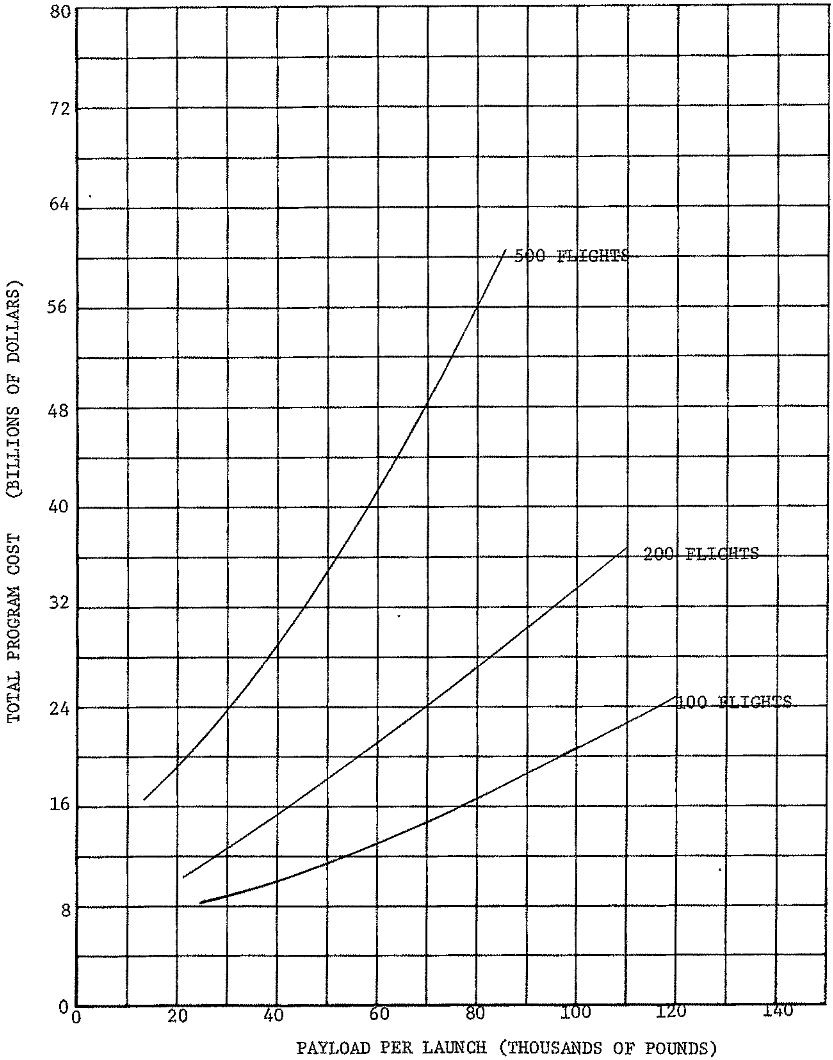


FIGURE 5-43

IIE COST VARIATIONS WITH NUMBER OF FLIGHTS

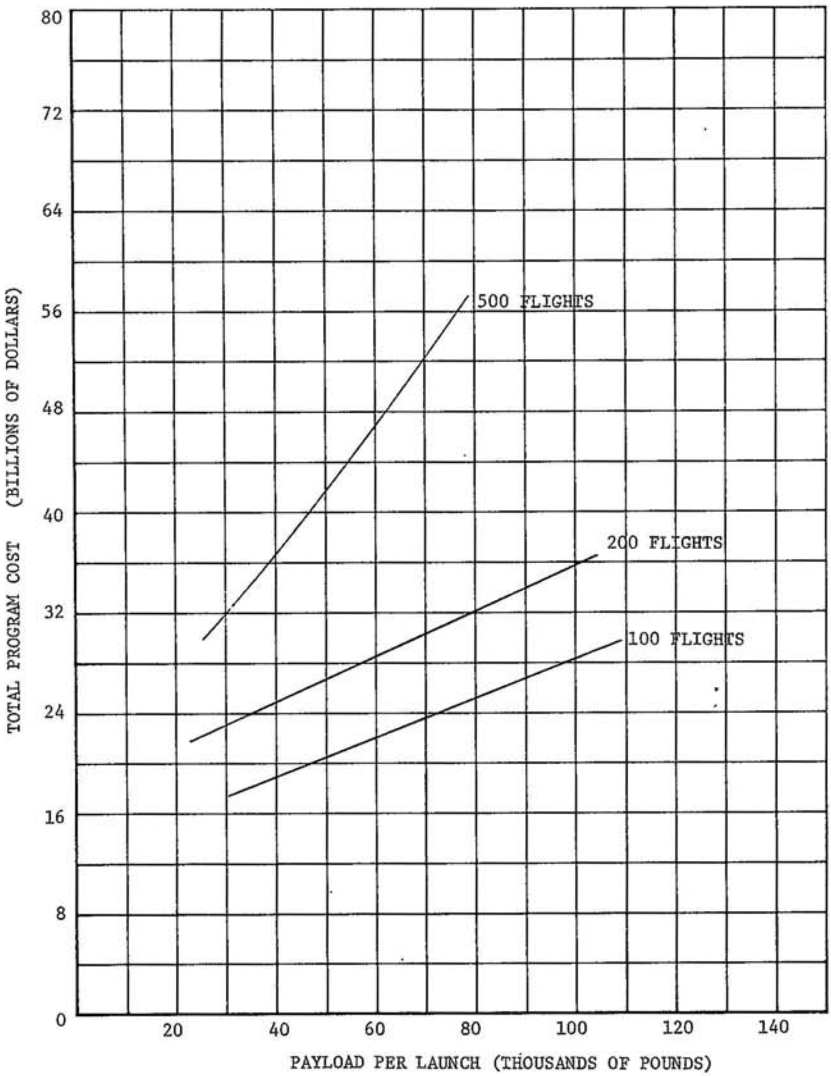
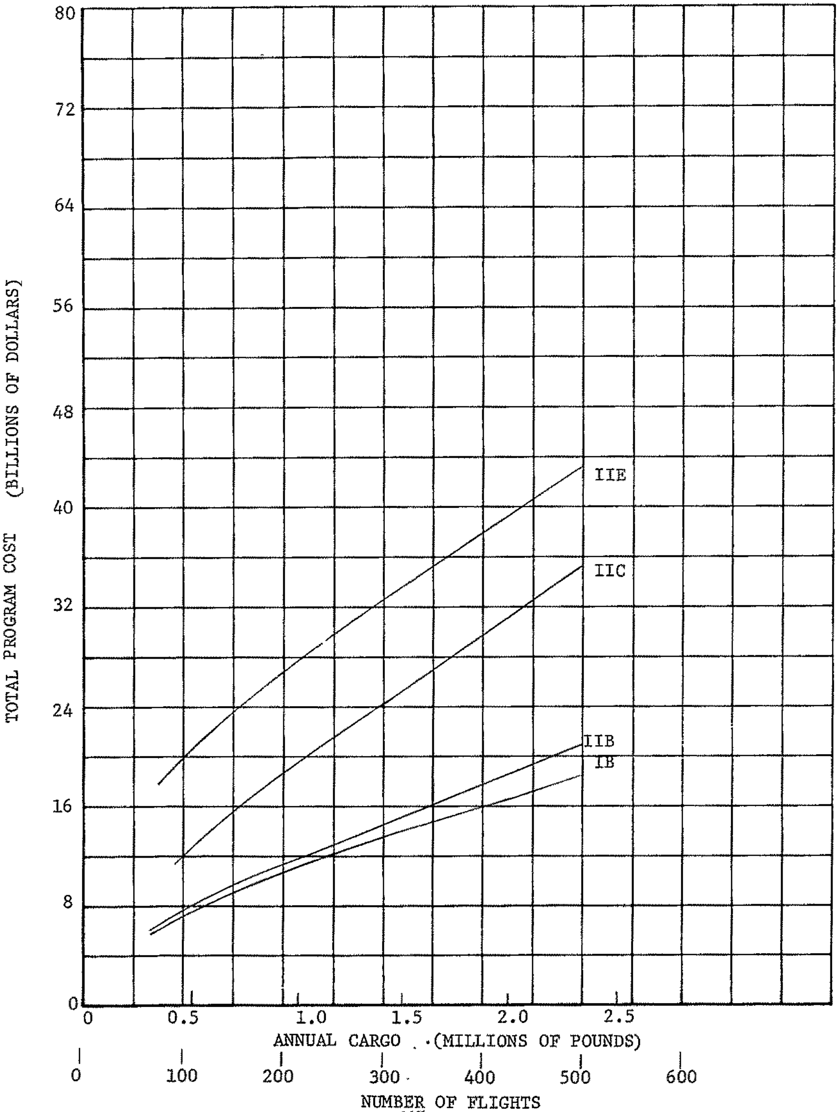


