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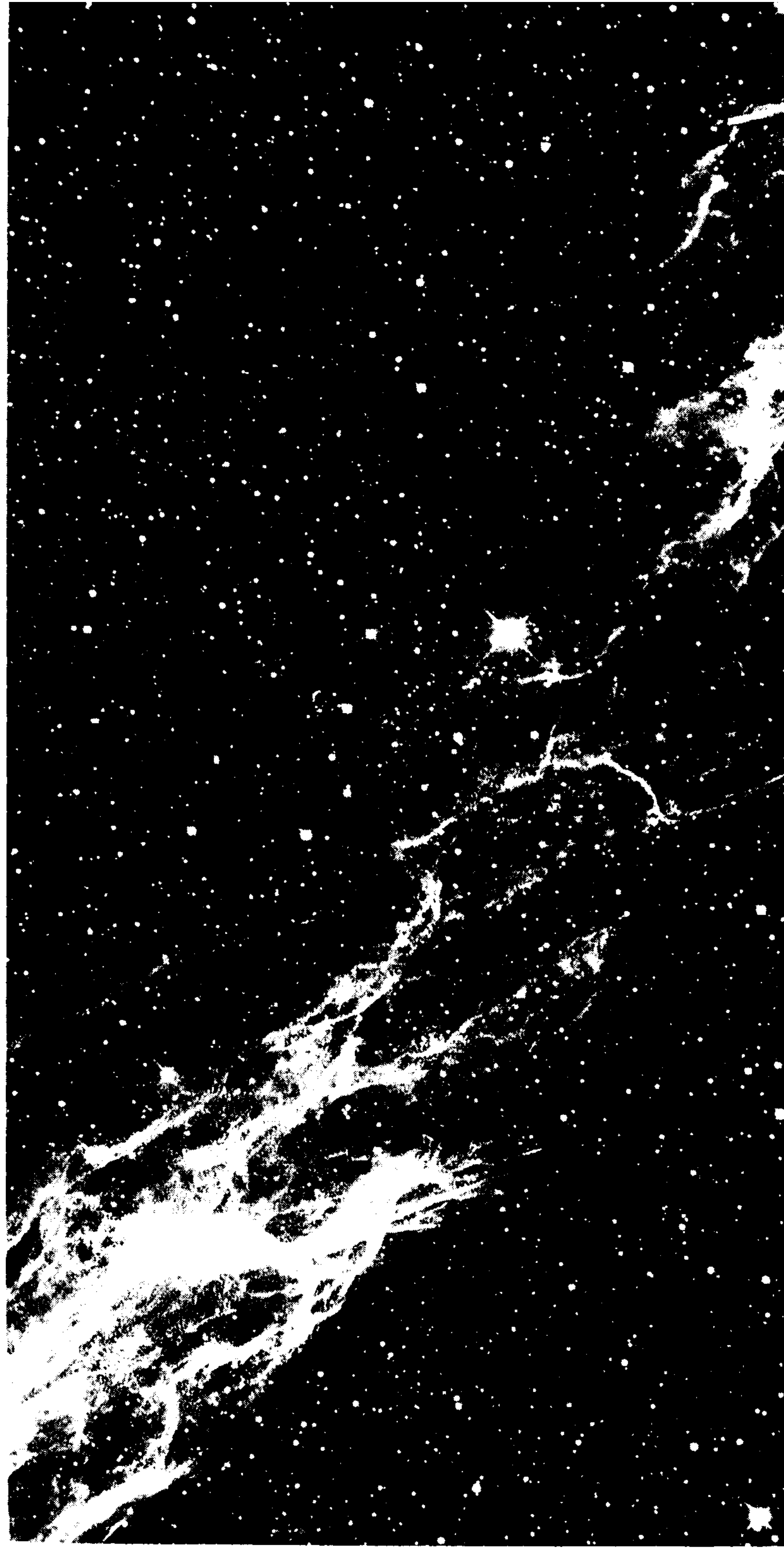

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Technical Memorandum No. C-10

COST ESTIMATION FOR UNMANNED LUNAR AND PLANETARY PROGRAMS

IIT RESEARCH INSTITUTE
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COST ESTIMATION FOR UNMANNED LUNAR AND PLANETARY PROGRAMS

by

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SUMMARY

A basic model is presented for estimating the cost of unmanned lunar and planetary programs. The level of input parameters required by the model and its accuracy in predicting cost are consistent with pre-Phase A type mission analysis.

Cost data was collected and analyzed for eight lunar and planetary programs. Total cost was separated into the following components: labor, overhead, materials, and technical support. This study determined, with surprising consistency, that direct labor cost of unmanned lunar and planetary programs comprises 30 percent of the total program cost.

Twelve program categories were defined for modeling: six spacecraft subsystem categories (science, structure, propulsion, electrical power, communications, and guidance and control); and six support function categories (assembly and integration, test and quality assurance, launch and flight operations, ground equipment, systems analysis and engineering, and program management). An analysis, by category, showed that on a percentage basis, direct labor cost and direct labor manhours compare on a one-to-one ratio. Therefore, direct labor hours is used as the parameter for predicting cost. This has the advantage of eliminating the effect of inflation on the analysis.

Figure S-1 is a flow diagram of the use of the cost model in forecasting. The boxes in the upper left involve the mission dependent information. Scaling laws, physical and mathematical relationships, and synthesis guidelines, provide the basic estimate of manhours. The remainder of the model deals with converting the basic cost element, direct labor hours, into cost.

This requires two additional steps. First, the average pay scale ($/hr) must be determined for the period of the program. If desired, the selected pay scale could include inflation between the time of the estimate and program execution. The final step involves converting direct labor cost into total program cost. Total program cost can be determined by dividing direct labor cost by its fraction of total cost. The relationship used throughout this study is:

$$\text{Total Program Dollars} = \frac{\text{Direct Labor Hours x Average Hourly Rate}}{.3} .$$

Figure S-2 presents cost estimates and errors for the programs used in developing the cost model. The Surveyor program did not follow clearly established trends of the other seven programs, and was subsequently not used in the development of the model. As an example, the model was used to predict the cost of the Mariner Venus/Mercury 1973 program. The model predicted a program cost of $120 Million, which is approximately 20 percent higher than current estimates.

Recommendations for further effort include: update the current data base by obtaining the latest Mariner 1971, Viking Orbiter and Viking Lander cost data; expand the data base by obtaining cost data for such programs as Mariner Venus 1967, Mariner Venus/Mercury 1973, and interplanetary and cis-lunar Pioneer and Explorer programs; and develop cost models for planetary atmospheric entry probes.

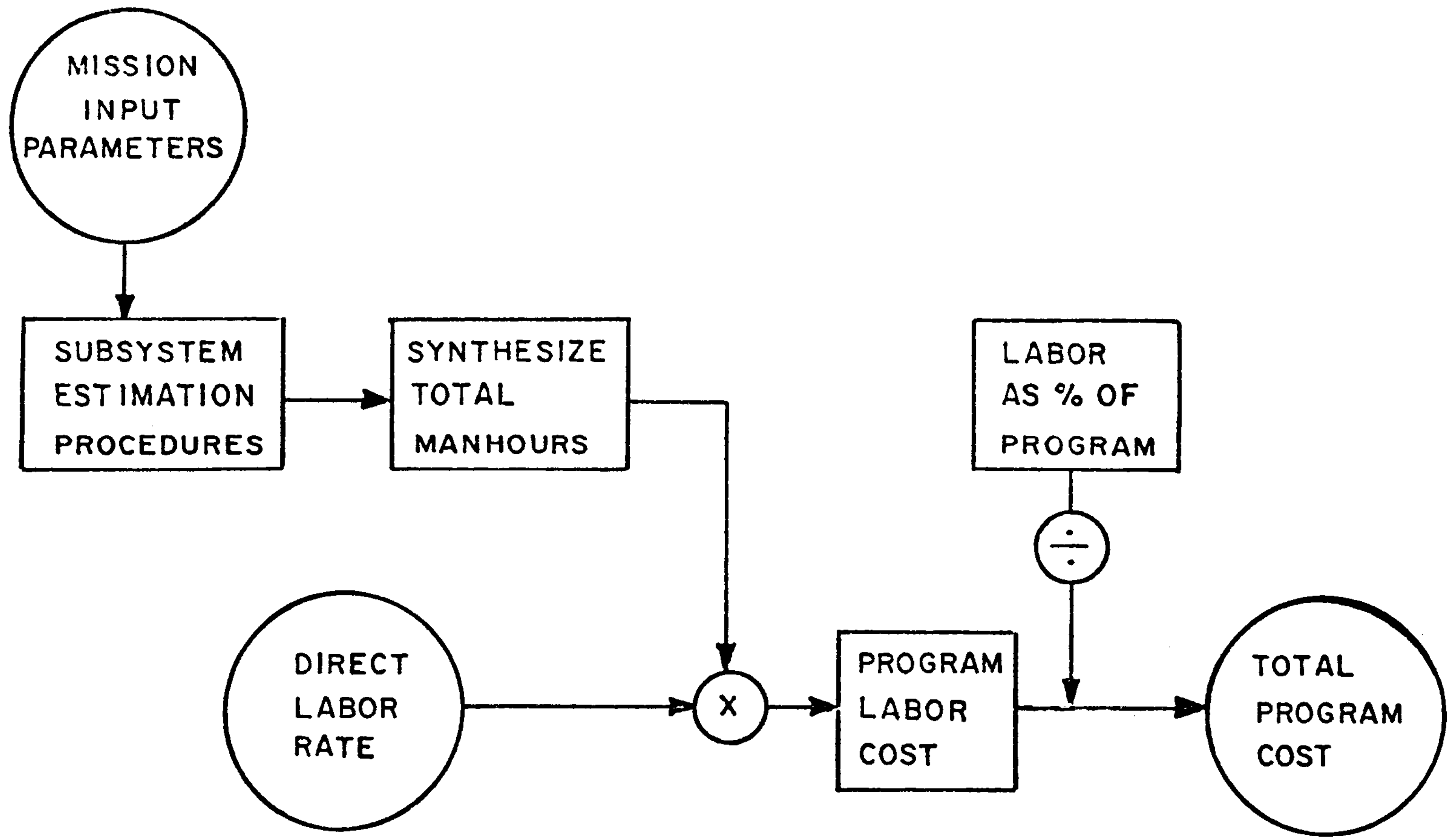

FIGURE S-1

COST MODEL SCHEMATIC

Figure S-2: Cost Model Prediction Error Analysis

Program	Actual Cost $1000	Predicted Cost $1000	% Error
Mariner 64	78104	62296	-20.2
Mariner 69	122052	100862	-17.4
Mariner 71	120647	150578	24.8
Pioneer F & G	83858	77842	- 7.2
Viking Orbiter	242870	245998	1.3
Viking Lander	327924	288094	-12.2
Lunar Orbiter	134534	164132	22.0
Surveyor *	423195	169908	-60.0

* not used in model derivation

COST ESTIMATION FOR UNMANNED LUNAR AND PLANETARY PROGRAMS

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GLOSSARY OF SYMBOLS

Symbol	Definition
CT	Mission cruise time (CT = MT - LD1), in days
DLH	Direct labor hours, in thousands of hours
EPT	Scientific experiment and data playback time, in days
I_{SP}	Specific impulse, in lb_f-sec/lb_m
I_T	Total impulse, in lb_f-sec
LD1	Launch date of first flight in mission
LER	Labor-hour estimating relationship
LO	Lunar Orbiter
MT	Date of mission termination (final spacecraft shutdown)
M64	Mariner Mars 1964
M69	Mariner Mars 1969
M71	Mariner Mars 1971
NL	Number of launches in total program
NR	Non-recurring direct labor hours, in thousands of hours
N_S	Number of flight spacecraft
N_U	Number of RTG units purchased from A.E.C.
PIO	Pioneer F & G
PPL	Resolution of imaging instrument, in pixels per line
PTM	Proof test model
P_T	Transmitter peak RF output power, in watts
P_U	Unit RTG power at BOL, in watts
P_O	Total conditioned power, in watts; at 1 A.U. for solar power; at beginning of life for RTG power
R	Recurring direct labor hours, in thousands of hours

GLOSSARY OF SYMBOLS (continued)

Symbol	Definition
r	Correlation coefficient of regression analysis
RMS	Root-mean-square error of regression analysis
S/C	Spacecraft
SU	Surveyor
T	Time from August 1960 to first launch date, in years
VL	Viking Lander
VO	Viking Orbiter
WAGE	Hourly wage rate, in dollars per hour
WT	Weight, in pounds

SUBSCRIPTS

Symbol	Definition
AI	Assembly and Integration
C	Communications
DRY	Dry Weight
EP	Electrical Power
EPR	Electrical Power from RTG's
EPS	Electrical Power from Solar Cells
GC	Guidance and Control
GE	Ground Equipment
LF	Launch and Flight Operations
P	Propulsion
PM	Program Management
PR	Propellant
S	Science
SE	Systems Analysis and Engineering
ST	Structure
TOT	Indicates Total
TQ	Test and Quality Assurance

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1. STUDY OBJECTIVE AND PLAN

STUDY OBJECTIVE

The primary objective of this study is to provide the Planetary Programs Office (SL) of NASA Headquarters with a capability for estimating the cost of future missions. This capability is intended for use in generating initial cost estimates of planetary missions for which pre-Phase A information is available. The procedure must be easy to use and sufficiently flexible to accomodate changing mission definitions (flyby, orbiters, landers, etc.) and varied levels of available mission information.

