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OPTIMIZED COST/PERFORMANCE DESIGN METHODOLOGY
VOLUME I - SUMMARY

CR-23410

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McDonnell Douglas Astronautics Company

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CONTRACT NAS 2-5022

MCDONNELL DOUGLAS

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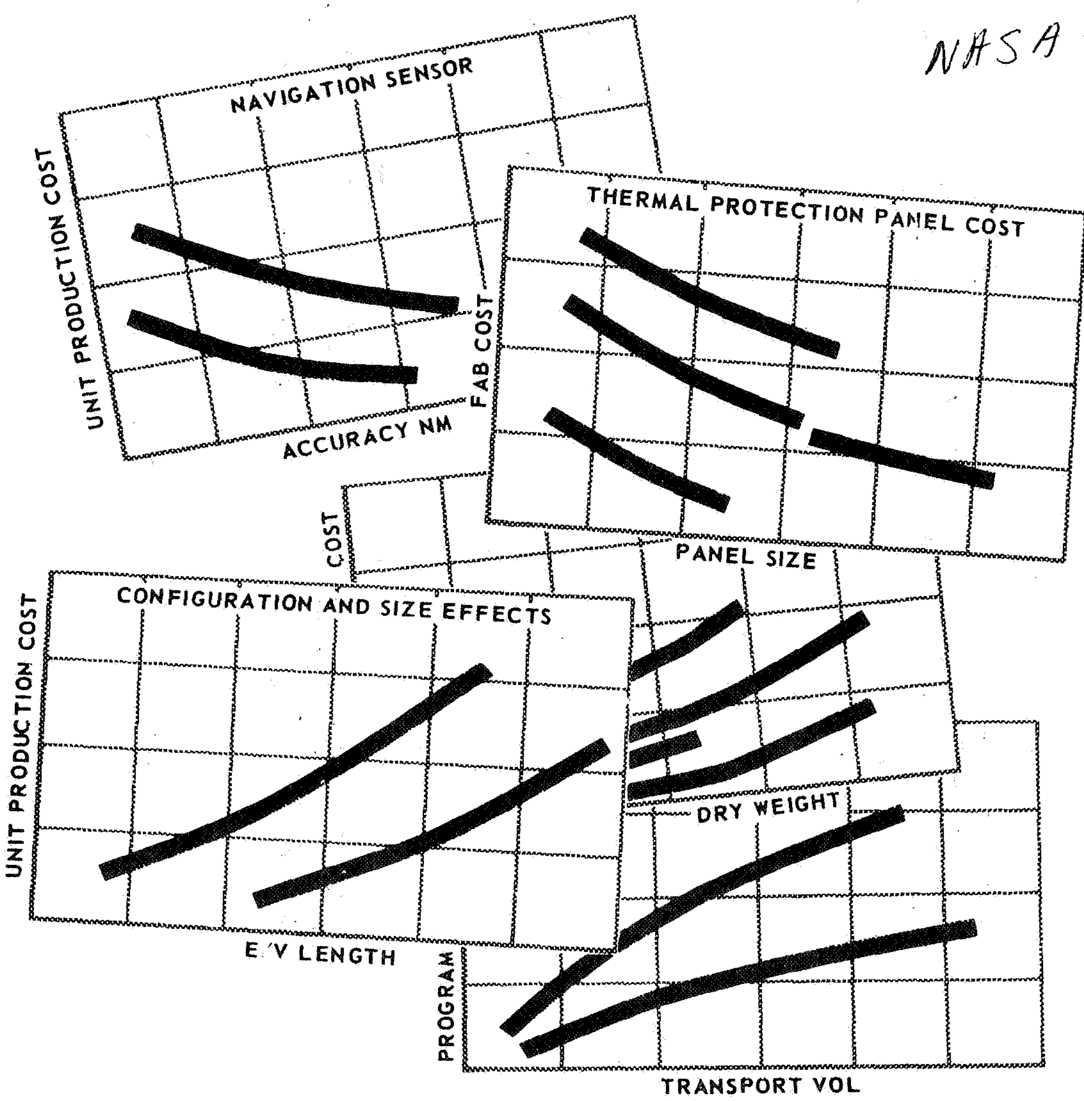

VOLUME I - SUMMARY
CONTRACT NAS 2-5022

MCDONNELL DOUGLAS CORPORATION

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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1. INTRODUCTION AND SUMMARY - The purpose of the Optimized Cost/Performance Design Methodology study was to provide a method of using cost as a basic design parameter in identifying and defining more economical space transportation systems. To this end, cost and design data from historical aerospace programs were examined for applicability in projecting the cost of future 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 data review and analysis phase consisted of an extensive investigation of the historical hardware programs. Figure 1 indicates the various sources of data from the McDonnell Douglas Corporation experience and also notes that nineteen subsystem manufacturers provided additional cost and design data in support of the study. These companies and their areas of contribution are listed in Volume II.

First of all, it was necessary to organize the cost data according to a cost element structure, adjusting data from different programs so that it would be referenced to a common base. The Saturn SIV-B and Gemini program data were completely organized and served as the primary data for the study; data from the other sources were used for specific relationships where available and applicable. This investigation of the historical data also included detailed analysis of both design and cost data in an effort to define the particular design or performance parameters associated with each subsystem which could be used to estimate costs. The results of this analysis of historical data were equations relating cost to one or more design parameters. These equations were written at or below the subsystem level.

The phase two system evaluation was quite broad in scope, requiring first the development of a cost and optimization model, and then investigation of program costs for two configuration concepts, a range of reuse concepts, and a parametric treatment of mission and program requirements.

Since the data resulting from these studies are based on analysis of historical programs, they 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 are 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.

FIGURE 1

DATA SOURCES

Manned Spacecraft
- Mercury
- Gemini
- MOL

Unmanned Spacecraft
- ASSET
- BGRV

Launch Vehicles
- Saturn S-IVB

Aircraft
- F-4

Vendors
- Nineteen Companies – Subsystem Data

2. STUDY OBJECTIVES - The objectives of this study were established as follows:

1. Develop an accurate cost model for orbital-transportation systems which can establish system design criteria for studying economic optimization of such systems.

2. Exercise this cost model and optimization procedure on example concepts of expendable, partially and completely reusable orbital-transportation systems.

3. Identify the critical problems and the key and pacing technologies and research areas oriented to the more promising systems.

4. Develop and provide the tools, programs, techniques, and data required to perform the above.

All study objectives have been met.

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3. RELATION TO NASA PROGRAMS - This study relates to other NASA programs in several ways. First of all the primary sources of historical data were the Gemini and Saturn IV-B programs. Secondly, the study addresses the question of cost which is paramount in the tradeoff analysis of future systems; and third, this study was directed toward space transportation or space shuttle systems.

The first relationship is important because, as mentioned in Section 1, it automatically means that the resulting cost estimate will reflect the NASA way of managing the Gemini and Saturn programs. The second relationship is important because a tool has been developed which will aid in the required trade studies. The third relationship is vital because the space shuttle program is current and necessary for continued space exploration. Therefore this study has addressed something of immediate interest and importance, and directly supports other current NASA programs.

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4. BASIC ASSUMPTIONS AND METHODS OF APPROACH - This section describes the assumptions and groundrules established for the study and then indicates the approach that has been used in meeting the study objectives.

4.1 Groundrules and Assumptions - The basic assumptions in this study have been of two types: those concerned with the organization and analysis of the cost data, and those concerned with the system evaluation. The groundrules and assumptions established for the data organization were especially significant because of the need to adjust and organize data from several sources, thereby affording a common reference. Some of the more important groundrules and assumptions are listed below.