FIGURE 5-44

COST VARIATION WITH CONFIGURATION
PAYLOAD = 50,000 POUNDS



IB RECURRING COST BREAKDOWN WITH NUMBER OF FLIGHTS
PAYLOAD = 50,000 POUNDS

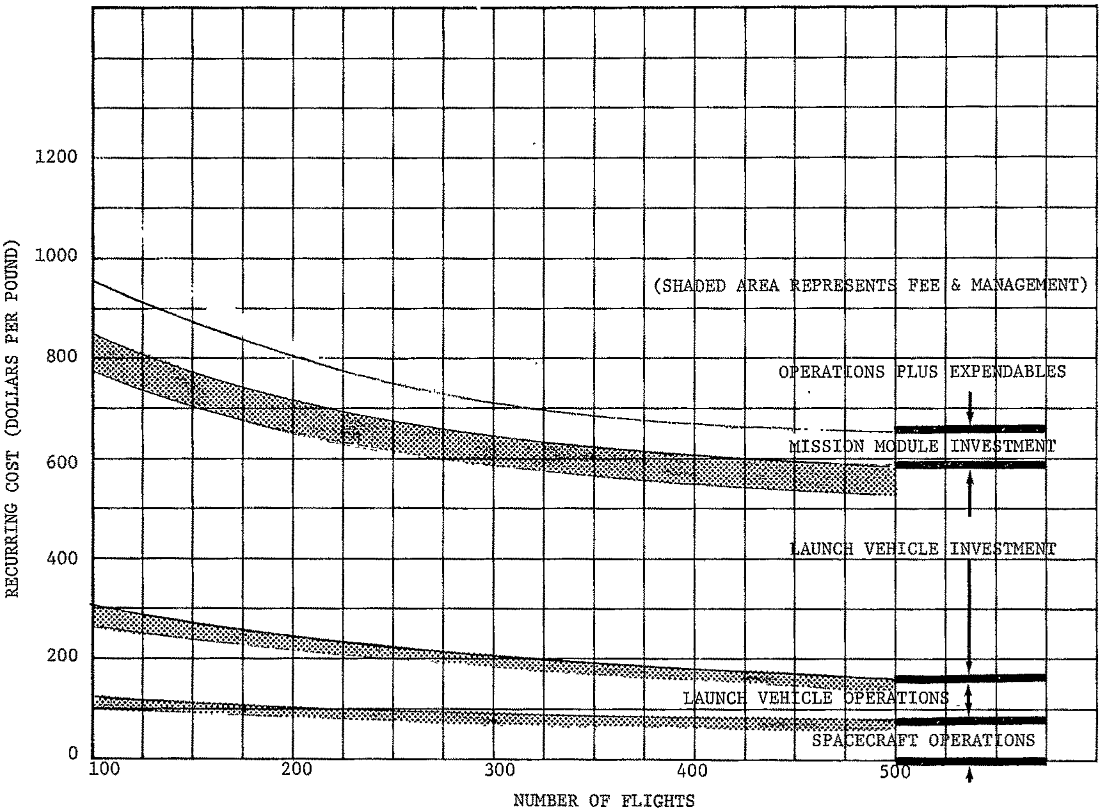


FIGURE 5-45

IIB RECURRING COST BREAKDOWN WITH NUMBER OF FLIGHTS
PAYLOAD = 50,000 POUNDS

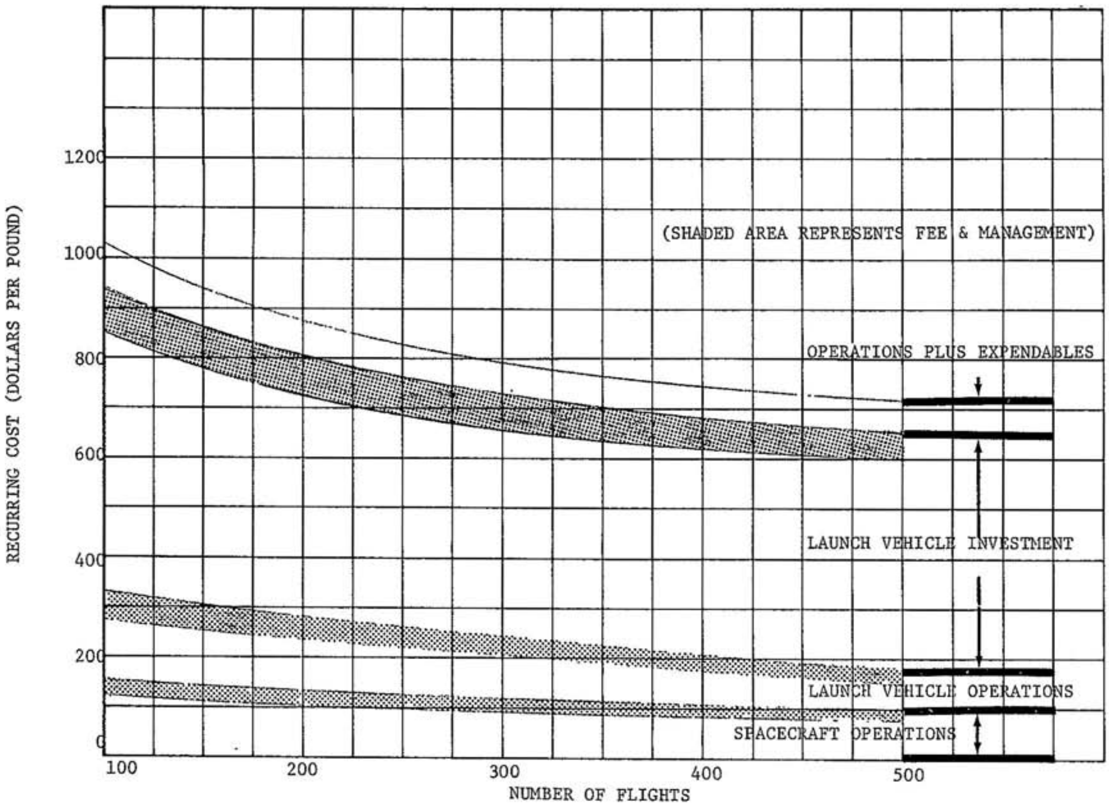


FIGURE 5-46

IIC RECURRING COST BREAKDOWN WITH NUMBER OF FLIGHTS

PAYLOAD = 50,000 POUNDS

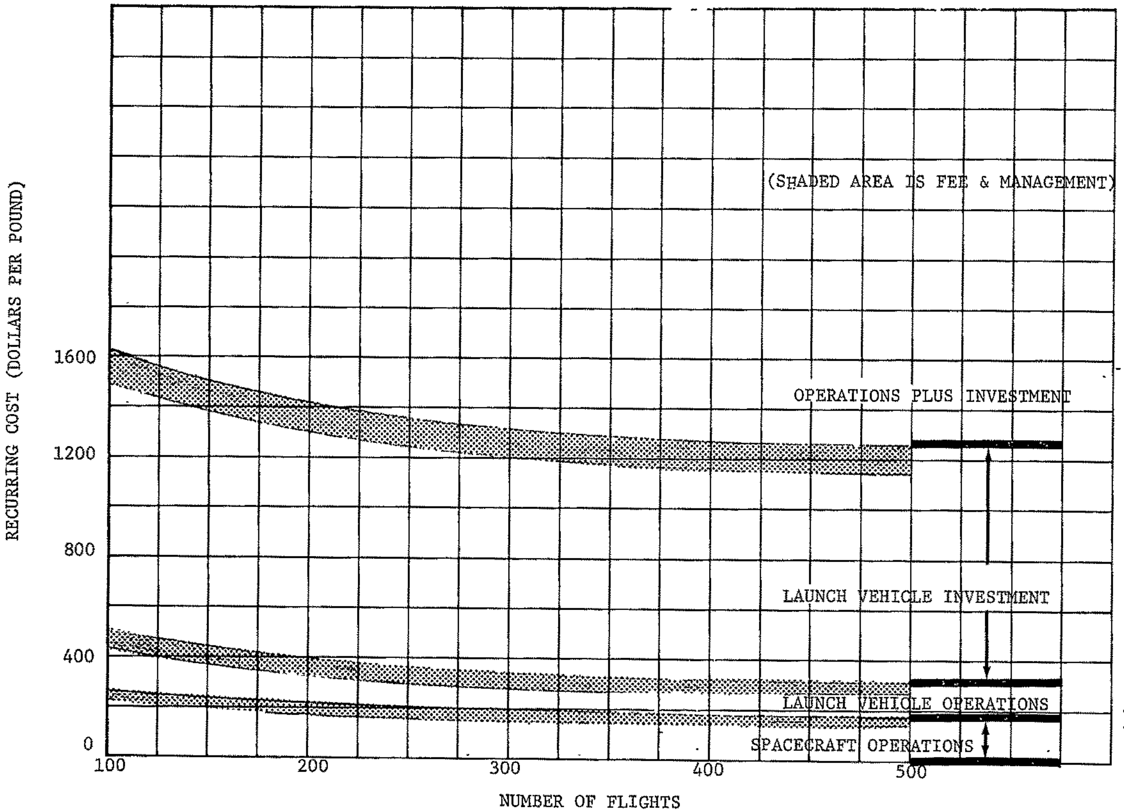


FIGURE 5-47

IIE RECURRING COST BREAKDOWN WITH NUMBER OF FLIGHTS

PAYLOAD = 50,000 POUNDS

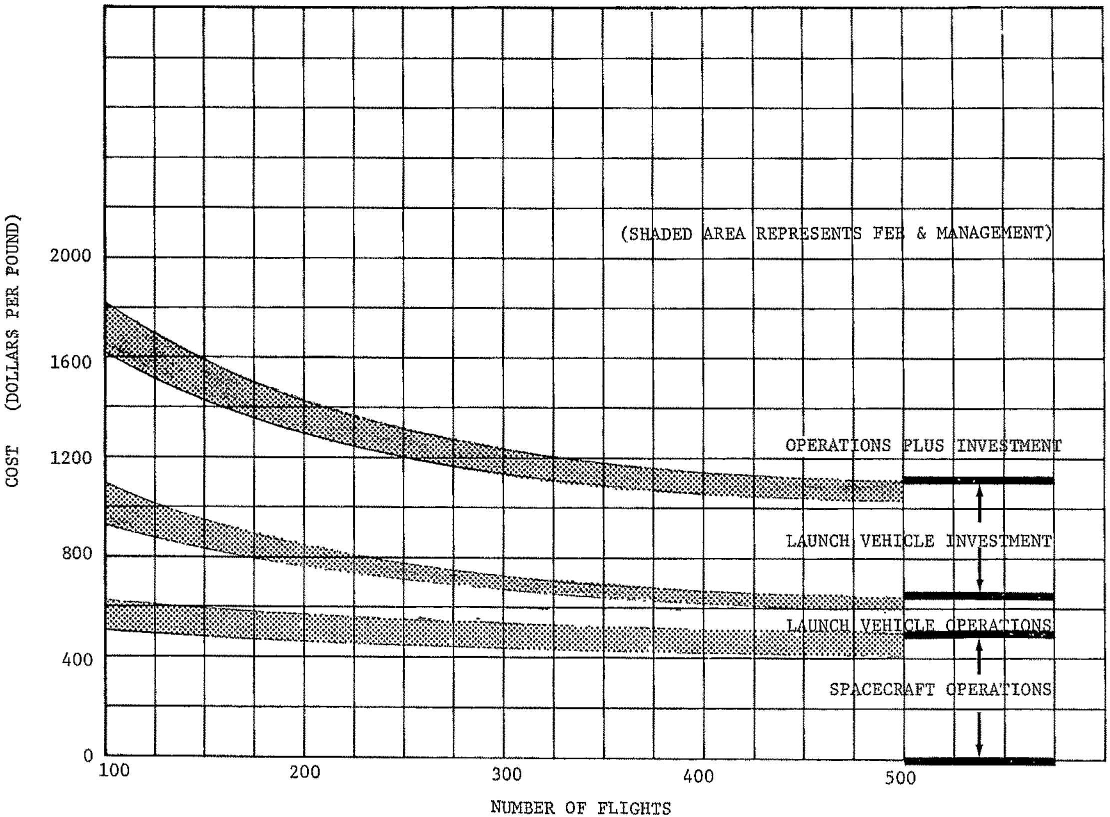


FIGURE 5-48

IB RECURRING COST BREAKDOWN WITH PAYLOAD VARIATION

BASED ON 100 FLIGHTS

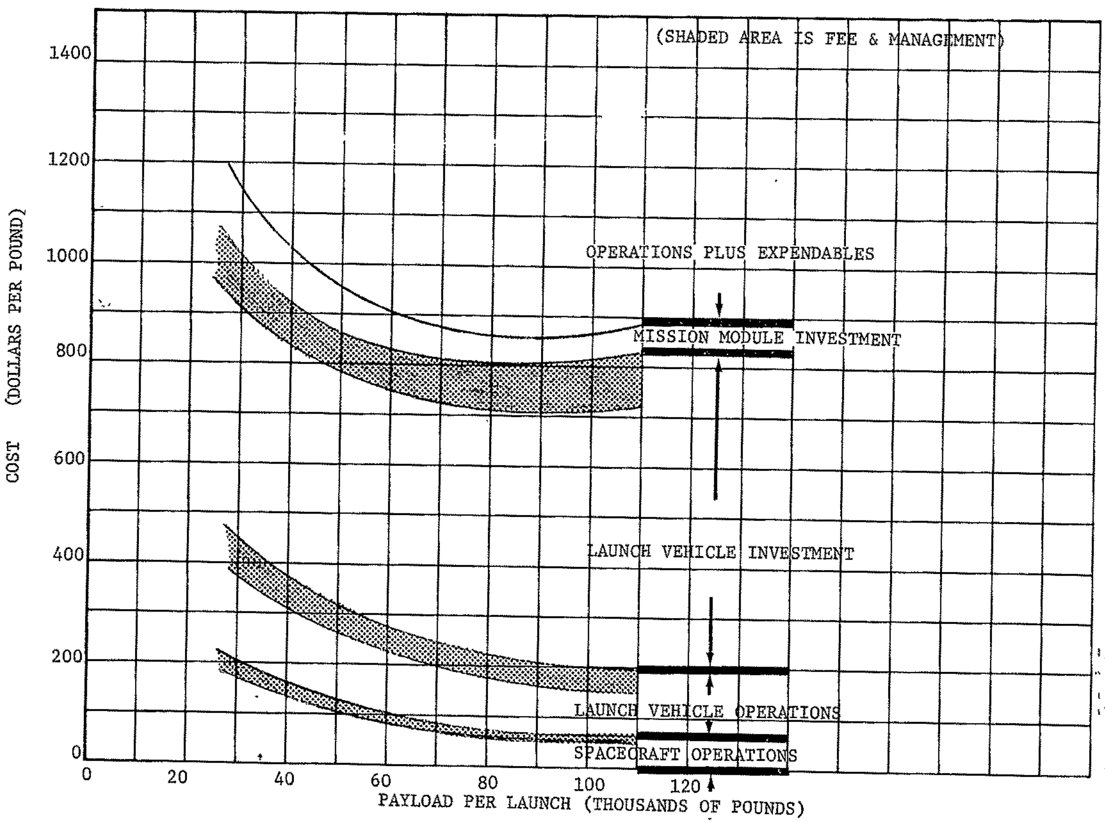


FIGURE 5-49

OPTIMIZED COST/PERFORMANCE
DESIGN METHODOLOGY

IIB RECURRING COST BREAKDOWN WITH PAYLOAD VARIATION
BASED ON 100 FLIGHTS

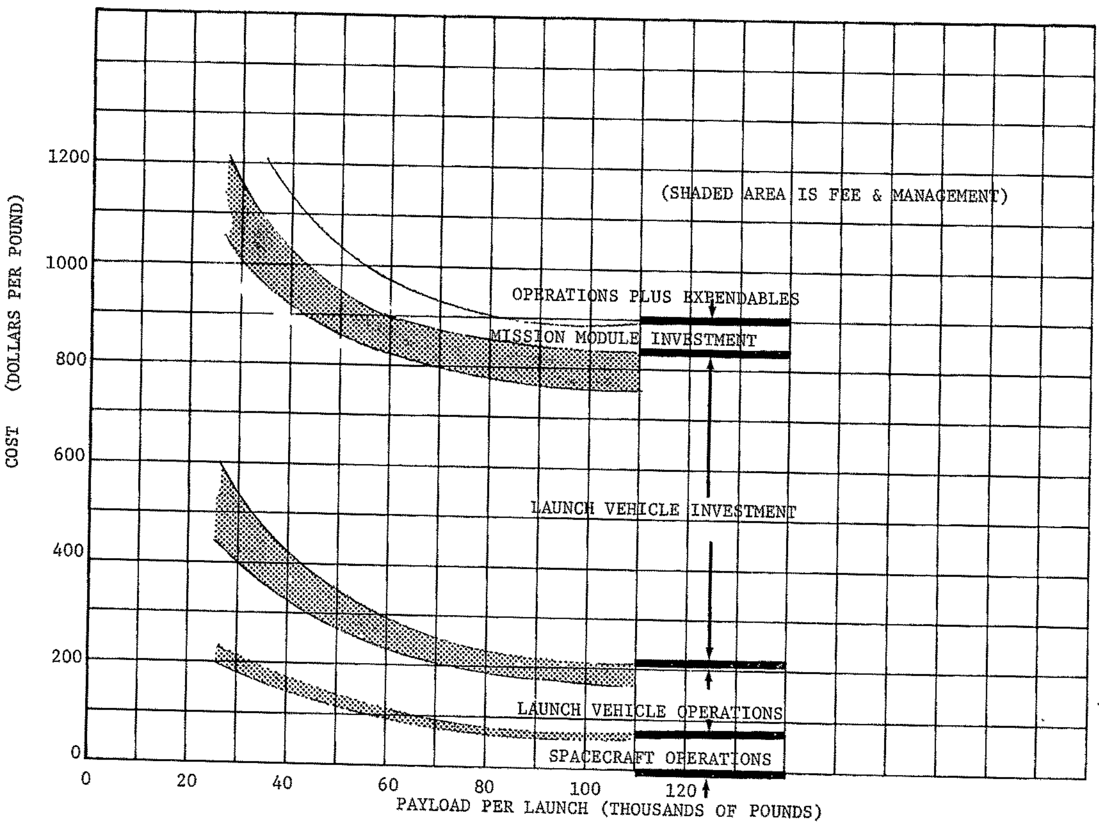


FIGURE 5-50

IIC RECURRING COST BREAKDOWN WITH PAYLOAD VARIATION

BASED ON 100 FLIGHTS

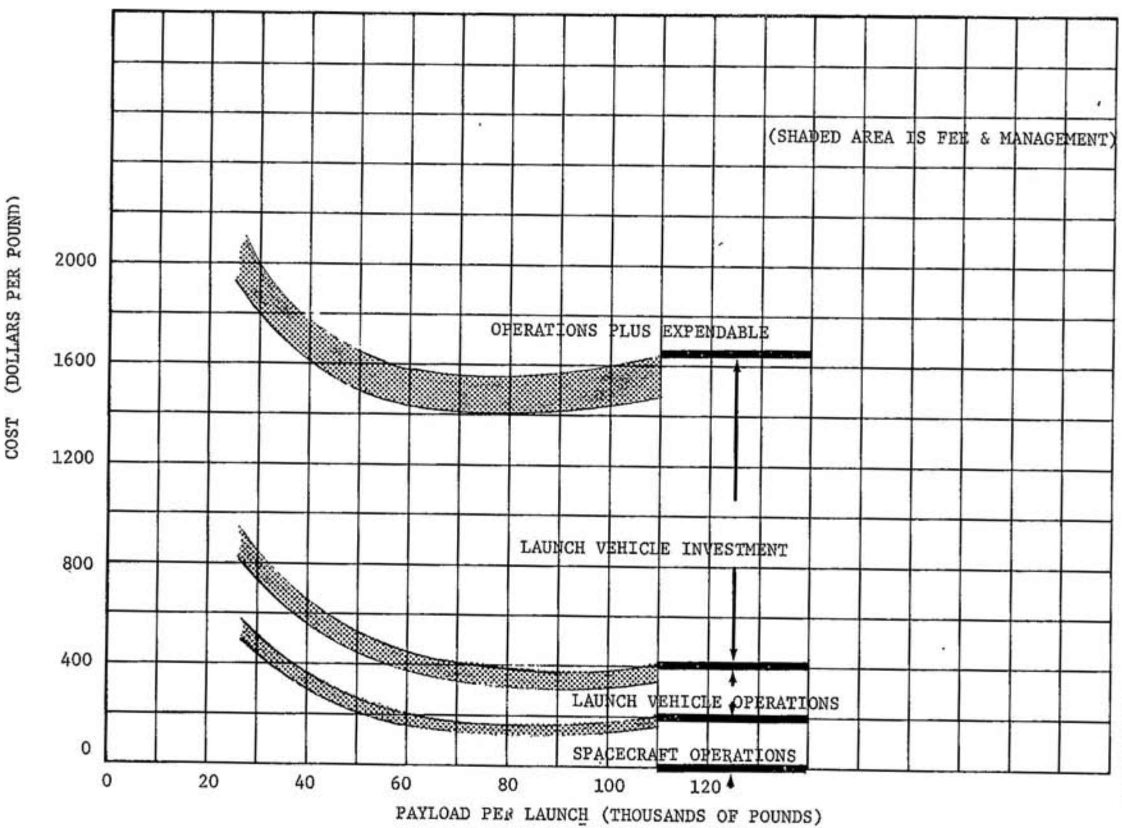


FIGURE 5-51

IIE RECURRING COST BREAKDOWN WITH PAYLOAD VARIATION

BASED ON 10C FLIGHTS

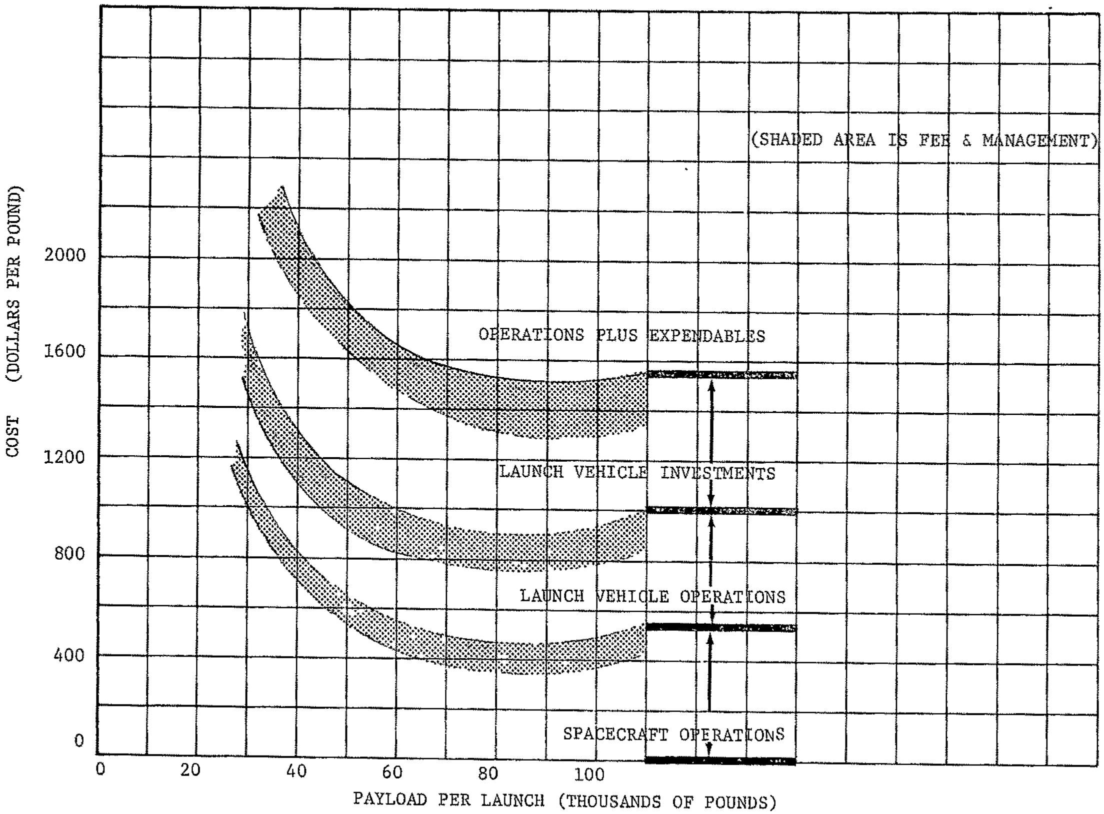


FIGURE 5-52

RECURRING OPERATIONAL COST VARIATION WITH CONFIGURATION
(EXCLUDING EXPENDABLE COST).

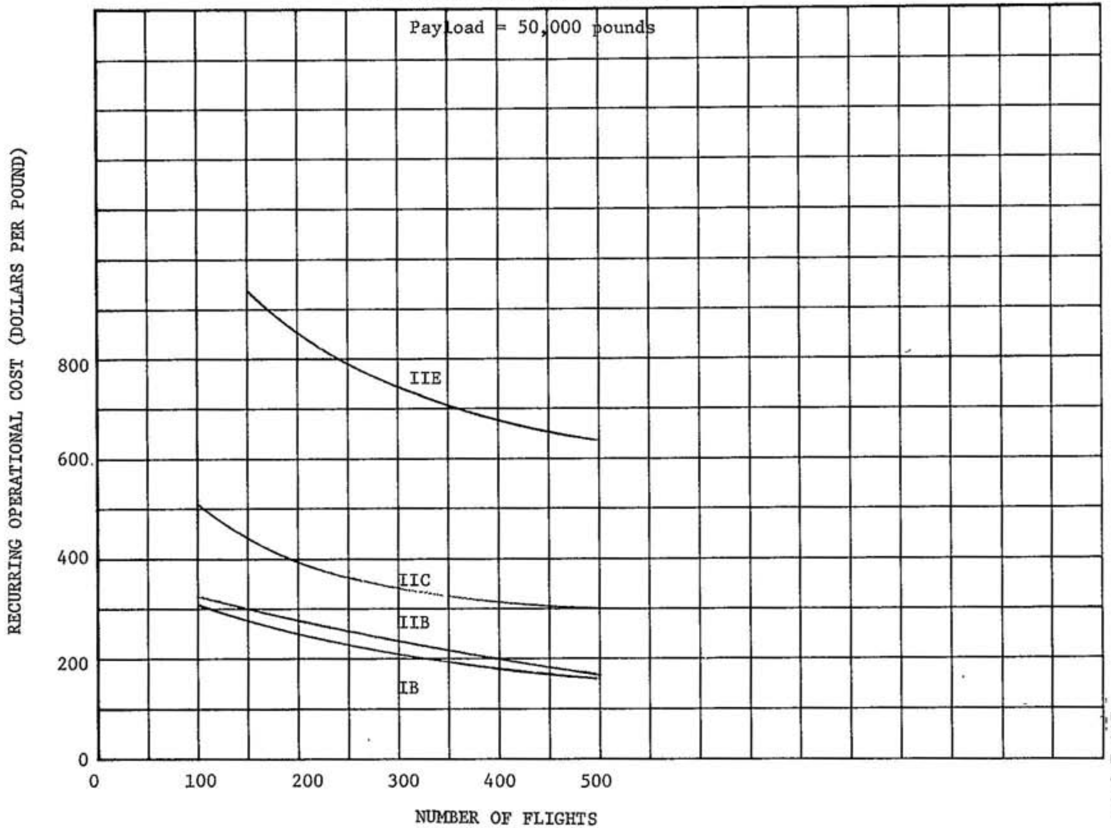


FIGURE 5-53

These curves indicate that the recurring operations cost drops to 160 dollars per pound with the IB configuration.

The spacecraft and launch vehicle operations cost per pound of payload continually decrease as the payload increases. However, an optimum payload size exists for minimizing expendable hardware costs. A low payload per launch results in many expendable launch vehicles and a very high payload results in large expensive expendable launch vehicles. The investment costs amount to 70 to 80 percent of the total recurring cost at the point where the recurring costs are minimized.