Previous spacecraft cost modeling by IITRI was developed from the costs of Ranger, IMP, Mariner, OGO, Relay, Syncom, and Surveyor programs. Program records for a number of small, highly instrumented spacecraft were used in the formulation of the model. The spacecraft program cost were shown to be a function of: number of flight spacecraft; total weight of the spacecraft plus experiments; weight of the spacecraft less experiments; structure weight; telemetry weight; and weight of the propulsion subsystem.

The Planning Research Corporation cost predictive model was developed for JPL using Mariner 64, 67, 69, and Lunar Orbiter cost data. The model relates unit and development cost to subsystem weights, but it is primarily a Phase B model which requires more detailed input information than is usually available from a pre-Phase A study.

Another unmanned spacecraft model was developed by the Air Force Space and Missles Systems Organization (SAMSO) for predicting total program cost through the use of cost estimating relationships (CER). The CER's were developed from primarily earth orbiting spacecraft programs. A total of fourteen programs were analyzed to formulate CER's for subsystems and operational recurring and non-recurring cost. The model was developed over a period of several years and is still being modified.

A basic premise of the analysis presented here is that cost forecasting can be improved by selecting manhours as the basic cost unit. Manhours have several advantages over forecasting total program dollars; separation of inflationary factors from estimates and improved costing of low volume production. Two programs separated in time are comparable on a cost basis only if some inflationary factor is applied to the older program. Such inflationary factors are difficult to formulate for total program costs and often fail to accurately represent the actual financial conditions within the industry. The space program has not yet been able to use mass production techniques and thus the total cost of each completed item is not substantially decreased through additional production. Hence, the cost of a program's hardware is directly connected to the manhours involved in development, fabrication, and testing.

STUDY PLAN

The plan of analysis for this study is outlined by the flow diagram in Figure 1 and proceeds in a sequential order. First, a framework of specific objectives and individual steps of analysis were established. A key result of this first effort was the selection of specific past and current programs for the data analysis. It was determined that manpower charged directly to all program contracts would have to be ascertained as well as dollar costs. Data collection was accomplished by contacting NASA Headquarters, NASA Research Centers, and Prime Contractors. Raw data have been divided into cost categories (e.g., program management, science, spacecraft subsystems, etc.) and these categories subsequently broken up into standard financial subdivisions (e.g., direct labor hours and dollars, overhead, material, and technical support). An analysis of these data comparing direct labor hours and dollars has confirmed the authenticity of labor hours for the modeling analysis. A feed-back loop to model definition is shown to indicate that one source of model improvement will come from testing and using the model itself. Another source, shown by the dotted square, is continued data collection to improve the data base on which many elements of the overall procedure are being founded.

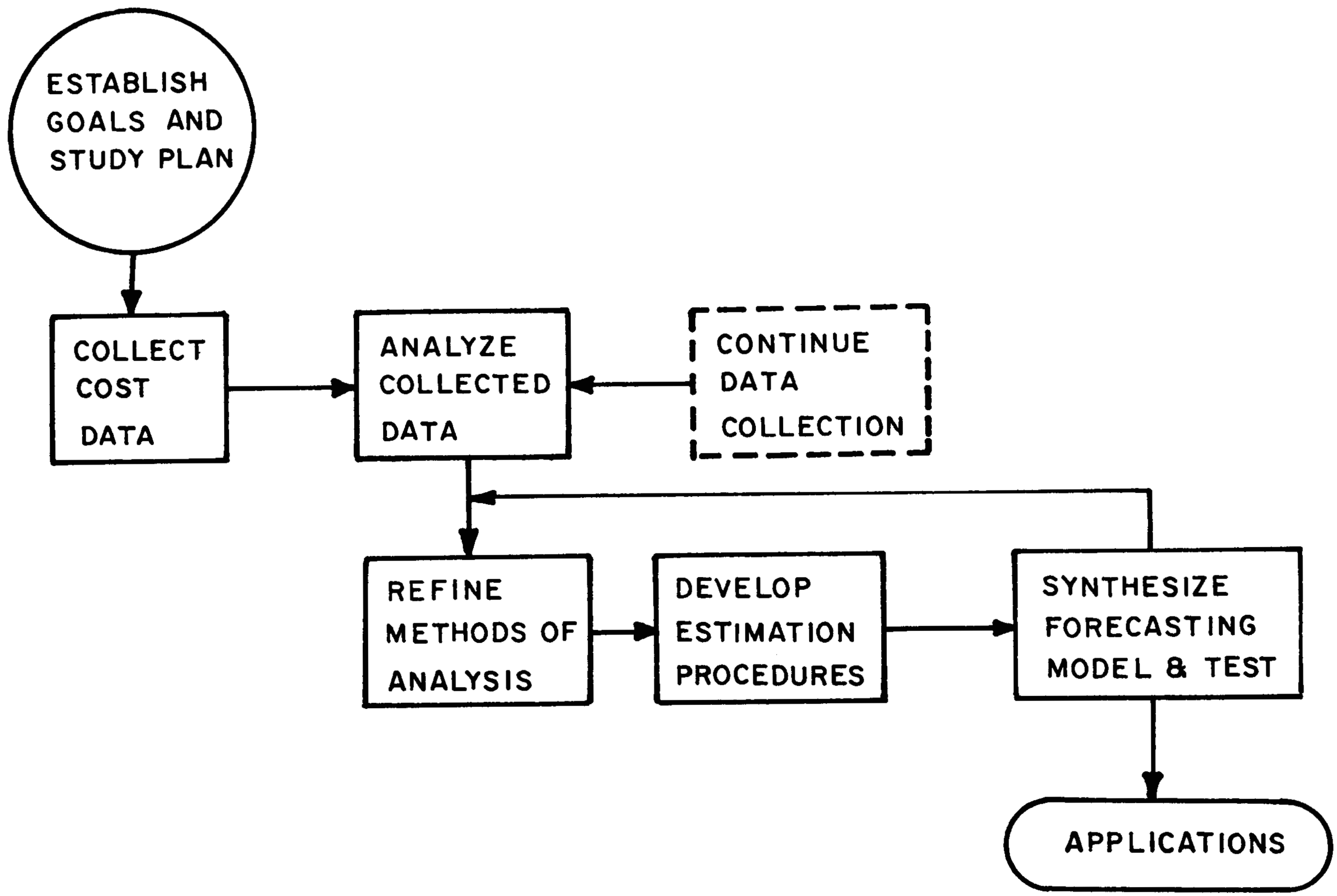

FIGURE 1.
COST STUDY PLAN

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2. PROGRAM COST DATA

TOTAL PROGRAM COST DATA

Cost data was obtained for eight programs and used as the basis for developing models. Figure 2 shows the costs for the eight programs and indicates the differences between total costs and the costs which were used for the model. The inconsistencies were due to such sources as unidentified center costs, costs labeled as miscellaneous and unobtainable subcontractor data.

Viking Lander and Viking Orbiter are on-going programs and the costs shown are estimates obtained from JPL and Martin Marietta. These costs will undoubtedly change as the programs progress, but they were used to include current planetary program experience in the model.

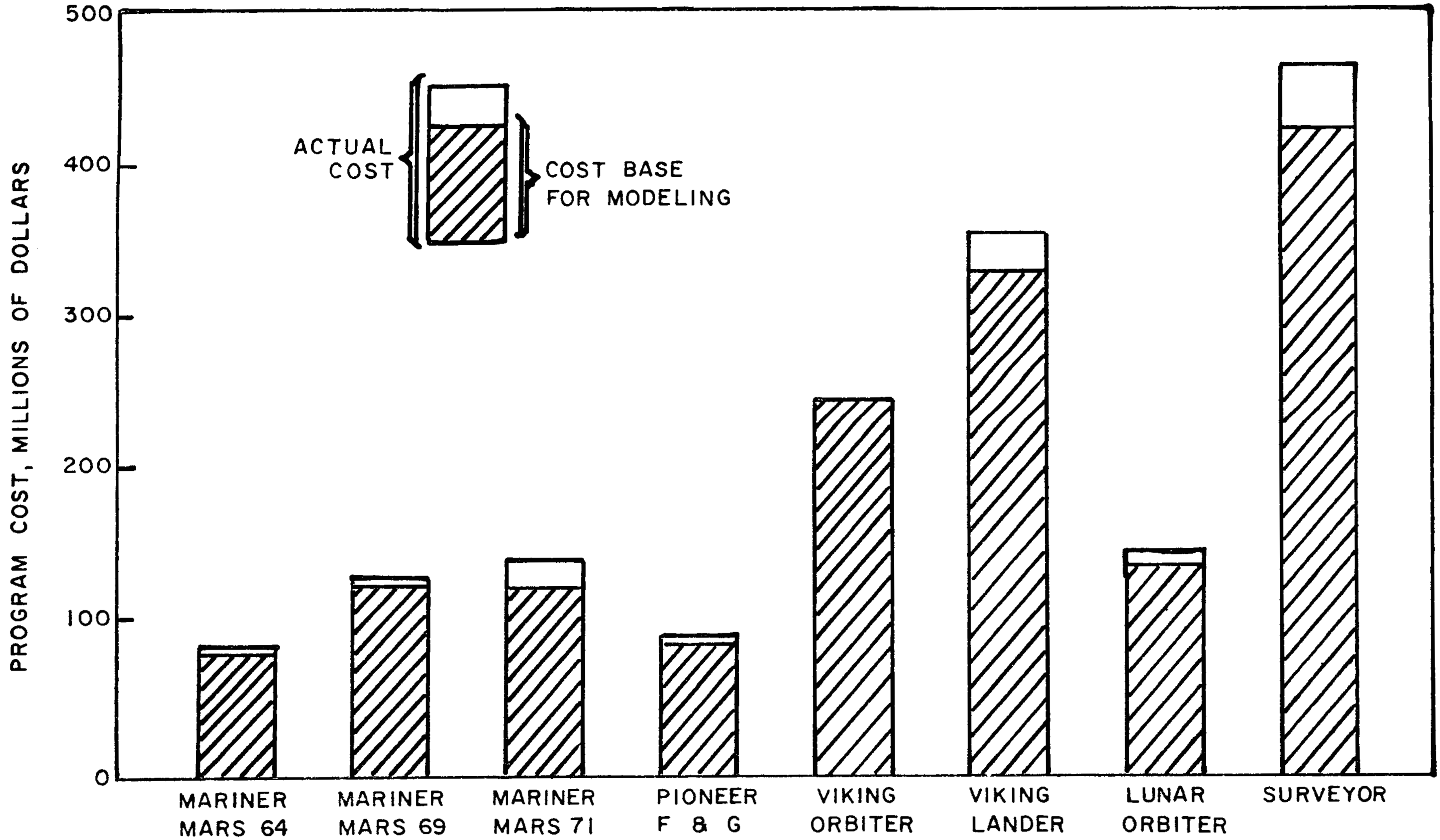

FIGURE 2. TOTAL PROGRAM COSTS.

COST COMPONENTS

Detailed cost data were obtained for eight programs but in the cases of Mariner 64 and Viking Orbiter the format of the cost information was not adequate for all types of analysis. In general, the cost printouts included information on dollars and manhours for line items as well as summaries indicating the division of costs by direct labor, overhead, materials and technical support. These data were usually available by program year or month enabling some studies of time line behavior. Figure 3 is a typical data sheet from Mariner 69. The assignment of cost components is shown in the figure.

PROJECT BUDGET PERFORMANCE REPORT

MAR MARS 69 PROPULSION SUBSYSTEM
R & D BUDGET YEAR 1969 MONTH OF JUN

PROJ.	SYST.	SUB SYST.	JOB	FUNC.	ORG.
548	2	GL	01		3840

EQUIVALENT MAN YEARS CLASSIFICATION	CURRENT MONTH S/T	CURRENT MONTH O/T	CURRENT MONTH TOTAL	AVERAGE, FY TO DATE S/T	AVERAGE, FY TO DATE O/T	AVERAGE, FY TO DATE TOTAL	PLAN S/T	PLAN TOTAL S/T & O/T
ENG & SCIENT	9		9	35	1	36	48	48
ADMINISTRATION				5		5	7	7
TECH & OTHER	1		1	19	1	20	24	24
TOTAL	10		10	59	2	61	79	79

COST CLASSIFICATION	OBLIGATIONS (IN DOLLARS) THIS MONTH	OBLIGATIONS (IN DOLLARS) F/Y TO DATE		% USED	COMMITMENTS IN PROCESS ($K) REQS.	COMMITMENTS IN PROCESS ($K) W/O's	COST INCURRED (FY TO DATE) (IN DOLLARS)
DIRECT LABOR	1359	80012	LABOR	70			80013
ADM SERV							
PHOTO	117	1282		691			1384
REPRO		70		35			71
REPORTS		51		51			51
PLANT ENG	64	1096		540		7	1096
OTHER		119		30			119
TOTAL	181	2718		302		7	2721
TECH DIV SERV			TECHNICAL SUPPORT				
COMP PROG		7211		721		2	7211
COMP DIG	500	9025		1280			9025
CHEM LAB		3594		1797			3594
DESIGN		2405		601		3	2405
INST REP & LN		3501		1167			3534
TEST CROSS CH		120		60			120
OTHER		1117		55			1118
TOTAL	500	26973		562		5	27007
MATL & OTHER							
PROCUREMENTS	95	63270		355			156565
FABRICATION		4312		862			4314
TOTAL	95	67582	MATERIALS	855			160879
TRAVEL	3117	12344		823			12344
TOTAL DIRECT	5252	189929		710		12	282564
TECH DIV BURDEN	283	22010		651			28009
TOT DIR & TDB	5535	217639		709		12	310573
APPLIED COSTS			OVERHEAD				
GENL BURDEN	620	29330		1126			29332
PROJ BURDEN	19	5533		922			5534
LAB BURDEN	565	42701		667			42702
TOTAL	1204	77564		808			77568
REPORT TOTAL	6739	295203		733		12	388541

FIGURE 3.