1. The Gemini program cost data defined in the cost element structure shall reflect a five flight test program. Development of the cost for the 5 vehicles and flights from the cost history of 12 vehicles shall be based on the unit cost and the appropriate learning curves.

2. The Saturn S-IVB Cost Data Analysis will employ the SAT-V configuration in order to account for SAT-IB/SAT-V common effort charged to SAT-V by NASA ground rule. The RDT&E phase of the Saturn S-IVB program will be defined as the time period from contract inception (June 1962) to delivery of the fifth test stage from the Sacramento Test Center (7/27/66). This includes 4 SAT-IB stages and 1 SAT-V stage, the total of 5 being comparable to that used in defining the Gemini RDT&E phase. The SAT-IB stages are included due to their scheduling prior to SAT-V and to avoid an unrealistically long RDT&E phase which would result from selection of all SAT-V stages. Flight test operations associated with the S-IVB RDT&E phase will be accounted for separately from all other costs due to abnormal elapsed time between delivery and launch of stages four and five which resulted from problems with the payload and other stages of the launch vehicle. S-IVB procurement for the RDT&E and investment phases will be determined in terms of a theoretical 1st unit cost for the SAT-V configuration along with recommended learning curves to be applied to each procurement cost category for quantity extensions.

3. The following mid-calendar 1969 labor rates which include direct labor, overhead, G.& A. and 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

4. All other program costs shall be adjusted to mid-calendar 1969 dollars using a 5% annually compounded factor.

5. A 10% fee is to be used at the program phase level.

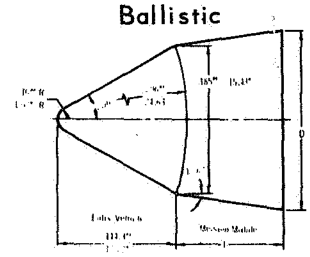
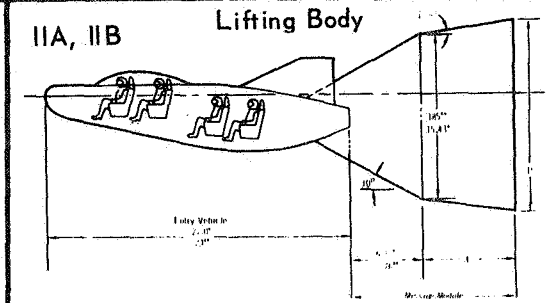
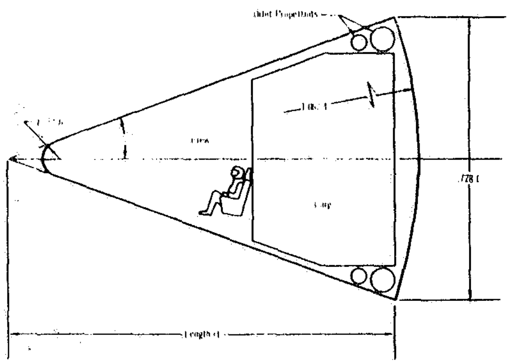
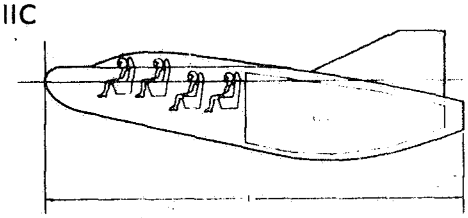
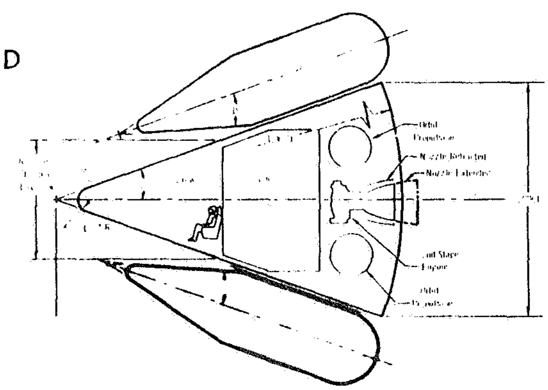
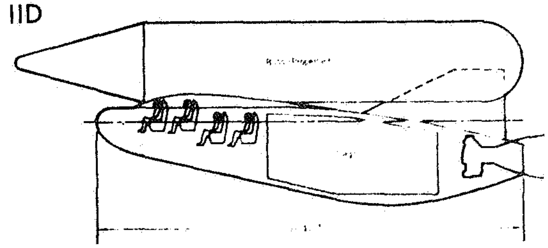
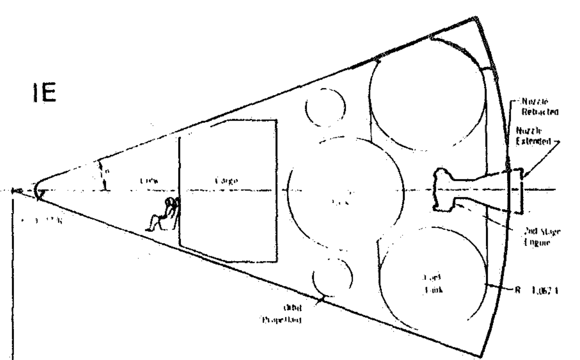
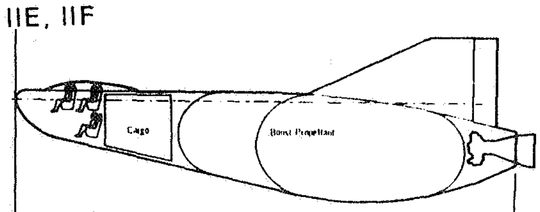
6. A 1963 technological base shall be assumed for both the Gemini and Saturn S-IVB programs and the provision shall be made in the cost model for the inclusion of a technology escalation factor to be applied to all RDT&E phase costs except system test hardware procurement and major subcontractors. This annually compounded factor should account for the increased documentation, test requirements, quality assurance and related type efforts which are imposed on a program as a function of time and tend to increase its complexity.

In the concept analysis the two entry vehicle concepts evaluated are a ballistic and an M2-F2 configuration. These cover a range of reuse concepts as shown in Figure 2. As indicated earlier, the emphasis of the study is spacecraft oriented; therefore launch vehicle costs have been treated parametrically in order to derive total program costs. The launch vehicle costs include RDT&E, investment, and operational costs for all payload sizes, whether or not an existing launch vehicle could meet the requirement.

No detailed designs were accomplished in this study; rather a computerized spacecraft sizing model based on geometric scaling relationships and semi-empirical design/performance characteristics has been used to derive the design data required for costing. The mission model and program assumptions established by NASA were as follows:

FIGURE 2

SYSTEM ALTERNATES VEHICLE PARAMETERS

Reuse Category	Aerodynamic Configuration	
	Ballistic	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 

1. The mission to be performed by the spacecaft under study is crew rotation and resupply of a 12 man space station.

2. The reentry spacecraft size will be varied over the range of crew sizes from two to twelve men and over the range of return cargo capacity from 200 to 2000 lb. occupying from 100 to 400 cu. ft.

3. Cargo space either integral with the reentry spacecraft or in an expendable cargo module, will be provided for delivered cargo over the range of from 20,000 lb. to 200,000 lb. with density variations between 5 and 10 lb. cu. ft.

4. 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.