The steep slopes of the curves showing recurring cost per pound of payload delivered to orbit are due to spacecraft operations. The spacecraft operations costs per launch are almost constant for low payloads. Therefore, the cost per pound varies as the reciprocal of the payload size for small payloads.

The interesting feature in Figure 5-54 is that the IIC and IIE curves intersect. The IIE is more expensive than the IIC at the low flight rates and less expensive at the high flight rates. The launch vehicle costs are the forcing function for these curves as was shown in the previous figures. The IIE cost per pound decreases rapidly with increasing number of flights. A less conservative refurbishment philosophy would show the IIE below the IIC at all flight rates.

The variation of recurring costs with payload size and annual cargo volume is presented in Figures 5-55 through 5-60. As shown, the cost per pound can be reduced substantially by increasing the annual cargo volume. Also, sizing for a 50,000 pound payload results in recurring costs that are near the minimum.

The effect of reducing cargo density from 10 to 5 pounds per cubic foot is shown in Figures 5-61 through 5-64. This density change affects the ballistic vehicle costs (total program RDT&E, and first unit) almost identically. The percent increase in the costs of the modular lifting body configuration (IIB) is only slightly higher than the cost increases of the ballistic vehicles (IB, & IE). The IIB cost increase is small because the entry vehicle is unaffected by the cargo density. The IIE configuration has a higher percentage increase because the entire entry vehicle must be resized.

The modular vehicles (IB and IIB) have a large increase in size while the reusable vehicles (IE and IIE) increase only slightly (Figure 5-64). However, the cost of extending the length of a mission module is less costly than

RECURRING COST VARIATION WITH CONFIGURATION
(INCLUDING EXPENDABLE COST)