COMPONENTS OF COSTS

An analysis of seven programs provided the rationale for using direct labor costs as the basis for modeling. Figure 4 shows the percentage allocation of costs to technical support, materials, overhead and direct labor where direct labor (DL) is the costs charged directly to the program for engineers, scientists, technicians, administrative and manufacturing personnel, and office and clerical help. For each of the seven programs the percentage of DL varies only slightly from the combined average of 30.1 percent.

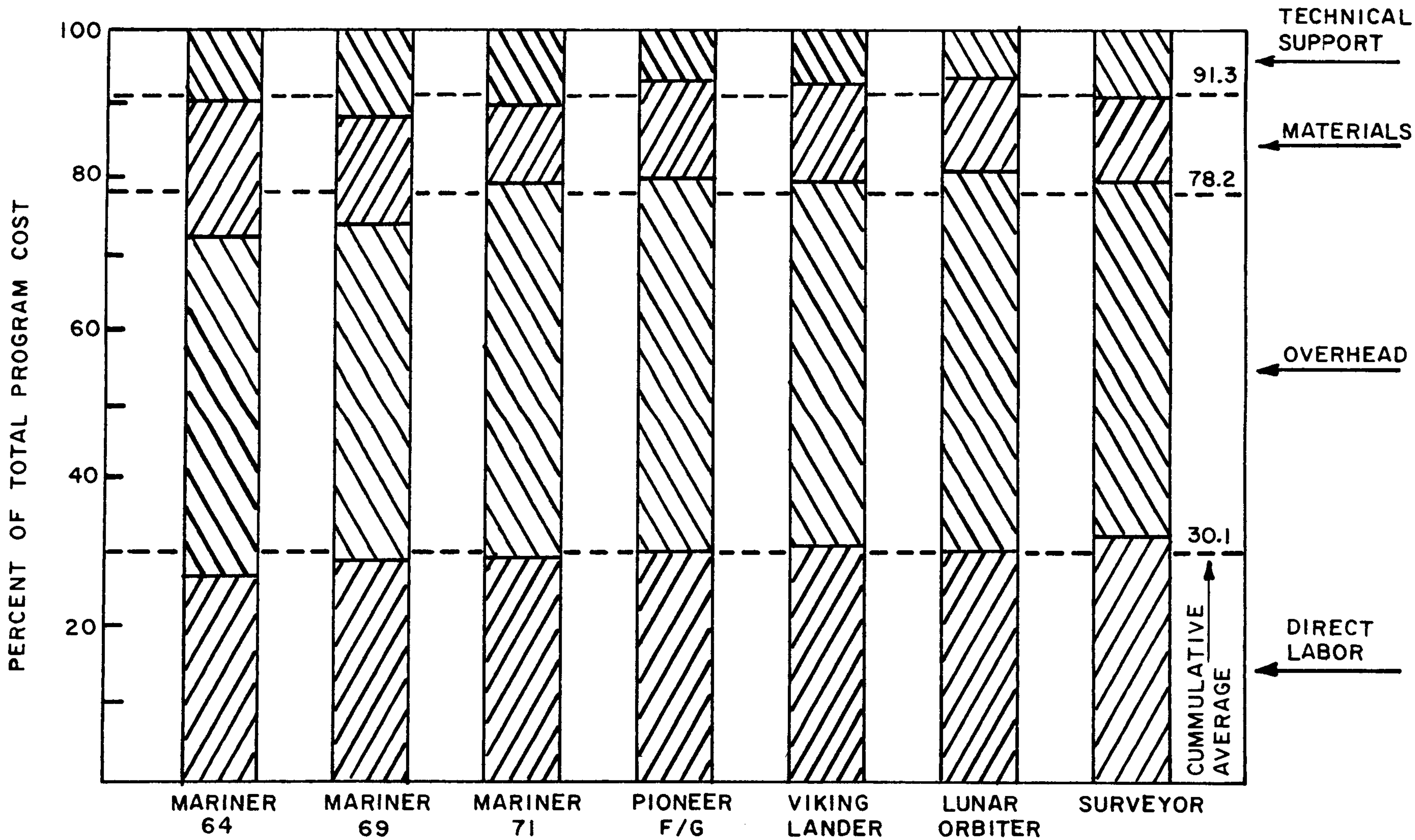

FIGURE 4. COMPONENTS OF PROGRAM COSTS

SUBSYSTEM AND PROGRAM CATEGORIES FOR COST MODELING

Twelve categories of program cost were established; six subsystem categories: science, structure, propulsion, electrical power, communications, and guidance and control; and six support function categories: assembly and integration, test and quality assurance, launch and flight operations, ground equipment, systems analysis and engineering, and program management.

A series of definitions were evolved to assist in the assignment of line items to each of twelve categories. Figure 5 lists the definitions that were employed. More elaborate and detailed definitions were considered but found to provide no advantages. Each program and contractor used somewhat different terminaology. No definition, however detailed, is able to unambiguously classify all line items.

It was necessary in a number of cases to submit questionable line items to a panel of IITRI/AS staff for review and decision. If a clear consensus was not obtainable from the panel, attempts were made to obtain clarification from the center or contractor involved. The lack of uniform cost reporting categories in terms of subsystem and functional definitions remains one of the more difficult problems of cost analysis. It is felt that within the accuracy of pre-Phase A estimates, the assignments made in this study are satisfactory.

Figure 5: Cost Category Definitions

- Science - all instruments which perform scientific experiments but not including apparatus used primarily for other mission functions, e.g. radio transmitters which, although used in occultation and tracking experiments, are classed as communications.

- Structure - spacecraft main body structure, mechanical devices, thermal control equipment, cabling and harnesses, pyrotechnic devices, payload adapters, scan platform, atmospheric entry equipment, booms and appendages.

- Propulsion - velocity control components such as propellants, engines, tanks, feed lines and valves, pressurization equipment.

- Electrical Power - all components of main power source such as solar cells or RTG's, conditioning components such as inverters and regulators, secondary power sources such as batteries, associated electronics for control and distribution.

- Communications - all components which handle data transmission and reception, data management and storage, data encoding and decoding, command data distribution, antennas.

- Guidance and Control - all flight control components such as attitude control equipment (e.g. cold gas systems) and electronics, attitude sensors and tracking devices, control computer and sequencer, lander terminal guidance equipment. Note: if TV is used for both science and terminal guidance, it should be assigned to science.

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Figure 5: Cost Category Definitions (continued)

- Assembly and Integration - system and subsystem integration analysis, design and control, system and subsystem packaging and assembly analysis and management, mockup assembly.

- Test and Quality Assurance - spacecraft subsystem and component testing, manufacturing quality assurance and control, environmental testing, quarantine assurance and control, subsystem and component reliability analysis, testing equipment.

- Launch and Flight Operations - launch control and operations, space flight control and management, mission operations, spacecraft team command and subsystem team monitors operations and training, scientific and engineering data processing, handling and management, telecommunications and tracking data analysis, field station operations, SFOF mission particulars.

- Ground Equipment - shipping and storage container, transportation and handling equipment, propulsion loading equipment, environmental test chamber, mission operations consoles and recording equipment, computers and peripheral equipment.

- Systems Analysis and Engineering - configuration management, analysis and control, mission planning and profile analysis, trajectory analysis, electronic parts engineering, computer software and implementation.

- Program Management - project management and control, project reporting, business operations and computer, management support, safety control, science team management, task allocations.

CATEGORIZATION OF COSTS

While the total program percentage of direct labor (DL) is surprisingly uniform, there was concern that this relationship would not hold for the individual spacecraft subsystem and program support categroies which were to be independently modeled. Line items were assigned to each category and the costs for DL were recalculated as a percentage of total category cost. These results are shown in Figure 6. Again the deviations from the average are reasonable, and the average direct labor cost as 30.1 percent of the total cost is substantiated.

PROGRAM COST CATEGORY	M64	M69	M71	PIO	VL	LO	SUR
Science	29.5%	29.1%	29.1%	27.0%	26.4%	28.1%	30.9%
Structure	23.1	31.7	29.6	33.0	31.0	36.9	32.5
Propulsion	22.2	33.5	22.3	28.1	24.6	29.1	27.2
Electrical Power	26.0	30.1	30.5	30.0	32.1	30.2	32.3
Communications	29.4	33.4	31.4	27.3	27.5	29.0	31.9
Guidance & Control	29.9	26.3	31.5	28.4	33.6	28.4	29.0
Average Subtotal	27.4	30.9	32.1	28.3	29.1	28.9	30.4
Assembly & Integration	28.8	31.9	34.4	32.7	37.7	38.0	26.3
Test & Quality Assurance	25.7	22.6	31.2	34.2	37.0	36.8	35.4
Launch & Flight Operations	22.3	28.4	31.9	42.7	31.5	32.4	34.4
Ground Equipment	30.5	26.4	24.4	21.5	25.0	25.6	29.9
Systems Analysis & Engineering	--	31.7	25.6	16.7	37.2	42.5	36.5
Program Management	27.0	41.8	30.5	35.5	30.6	35.6	34.2
Average Subtotal	26.0	27.5	29.9	34.3	33.4	32.3	33.9
Average Total	27.0	29.5	29.4	30.6	31.2	30.6	32.2

Figure 6

Category Labor Cost as a Percent of Category Total Cost

LABOR HOURS AS A BASIS FOR COST MODELING

The relationship between DL costs and DL hours was examined for all programs for which both classes of data were available. Figure 7 typifies the correlation obtained on a program by program basis. Thus it was concluded that direct labor hours (DLH) could be used as an inflation-free basis for cost modeling.

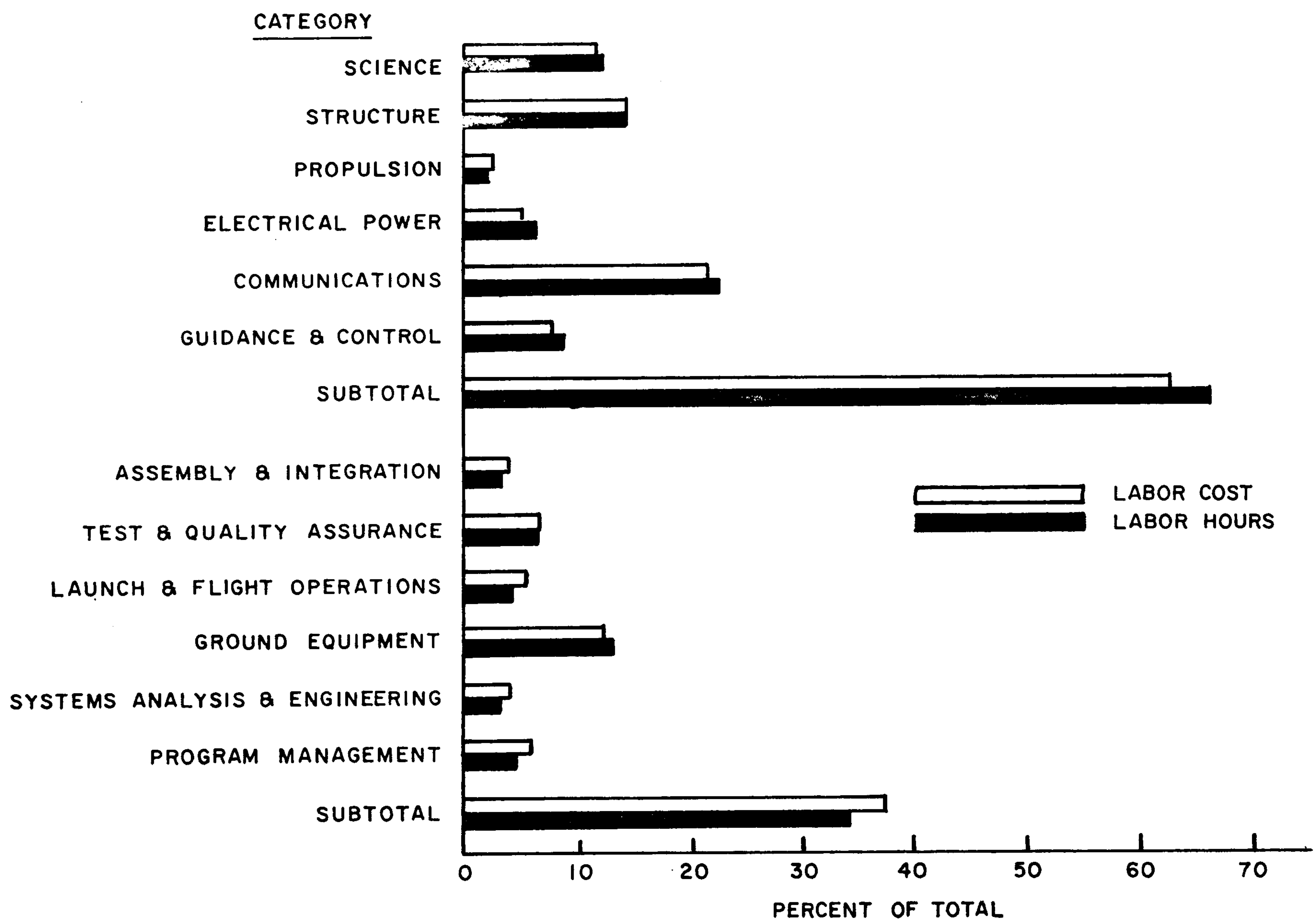


FIGURE 7. COMPARISON OF LABOR COST AND LABOR HOURS FOR MARINER 1969.