5. Both land and water landings will be considered as primary landing modes.

6. The time for return from orbit will be variable over the range of from two to twenty four hours.

4.2 Approach - The approach throughout the study has been to make cost a basic design parameter which can influence decision making early in the development phase of a program. Therefore, the emphasis was placed on providing visibility of how the costs accrue. The organization of the historical data followed the standard technique of establishing a cost element structure based on a program-project-subsystem type breakdown for each of three phases, RDT&E, Investment and Operations. The detailed cost accounting records were researched to establish the breakdown of the data according to the cost element structure and to determine adjustments or transfers to match the study groundrules. Once the data were organized, the analysis and comparison of design and performance characteristics provided the basis for normalizing the costs so that estimating equations could be written. These equations were written from the standpoint of a prime contractor who would have overall project responsibility for the spacecraft design/development and would use major subcontractors for subsystems other than the structure and thermal protection. Design/development costs are estimated according to labor categories including engineering, tooling, and production, plus material, contractor furnished equipment, and subcontract costs. For the investment phase, first unit costs are derived for each subsystem; the investment costs are then derived through combination of first unit costs, inventory requirements, and learning curves. The investment phase costs are broken down by sustaining engineering, and sustaining tooling for each spacecraft module, and then the production labor, material, CFE and subcontract costs for each subsystem. Operations costs are derived according to a functional organization and are not identified according to subsystems; however, labor and material costs are separated.

In the second phase of the study the approach was to incorporate the equations in a cost/optimization model and evaluate a series of concepts. Preparation of the cost model was straightforward and simply involved solving each equation for the cost associated with the particular design/performance characteristics. Definition of the design/performance characteristics in the detail required for the cost equations was handled by means of a spacecraft sizing model. This is a parametric design tool which includes the spacecraft geometry characteristics, design definition of various subsystem alternatives, and the performance/design requirement relationships. The vehicle is scaled to meet mission and program requirements, taking into account all the subsystem interactions that result from changes in weight, size, impulse requirements, etc. The output of this sizing model is fed directly to the cost model to derive the cost estimates.

The concept analysis required application of the model to the various spacecraft and reuse concepts, varying mission and program requirements, subsystem compositions, etc. Least cost approaches were defined for all concepts in terms of the amount of cargo carried per launch, operational mode, etc. for the baseline program; cost sensitivities were derived for variations from the baseline.

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5. DATA GENERATED APPLICABLE FOR GENERAL USE - The basic data generated in this study includes the Gemini and Saturn IV B program cost history organized according to a common basis, specific data points from other programs across the spectrum of aerospace development experience, extensive subsystem design/cost data, and several hundred cost estimating relationships.

Another major output of the study is the computer model that was developed. The cost estimating relationships were organized into a cost model and coupled to a parametric design model; the total computer model includes blocks of logic to derive operational program characteristics so that total program costs can be derived. A final output was development of some general cost trends, based on exercising the computer model.

The Gemini and Saturn IV B cost data are summarized in Tables 1 and 2 respectively. It is important to recognize that these data are adjusted to the ground rules of this study and reflect the test hardware requirements and labor rates indicated in Section 4. The significance of these is apparent from the fact that the total Gemini program had an actual cost (combined recurring and nonrecurring) of about $700 million, whereas the adjusted data in Table 1 shows an RDT&E cost of over $800 million.

The cost estimating relationships cannot be easily summarized because each equation uses the design characteristics peculiar to the particular item or system being estimated. However, the need for a detailed definition of a system is evidenced by the data shown in Figure 3. This summarizes the effect of the design parameters' influence in estimating the design/development costs of therm/structure and the production costs of structure. For these items, weight is used as a primary variable with the other parameters used as complexity factors. The application (i.e., use of the structure for a simple adapter versus a mission module versus an entry vehicle, etc.) results in a factor of 4 difference in the design and 3 in the production. Furthermore, if the structure is an entry vehicle, there is an additional design complexity factor ranging up to about 3 to account for differences between a body of revolution and a lifting shape with compound curvatures, etc. This is a multiplier and therefore indicates more than an order of magnitude spread in going from the simple adapter to the lifting entry vehicle. The environment factor was established to account for the thermal environment of an entry vehicle and was separated from the application factor because different missions

GEMINI COST SUMMARY
(ALL FIGURES IN THOUSANDS)

TABLE 1

		PRIME CONTRACTOR LABOR MANHOURS				1969 DOLLAR COST				
		ENGR.	TOOL	PROD	TOTAL	ENGR.	TOOL	PROD	MAT CFE, SUBCON	TOTAL
1.0	SPACECRAFT (S/C)							–		810,685
1.0A	PROJECT MANAGEMENT & ADMINISTRATION	502			502	10,040			600	10,640
1.1	ENTRY VEHICLE (E/V) (DESIGN AND DEVELOPMENT)	2,452	806		3,258	49,040	10,796		153,933	213,769
1.1.1	THERMAL STRUCTURE	848	806		1,654	16,960	10,796		4,540	32,296
1.1.2	INFLATABLE AERO DEVICES	97			97	1,940			8,735	10,675
1.1.3	POWER SUPPLY & ORDNANCE	344			344	6,880			2,357	9,237
1.1.4	ENVIRONMENTAL CONTROL & LIFE SUPPORT	293			293	5,860			23,975	29,835
1.1.5	AVIONICS	786			786	15,720			87,307	103,027
1.1.6	PROPULSION	84			84	1,680			27,019	28,699
1.2	MISSION MODULE (M/M) (DESIGN & DEVELOPMENT)	798	142		940	15,960	1,902		90,761	108,623
1.2.1	THERMAL/STRUCTURE	256	142		398	5,120	1,902		557	7,579
1.2.2	POWER SUPPLY & ORDNANCE	227			227	4,540			41,502	46,042
1.2.3	ENVIRONMENTAL CONTROL & LIFE SUPPORT	105			105	2,100			6,893	8,993
1.2.4	AVIONICS	91			91	1,820			1,591	3,411
1.2.5	PROPULSION	119			119	2,380			40,218	42,599
1.3	AEROSPACE GROUND EQUIPMENT (AGE)	1,027		1,277	2,304	20,540		15,072	71,833	107,445
1.4	TRAINERS & SIMULATORS	238		244	482	4,760		2,878	19,892	27,530
1.5	SYSTEM INTEGRATION									342,678
1.5.1	SYSTEM ENGINEERING									(31,302)
1.5.2	SYSTEM TEST OPERATIONS									(70,659)
1.5.2.1	GROUND TEST									7,980
1.5.2.2	BOOSTED FLIGHT TEST (5 FLIGHTS)									62,679
1.5.3	SYSTEM TEST HARDWARE									(231,476)
1.5.3.1	GROUND TEST HARDWARE (S/C)									89,032
1.5.3.2	BOOSTED FLIGHT TEST HARDWARE (5 S/C)									142,444
1.5.3.2.1	AVE PROCUREMENT (5 E/V) & SPARES									105,366
	SUSTAINING ENGINEERING									19,680
	SUSTAINING TOOLING									3,896
	PRODUCTION, MATERIAL, CFE, SUBC.									64,941
	SPARES									
1.5.3.2.2	AVE PROCUREMENT (5 M/M) & SPARES									16,849
	SUSTAINING ENGINEERING									37,078
	SUSTAINING TOOLING									6,667
	PRODUCTION MATERIAL, CFE, SUBC.									781
										22,494
	SPARES									7,136
1.5.4	MOCKUPS	(54)		(635)	(689)	(1,080)		(7,488)	(673)	(9,241)