PAYLOAD = 50,000 POUNDS

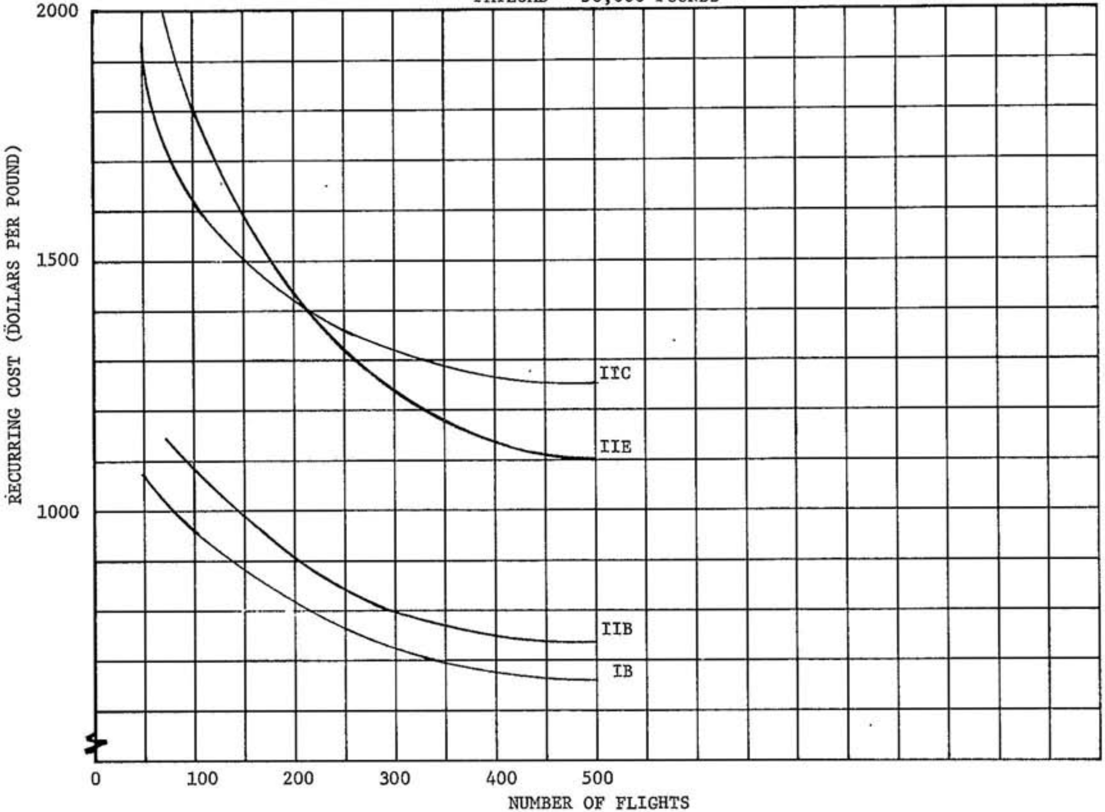


FIGURE 5-54

IB RECURRING PLUS INVESTMENT COST VARIATION WITH PAYLOAD SIZE

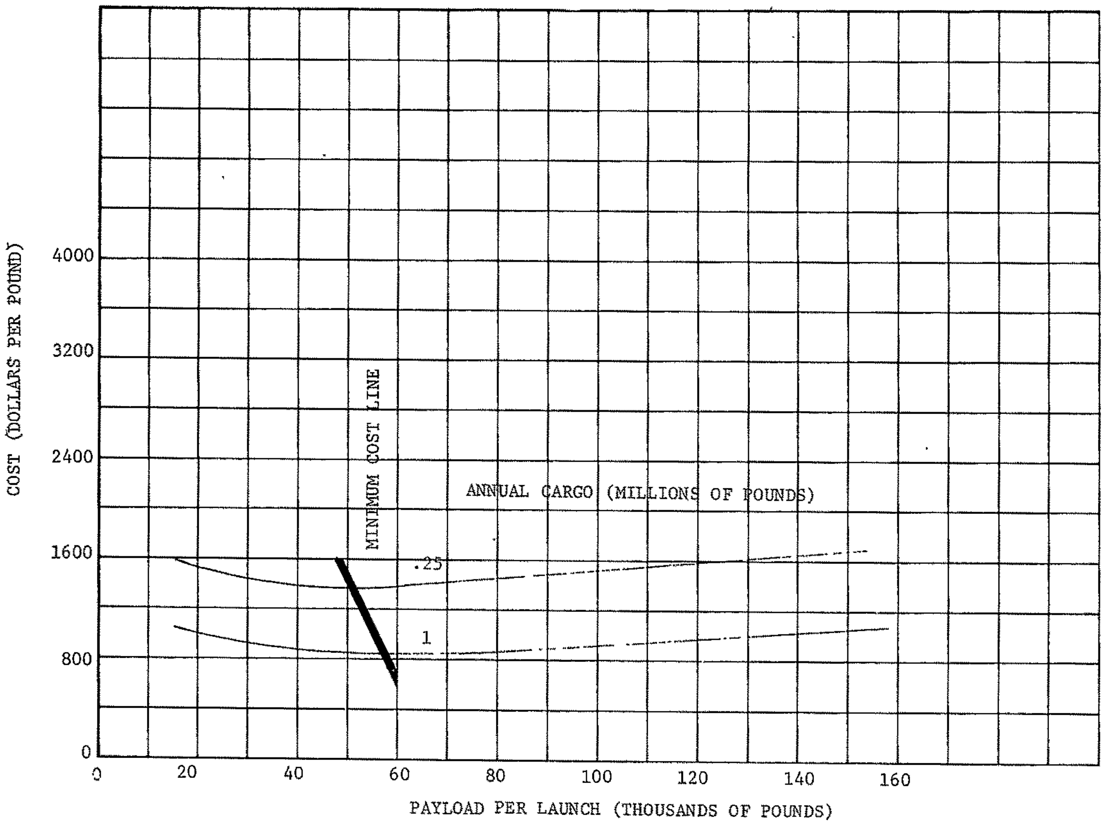


FIGURE 5-55

IC RECURRING PLUS INVESTMENT COST VARIATION WITH PAYLOAD SIZE

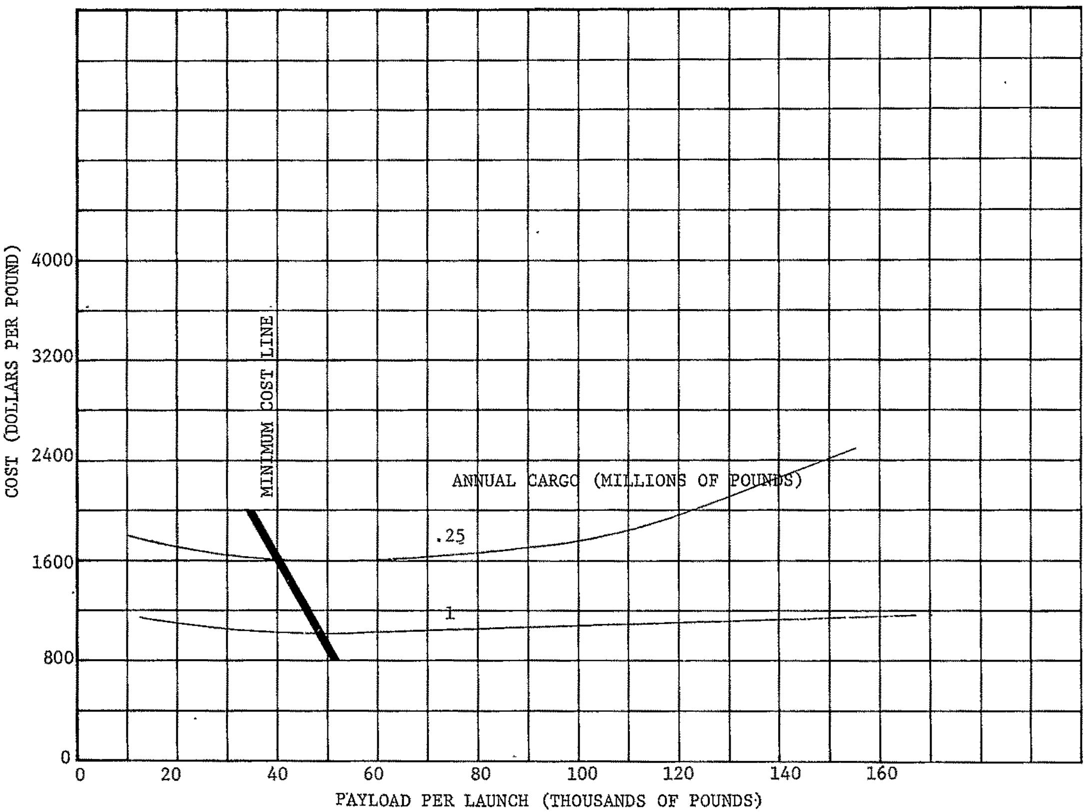


FIGURE 5-56

IIA RECURRING PLUS INVESTMENT COST VARIATION WITH PAYLOAD SIZE

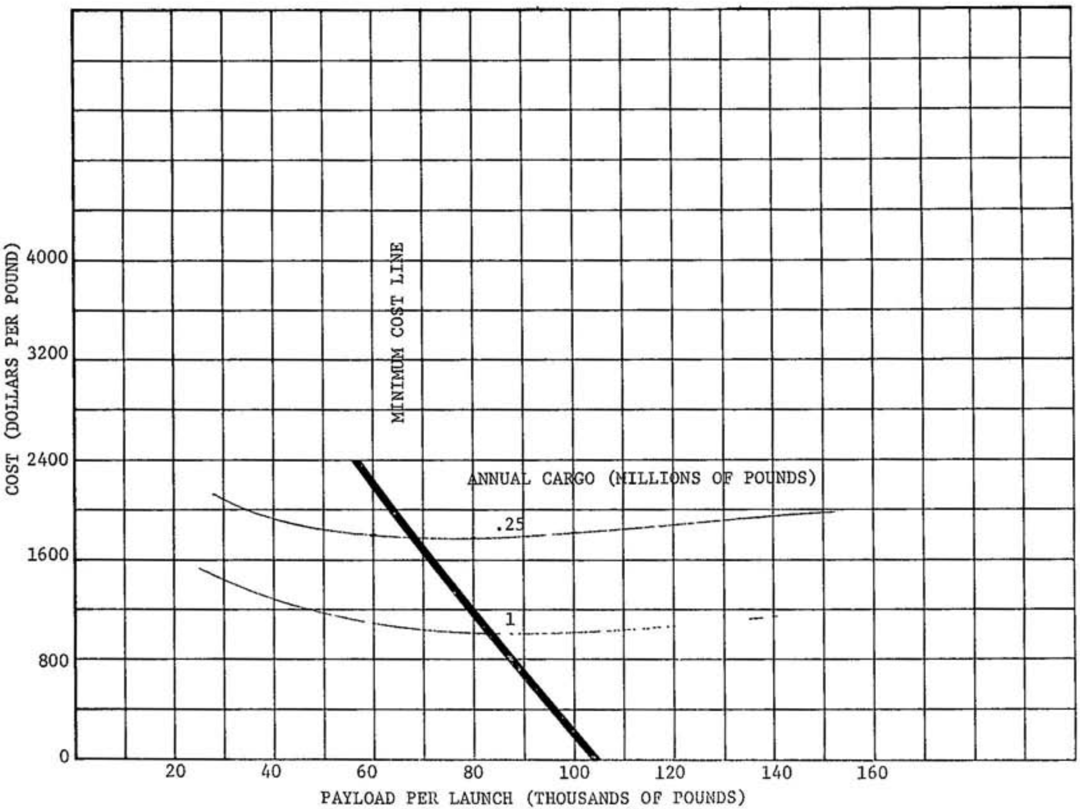


FIGURE 5-57

IIB RECURRING PLUS INVESTMENT COST VARIATION WITH PAYLOAD SIZE

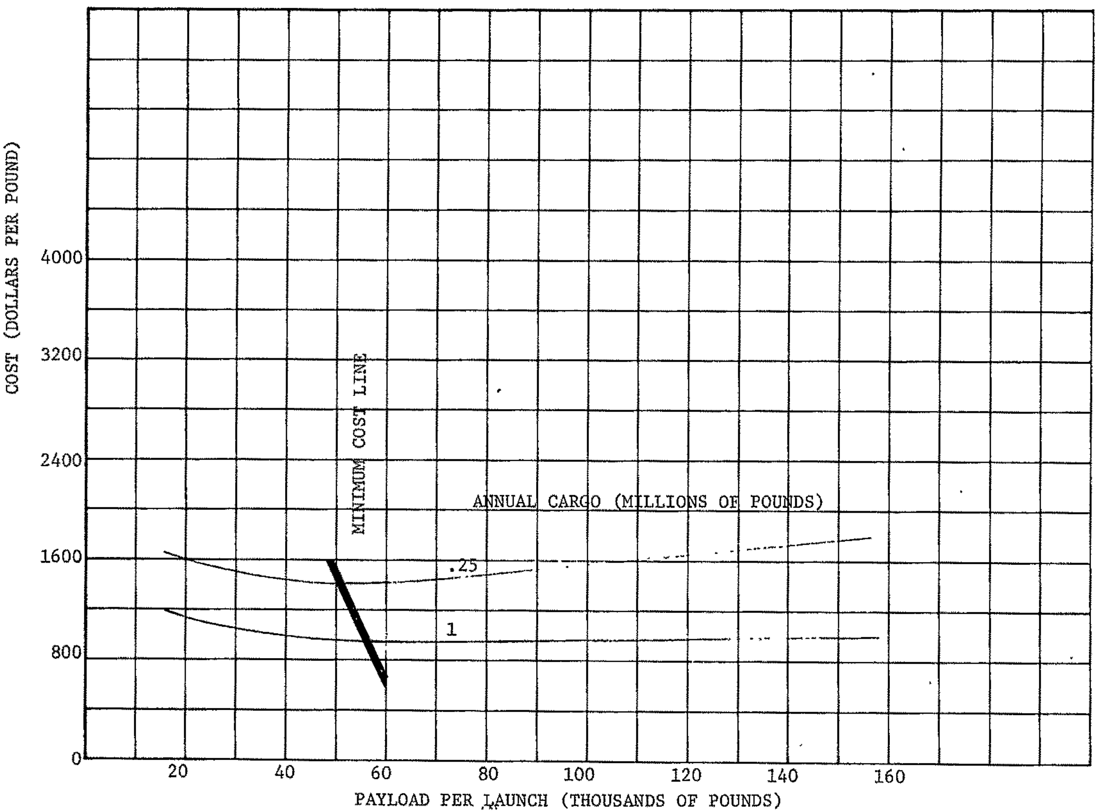


FIGURE 5-58

IIC RECURRING PLUS INVESTMENT COST VARIATION WITH PAYLOAD SIZE

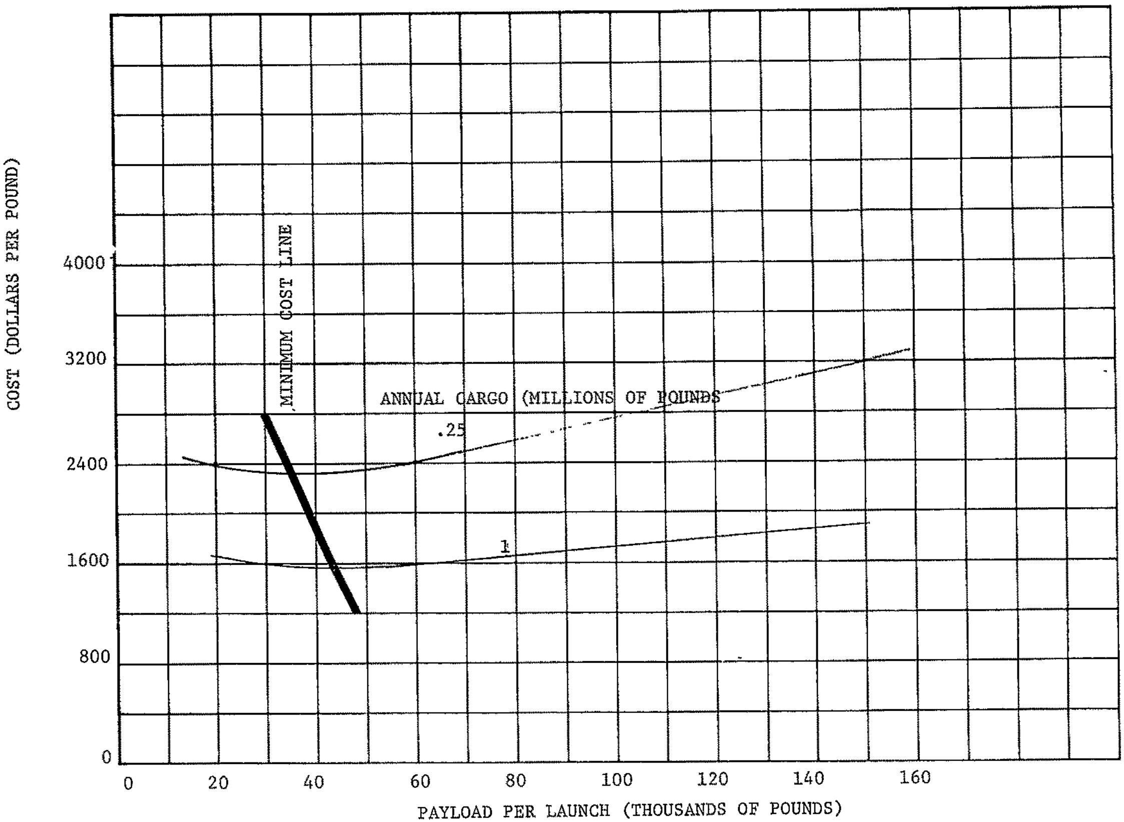


FIGURE 5-59

IIE RECURRING PLUS INVESTMENT COST VARIATION WITH PAYLOAD SIZE

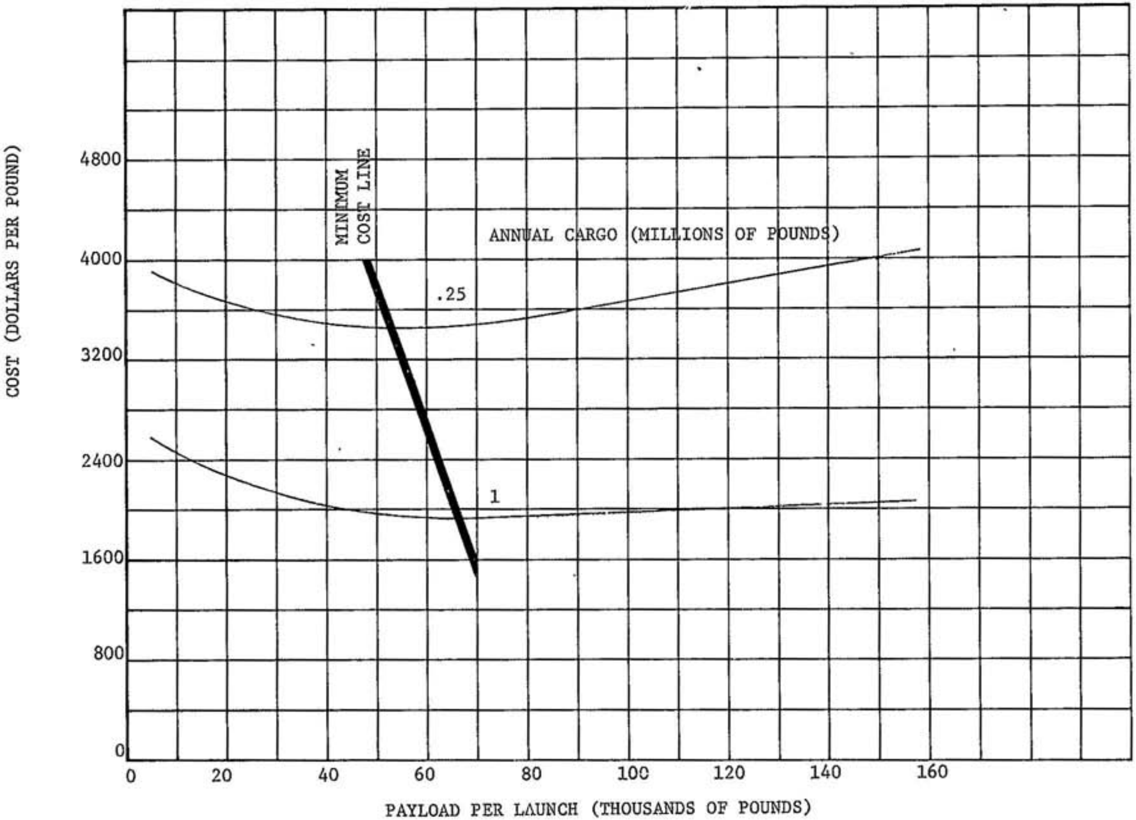


FIGURE 5-60

EFFECT OF DECREASING CARGO DENSITY
FROM 10 TO 5 POUNDS PER CUBIC FOOT

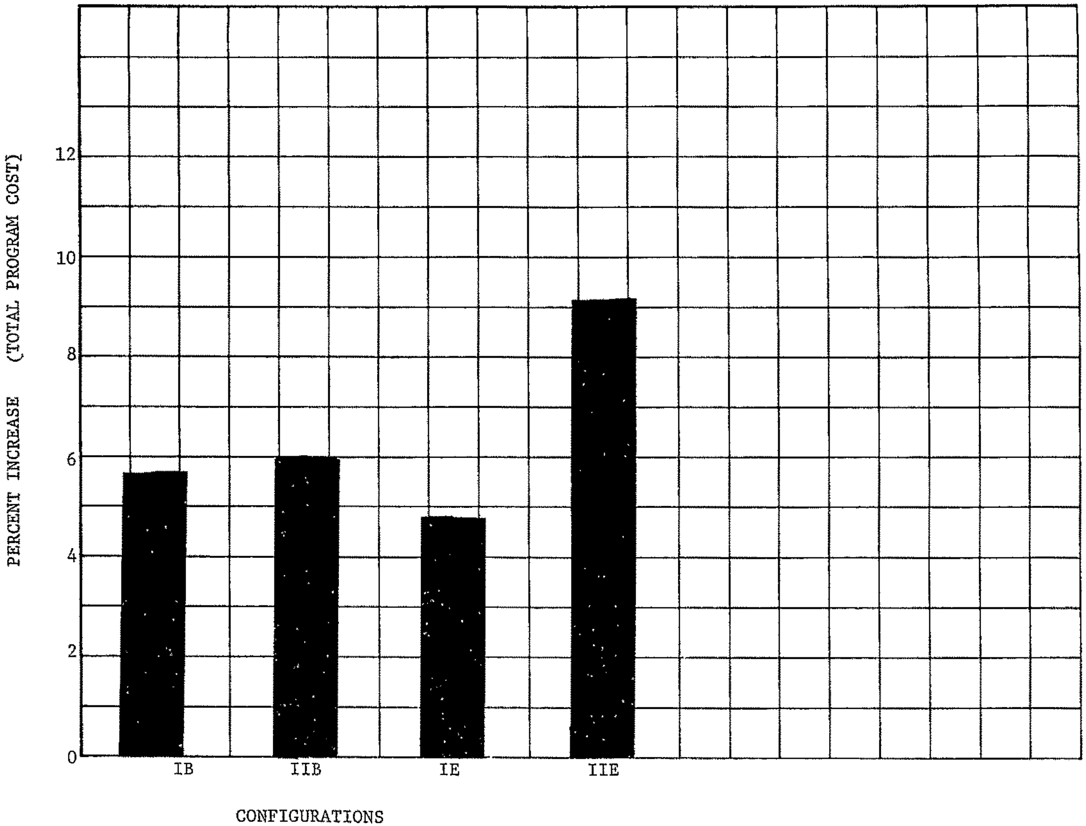


FIGURE 5-61

EFFECT OF DENSITY ON RDT&E COST
DENSITY IS REDUCED FROM 10 TO 5 POUNDS PER CUBIC FOOT

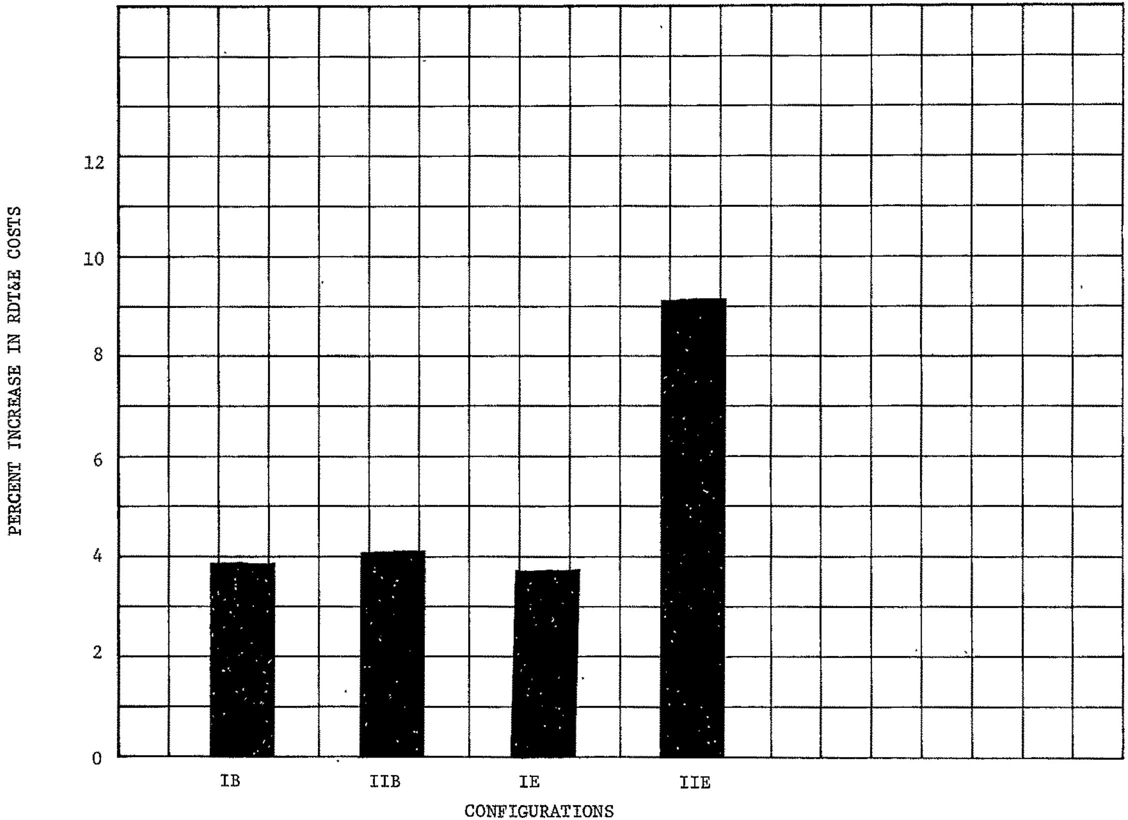


FIGURE 5-62

EFFECT OF DENSITY ON FIRST UNIT COST
DENSITY IS REDUCED FROM 10 TO 5 POUNDS PER CUBIC FOOT

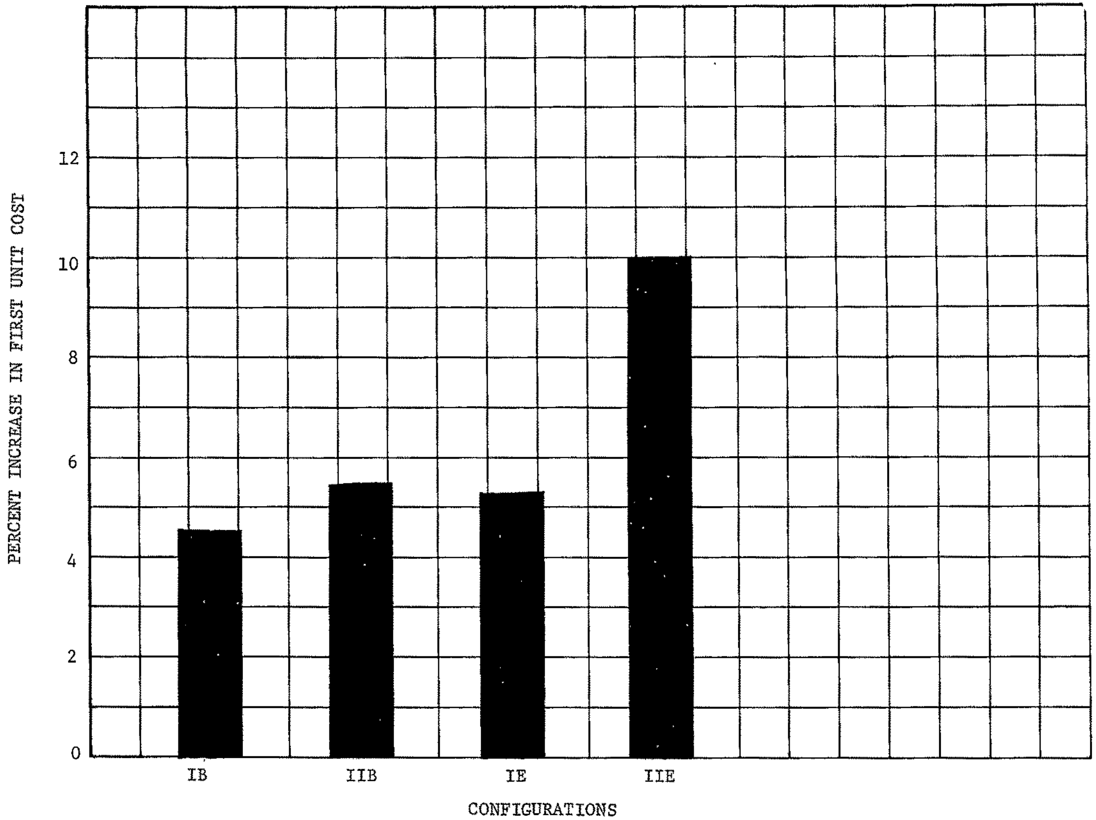


FIGURE 5-63

EFFECT OF DENSITY ON SPACECRAFT LENGTH
DENSITY IS REDUCED FROM 10 TO 5 POUNDS PER CUBIC FOOT

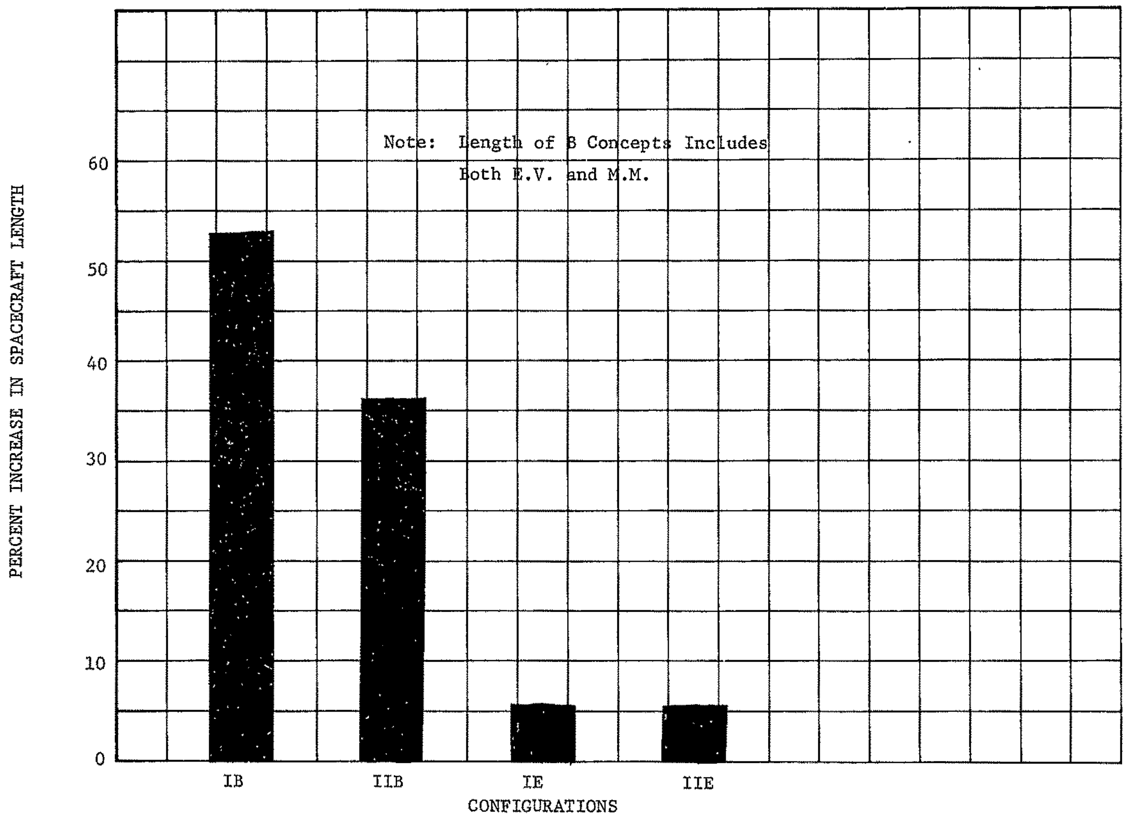


FIGURE 5-64

increasing the length of an entry vehicle. Also, a ballistic configuration's length can be extended 5 percent at less cost than extending the length of a lifting entry vehicle by 5 percent.

5.2.3 Subsystem Technology - The study of alternate subsystem approaches was based on using the standard baseline configuration and subsystems definition at the optimized payload as a reference.

The subsystem which had the greatest affect on total program cost was primary structure. The primary structural concept affects total program cost through material costs, fabrication costs, and spacecraft dry weight. A reduction in dry weight may reduce total program cost even if the entry vehicle cost increases. Cost variations for the spacecraft primary structural concepts are presented in Figures 5-65 through 5-68. These figures compare four materials and three fabrication techniques.

The aluminum single skin design gives the lowest total program cost for the B configurations. These are small vehicles where weight and cost savings are likely to be small and minimum gauges play an important part in the design. In these cases the minimum cost concept and the study baseline concept are of nearly equal cost.

In the larger configurations (IE and IIE) there is a trade-off between titanium sheet-stringer which is light and efficient and magnesium sheet stringer which is less costly per pound. In this case the titanium was best for the ballistic configurations and magnesium was best for the lifting body. Figure 5-68 shows about $1 billion savings for using magnesium sheet stringer instead of the baseline aluminum sheet stringer. About $300 million of this is attributed directly to the spacecraft and the rest results from savings in all the side effects. The magnesium spacecraft is about 67,000 lbs lighter than the aluminum and therefore a major part (almost $600 million) of the additional $700 million savings is in the launch vehicle cost.