RECURRING AND NON-RECURRING COSTS

The number of flight spacecraft associated with past and current planetary programs has been small; Lunar Orbiter with five S/C and Surveyor with seven S/C represent the largest "production runs" to date. In general, there have been changes from one spacecraft to another within the same program. Nonetheless, it seems reasonable to attempt to separate recurring (R) and non-recurring (NR) costs to provide a better basis for estimating a variety of future program options.

There is a wide variation in the definition of recurring vs non-recurring costs by the space industry. For example, some contractors confine recurring costs to the production of flight subsystems while others include operational categories such as test, launch/flight, etc. Our analysis of the nature of the operational categories and their cost/time history led to a definition of ground equipment and system analysis/engineering as entirely non-recurring. Launch/flight and assembly and integration were found to be essentially recurring. All other categories were a mixture of recurring and non-recurring costs.

A study of the time history of program costs led to the conclusion that the date of completion of assembly and test of the proof test model (PTM) provided a reasonable split of costs into the two categories. This is a somewhat arbitrary definition but on the average agrees with the data supplied. Figure 8 lists the PTM dates used to classify the programs. Lunar Orbiter costs were supplied as recurring and non-recurring based on the contractor definition. Since a time history was not available these data were used as supplied. During the detailed modeling (section 3) it was found that total costs with no distinction between non-recurring and recurring costs provided the best basis for operational support category models.

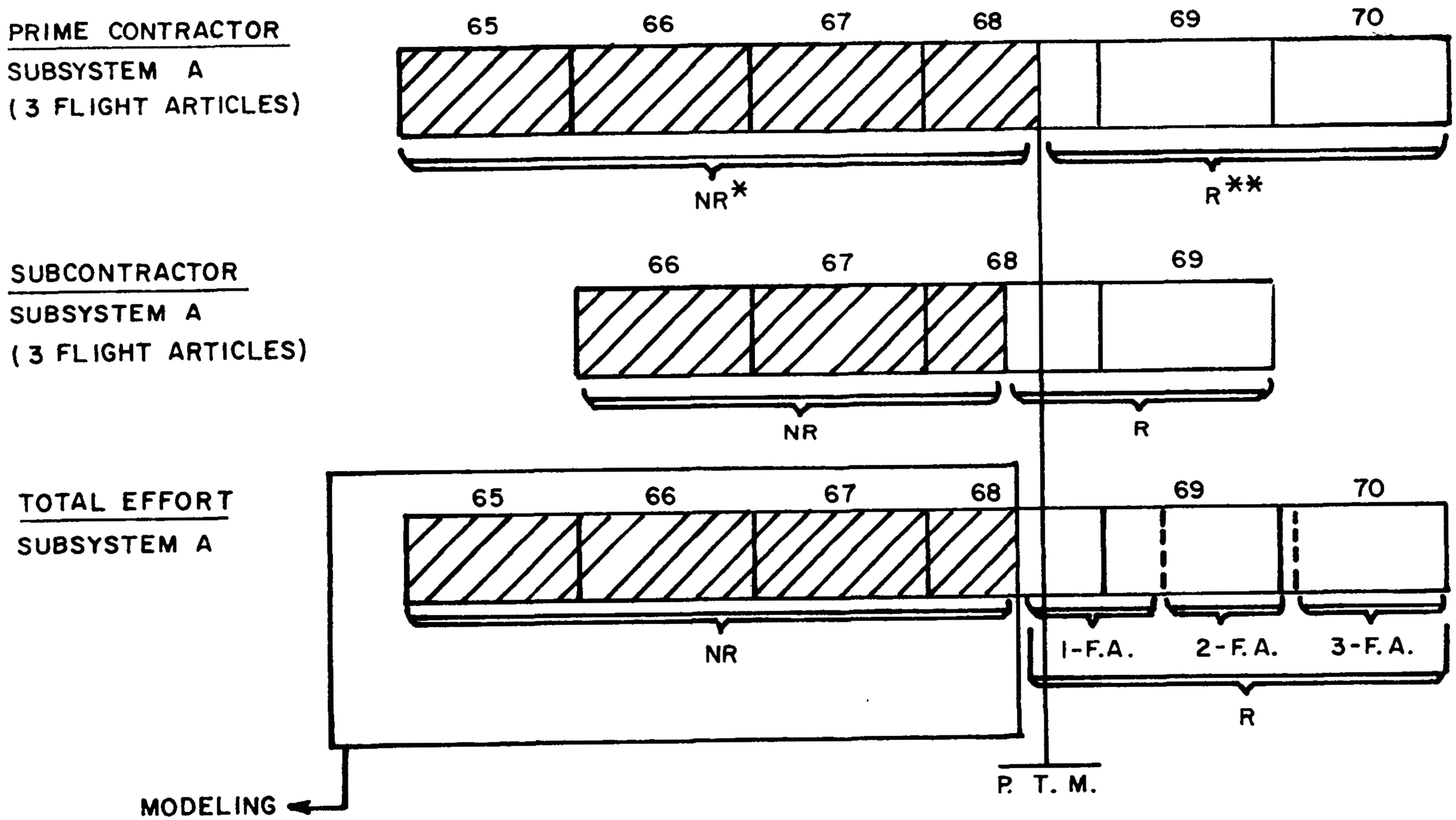
Figure 8

Program Dates for Non-Recurring and Recurring Determination

PROGRAM	PROOF TEST MODEL ASSEMBLY AND TEST COMPLETION DATE	FIRST FLIGHT DATE
Pioneer	June 71	March 72
Viking	June 74	March 75
Surveyor	October 63	May 66
Mariner 64	May 64	November 64
Mariner 69	March 68	February 69
Mariner 71	October 70	May 71

RECURRING AND NON-RECURRING COSTS

Further analysis of the contractor/subcontractor relationship showed that subcontractor preceeded the PTM date by approximately three months. This is illustrated in Figure 9. This definition was used in partitioning all subcontractor costs.



*NR
NON-RECURRING DIRECT LABOR HOURS

**R
RECURRING DIRECT LABOR HOURS

FIGURE 9. CONTRACTOR / SUBCONTRACTOR LABOR ANALYSIS

RECURRING COSTS

Using the PTM dates, labor hours were apportioned as non-recurring and recurring. The recurring costs per unit flight article were then calculated as a fraction of non-recurring costs. These data are shown in Figure 10. There is nominal consistency within S/C subsystem categories and the average fraction for each category was used to estimate recurring labor hours from the non-recurring labor hours.

Figure 10: Recurring DLH Fractions per Flight Spacecraft for Subsystem Categories

	Science	Structure	Propulsion	Electrical Power	Communications	Guidance & Control
M64	.235	.107	.137	.137	.188	.121
M69	.223	.099	.147	.164	.202	.133
M71	.171	.095	.152	.159	.150	.119
PIO	.168	.110	.107	.146	.210	.090
VO	.168	.086	.150	.150	.181	.140
VL	.128	.095	.211	.174	.172	.139
LO	.060	.097	.140	.150	.180	.110
SU	.099	.080	.095	.150	.164	.087

FINAL ALLOCATION OF PROGRAM COSTS

The allocation and categorization of costs for the eight programs is summarized in Figures 11 through 18. These data were the inputs to all modeling studies and error analyses which were performed.

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	7319	458.4	311.7	146.7
Structure	10226	454.0	374.2	79.8
Propulsion	1280	59.0	46.3	12.7
Electrical Power	4839	285.6	224.1	61.5
Communications	10847	723.4	525.7	197.7
Guidance & Control	8672	554.4	446.3	108.1
Subtotal	43183	2534.8	1928.3	606.5
Operations & Support				
Assembly & Integration	4089	226.7		
Test & Quality Assurance	6654	374.6		
Launch & Flight Ops.	10736	480.2		
Ground Equipment	9029	600.8		
Systems Analysis & Eng.	-----	-----		
Program Management	4413	217.8		
Subtotal	34921	1900.1		
Total Base Cost	78104	4434.9		
Fee and other unassignable costs	4030			
Total Actual Cost	82134			

Figure 11: Cost and Labor Hour Allocations for Mariner 64

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	14457	800.1	553.3	246.8
Structure	16420	937.2	781.7	155.5
Propulsion	2516	150.9	116.7	34.2
Electrical Power	6129	418.4	315.2	103.2
Communications	23529	1468.7	1045.5	423.2
Guidance & Control	10501	563.1	444.6	118.5
Subtotal	73552	4338.4	3257.0	1081.4
Operations & Support				
Assembly & Integration	4377	207.0		
Test & Quality Assurance	11193	423.5		
Launch & Flight Ops.	6663	265.3		
Ground Equipment	17200	846.6		
Systems Analysis Eng.	4373	210.0		
Program Management	5694	290.1		
Subtotal	49500	2242.5		
Total Base Cost	122052	6580.9		
Fee and other unassignable costs	3190			
Total Actual Cost	126242			

Figure 12: Cost and Labor Hour Allocations for Mariner 69

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	13970	684.4	510.0	174.4
Structure	6341	254.8	214.1	40.7
Propulsion	12857	451.1	346.2	104.9
Electrical Power	4913	263.4	199.9	63.5
Communications	15875	908.5	699.2	209.3
Guidance & Control	10855	502.8	406.3	96.5
Subtotal	64811	3065.0	2375.7	689.3
Operations & Support				
Assembly & Integration	3932	204.4		
Test & Quality Assurance	12232	572.6		
Launch & Flight Ops.	15917	670.2		
Ground Equipment	9049	311.4		
Systems Analysis & Eng.	5353	217.8		
Program Management	9353	370.5		
Subtotal	55836	2346.9		
Total Base Cost	120647	5411.9		
Fee and other unassignable costs	16974			
Total Actual Cost	137621			

Figure 13: Cost and Labor Hour Allocations for Mariner 71

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	16347	556.6	416.9	139.7
Structure	5824	182.0	149.1	32.9
Propulsion	3303	150.1	123.6	26.5
Electrical Power	6054	360.9	279.2	81.7
Communications	10266	461.6	325.1	136.5
Guidance & Control	2919	101.4	85.9	15.5
Subtotal	44713	1812.6	1379.8	432.8
Operations & Support				
Assembly & Integration	1265	69.4		
Test & Quality Assurance	9712	519.6		
Launch & Flight Ops.	20511	890.4		
Ground Equipment	2783	96.9		
Systems Analysis & Eng.	578	6.6		
Program Management	4295	190.5		
Subtotal	39144	1773.4		
Total Base Cost	83858	3586.0		
Fee and other unassignable costs	6115			
Total Actual Cost	89973			

Figure 14: Cost and Labor Hour Allocations for Pioneer F&G

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	23163	926.5	693.9	232.6
Structure	30750	1230.0	1050.0	180.0
Propulsion	15760	630.4	484.9	145.5
Electrical Power	11700	468.0	360.1	107.9
Communications	41338	1653.5	1214.0	439.5
Guidance & Control	19250	770.0	602.0	168.0
Subtotal	141961	5678.4	4404.9	1273.5
Operations & Support				
Assembly & Integration	14093	563.7		
Test & Quality Assurance	21813	872.5		
Launch & Flight Ops.	24898	995.9		
Ground Equipment	8850	354.0		
Systems Analysis & Eng.	20735	829.4		
Program Management	10520	420.8		
Subtotal	100909	4036.3		
Total Base Cost	242870	9714.7		
Fee and other unassignable costs	------			
Total Actual Cost	242870			

Figure 15: Cost and Labor Hour Allocations for Viking Orbiter

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	49276	1757.8	1399.2	358.6
Structure	33367	1482.7	1246.1	236.6
Propulsion	9115	322.8	227.1	95.7
Electrical Power	6976	340.9	252.8	88.1
Communications	36255	1434.0	1067.4	366.6
Guidance & Control	32033	1516.7	1185.9	330.8
Subtotal	167022	6854.9	5378.5	1476.4
Operations & Support				
Assembly & Integration	8467	407.2		
Test & Quality Assurance	58686	3063.3		
Launch & Flight Ops.	18062	776.1		
Ground Equipment	22247	895.6		
Systems Analysis & Eng.	20521	1083.1		
Program Management	32919	1779.8		
Subtotal	160902	8005.1		
Total Base Cost	327924	14860.0		
Fee and other unassignable costs	25310			
Total Actual Cost	353234			

Figure 16: Cost and Labor Hour Allocations for Viking Lander

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	29814	1901.1	1463.8	437.3
Structure	2490	193.0	130.1	62.9
Propulsion	4486	244.2	143.6	100.6
Electrical Power	5173	322.1	184.1	138.0
Communications	14749	815.6	429.3	386.3
Guidance & Control	12379	759.8	490.2	269.6
Subtotal	69091	4235.8	2841.1	1394.7
Operations & Support				
Assembly & Integration	6009	459.0		
Test & Quality Assurance	11103	892.7		
Launch & Flight Ops.	14082	759.4		
Ground Equipment	26326	1592.2		
Systems Analysis & Eng.	3800	277.0		
Program Management	4123	291.9		
Subtotal	65443	4272.2		
Total Base Cost	134534	8508.0		
Fee and other unassignable costs	8693			
Total Actual Cost	143227			

Figure 17: Cost and Labor Hour Allocations for Lunar Orbiter

CATEGORY	Cost in 1000 $	DLH in 1000 hours	NR in 1000 hours	R in 1000 hours
Spacecraft Subsystems				
Science	34948	2107.5	1243.4	864.1
Structure	39463	2594.6	1664.0	930.6
Propulsion	43687	1169.5	701.2	468.3
Electrical Power	10512	688.0	335.6	352.4
Communications	30185	1765.9	822.0	943.9
Guidance & Control	34226	2193.7	1364.4	829.3
Subtotal	193021	10519.2	6130.6	4388.6
Operations & Support				
Assembly & Integration	12887	710.1		
Test & Quality Assurance	67868	5066.2		
Launch & Flight Ops.	38411	2486.3		
Ground Equipment	41827	2529.9		
Systems Analysis & Eng.	36860	2628.9		
Program Management	32321	2129.0		
Subtotal	230174	15550.4		
Total Base Cost	423195	26069.6		
Fee and other unassignable costs	40292			
Total Actual Cost	463487			

Figure 18: Cost and Labor Hour Allocations for Surveyor

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ADDITIONAL COSTS FOR RTG'S

The Atomic Energy Commission has been funded separately for the development and fabrication of RTG's. These costs are in addition to the NASA expenditures incurred in integrating the RTG into the S/C system. Figure 19 presents data provided by the A.E.C. for RTG development and unit costs. The data was provided in dollar form and was converted to direct labor hours for modeling purposes. The formula for hourly labor rate for the median year of program development was used in the conversion.