TABLE 2

S-IVB COST SUMMARY
(ALL FIGURES IN THOUSANDS)

		PRIME CONTRACTOR LABOR MANHOURS						1969 DOLLAR COST						
		ENGINEERING						ENGINEERING						
		DESIGN	TEST	SUB TOTAL	TOOL	PROD	TOTAL	DESIGN	TEST	SUB TOTAL	TOOL	PROD	MAT'L. CFE. SUBCON	TOTAL
1.0	SPACECRAFT (S/C)													563,446
1.0.A	PROJECT MANAGEMENT & ADMINISTRATION	848	31	879	3	154	1,036	16,960	620	17,580	40	1,817	840	20,277
1.1	MISSION MODULE (M M) DESIGN AND DEVELOPMENT	1,889	3,908	5,797	1,485		7,282	37,780	78,160	115,940	19,899		5,202	141,041
1.1.1	THERMAL STRUCTURE	380	1256	1636	1328		2964	7600	25,120	32,720	17,795		3,185	53 700
1.1.2	POWER SUPPLY & ORDNANCE	275	557	832			832	5,500	11,140	16,540			257	16 837
1.1.3	AVIONICS	385	608	993	40		1033	7,700	11,960	19,860	536		460	20 856
1.1.4	PROPULSION	849	1,487	2,336	117		2,453	16,980	29,740	46,720	1,568		1,300	49 588
1.2	AEROSPACE GROUND EQUIPMENT (AGE)	2,623	714	3,337	489	4,976	8,811	52,460	14,280	66,740	6,673	58,717	32,002	164 132
1.3	SYSTEM INTEGRATION													242,996
1.3.1	SYSTEM ENGINEERING													64,593
1.3.2	SYSTEM TEST OPERATIONS													48,570
1.3.2.1	GROUND TEST OPERATIONS													26,152
1.3.2.2	BOOSTED FLIGHT TEST OPERATIONS(5 FLT)													22,418
1.3.3	SYSTEM TEST HARDWARE													125,595
1.3.3.1	GROUND TEST HARDWARE													61,542
1.3.3.2	BOOSTED FLIGHT TEST HARDWARE (5 VEH)													
	AVE PROCUREMENT (M·M) SPARES													64,053
	SUSTAINING ENGINEERING													15,200
	SUSTAINING TOOLING													4,208
	PRODUCTION, MAT'L, CFE, SUBC													41,034
	SPARES													3 61[illegible]
1.3.4	MOCKUPS	50	149	199		5	204	1,000	2,980	3,980		59	198	4 23[illegible]

FIGURE 3

THERMO/STRUCTURE COST – DESIGN CORRELATION

Design Parameters	Design Costs Spread	Production Costs Spread
Weight	0.485 Power	0.766 Power
Application (Adapter–E.V.)	1–4	1–3
Configuration Complexity	1–3	–
Environment	1–1.15	–
Type Construction and Material	–	1–4.5 Str
	–	1–20 Thermal
Access Area	1–1.7	1–2.4
Density	0.25 Power	–

can impose different design requirements. The data spread indicated assumes low heating trajectories consistent with routine logistics missions as defined for this study. The type of construction and material is shown to influence the production costs significantly but not the design. Some of the reasoning for not including a design factor for construction and material is that a designer or analyst in making a drawing or going through a set of calculations does essentially the same thing regardless of what type material or construction is employed. This is not completely correct and it is recognized that some effect is probably buried in the other parameters; however it could not be separated out at this time. The same reasoning applies to the density factor in the production area.

The operations cost estimates developed in this study are based on the same philosophy discussed in Section 1 and therefore are generally higher than the costs currently being suggested. The most important difference is in the refurbishment/recertification cost. The model as constructed assumes that even reradiative thermo structure would require 100% inspection, and replacement of 20% of the surface each cycle. A similarly conservative philosophy is applied to all scheduled maintenance as indicated in Volume II, Book 2. Since this approach is quite different from the current ground rules imposed in other recent studies, the total program cost trends that result are also different. Therefore in addition to showing total program costs, some data are presented showing only the spacecraft development costs and first unit costs. These data are considered more general than total program costs in any event because they are not affected by the assumption of traffic rate, total transport volume, launch vehicle costs, etc.

The cost model output provides three levels of detail, ranging from a top level summary to printing out the results of each equation. In addition these data may be organized by program phase or by labor category. Figure 4 shows a sample print out for the second level cost summary as an example of the detail available. In addition, a separate output provides the detailed design description of the vehicle.

FIGURE 4

TYPICAL COST MODEL PRINTOUT

(MODULAR LIFTING BODY SPACECRAFT)

	CONTRACT DEFINITION	RDT & E PHASE	INVESTMENT PHASE	OPERATIONAL PHASE	TOTAL PROGRAM
SPACECRAFT (S/C)					
ENTRY VEHICLE (E/V)					
THERMAL STRUCTURE		71.805	36.312		108.117
INFLATABLE AERO DEVICES		26.747	0.970		27.717
POWER SUPPLY & ORDNANCE		25.374	11.673		37.047
ECLS		19.957	6.818		26.775
AVIONICS		125.853	30.531		156.385
PROPULSION		20.200	4.170		24.371
FINAL ASSEMBLY & CHECKOUT			14.167		14.167
SUSTAINING ENGINEERING			13.880		13.880
SUSTAINING TOOLING			4.212		4.212
INITIAL SPARES			12.273		12.273
TOTAL ENTRY VEHICLE		289.936	135.008		424.944
MISSION MODULE					
THERMAL STRUCTURE		22.400	76.319		98.719
POWER SUPPLY & ORDNANCE		13.018	32.855		45.872
ECLS		6.965	15.902		22.867
AVIONICS		2.778	3.023		5.801
PROPULSION		41.424	98.092		139.516
FINAL ASSEMBLY & CHECKOUT			32.742		32.742
SUSTAINING ENGINEERING			23.962		23.962
SUSTAINING TOOLING			8.663		8.663
INITIAL SPARES			29.156		29.156
TOTAL MISSION MODULE		86.585	320.714		407.299
AGE					
NON-RECURRING		46.410			46.410
RECURRING		125.004	24.039		149.043
TOTAL AGE		171.414	24.039		195.454
LAUNCH FACILITIES		28.769	0.0		28.769
TRAINERS & SIMULATORS		40.489			40.489
SYSTEM INTEGRATION					
SYSTEM ENGINEERING		57.219			57.219
SYSTEM TEST OPERATIONS					
AIRDROP TEST		29.786			29.786
GROUND TEST		28.568			28.568
BOOSTED FLIGHT TEST		82.832			82.832
TOTAL SYSTEM TEST OPER.		141.186			141.186
SYSTEM TEST HARDWARE					
AIRDROP TEST HARDWARE		48.180			48.180
GROUND TEST HARDWARE					
ENTRY VEHICLE		114.570			114.570
MISSION MODULE		23.171			23.171
TOTAL GROUND TEST HDW.		137.741			137.741
BOOSTED FLIGHT HARDWARE					
ENTRY VEHICLE		183.381			183.381
MISSION MODULE		44.397			44.397
TOTAL BOOST FLT. HDW.		227.779			227.779
TOTAL SYS. TEST HDW.		413.700			413.700
MOCKUPS		5.898			5.898
TOTAL SYSTEM INTEGRATION		618.003			618.003
OPERATIONS PHASE (S/C)					
LAUNCH OPERATIONS				70.869	70.869
LAUNCH AREA SUPPORT				113.486	113.488
MISSION CONTROL SUPPORT				14.550	14.550
AGE MAINTENANCE				18.515	18.515
FACILITY MAINTENANCE				4.057	4.057
RECOVERY OPERATIONS				33.993	33.993
RECERTIFICATION				151.913	151.913
TRANSPORTATION				10.698	10.698
TECHNICAL SUPPORT				10.580	10.580
TOTAL OPERATIONS PHASE				428.663	428.663
CONTRACT DEFINITION	12.352				12.352
TOTAL BASIC SPACECRAFT	12.352	1235.197	479.761	428.663	2155.973
S/C PROJECT MANAGEMENT	1.235	20.041	3.827		25.103
SUBTOTAL	13.587	1255.238	483.588	428.663	2181.076
S/C FEE	1.359	125.524	48.359	42.866	218.108
SUBTOTAL	14.946	1380.761	531.947	471.529	2399.183
S/C PROGRAM OFFICE MGMT	1.359	125.524	48.359	42.866	218.108
TOTAL SPACECRAFT	16.305	1506.285	580.306	514.395	2617.291
LAUNCH VEHICLE (L/V)					
BASIC LAUNCH VEHICLE	4.978	497.754	1359.174	498.021	2359.927
L/V FEE	0.498	49.775	135.917	49.802	235.993
SUBTOTAL	5.475	547.530	1495.091	547.824	2595.920
L/V PROGRAM OFFICE MGMT	0.498	49.775	118.725	145.108	314.106
TOTAL LAUNCH VEHICLE	5.973	597.305	1613.816	692.932	2910.025
TOTAL SPACECRAFT & LAUNCH VEH	22.278	2103.590	2194.122	1207.327	552[illegible].116
QUANTITY OF ENTRY VEHICLES		5.	6.		11
QUANTITY OF MISSION MODULES		5.	78.		83.
QUANTITY OF LAUNCH VEHICLES		5.	78.		83.
QUANTITY OF FLIGHTS		5.		78.	83