The orbit maneuver concept which gives the lowest total program cost for the IB and IIB configurations is OM-1 (all functions use NTO/MMH with a single engine group). The best concept for the IE and IIE configurations is OM-4 (NTO/MMH for docking and attitude control, and O_2/H_2 for ascent, phasing, and deorbit with a dual engine group for NTO/MMH). These data are presented in Figures 5-69 through 5-72.

IB COST DIFFERENCES FOR ALTERNATE PRIMARY STRUCTURAL CONCEPTS

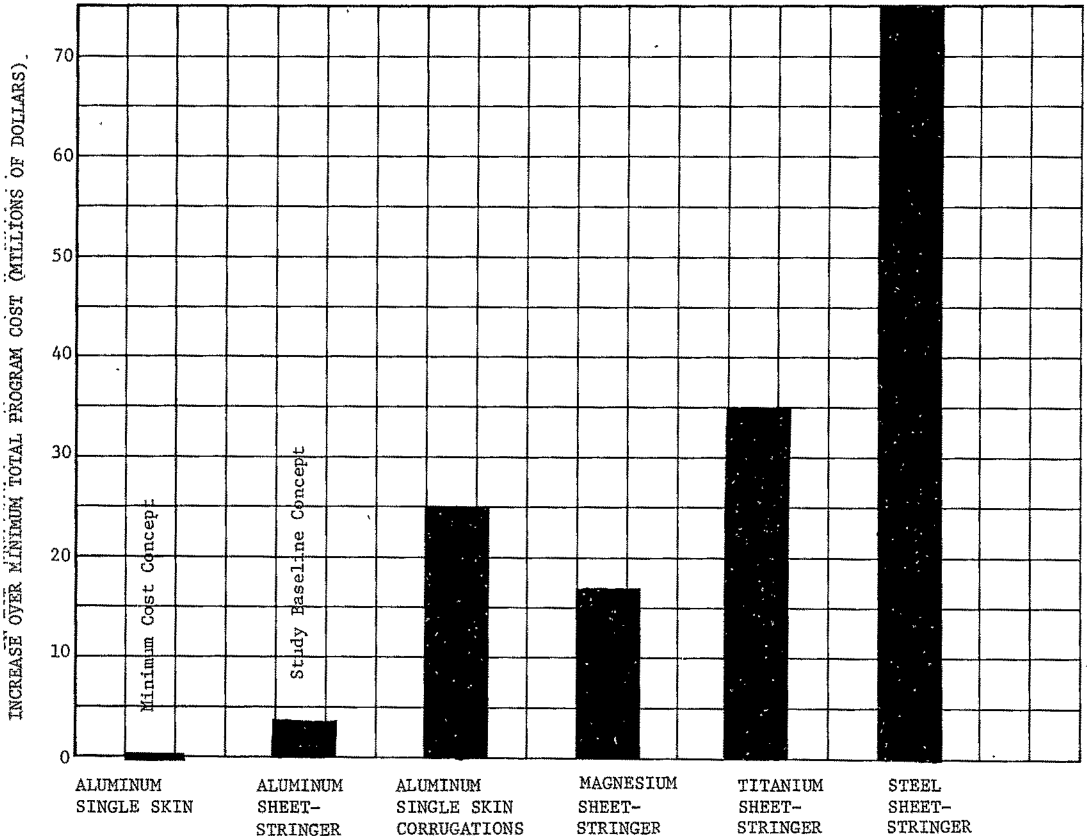


FIGURE 5-65

IIB COST DIFFERENCES FOR ALTERNATE PRIMARY STRUCTURAL CONCEPTS

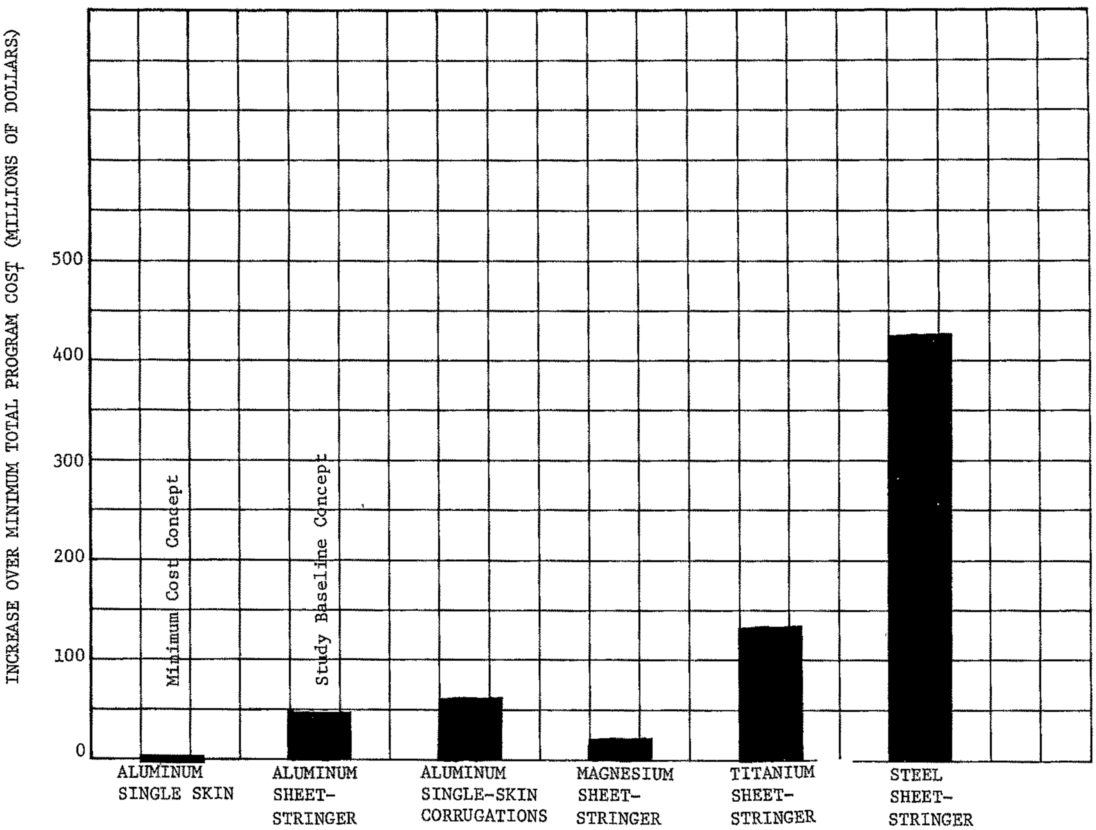


FIGURE 5-66

IE COST DIFFERENCES FOR ALTERNATE PRIMARY STRUCTURAL CONCEPTS

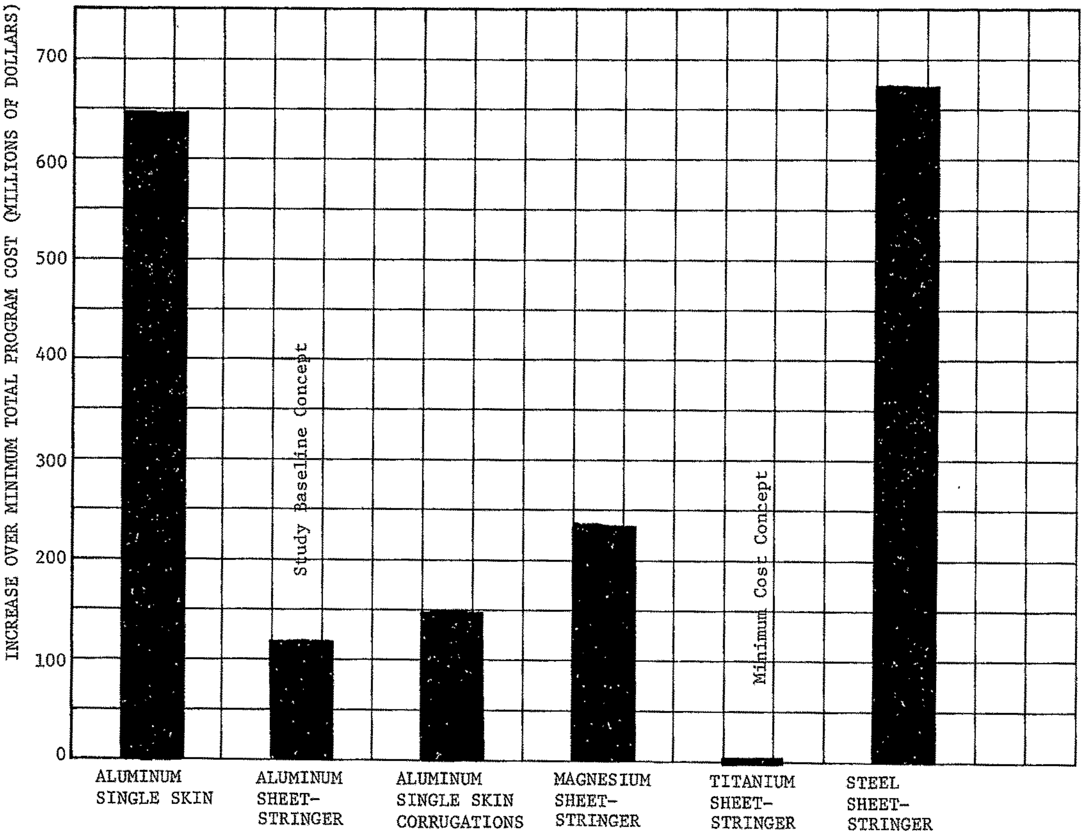


FIGURE 5-67

IIE COST DIFFERENCES IN ALTERNATE PRIMARY STRUCTURAL CONCEPTS

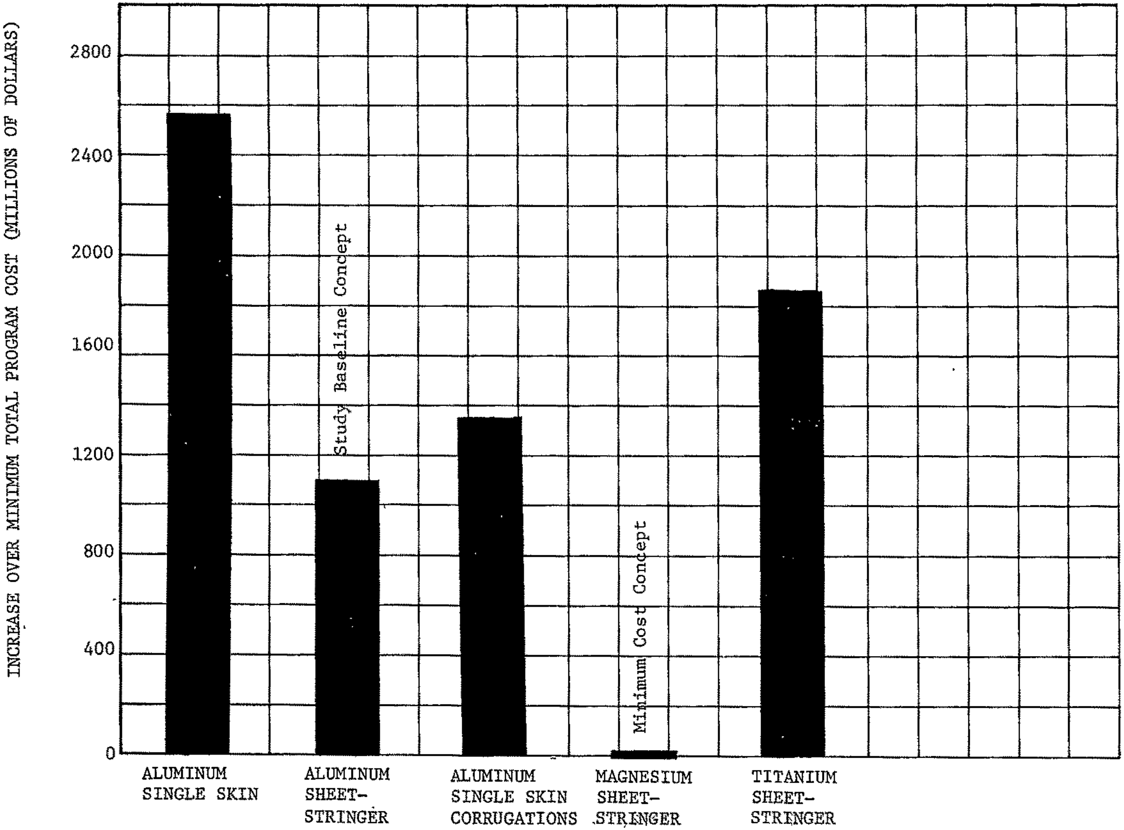


FIGURE 5-68

IB COST DIFFERENCE FOR ALTERNATE ORBITAL MANEUVER CONCEPTS

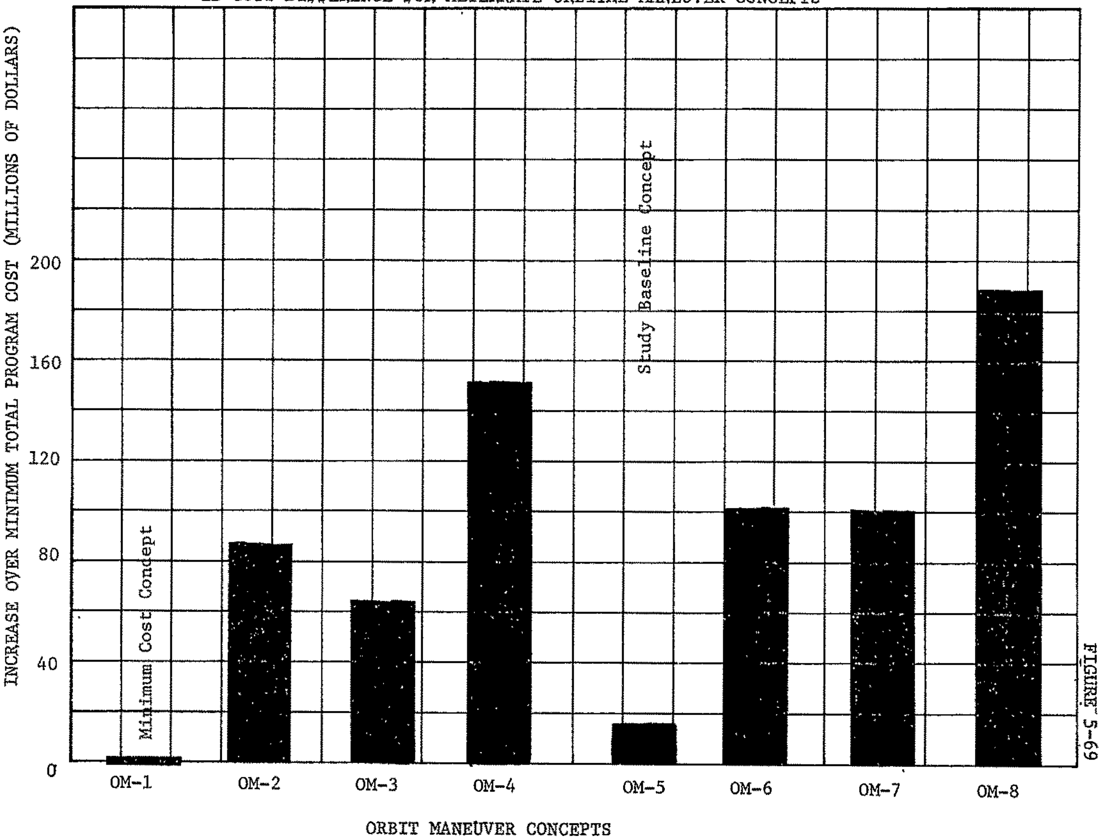


FIGURE 5-69

IIB COST DIFFERENCE FOR ALTERNATE ORBITAL MANEUVER CONCEPTS

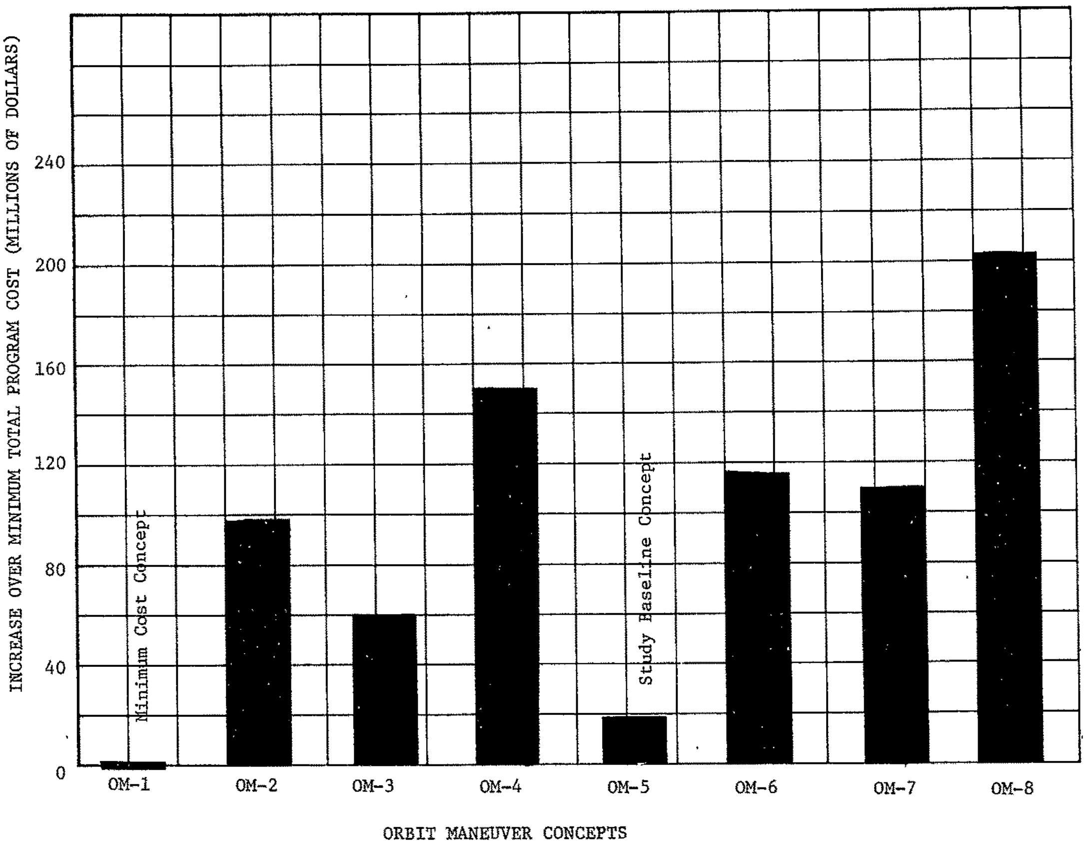


FIGURE 5-70

IE COST DIFFERENCES FOR ALTERNATE ORBITAL MANEUVER CONCEPTS

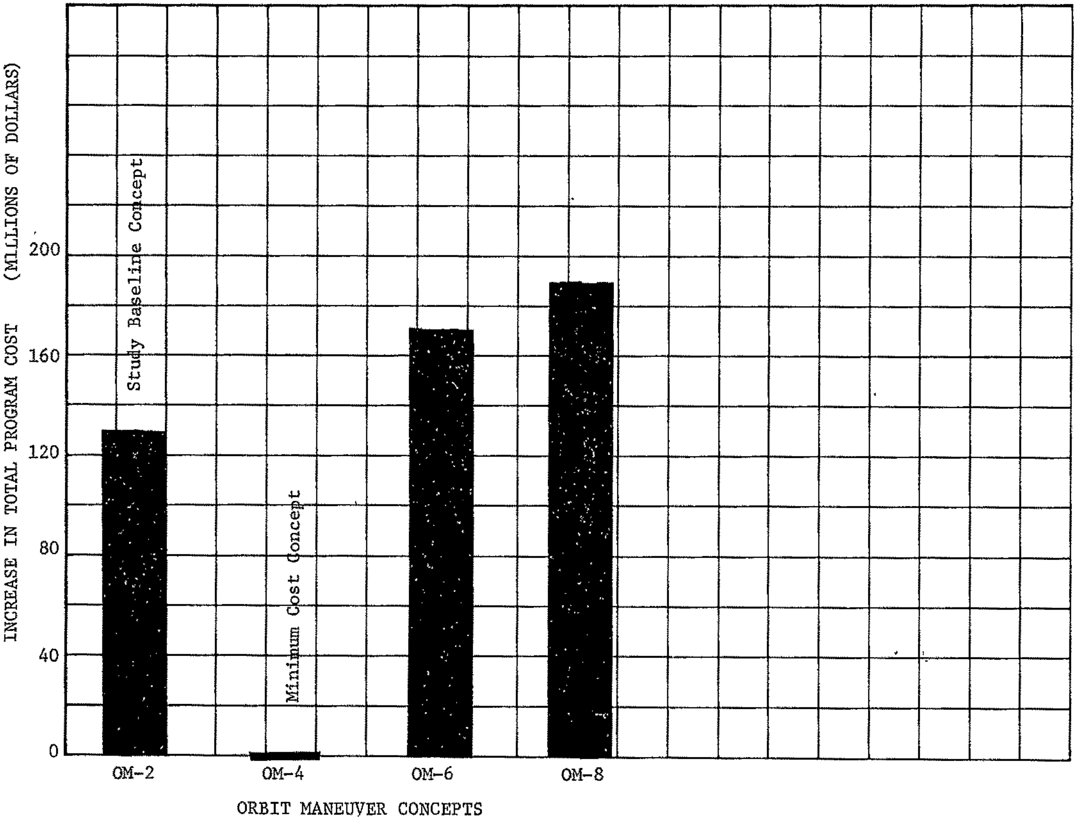


FIGURE 5-71

IIE COST DIFFERENCE FOR ALTERNATE ORBITAL MANEUVER CONCEPTS

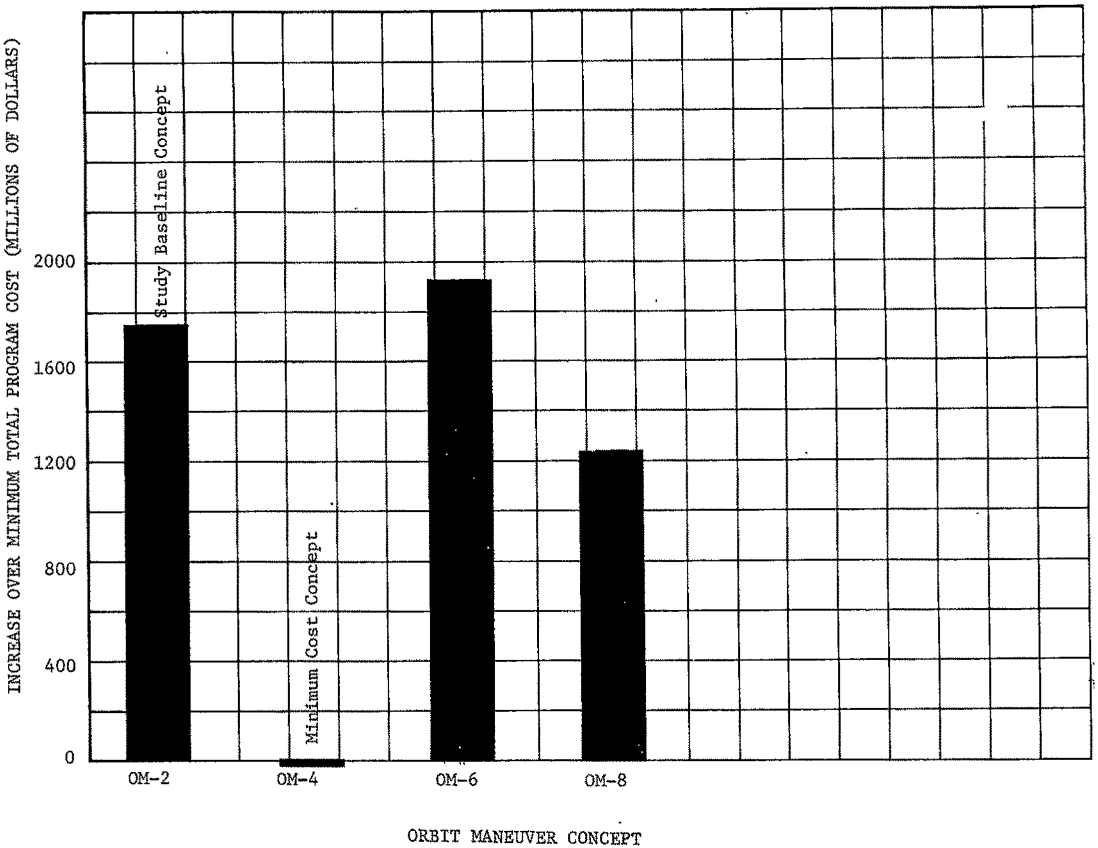


FIGURE 5-72

The IB and IIB configurations are small and have low inertias and short lever arms. Therefore, the simple Gemini type single propellant with a single engine group is optimum. As the vehicles become large (IE and IIE configurations) it pays to have the propulsion specialized to take advantage of the longer lever arms and higher ISP's to reduce to propulsion weight. Figure 5-72 shows a 1.7 billion dollar saving over the baseline. This type of cost optimization is difficult to make without a mechanized computer program because all subsystems must be resized and recosted down through the booster (under consistent groundrules) before the cost differences can be determined.