Figure 19: AEC Costs for RTG's

Program	RTG Development Cost in $1000	NR in 1000 hours	RTG Unit Cost in $1000	R in 1000 hour
Transit	15900	1109.3	850	59.3
Nimbus	12900	662.7	650	33.4
Pioneer	10400	489.8	700	33.0
Viking	7550	315.0	715	29.8
TOPS-GT	15000	579.2	2615	101.0

DETERMINATION OF DIRECT LABOR RATE FOR CONVERSION OF PREDICTED DLH TO DIRECT LABOR COST

Figure 20 can be used to determine inflated dollar rates for converting labor manhours into labor dollars. Average direct labor rate is plotted against calendar year for the period 1960-1975. The broken sloping line represents the growth rate of wages of production workers as compiled by the Bureau of Labor Statistics from 1960 to 1970, which coincides with the growth rate curve found by regression analysis of the NASA program data. Average wages paid out during each of the seven programs are represented by horizontal lines at the proper wage level. The dots represent the points at which approximately 50 percent of the program funds had been expended.

The growth line can be used to determine the wages for a cost estimate, provided the median date of program funding is known. This date is located on the abcissa and the point directly above it on the dotted line represents the correct wage rate on the ordinate for converting hours to dollars. Coupled with the direct labor manhour estimate the direct labor cost can be quickly determined.

The regression equation for the Direct Labor Rate is

$$\ln(\text{WAGE}) = 0.044y - 1.245$$

where

ln = natural logarithm
WAGE = hourly wage rate in dollars/hour
y = calendar year of median cumulative expenditure minus 1900

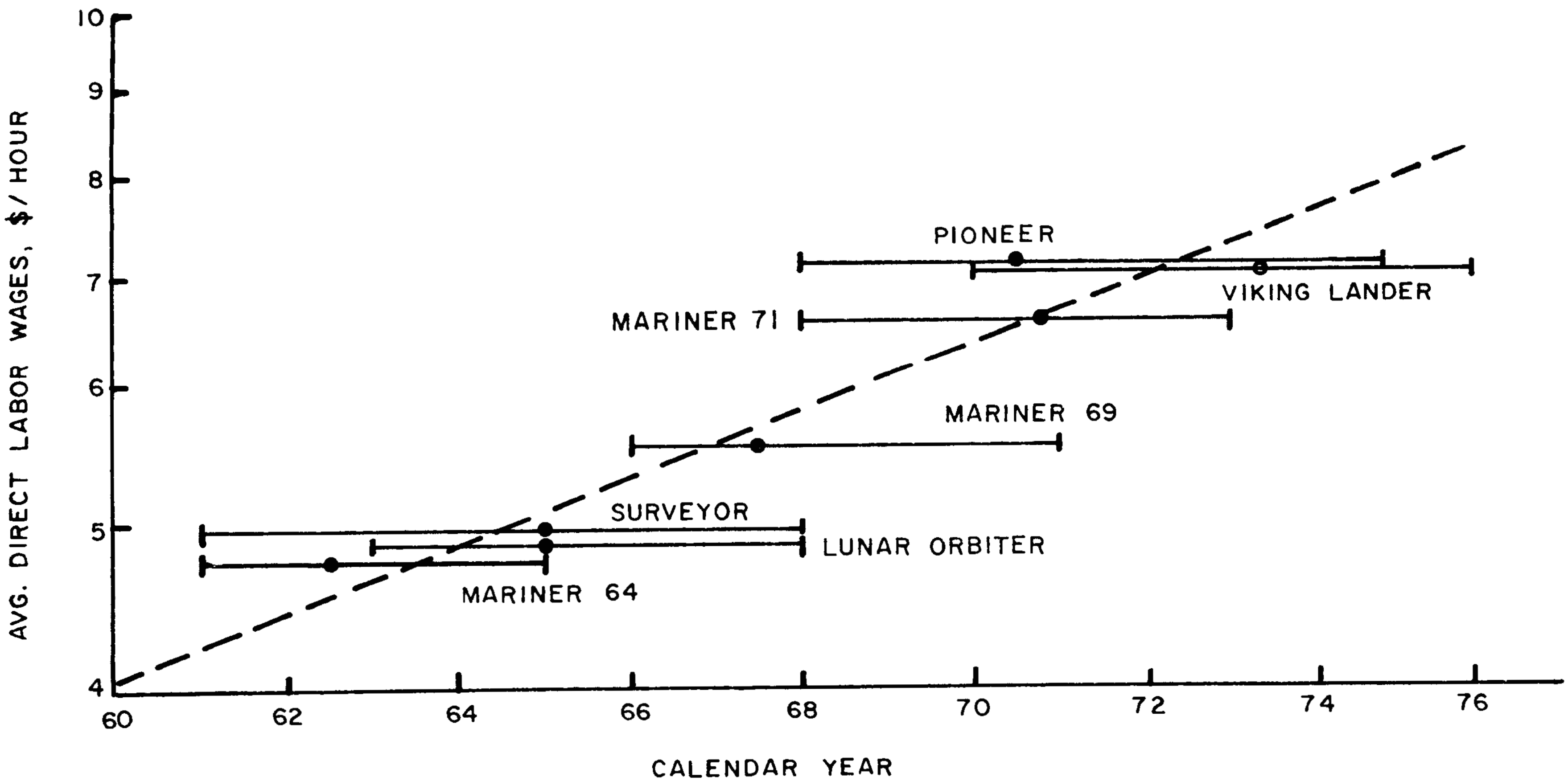

FIGURE 20. COMPARISON OF AVERAGE DIRECT LABOR RATES OF PROGRAMS.

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3. SPACECRAFT SUBSYSTEM AND SUPPORT CATEGORY MODELING

COST MODEL OUTLINE

Figure 21 is a flow diagram of the use of the cost model in forecasting. The boxes in the upper left involve the mission dependent information. Scaling laws, physical and mathematical relationships, and synthesis guidelines, provide the basic estimate of manhours. The remainder of the model deals with converting the basic cost element, direct labor manhours, into cost. This requires two additional steps. First, the average pay scale ($/hrs) must be determined for the period of the program. If desired, the selected pay scale could include inflation between the time of the estimate and program execution. The final step involves converting direct labor cost into total program cost. This study determined, with surprising consistency, that direct labor cost of unmanned lunar/planetary programs comprises 30 percent of total program cost. Hence, total program cost can be determined by dividing direct labor cost by its fraction of total cost. The relationship used throughout this study therefore is:

$$\text{Total Program Dollars} = \frac{\text{Direct Labor Hours x Average Hourly Rate}}{.3} .$$

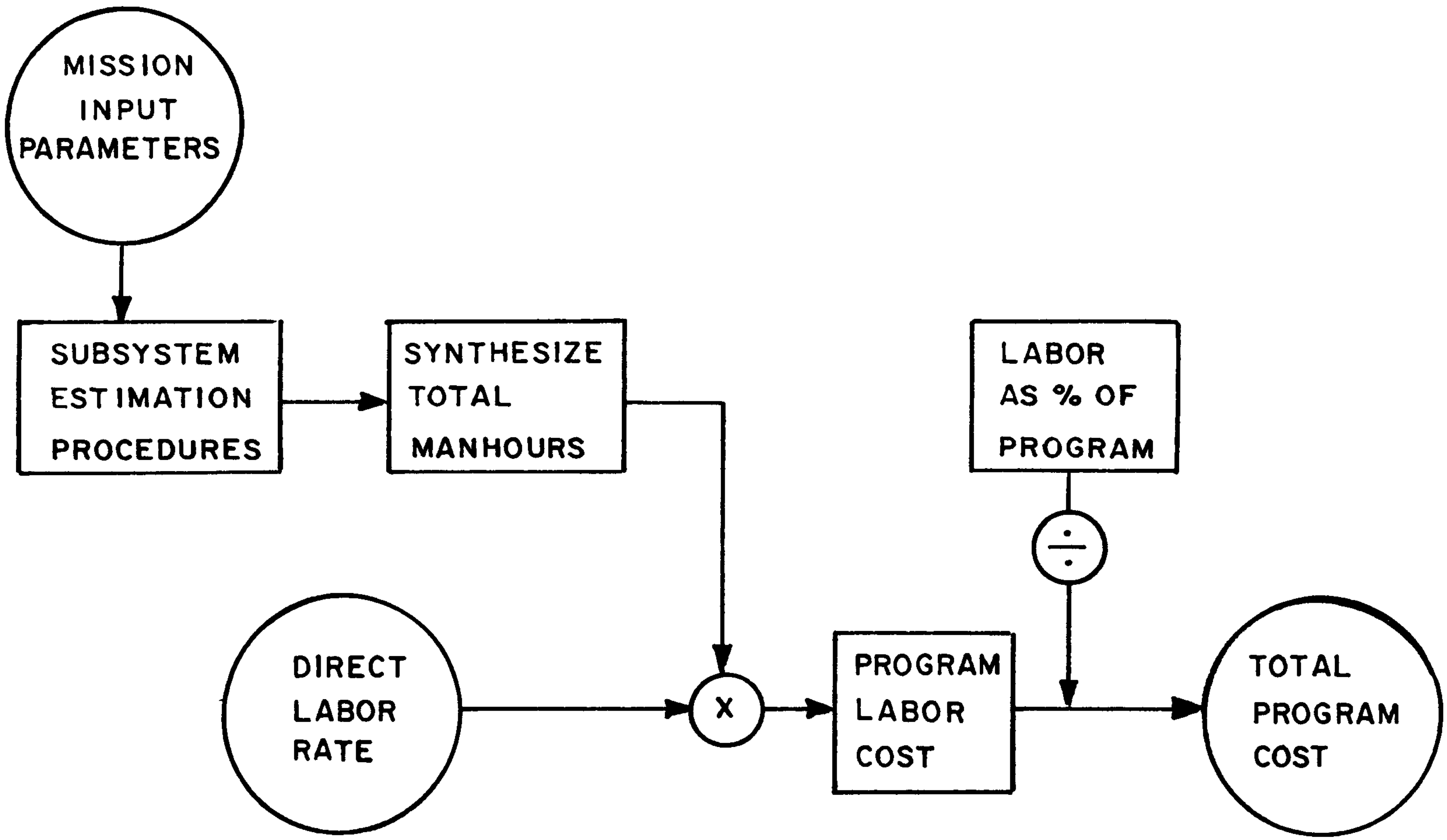

FIGURE 21.

COST MODEL SCHEMATIC

MODEL PARAMETERS

The purpose of this study is to develop cost models for the estimation of future Planetary mission costs in the early planning stage. The program and spacecraft definitions available from pre-Phase A planning studies are limited in their detail and depth. Thus, the cost related parameters considered in this study were limited to those for which pre-Phase A information would be available. Figure 22 lists those which were considered for the various individual models.

Figure 22: Parameters Considered for Modeling

SUBSYSTEM CATEGORIES		
<u>Science</u> total science weight, number of instruments, science power requirements, data rate, data storage requirements, number of investigators, maximum resolution, mission duration, encounter sequence time.	<u>Structure</u> structure weight, thermal control weight, number and weight of mechanical devices, cabling weight, pyrotechnics weight, launch weight, dry weight, type of spacecraft.	<u>Propulsion</u> incremental velocity capability, spacecraft dry weight, propulsion weight, specific impulse, total impulse, number of ignitions, burn time, type of propellant, thrust.
<u>Electrical Power</u> maximum power, power at encounter, subsystem weight, type of power source, conditioning weight, solar distance at encounter.	<u>Communications</u> Earth-target distance at encounter, communications equipment weight, mission duration, science weight, maximum data rate, transmitter output power, antenna gain, storage capacity.	<u>Guidance and Control</u> type of stabilization, launch weight, dry weight, computer capacity, G & C subsystem weight, number of maneuvers, mission duration.
SUPPORT CATEGORIES		
Many of the above parameters program duration, program initiation date, number of flight spacecraft, first launch date, number of launches, percent of spacecraft development costs, percent of total spacecraft costs, percent of cost based on subtotal of previously estimated categories.		