ENTRY VEHICLE FIRST UNIT COST -	47.570
MISSION MODULE FIRST UNIT COST -	11.428
ENGINEERING LABOR RATE -	20.00
TOOLING LABOR RATE -	13.40
PRODUCTION LABOR RATE -	11.80
REMOTE SITE LABOR RATE -	16.00
ECONOMIC ESCALATION -	1.000

6. SIGNIFICANT RESULTS - One of the most significant results of this study was the development of the detailed cost model. While this was applied to specific configuration concepts for this study, it is a general tool and can be applied to any spacecraft concept if the design characteristics are known. The limitations of the model are only those associated with the ground rules of this study. For example, there is presently no provision for estimating either air breathing engines or variable geometry wings; however, the addition of other items does not pose a significant problem.

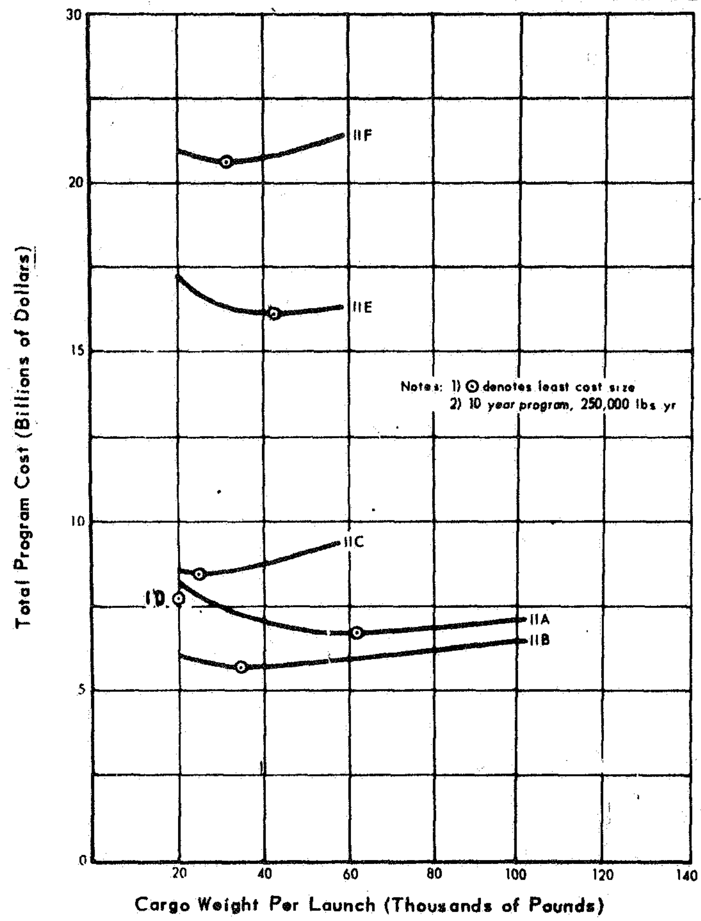
Some of the total program cost trends are shown in Figures 5 and 6. The vehicle concepts were defined in Figure 2. These costs are true total program and include all design/development, investment and operations costs of both the launch vehicle and the spacecraft. Also included are the AGE, launch facilities, trainers and simulators, program and project office management, and a 10% fee.

As indicated in Figures 5 and 6, most of the concepts have a least cost cargo size in the range of 25,000 to 55,000 lbs., and are generally less sensitive to being oversized than undersized. When comparing a B (modular) concept with a C (integral cargo/propulsion) or an E (integral upper stage), as shown in the figures, it is necessary to have some insight into the variations in the design characteristics. For a nine man lifting body vehicle (configuration II), with 20,000 lbs. of cargo, the entry vehicle length goes from about 30 ft to 50 ft to 110 ft. The wetted area goes from about 750 ft^2 to 2400 ft^2 to 10,900 ft^2 and the dry weight from 13,000 to 37,000 to 260,000 lbs. Figure 7 shows the variation of dry weight with cargo size.

The relative costs of the concepts as shown in Figures 5 and 6 are primarily the result of three interacting factors: the vehicle size, the operations philosophy, and the launch vehicle cost. Figure 7 indicates a significant increase in the dry weight going from a B to C configuration with a resulting increase in the operations and launch vehicle costs. All these things combine to more than offset the savings achieved in the investment of the cargo/propulsion module. The size of the IIE configurations 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.