Using F_2/H_2 in the upper stage engines is shown in Figures 5-73 and 5-74 to be optimum for the IE and IIE configurations. The F_2/H_2 engine requires more technology advancement and may involve greater risks than an O_2/H_2 engine. However the greater efficiency of the F_2/H_2 engine overcomes this disadvantage when the engines are compared on a total program cost basis.

The baseline design for the mission module (aluminum sheet-stringer) is shown to be optimum in Figure 5-75. The aluminum single skin concept which was optimum for the IB and. IB and IIB configurations is the poorest. This single skin concept would probably be the best for the mission module if the mission module were pressurized. Since it is not, the sheet-stringer concept is superior.

Twelve alternates were evaluated in the design of the thermal protection system. The difference between these concepts were negligible based on a total program cost. This results from the fact that the alternates that are inexpensive themselves are heavy, thus, increasing the size of the propulsion systems while the light-weight alternates use expensive materials such as columbium and molybdenum.

5.2.4 Crew Size - The standard baseline configuration with an optimized payload was the reference configuration for the crew size evaluation.

Figure 5-76 shows the results on total program cost due to varying crew size. These vehicles are large enough that the crew compartment can be enlarged with only a small change in spacecraft length, dry weight, and wetted area. However, to increase the crew size from 2 to 12 costs 500 million dollars or more in every case.