MODELING PROCEDURES

An initial screening of parameters was done by graphical analysis. The values of spacecraft and program parameters were plotted against category costs linearly and logarithmically to identify any simple correlations which might exist. As a second step, multivariate models were developed using the most likely variables from the initial screening and/or the seemingly most logical parameters. These multivariate models were then fitted to the cost data using a series of computerized linear regression analyses. Parameters were dropped, changed or added based upon the individual and combined correlation coefficients. Figures 23 and 24 contain the parameter values used to test and develop the models.

Figure 23: Spacecraft Subsystem Weights, In Pounds

PROGRAM / SUBSYSTEM	M64	M69	M71	PIO	VO	VL	LO	SUR
Science	40.8	129.8	149.9	66.3	145.2	91.2	143.5	88.4
Structure	158.7	331.8	476.3	157.4	759.5 a)	1217.8 b)	155.2	299.0
Propulsion (Dry)	27.3	19.7	216.1	24.2	371.2	179.1	62.8	219.5
Electrical Power	150.0	116.4	165.4	47.8	304.6	158.4	91.0	73.4
RTG's	-----	-----	-----	120.0	-----	70.7	-----	-----
Communications	103.0	133.5	127.9	76.8	215.3 c)	169.1 c)	61.2	63.0
Guidance & Control	74.7	83.2	88.2	12.6	139.1	139.1	72.5	92.1
Dry Weight	554.5	814.4	1223.8	505.1	1924.6	2025.4	586.2	835.4
Propellant	22.7	23.1	1049.6	56.7	3120.8	335.7	266.8	1432.0
Total Weight	577.2	837.5	2273.4	561.8	5055.7	2361.1	853.0	2267.4

a) Includes VO-VL adapter

b) Includes aeroshell, parachute and bioshield

c) Includes relay communications equipment

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Figure 24: Program and Mission Parameters

PARAMETER / PROGRAM	Ns	PPL	P_T (watts)	P_o (watts)	P_U (watts)	I_{SP} $\left(\frac{lb_f\text{-sec}}{lb_m}\right)$	I_{TOT} (lb_f-sec)	CT (days)	EPT (days)	T (years)
M64	2	200	10	700	----	232	5266.4	533	30	4.25
M69	2	945	20	860	----	230	5313.0	166	6	8.58
M71	2	832	20	860	----	283	279036.8	352	180	10.83
PIO	2	462	8	150	37.5	215	12190.5	1300	70	11.58
VO	2	1182	20	1000	----	283	883186.4	381	180	15.0
VL	2	512	30	70	35	235	78889.5	381	280	15.0
LO	5	9880	10	448	----	276	73636.8	144	104	6.0
SUR	7	----	10	90	----	289	413848.0	161	117	5.83

SELECTION OF LABOR ESTIMATING RELATIONSHIPS (LER)

There are a variety of multivariable models that can be developed to fit a given set of data. A number of rules and guidelines were used to select the final models contained in this report. The primary selection was, of course, based on a high correlation coefficient, r. Models derived from seven or more program data points have a probability of less than 0.05 (1 in 20) of being a chance correlation if $r \geq 0.754$. Where several models had only nominal differences in correlation, a selection was made on the basis of minimum number of variables and ease of computation. As an example, a choice between the two LER's in Figure 25 was made for the communications subsystem with Model 2 clearly being preferable.

It was also decided that any individual data point which significantly exceeded two times the RMS error* associated with its particular category would not be used in the derivation of the LER for that category. This resulted in the decision to completely eliminate Surveyor since there was only one category (A & I) in which the error was in bounds. Viking Lander was not used in the determination of the Science and Program Management models for the same reason.

The models developed and the comparison with program data follow.

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* RMS error in this context is defined as

$$\sqrt{\frac{\sum^{n} d^2}{n}}$$

where

d is the difference between actual and predicted DLH,
n is number of data points in the regression analysis.

Model 1

$$NR_c = 3.9\ (P_T^{0.433})\ (WT_c^{0.928})\ (R_c^{-0.051})\ (T^{-0.085})$$

$$r = 0.985$$

Model 2

$$NR_c = 16.9\ P_T + 4.2\ WT_c - 37.1$$

$$r = 0.976$$

where NR_c = non-recurring labor hours for communications

P_T = peak transmitter output power in watts

WT_c = weight of communication subsystem in pounds

R_c = maximum communication distance in AU

T = year of launch minus 1960

Figure 25

Example Selection Of Communications LER

SCIENCE

The model developed for the science system is a two variable linear equation based on the resolution of the imaging experiment (pixels per line) and the total weight of the science instruments. This provides a good fit to all programs except Viking which had such a large error that it was not included in the regression fit.

This is apparently due to the large costs associated with the Viking biological experiments which do not substantially increase the weight of the science package. A number of other models were tried in an effort to fit the Viking data but none were successful. Further effort should be devoted to improving the science model. The comparison of actual and predicted labor are given in Figure 26.

$$NR_S = 0.1\ PPL + 1.8\ WT_S + 234.2 \qquad r = 0.9939$$

$$R_S = 0.182\ NR_S\ (N_S) \qquad r = 0.9442$$

Figure 26: Science Category Prediction and Error

Program	Actual NR_S	Predicted NR_S	Actual R_S	Predicted R_S	Actual DLH_S	Predicted DLH_S	% Error
M64	311.7	327.6	146.7	119.2	458.4	446.8	- 2.5
M69	553.8	562.3	246.8	204.7	800.1	767.0	- 4.1
M71	510.0	587.2	174.4	213.7	684.4	800.9	17.0
PIO	416.9	399.7	139.7	145.5	556.6	545.2	- 2.0
VO	693.9	613.8	232.6	223.4	926.5	837.2	- 9.6
VL*	1399.2	450.0	358.6	163.8	1757.8	613.8	-65.1
LO**	1463.8	1480.5	437.3	1347.3	1901.1	2827.8	48.7
SU*	1243.4	453.3	864.1	577.5	2107.5	1030.8	-51.1

* not used in non-recurring LER derivation

** not used in recurring LER derivation

STRUCTURE

The LER developed for the structure subsystem is a linear fit based on the structure subsystem weight. This includes the weight of thermal control equipment, cabling, booms, pyrotechnic and mechanical devices and, if the spacecraft uses one, the scan platform. The aeroshell and bioshield are included for Viking Lander, and the VO-VL adapter is included for Viking Orbiter.

Figure 27 shows actual and predicted values of DLH for the structure subsystem. The predictions are only in generally fair agreement with the actual values. The major variance occurs in the M71 program.

$$NR_{ST} = 1.18\ WT_{ST} + 50.1 \qquad r = 0.8971$$

$$R_{ST} = 0.098\ NR_{ST}\ (N_S) \qquad r = 0.892$$

Figure 27: Structure Category Prediction and Error

Program	Actual NR_{ST}	Predicted NT_{ST}	Actual R_{ST}	Predicted R_{ST}	Actual DLH_{ST}	Predicted DLH_{ST}	% Error
M64	374.2	237.4	79.8	46.5	454.0	283.9	- 37.5
M69	781.7	441.6	155.5	86.6	937.2	528.2	- 43.6
M71	214.1	612.1	40.7	120.0	254.8	732.1	187.3
PIO	149.1	235.8	32.9	46.2	182.0	282.0	55.0
VO	1050.0	946.3	180.0	185.5	1230.0	1131.8	- 8.0
VL	1246.1	1487.1	236.6	291.5	1482.7	1778.6	20.0
LO	130.1	233.2	62.9	114.3	193.0	347.5	80.0
SU*	1664.0	402.9	930.6	276.4	2594.6	679.3	- 73.8

* not used in model derivation

PROPULSION

The LER for predicting non-recurring direct labor hours for the propulsion subsystem was found to be a power law function of the total impulse of the engine. Total impulse is defined as specific impulse times propellant weight, or alternately, total burn time times vacuum thrust. For the planetary programs, all engines used either the monopropellant N_2H_4 or the bipropellant N_2O_4/MMH whereas Lunar Orbiter used N_2O_4/A-50. The engines for M64, M69 and PIO were used for midcourse correction only while those for other programs are used primarily for orbit insertion or terminal landing. Obviously, these latter engines require more propellant (or equivalently, a longer burning time) and will cost more. The derived and program data are given in Figure 28. The Lunar Orbiter propulsion system was partially supported by DOD and those costs were not available. This may explain part of the overestimate.

$$NR_P = 3.51\ (I_T)^{.359} \qquad r = 0.9175$$

$$R_P = 0.149\ NR_P\ (N_S) \qquad r = 0.972$$

Figure 28: Liquid Propulsion Category Prediction and Error

Program	Actual NR_P	Predicted NR_P	Actual R_P	Predicted R_P	Actual DLH_P	Predicted DLH_P	% Error
M64	46.3	76.1	12.7	22.7	59.0	98.8	67.4
M69	116.7	76.3	34.2	22.7	150.9	99.0	-34.4
M71	346.0	323.6	104.9	96.4	451.1	420.0	- 6.9
PIO	123.6	102.8	26.5	30.6	150.1	133.4	-11.1
VO	484.9	478.6	145.5	142.6	630.4	621.2	- 1.5
VL	227.1	201.1	95.7	59.9	322.8	261.0	-19.1
LO	143.6	196.2	100.6	146.2	244.2	342.4	40.2
SU	701.2	364.5	468.3	380.2	1169.5	744.8	-36.3

* not used in model derivation

ELECTRICAL POWER

The model developed for the electrical power subsystem is a multiple linear relationship based on total power supplied to the spacecraft from the power conditioning equipment and the weight of the power subsystem including weight of all conditioning equipment and auxiliary power supplies such as batteries.

Separate estimating relationships have been developed for power subsystems whose primary energy source is solar energy conversion and those using radioisotope thermoelectric energy conversion. For the latter case, the model has two parts: one for the power conditioning and auxiliary power equipment and the second for the radioisotope thermoelectric generators (RTG). The expenditure for RTG's is assumed to be an additional cost to the program, and as such is modeled separately.

The LER for solar power subsystems includes the cost of the solar arrays. The power is that generated at 1 A.U.

The LER for RTG powered subsystems does not include the cost of the RTG's, and the weight term does not include the RTG weights. The power is the total beginning-of-life power supplied by the subsystem. The results are given in Figure 29.

$$NR_{EPS} = 0.21\ P_o + .2\ WT_{EPS} + 55.3 \qquad r = 0.830$$

$$NR_{EPR} = 1.57\ P_o + 0.9\ WT_{EPR} \qquad r = 1.00$$

The recurring DLH relationship is used for either solar power or RTG power.

$$R_{EP} = 0.154\ NR_{EP}\ (N_S) \qquad r = 0.955$$

Figure 29: Electrical Power Category Prediction and Error

Program	Actual NR_{EP}	Predicted NR_{EP}	Actual R_{EP}	Predicted R_{EP}	Actual DLH_{EP}	Predicted DLH_{EP}	% Error
M64	224.1	236.8	61.5	72.9	285.6	309.7	8.4
M69	315.2	262.7	103.2	80.9	418.4	343.6	-17.9
M71	199.9	273.9	63.5	84.4	263.4	358.3	36.0
PIO	279.2	278.5	81.7	85.8	360.9	364.3	0.9
VO	360.1	335.4	108.0	103.3	468.0	438.7	- 6.3
VL	252.8	252.5	88.1	77.8	340.9	330.3	- 3.1
LO	184.1	170.3	138.0	131.1	322.1	301.4	- 6.4
SU *	335.6	91.1	352.4	98.2	688.0	189.3	-72.5

* not used in model derivation

RTG ADDITIONAL COSTS

The data for RTG costs was obtained from the Atomic Energy Commission in the form of development (non-recurring) dollars and unit (recurring) dollars. The dollar data was converted to direct labor hours assuming 30 percent total program cost for labor and the wage rate at the median year of program development.

The relationship for NASA funded RTG costs is a function of unit power at beginning-of-life and time, in years, from August 1960 to date of first flight (ln denotes natural logarithm).

Data on total number of units purchased were not available for all missions nor were total costs known in all cases. The data in Figure 30 are based on single unit data and errors are therefore not shown.

$$NR_{RTG} = 1.7\ P_U - 265.7\ \ln(T) + 1059.0 \qquad r = 0.9830$$

$$R_{RTG} = (0.6\ P_U + 0.04\ NR_{RTG} - 6.4)\ N_U \qquad r = 0.9968$$

Figure 30: RTG Cost Prediction and Error

Program	Actual NR_{RTG}	Predicted NR_{RTG}	Actual R_{RTG}	Predicted R_{RTG}
Nimbus	662.7	526.6	33.4	29.7
Pioneer	489.8	470.9	33.0	34.9
Viking	315.0	397.9	29.8	30.5
Transit	1109.3	1139.6	59.3	60.2
TOPS - GT	579.2	538.8	101.0	99.2

COMMUNICATIONS

The LER for the communication subsystem is a multiple linear relation in transmitter power and communication subsystem weight. The subsystem weight as utilized here includes the weight of such items as data acquisition and storage equipment, data encoding and decoding devices and flight command equipment. Transmitter power is peak RF power transmitted. The unique relay communication equipment on the Viking Orbiter and Lander were not modeled separately, but are taken into account in the subsystem weight term.