LIFTING BODY SPACECRAFT TOTAL PROGRAM COST

FIGURE 5



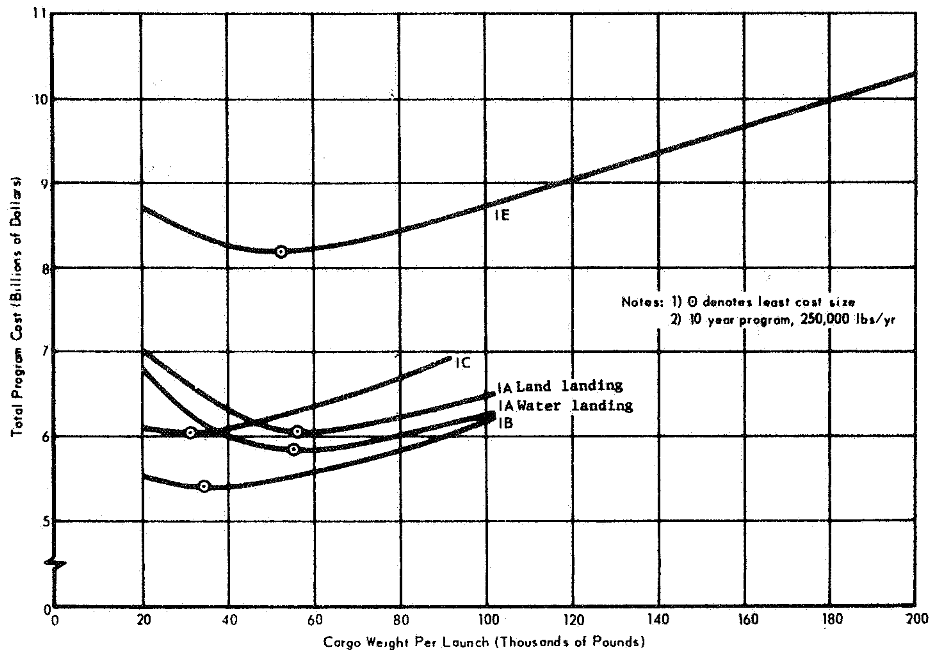
Furthermore the vehicle definition is the result of parametric relationships and for the reusable upper stage concepts tends to be heavier than similar size vehicles defined in recent point design studies.

To see the effect of the operations philosophy, a comparison can be made between the IB and IE configurations. 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 (exluding 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 turnaround time. These vehicles are so large that in some cases, the time for recertification (under the study assumptions) 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 turnaround time.

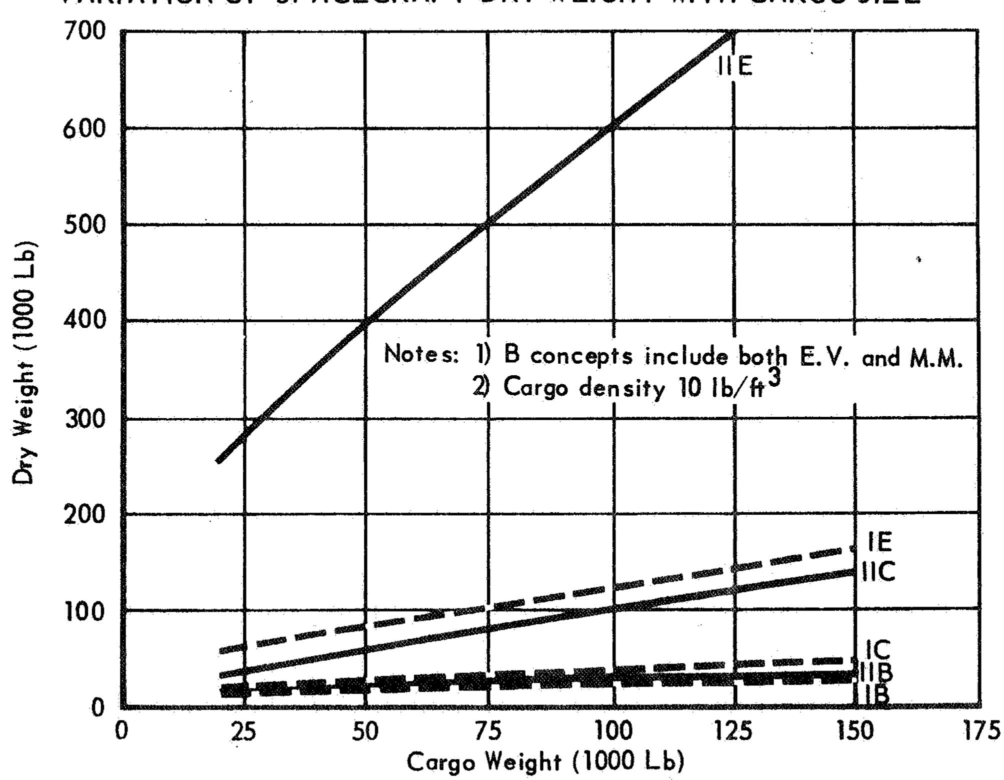
BALLISTIC SPACECRAFT TOTAL PROGRAM COST

FIGURE 6



VARIATION OF SPACECRAFT DRY WEIGHT WITH CARGO SIZE

FIGURE 7



The influence of the launch vehicle costs can be seen from the fact that for the conditions shown, the launch vehicle represents about 30% of the total cost for the modular concepts and about 60% for the upper stage concepts. For the modular concepts - A through C, the launch vehicle is a two stage expendable consisting of a solid first stage and a LO_2/LH_2 upper stage. The D and E concepts include the upper stage with the spacecraft and therefore have only an expendable 260 inch solid first stage (the upper stage propellant tanks are also expended in the D concept). The completely reusable IIF concept uses an M2-F2 as a boost vehicle as defined in a previous study for NASA, NAS 2-3191.

Figures 8 and 9 show the spacecraft Design/Development costs by subsystem for ballistic and lifting body concepts, and indicate the effect of going from a modular concept (B) to a reusable (E). The trends are as would be expected with relative increases for structure and propulsion and decreases in the others. The structural increase in the lifting body is somewhat higher than might be expected because the design assumes the launch bending loads are carried through the adapter attached to the base of the vehicle. Removing part of the load with an attachment farther forward would significantly reduce the structural weight and therefore the cost.

The effect of the subsystem cost can also be seen indirectly in Figure 10 which shows basic spacecraft development costs with dry weight. For the very large lifting body vehicles, the cost varies almost directly with weight to the 0.485 power, indicating the dominance of the thermo structure (see Figure 3). However, for the smallest modular vehicles, the slope is much less, indicating the importance of the other subsystems.

Figures 11 and 12 show first unit costs for the ballistic and lifting body concepts respectively. The smoothness of the curve in going from one reuse concept to another (B to C to E) would seem to be a very significant result of the study and seems even more so if the data from the two figures are overlaid. The ballistic and lifting vehicles follow the same trend and have essentially the same cost for a given dry weight even though the vehicle function differs (i.e. the IIC and IE overlap). This weight includes all subsystems and not just structure but, again, as the vehicle size increases, structure costs become dominant and the total vehicle cost varies as the structure cost.

FIGURE 8

BALLISTIC SPACECRAFT COST BREAKDOWN BY SUBSYSTEM
(RDT&E Costs)