FIGURE 5-73
IE COST DIFFERENCE FOR UPPER STAGE PROPELLANTS

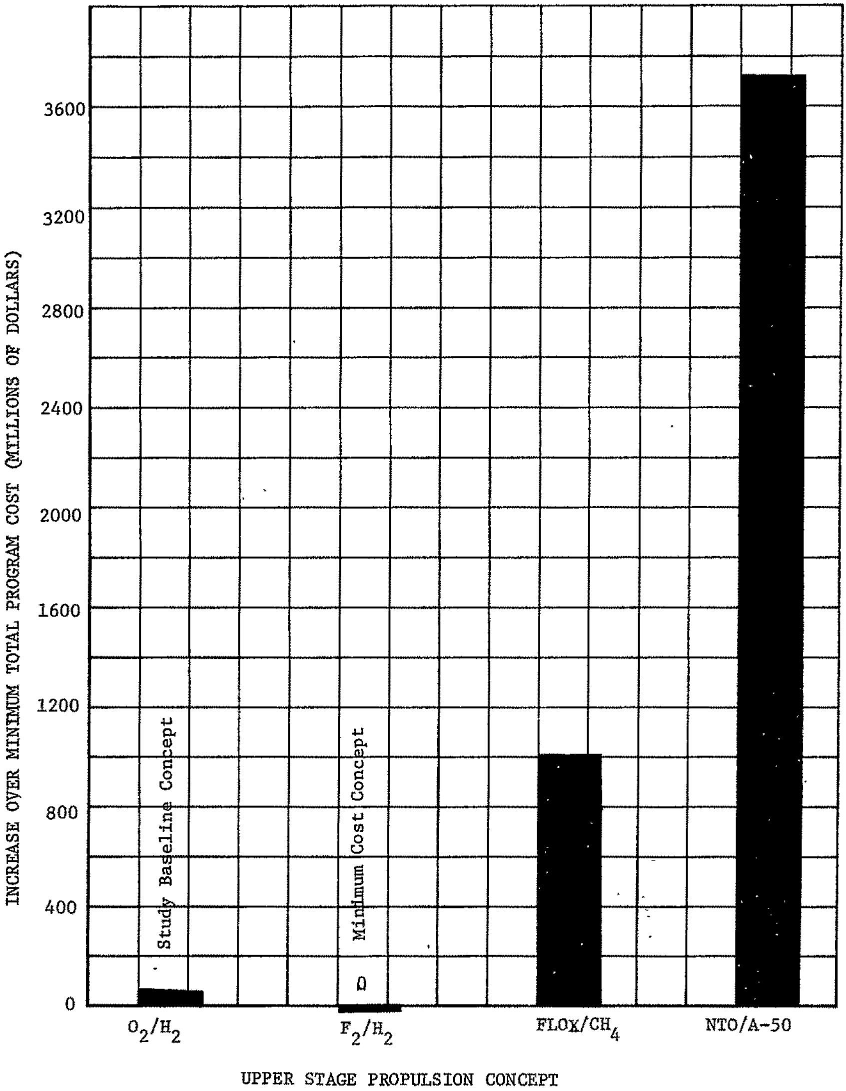
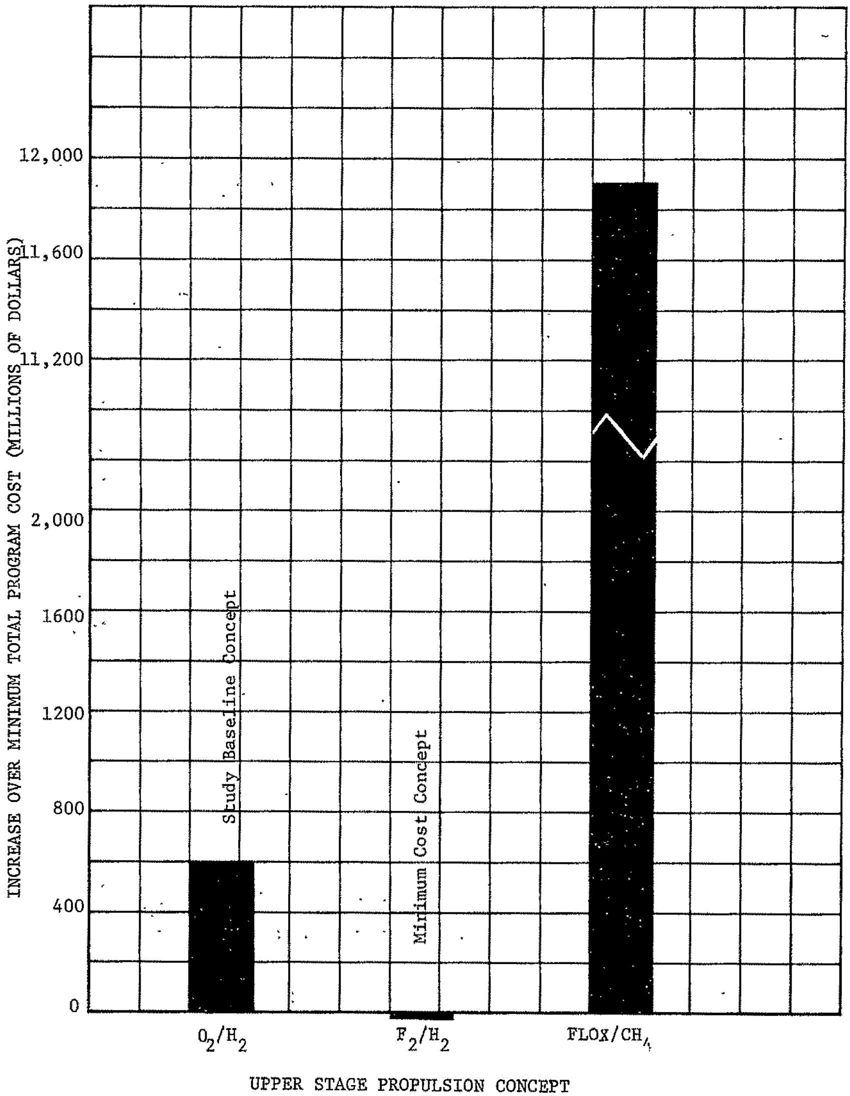


FIGURE 5-74

IIE COST DIFFERENCE FOR UPPER STAGE PROPELLANTS



MISSION MODULE COST DIFFERENCES FOR ALTERNATE PRIMARY STRUCTURAL CONCEPTS

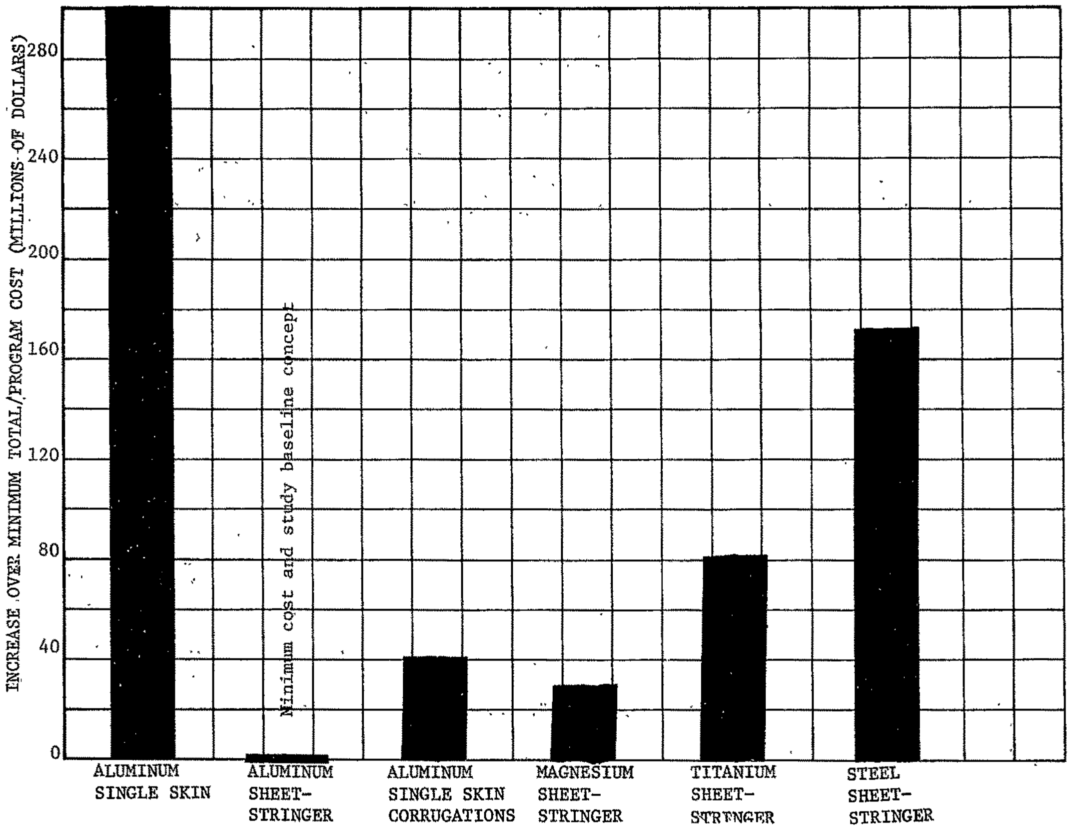
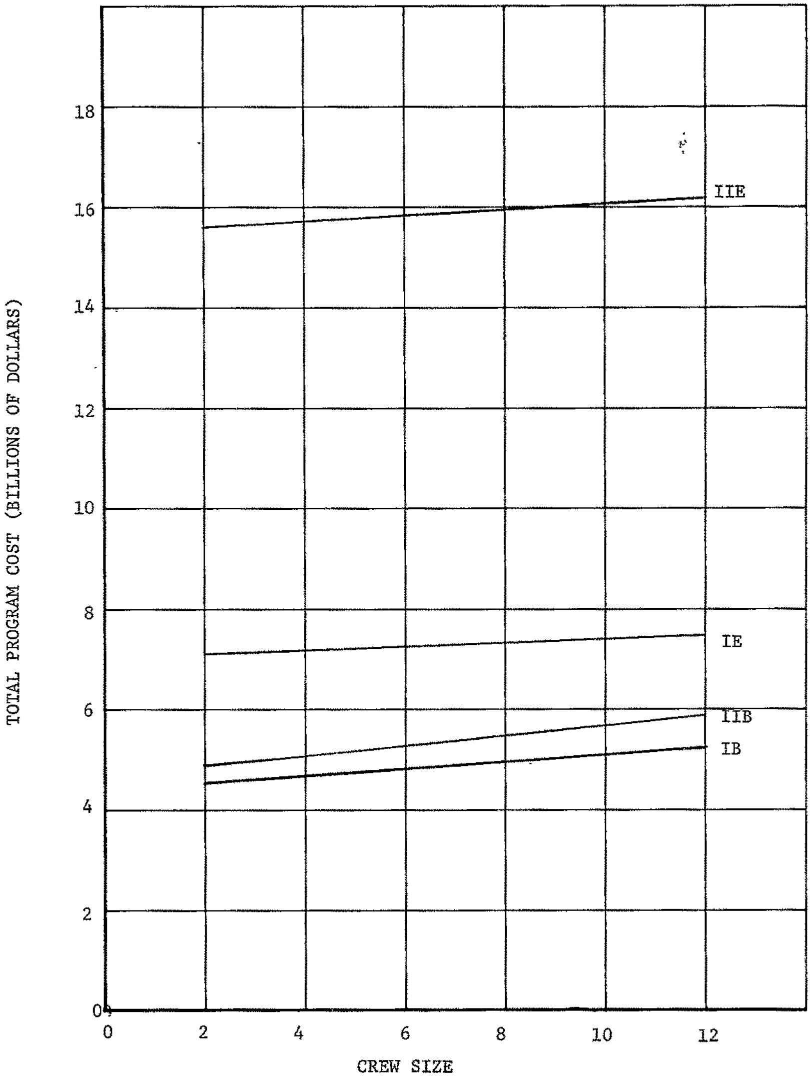


FIGURE 5-75

COST VARIATION WITH CREW SIZE

FIGURE 5-76



CRITICAL PROBLEMS AND
PACING TECHNOLOGY—

6.0 CRITICAL PROBLEMS AND PACING TECHNOLOGY - There are three critical or pacing technology areas which were identified during this phase of the study; they are (1) fluorine propellants and the engines to utilize them in the upper stage boost system, (2) the gliding parachutes or horizontal landing capacity necessary for terminal maneuver and land recovery, and (3) subsystem expected life and refurbishment costs. The use of composite structural materials were not investigated in this study because the present state-of-the-art of these materials does not provide a firm data base from which to develop cost estimating relationships. Therefore, the advantages of the higher strength-to-weight ratio of these materials could not be evaluated.

The results of the effects of subsystem choice on total program cost indicated a slight reduction in cost with the use of a fluorine/hydrogen fueled upper stage boost system. Fluorine propellants are very toxic and have many handling problems. The quality control procedures, the proof testing criteria, and the actual launch operations for vehicles utilizing these propellants have not been fully developed, and can not be until there is a body of test data available on the use of fluorine as a propellant. This model assumes that all of this type of work is done separate from the application development, and that the procedures that will be used are as anticipated at present. If fluorine propellants require special packaging or handling over and above that presently anticipated, the costs will increase accordingly and the flow time for cycling a vehicle will also increase, requiring more vehicles in the pipeline and higher costs If reuse of fluorine engines or tanks requires more time to recondition than presently anticipated, the recertification flow time and costs will be higher. Thus the fluorine propellants pose a critical cost problem because of the uncertainties about their use.

Terminal maneuvering and land recovery require either steerable gliding parachutes or competence in landing lifting body vehicles horizontally. Both technologies are in their infancy and may change considerably as more experience is gained. This model utilized the latest data available on parawings in formulating the performance and cost subroutines; however, these data were based on limited testing of small scale models. For example, the parawing data was based on drops of a 4000 pound vehicle which may not apply to the 20,000 pound or larger vehicles which are a result of the optimum sizing of this model. Routine horizontal landing at the high speeds and high sink rates of lifting body vehicles has not been demonstrated. There are several programs presently underway which aim to develop the techniques to do this but, other than the X-15 program, there has been limited effort to date. Experience may indicate a different technique than that currently preferred which could change the vehicle and/or recovery costs significantly.

As the expected life of subsystems is increased and as more use is made of integrated electronics, the amount of replacement and testing necessary during recertification will be reduced. The cost of the replacement parts is the major portion of the recertification costs in this model. Improvements in technology which reduces the quantity of replacement parts necessary during a program will have a large effect upon the recertification costs - primarily in reduced material costs. Thermo-structural reconditioning costs are based upon a certain replacement schedule. It may be possible, through the use of more exotic materials to change the replacement schedule until there is little or no scheduled replacement of the thermo-structure during the life of the vehicle. This is nearly possible now on ballistic vehicles for all portions of the thermo-structure, except the heat shield, through the use of nickel alloys and high temperature steel alloys.

7. UNCERTAINTIES IN COST DATA AND SPACECRAFT COST MODEL - The accuracy of any cost estimating routine will be dependent on the quantity, quality, and application of the historical cost data, the quality of the Cost Estimating Relationships (CER's) derived, and the quality of the vehicle and program definition for the vehicle estimated.

All historical cost data contain errors or mischarges and apparently high or low cost elements that are a function of the mistakes and problems encountered on a particular program. These items are extremely difficult to identify since the accounting system cannot separate these costs. These factors can only be estimated and the cost history reallocated accordingly. The resulting cost history will therefore be influenced greatly by the experience, discretion, and bias of the particular analyst involved.

Any CER that is developed cannot be expected to exactly predict cost since only a few cost parameters are included in the CER. All of the factors that affect cost are simply too numerous and complex to be put into a mathematical cost relationship. Each CER in a cost model will have its own accuracy and vary greatly dependent on the validity of the cost data used to develop the CER, the similarity of the vehicle to be estimated to the vehicle from which the cost history was derived, and the amount of extropolation beyond the range of the data base from which the CER was derived. The accuracy or confidence level of any CER therefore must be assessed individually and specifically for the application at hand. For example, if weight is the estimating parameter and is within the limits of the data used to develop the CER, the accuracy of an estimate for a subsystem that is similar to the data base is good, but if the subsystem is not similar, the accuracy may be very poor. Because the accuracy or confidence level is dependent on many variable factors and must be assessed for each application it would be impossible to quantify the accuracy of the cost model. It is expected, of course, that the individual results are both on the high side and the low side and that the total estimate is within acceptable limits for advanced planning purposes, and will pave the way for more detail studies.

The validity of vehicle and program definition will influence the results of any cost model since the cost model must utilize these definitions for estimating.

The development of a cost model in the great depth of detail provided in this study does not necessarily mean that the resulting estimates will be more accurate than estimates provided by cost models in lesser detail. However, added visibility and detail will provide the user specific cost information that will indicate area- of sensitivity and non-sensitivity of the cost to vehicle and program definition. The added detail also allows for easier improvement in the cost model as more data and improved estimating methods become available.