Figure 31 presents the actual and predicted data for communications. The predicted values of DLH are in generally good agreement with the actual values, the major variances being M69 and M71.

$$NR_C = 16.9\ P_T + 4.2\ WT_C - 37.1 \qquad r = 0.9758$$

$$R_C = 0.183\ NR_C\ (N_S) \qquad r = 0.973$$

Figure 31: Communications Category Prediction and Error

Program	Actual NR_C	Predicted NR_C	Actual R_C	Predicted R_C	Actual DLH_C	Predicted DLH_C	% Error
M64	525.7	564.5	197.7	206.6	723.4	771.1	6.6
M69	1045.5	861.6	423.2	315.3	1468.7	1176.9	-19.9
M71	699.2	838.1	209.3	306.7	908.5	1144.8	26.0
PIO	325.1	420.7	136.5	154.0	461.6	574.7	24.5
VO	1214.0	1205.2	439.5	441.1	1653.5	1646.3	- 0.4
VL	1067.4	1101.6	366.6	403.2	1434.0	1504.8	4.9
LO	429.3	388.9	386.3	355.8	815.6	744.7	- 8.7
SU *	822.0	396.5	943.9	507.9	1765.9	904.4	-48.8

* not used in model derivation

GUIDANCE AND CONTROL

The LER for the guidance and control subsystem was found to be a function of total spacecraft weight and type of spacecraft and stabilization. Because of the limited number of data points, the slope of the LER developed for 3-axis stabilized flyby and orbiter spacecraft was applied to both landers and spin stabilized spacecraft. Total spacecraft weight is defined as launch weight. In the case of Viking Orbiter, it includes the weight of the Lander since the G & C of the Orbiter must account for the Lander from launch through orbit insertion. The actual and predicted labor hours are given in Figure 32.

3 - Axis Stabilized Flybys & Orbiters:

$$NR_{GC} = 428.9 \exp(4 \times 10^{-5} WT_{TOT}) \qquad r = 0.7958$$

3 - Axis Stabilized Landers:

$$NR_{GC} = 1079.0 \exp(4 \times 10^{-5} WT_{TOT})$$

Spin Stabilized Flybys & Orbiters:

$$NR_{GC} = 84.0 \exp(4 \times 10^{-5} WT_{TOT})$$

The recurring DLH relationship is used with all three of the above relationships.

$$R_{GC} = 0.122\ NR_{GC}\ (N_S) \qquad r = 0.955$$

Figure 32: Guidance and Control Category Prediction and Error

Program	Actual NR_{GC}	Predicted NR_{GC}	Actual R_{GC}	Predicted R_{GC}	Actual DLH_{GC}	Predicted DLH_{GC}	% Error
M64	446.3	438.9	108.1	106.8	554.4	554.4	- 1.6
M69	444.6	443.5	118.5	108.2	563.1	551.7	- 2.0
M71	406.3	469.7	96.5	114.6	502.8	584.3	16.2
PIO	85.9	85.9	15.5	21.0	101.4	106.9	5.4
VO	602.0	577.0	168.6	140.8	770.0	717.8	- 6.8
VL	1185.9	1185.9	330.8	289.4	1516.7	1475.3	- 2.7
LO	490.2	443.8	269.6	270.5	759.8	714.3	- 6.0
SU*	1364.4	1181.4	829.3	1008.7	2193.7	2190.1	- 0.2

* not used in model derivation

ASSEMBLY AND INTEGRATION

The model developed for assembly and integration is a multiple linear fit based on the number of flight spacecraft and the total dry weight of the spacecraft minus the weight of the structure subsystem. This last parameter, $WT_{DRY} - WT_{ST}$, is perhaps an indication of the complexity of the spacecraft to be assembled. Total dry weight as a parameter was found to have very little correlation with the data. Figure 33 presents values of predicted and actual DLH for assembly and integration. The predicted values are in only fair agreement with actual values.

$$DLH_{AI} = 64.0\ N_S + 0.4\ (WT_{DRY} - WT_{ST}) - 78.2 \qquad r = .9182$$

Figure 33: Assembly and Integration Category Prediction and Error

Program	Actual DLH_{AI}	Predicted DLH_{AI}	% Error
M64	226.7	200.2	- 11.7
M69	207.0	233.2	12.7
M71	204.4	333.9	63.4
PIO	69.4	181.9	162.1
VO	563.7	429.5	- 23.8
VL	407.2	356.7	- 12.4
LO	459.0	405.6	- 11.6
SU *	710.1	662.6	- 6.7

* not used in model derivation

TEST AND QUALITY ASSURANCE

The LER developed for test, quality assurance and reliability analysis is a double parameter fit based on the number of flight spacecraft and the weight of the structure subsystem. Figure 34 presents actual and predicted values of DLH for test and quality assurance. The predictions are in generally good agreement with the actual values. The largest variances occur in the Pioneer and Viking Orbiter programs.

$$DLH_{TQ} = N_S \ (127.5 + 8.9 \times 10^{-4} \ WT_{ST}^2) \qquad r = 0.9769$$

Figure 34

Test and Quality Assurance Category Prediction and Error

Program	Actual DLH_{TQ}	Predicted DLH_{TQ}	% Error
M64	374.6	299.8	-20.0
M69	423.5	451.0	6.5
M71	572.6	658.8	15.1
PIO	519.6	299.1	-42.4
VO	872.5	1281.8	46.9
VL	3063.3	2894.8	- 5.5
LO	892.7	744.7	-16.6
SU *	5066.2	894.4	-82.3

* not used in model derivation

LAUNCH AND FLIGHT OPERATIONS

The LER developed for launch and flight operations is a multiple linear relation based on mission time and number of launches in the total program. The mission time comprises two terms in the model. The first, CT, accounts for mission operations during interplanetary cruise. This time, in days, is counted from launch day to date of mission termination. If there is more than one spacecraft in the mission, CT is counted from launch of the first vehicle to shutdown of the final one (thus for Pioneer F & G program, CT = 1300 days). Periods of time overlap are counted only once.

The second time term, EPT, accounts for increased operations during times of encounter science (or landed science) and times of scientific data transmission, both in real time and stored/playback time.

Two launches were modeled for both the M64 and M71 programs although one flight in each program failed. The times modeled for M71 reflect allocated operations costs and times for the planned mission since at the time the model was developed, run-out costs for the remaining spacecraft mission were not available. Figure 35 shows actual and predicted values of DLH for launch and flight operations. The predicted values are in very good agreement with the actual values.

$$DLH_{LF} = 95.7\ NL + 0.4\ CT + 2.7\ EPT - 17.5 \qquad r = 0.9925$$

Figure 35

Launch and Flight Operations Category Prediction and Error

Program	Actual DLH_{LF}	Predicted DLH_{LF}	% Error
M64	480.2	471.5	- 1.8
M69	265.3	259.0	- 2.4
M71	670.2	734.4	9.6
PIO	890.4	892.4	0.2
VO	995.9	974.0	- 2.2
VL	776.1	746.8	- 3.8
LO	759.4	759.4	~ 0
SU *	2486.3	1032.7	-58.5

* not used in model derivation

GROUND EQUIPMENT

The LER developed for ground equipment is a multiple power fit based on the following parameters; structure subsystem weight, imaging experiment resolution in terms of picture elements per line, and time, in years, counted from August 1960 to the program's first launch date. Total spacecraft weight and maximum downlink data rate were examined, but proved to have very low correlation. The time parameter appears as a psuedo-inheritance factor, accounting for inheritance of certain equipment from one program to another. Figure 36 presents actual and predicted values of DLH for ground equipment. As can be seen, the predicted values are only in fair agreement with the actual values.

$$DLH_{GE} = \frac{4.29 \sqrt{PPL} \quad (WT_{ST})}{T^2} \qquad r = 0.9344$$

Figure 36

Ground Equipment Category Prediction and Error

Program	Actual DLH_{GE}	Predicted DLH_{GE}	% Error
M64	600.8	533.0	-11.3
M69	846.6	594.4	-29.8
M71	311.4	502.5	61.4
PIO	96.9	108.2	11.7
VO	354.0	497.9	40.6
VL	895.6	525.4	-41.3
LO	1592.2	1838.3	15.5
SU *	2529.9	924.4	-63.5

* not used in model derivation

SYSTEMS ANALYSIS AND ENGINEERING

The LER developed for the category defined as systems analysis and engineering is a multiple linear model based on the total dry weight of the spacecraft and a percentage of the total direct labor hours required for the ten categories previously discussed. Although the data for M64 showed no cost allocation for this category and the cost category Pioneer was relatively small, for consistency these two programs appear in the data base. Figure 37 presents actual and predicted values of DLH for systems analysis and engineering. Due to the nature of the model (a linear function with a relative large negative constant), it is possible that the LER may predict negative hours, as is the case for both M64 and Pioneer. An arbitrary solution to this is to set the DLH_{SE} to zero. The true predictions for M64 and PIO are shown in parentheses.

$$DLH_{SE} = 0.353\ WT_{DRY} + 0.067\ \left(\sum_{1}^{10} DLH \right) - 467.8 \qquad r = 0.9954$$

Figure 37

Systems Analysis and Engineering Category
Prediction and Error

Program	Actual DLH_{SE}	Predicted DLH_{SE}	% Error
M64	0.0	0.0 (-6.1)	0.0
M69	210.0	155.0	- 26.2
M71	217.8	384.3	76.4
PIO	6.6	0.0 (-55.6)	-100.0
VO	829.4	786.2	- 5.2
VL	1083.1	949.8	- 12.3
LO	277.0	343.9	24.1
SU*	2628.9	447.0	- 83.0

* not used in model derivation

PROGRAM MANAGEMENT

The LER for program management is a simple percentage of the total direct labor hours predicted for the previous eleven categories. Models based on measures of program size, complexity and duration showed little correlation with the actual DLH for program management. Again, as with the science category, the DLH_{PM} for Viking Lander did not follow the trend established by the other six programs (a 13.6% program management as compared to an average of 5.1%). Thus, Viking Lander was not used in the data base for this category. It is noted that the correlation here is slightly below the established minimum, due to including Lunar Orbiter (at 3.6% program management) in the program management data base. The LO data was used, however, to allow for the largest possible data base, and the resulting correlation accepted as is. Figure 38 shows values of actual and predicted DLH for program management. The predicted values are in reasonable agreement with the actual values.

$$DLH_{PM} = 0.051 \left(\sum_{1}^{11} DLH \right) \qquad r = 0.7334$$

Figure 38: Program Management Category Prediction and Error

Program	Actual DLH_{PM}	Predicted DLH_{PM}	% Error
M64	217.8	202.4	- 7.1
M69	290.1	263.1	- 9.3
M71	370.5	339.4	- 8.4
PIO	190.5	177.9	- 6.6
VO	420.8	477.5	13.5
VL	1779.8	583.3	-67.2
LO	291.9	477.9	63.7
SU*	2129.0	494.7	-76.8

* not used in model derivation

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4. SUMMARY RESULTS

COMBINED PROGRAM DLH ESTIMATES

The estimates from the 12 individual LER's have been combined to estimate total program costs. Figure 39 provides the program estimates of DLH together with an expression of the errors. The percent error is the difference between the combined estimate and the actual DLH divided by the actual DLH. The RMS percent error is calculated from the values of the individual subsystem percent errors for each program. The range of percentage errors is consistent with the accuracy one might expect from a pre-Phase A mission analysis. However, the relatively low errors for Pioneer and Viking Orbiter as compared with the RMS errors is indicative of the cancellation of large errors which has occured in summing individual category DLH's.

The effect of inheritance from Mariner 69 to Mariner 71 is evident. Inheritance was found to be a major factor in eight of twelve cost categories between M69 and M71. That is, for a particular category, the independent parameter for M71 (e.g. structure weight) was "larger" than the same parameter for M69 while the direct labor hour value (e.g. non-recurring DLH for structure) for M71 was less than that of M69. This produced an averaging effect in the model, tending to depress the Mariner 69 cost at the same time inflating the Mariner 71 cost.

Figure 39: Direct Labor Hours Error Analysis

Program	Actual DLH 1000 hours	Predicted DLH 1000 hours	% Error	RMS % Error
M64	4434.9	4171.6	- 5.9	23.8
M69	6580.9	5422.7	-17.6	21.8
M71	5411.9	6992.8	29.2	66.3
PIO	3586.0	3666.0	2.2	59.2
VO	9714.7	9839.9	1.3	20.2
VL	14860.0	12020.6	-19.1	31.1
LO	8505.0	9847.9	15.7	36.3
SU *	26069.6	10194.5	-60.9	

Mean RMS % Errors: 40.0

* not used in model derivation

COMBINED PROGRAM DOLLAR ESTIMATES

The ultimate test, however, is the ability of the model to predict total program cost. Figure 40 shows the predicted dollar costs versus the actual costs and the percentage error. The percentage dollar errors follow closely the percentage labor hour errors, thus establishing direct labor hours as the basis of the model. The only significant exception is Mariner 64, for which the error introduced by predicting average wage rate from Figure 20 is more noticeable.

Thus, although there are a number of areas for improvement of the individual LER's, the procedure for estimating recurring costs, and the question of "inheritance", the model developed provides an operational beginning to estimating future program costs and the component cost factors. It should be emphasized that the estimates of the individual subsystem and support functions are significantly less reliable than the combined estimates. Further LER development should reduce these errors.