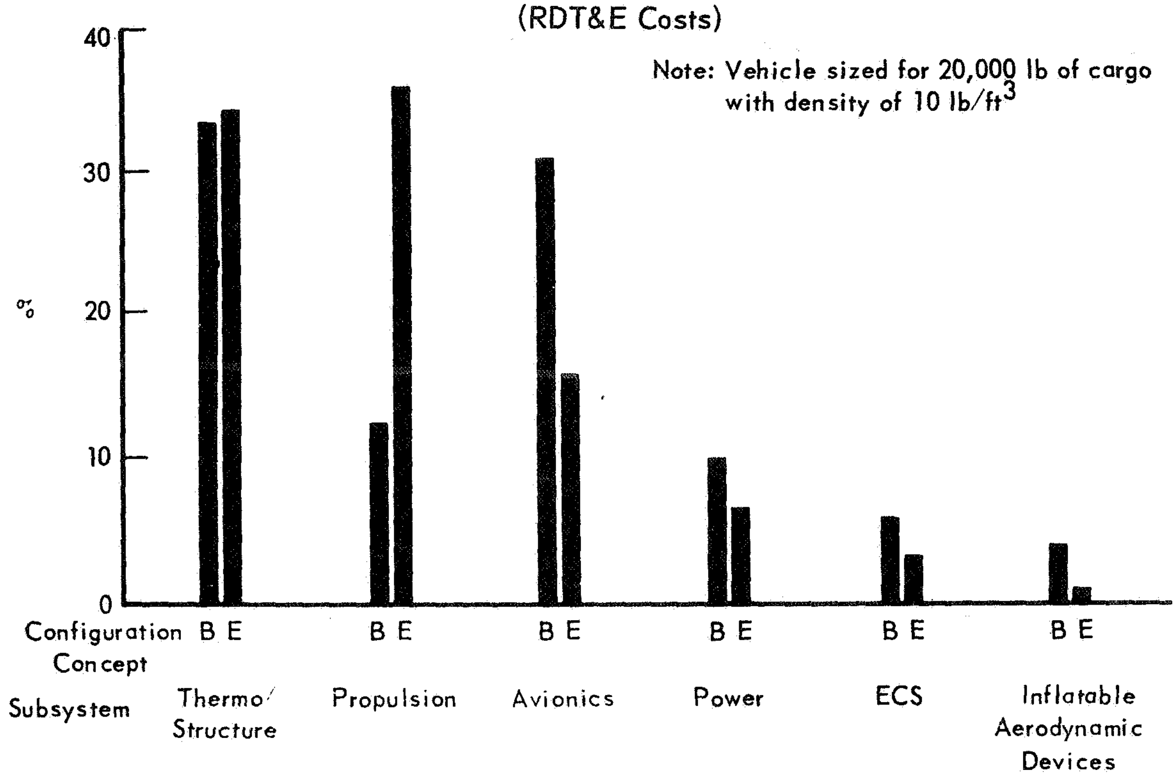
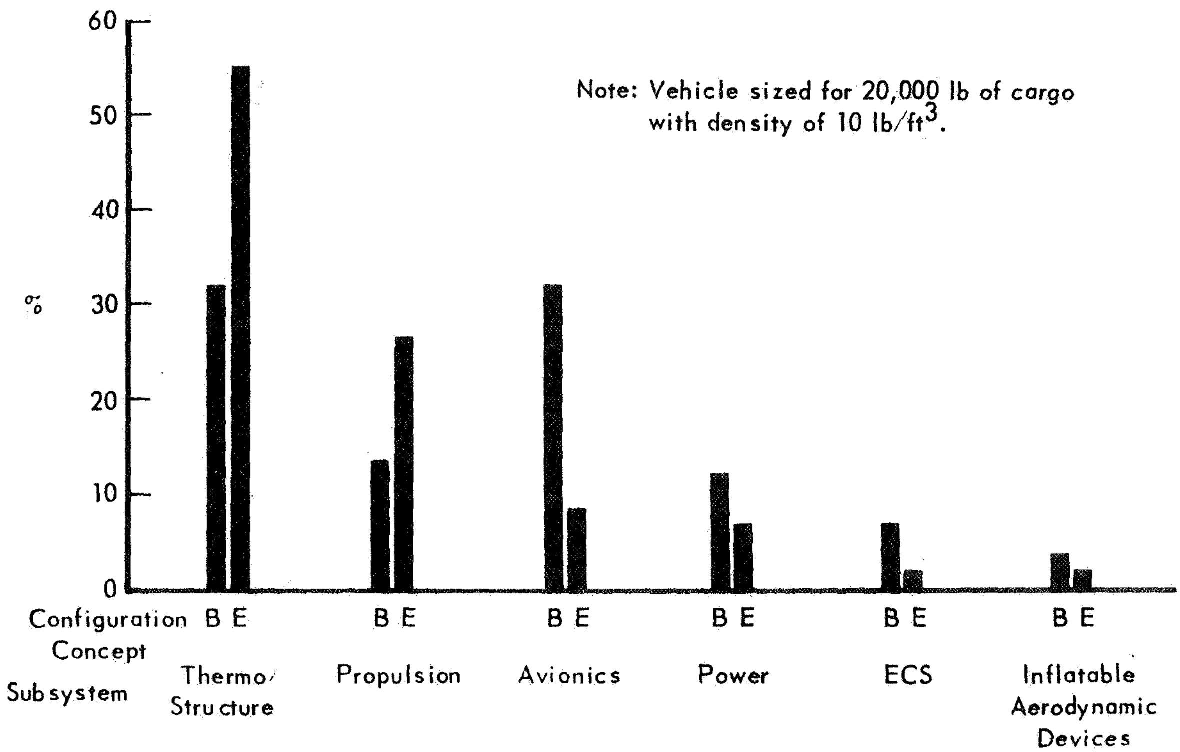


FIGURE 9

LIFTING BODY SPACECRAFT COST BREAKDOWN BY SUBSYSTEM
(RDT&E Costs)