Figure 40: Cost Model Prediction Error Analysis

Program	Actual Cost $1000	Predicted Cost $1000	% Error
M64	78104	62296	-20.2
M69	122052	100862	-17.4
M71	120647	150578	24.8
PIO	83858	77842	- 7.2
VO	242870	245998	1.3
VL	327924	288094	-12.2
LO	134534	164132	22.0
SU *	423195	169908	-60.0

* not used in model derivation

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5. RECOMMENDATIONS

RECOMMENDATIONS FOR FURTHER STUDY AND ANALYSIS

A basic model for predicting total program costs for unmanned lunar and planetary missions has been presented. Recommended areas to further broaden and enhance the model consist of:

- Update the current data base by obtaining the latest cost data available for Viking Lander, Viking Orbiter and Mariner 71. More up-to-date Viking Lander data may lead to reintroducing Surveyor into the data base and the development of separate LER's for lander spacecraft, where the situation warrants separate models (as in Guidance & Control).

- Broaden the data base by obtaining cost data for such programs as Mariner Venus 1967, Mariner Venus/Mercury 1973, and earlier Pioneer and Explorer programs for particle and field exploration of interplanetary and cis-lunar space. Certain of these programs, together with Mariner 71, should be useful in establishing inheritance factors or relationships.

- Begin development of LER's for outer planet atmospheric entry vehicles by obtaining the most up-to-date technical and cost data predictions for this type of program. Separation of the Mars entry development and cost data from the rest of the Viking Lander program should be useful in this respect.

- Refine the methodology for estimating recurring costs. The present averaging method has a high variance and preliminary examination of the errors for Lunar Orbiter and Surveyor indicate that the recurring costs are not directly proportional to the number of flight articles.

- Analyze the individual errors by cost category. The magnitude and sign of the errors associated with each category can provide clues to reassessment of line item data and model variables which can serve to improve the sub models. The acquisition of additional program data can serve as a valuable check to avoid "historical" data fits which have inadequate predictive capability.

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APPENDIX

COST MODEL EXAMPLE AND WORK SHEETS

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COST MODEL EXAMPLE AND WORKSHEETS

The following pages present the application of the cost model to the Mariner Venus/Mercury 1973 program. The model predicts a total program direct labor of 5159.0 thousand hours. Assuming a $7.00 per hour wage rate, based on a median expenditure year of mid 1972, this leads to a total program cost prediction of $120,377,000 which is approximately 20 percent higher than the current estimate for M73. Since this program is known to have significant inheritance, this error is not unexpected.

Following the example, blank input preparation and worksheets are provided for user application.

COST MODEL INPUT PREPARATION SHEET

For Mariner 1973 Program

Spacecraft Subsystem Weights

Science (WT_S)	168.2	pounds
Structure (WT_{ST})	460.0	
Propulsion, dry*	27.9	
Electrical Power (WT_{EP}) (do not include RTG weight)	152.1	
Communications (WT_C)	145.0	
Guidance & Control*	91.7	
Total, dry (WT_{DRY})	1044.9	
Propellant (WT_{PR})	51.8	
Total, wet (WT_{TOT})	1096.7	

* not individually required by model

COST MODEL INPUT PREPARATION SHEET

Other Parameters

Total S/C conditioned power (P_O) (solar power at 1 AU) (RTG power at BOL)	400 watts
Unit RTG power at BOL (P_U)	----- watts
Number of RTG units purchased (N_U)	-----
Transmitter peak RF output power (P_T)	20 watts
Specific impulse (I_{SP}) 230	lb_f-sec/lb_m
Total impulse ($I_T = I_{SP} \times WT_{PR}$)	11914 lb_f-sec
Imaging experiment resolution (PPL)	832 pixels per 1
Number of launches (NL)	1
Number of flight spacecraft (N_S)	1
Date of first launch (LD1) 11/3/73	
Time factor (T = LD1 - August 1960)	13.25 years
Date of mission termination (MT) 4/13/74 (shut-down of final S/C)	
Cruise time (CT = MT -LD1)	192 days
Experiment and data playback time (EPT) (total for all S/C in mission)	41 days

Hourly labor rate

WAGE = exp (0.044y - 1.25) = 7.00 dollars/hour

where: y = median year of program funding minus 1900

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COST MODEL WORK SHEET (1 of 3)

For Mariner 1973 Program

Science

$NR_S = 0.1\ PPL + 1.8\ WT_S + 234.2 =$	620.2	
$R_S = 0.182\ NR_S\ (N_S) =$	112.9	
$DLH_S = NR_S + R_S$		733.1

Structure

$NR_{ST} = 1.18\ WT_{ST} + 50.1 =$	592.9	
$R_{ST} = 0.098\ NR_{ST}\ (N_S) =$	58.1	
$DLH_{ST} = NR_{ST} + R_{ST} =$		935.0

Propulsion

$NR_P = 3.51\ (I_T)^{.359} =$	102.0	
$R_P = 0.149\ NR_P\ (N_S) =$	15.2	
$DLH_P = NR_P + R_P =$		117.2

Electrical Power

Solar: $NR_{EP} = 0.21\ P_0 + 0.23\ WT_{EP} + 55.3 =$	174.3	
RTG: $NR_{EP} = 1.57\ P_0 + 0.9\ WT_{EP} =$	------	
$R_{EP} = 0.154\ NR_{EP}\ (N_S) =$	26.8	
$DLH = NR_{EP} + R_{EP} =$		201.1

Communications

$NR_C = 16.9\ P_T + 4.2\ WT_C - 37.1$	=	909.9	
$R_C = 0.183\ NR_C\ (N_S)$	=	166.5	
$DLH_C = NR_C + R_C$	=		1076.4

Guidance & Control

3-Axis Flyby or Orbiter:

$NR_{GC} = 428.9\ \exp\ (4 \times 10^{-5}\ WT_{TOT})$ = 448.1

3-Axis Lander:

$NR_{GC} = 1079.0\ \exp\ (4 \times 10^{-5} WT_{TOT})$ = ------

Spin Flyby or Orbiter:

$NR_{GC} = 84.0\ \exp\ (4 \times 10^{-5}\ WT_{TOT})$ = ------

$R_{GC} = 0.122\ NR_{GC}\ (N_S)$ = 56.7

$DLH_{GC} = NR_{GC} + R_{GC}$ = 504.9

Assembly & Integration

$DLH_{AI} = 64.0\ N_S + 0.4\ (WT_{DRY} - WT_{ST})$ = 219.8

Test & Quality Assurance

$DLH_{TQ} = N_S * (127.5 + 8.9 \times 10^{-4}\ WT_{ST}{}^2)$ = 315.8

Launch & Flight Operations

$DLH_{LF} = 95.7\ N_L + 0.4\ CT + 2.7\ EPT - 17.5$ = 265.7

Ground Equipment

$$DLH_{GE} = \frac{4.29\ PPL\ (WT_{ST})}{T^2}$$ = 324.2

Subtotal

$\sum_{1}^{10} DLH =$ 4693.2

COST MODEL WORKSHEET (3 of 3)

Systems Analysis & Engineering

$$DLH_{SE} = 0.353\ WT_{DRY} + 0.067\ \left(\sum^{10} DLH\right) - 467.8 = \underline{\underline{215.5}}$$

$$(\text{if } DLH_{SE} < 0.0, \text{ set } DLH_{SE} = 0.0)$$

Subtotal

$$\sum^{11} DLH = \underline{4908.7}$$

Program Management

$$DLH_{PM} = 0.051\ \left(\sum^{11} DLH\right) = \underline{\underline{250.3}}$$

Total Program Direct Labor Hours

DLH_{TOT} = 5159.0 thousand hours

RTG's

no

yes

A.E.C. Costs

$$NR_{RTG} = 1.7\ P_U - 265.7\ \ln T + 1059.0 = \_\_\_\_$$

$$R_{RTG} = (0.6\ P_U + 0.04\ NR_{RTG} - 5.9) N_U = \_\_\_\_$$

Adjusted Total DLH

$$DLH_{TOT} = DLH_{TOT} + NR_{RTG} + R_{RTG} = \_\_\_\_$$

Total Program Cost

$$COST = \frac{DLH_{TOT}\ (WAGE)}{0.3} = \$\ 120{,}377\ (\times 1000)$$

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COST MODEL INPUT PREPARATION SHEET

For ______________________ Program

Spacecraft Subsystem Weights

Science (WT_S)	________	pounds
Structure (WT_{ST})	________	
Propulsion, dry*	________	
Electrical Power (WT_{EP}) (do not include RTG weight)	________	
Communications (WT_C)	________	
Guidance & Control*	________	
Total, dry (WT_{DRY})	________	
Propellant (WT_{PR})	________	
Total, wet (WT_{TOT})	________	

* not individually required by model

COST MODEL INPUT PREPARATION SHEET

Other Parameters

Total S/C conditioned power (P_0) _______ watts
(solar power at 1 AU)
(RTG power at BOL)

Unit RTG power at BOL (P_U) _______ watts
Number of RTG units purchased (N_U) _______
Transmitter peak RF output power (P_T) _______ watts

Specific impulse (I_{SP}) _______ lb_f-sec/lb_m
Total impulse ($I_T = I_{SP} \times WT_{PR}$) _______ lb_f-sec
Imaging experiment resolution (PPL) _______ pixels per line
Number of launches (NL) _______
Number of flight spacecraft (N_S) _______
Date of first launch (LD1) _______
Time factor (T = LD1 - August 1960) _______ years
Date of mission termination (MT) _______
(shut-down of final S/C)
Cruise time (CT = MT -LD1) _______ days
Experiment and data playback time (EPT) _______ days
(total for all S/C in mission)

Hourly labor rate

WAGE = exp (0.044y - 1.25) = _______ dollars/hour

where: y = median year of program funding minus 1900

COST MODEL WORK SHEET (1 of 3)

For ________________ Program

Science

$NR_S = 0.1\ PPL + 1.8\ WT_S + 234.2 =$ ________

$R_S = 0.182\ NR_S\ (N_S) =$ ________

$DLH_S = NR_S + R_S$ ________

Structure

$NR_{ST} = 1.18\ WT_{ST} + 50.1 =$ ________

$R_{ST} = 0.098\ NR_{ST}\ (N_S) =$ ________

$DLH_{ST} = NR_{ST} + R_{ST} =$ ________

Propulsion

$NR_P = 3.51\ (I_T)^{.359} =$ ________

$R_P = 0.149\ NR_P\ (N_S) =$ ________

$DLH_P = NR_P + R_P =$ ________

Electrical Power

Solar: $NR_{EP} = 0.21\ P_O + 0.23\ WT_{EP} + 55.3 =$ ________

RTG: $NR_{EP} = 1.57\ P_O + 0.9\ WT_{EP} =$ ________

$R_{EP} = 0.154\ NR_{EP}\ (N_S) =$ ________

$DLH = NR_{EP} + R_{EP} =$ ________

COST MODEL WORKSHEET (2 of 3)

Communications

$NR_C = 16.9\ P_T + 4.2\ WT_C - 37.1 =$ ________

$R_C = 0.183\ NR_C\ (N_S) =$ ________

$DLH_C = NR_C + R_C =$ ________

Guidance & Control

3-Axis Flyby or Orbiter:

$NR_{GC} = 428.9 \exp (4 \times 10^{-5}\ WT_{TOT}) =$ ________

3-Axis Lander:

$NR_{GC} = 1079.0 \exp (4 \times 10^{-5} WT_{TOT}) =$ ________

Spin Flyby or Orbiter:

$NR_{GC} = 84.0 \exp (4 \times 10^{-5}\ WT_{TOT}) =$ ________

$R_{GC} = 0.122\ NR_{GC}\ (N_S) =$ ________

$DLH_{GC} = NR_{GC} + R_{GC} =$ ________

Assembly & Integration

$DLH_{AI} = 64.0\ N_S + 0.4\ (WT_{DRY} - WT_{ST}) =$ ________

Test & Quality Assurance

$DLH_{TQ} = N_S * (127.5 + 8.9 \times 10^{-4}\ WT_{ST}^{\ 2}) =$ ________

Launch & Flight Operations

$DLH_{LF} = 95.7\ N_L + 0.4\ CT + 2.7\ EPT - 17.5 =$ ________

Ground Equipment

$$DLH_{GE} = \frac{4.29\ \ PPL\ \ (WT_{ST})}{T^2} =$$ ________

Subtotal

$\sum_{1}^{10} DLH =$ ________

COST MODEL WORKSHEET (3 of 3)

Systems Analysis & Engineering

$$DLH_{SE} = 0.353\ WT_{DRY} + 0.067\ \left(\sum^{10} DLH\right) - 467.8 = \underline{\qquad\qquad}$$

(if $DLH_{SE} < 0.0$, set $DLH_{SE} = 0.0$)

Subtotal

$$\sum^{11} DLH = \underline{\qquad\qquad}$$

Program Management

$$DLH_{PM} = 0.051\ \left(\sum^{11} DLH\right) = \underline{\qquad\qquad}$$

Total Program Direct Labor Hours

DLH_{TOT} = ______________ thousand hours

RTG's

no

yes

A.E.C. Costs

$$NR_{RTG} = 1.7\ P_U - 265.7\ \ln T + 1059.0 = \underline{\qquad\qquad}$$

$$R_{RTG} = (0.6\ P_U + 0.04\ NR_{RTG} - 5.9)N_U = \underline{\qquad\qquad}$$

Adjusted Total DLH

$$DLH_{TOT} = DLH_{TOT} + NR_{RTG} + R_{RTG} = \underline{\qquad\qquad}$$

Total Program Cost

$$COST = \frac{DLH_{TOT}\ (WAGE)}{0.3} = \$\underline{\qquad\qquad}\ (\times 1000)$$