BASIC SPACECRAFT DEVELOPMENT COSTS

FIGURE 10

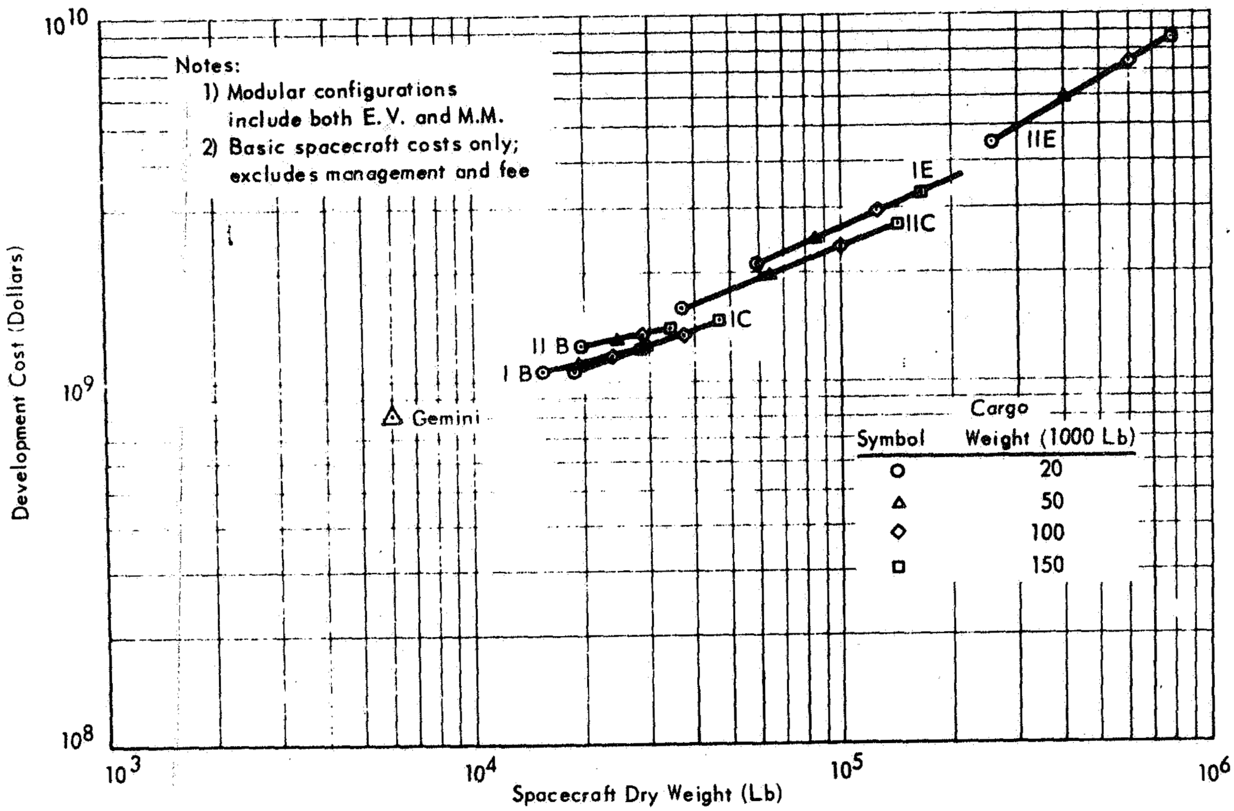


FIGURE 11

BALLISTIC SPACECRAFT FIRST UNIT COSTS

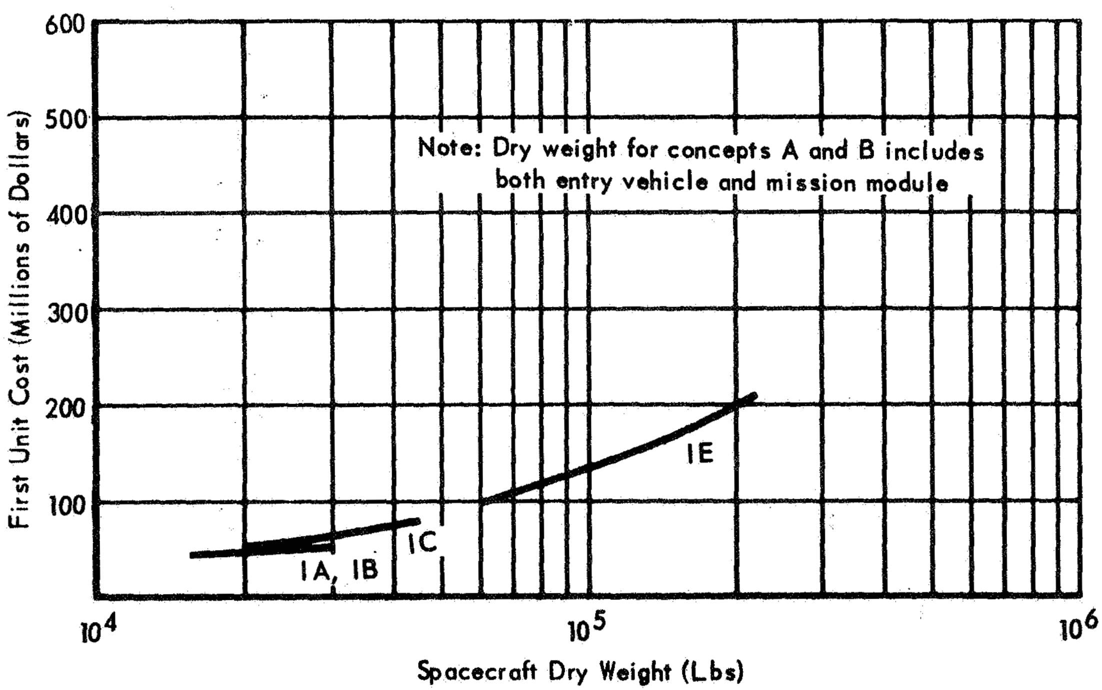
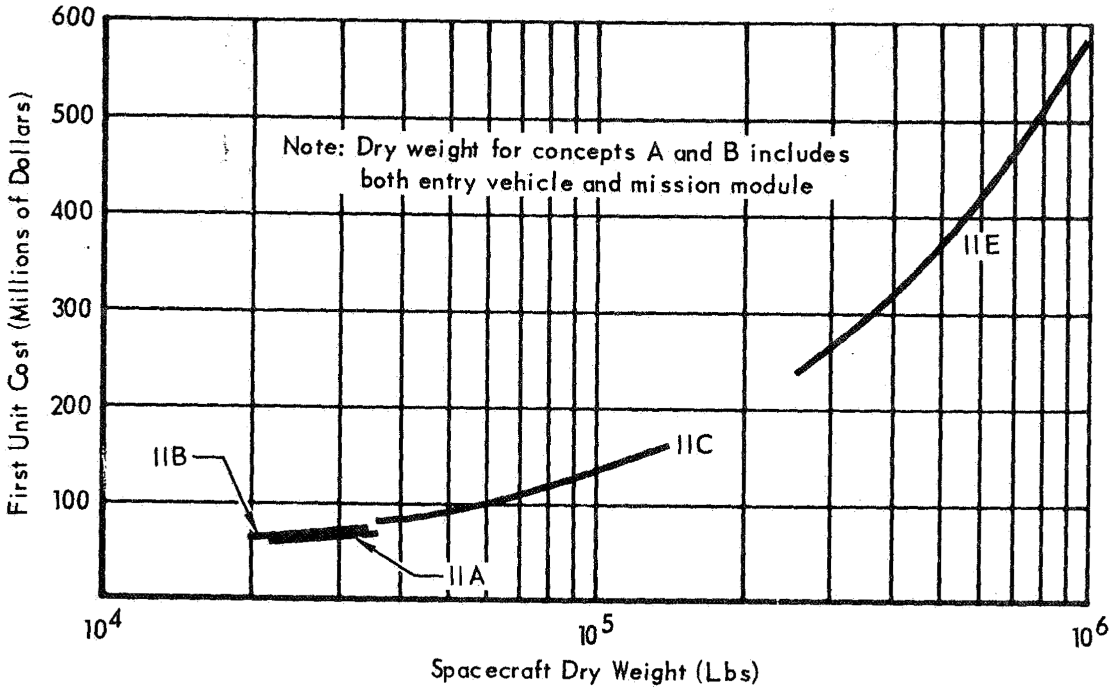


FIGURE 12

LIFTING BODY SPACECRAFT FIRST UNIT COSTS



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7. SUGGESTIONS FOR FUTURE WORK - This study was necessarily constrained by funding and schedule limitations. Therefore, while the cost model is a general tool, it was only exercised for ballistic and M2/F2 spacecraft. One of the most valuable areas of additional work would be to examine other concepts which are being suggested as candidates for the space shuttle task. The emphasis of other current work in the area of space shuttle vehicles is on completely reusable two stage configurations. While this study has included a two stage reusable concept, the emphasis of the study was on spacecraft and the reusable booster data were assumed from a previous study accomplished for MAD/OART. Therefore additional work could be accomplished in two areas: other spacecraft configurations, and better definition of the reusable boost stage.

Another area of potentially valuable future work is operations costs. These costs are always quite dependent on the ground rules established and therefore reflect a certain degree of arbitrariness. Since there is very little basis for projecting these costs with any certainty it seems desirable to at least do some studies which bound the problem and show the sensitivity of various concepts to the assumptions. This study has indicated that with a conservative approach to reuse (i.e., complete inspection, 20% replacement of reradiative material, etc.) a completely reusable upper stage may not be the least cost approach. However, this is spacecraft, launch vehicle, launch rate, and program dependent, as well as being dependent on the operational philosophy; it is not a general conclusion, although it is a correct conclusion for this system with the ground rules of this study. It would seem highly desirable to conduct further analyses so that general conclusions may be drawn.

A final suggestion for future work would be in showing the effect of the management approach. The data generated in this study are based on historical programs and therefore reflect the historical management techniques. Since these techniques are assumed to have contributed to high program costs, some people suggest that a different approach could result in reduced costs. The effect of a management approach is difficult to quantify but it might be profitable to employ a "what if" attitude and determine some total program cost sensitivities.

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