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Volume II

SUMMARY REPORT

MANNED SPACECRAFT SYSTEMS COST MODEL

CONTRACT NAS9-3954

Prepared for the
MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HOUSTON, TEXAS

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FOREWORD

This document contains a summary of the results of the Manned Spacecraft Systems Cost Model Study. The study, Contract NAS9-3954, was performed by the Fort Worth Division of General Dynamics Corporation during the period beginning April 1965 and ending June 1966. The technical performance of the study has been under the supervision of the Office of Long Range Planning, Manned Spacecraft Center, National Aeronautics and Space Administration.

The complete results of the Cost Model Study are contained in the following volumes:

VOLUME 1	CONDENSED SUMMARY
VOLUME 2	SUMMARY
VOLUME 3	TECHNICAL REPORT
VOLUMES 4, 5 AND 6	APPENDICES TO TECHNICAL REPORT

ACKNOWLEDGEMENTS

This study has been conducted for the NASA Manned Spacecraft Center. The work was performed under the technical direction and assistance of Mr. D. E. Wagner, Technical Manager.

During the development of the Manned Spacecraft Systems Cost Model, significant contributions were made by the following General Dynamics/Fort Worth Division personnel:

T. E. Brents	Project Leader
C. E. Craig	Programming
C. E. Dreyfus	Model Implementation
F. M. Howe	Model Formulation and Implementation
J. S. McKnight	Project Consultant
C. B. Moore	General Direction and Consultation
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G. D. Self	Contingency Planning Model
M. F. Schwartz	Contingency Planning Model
G. G. Tharp	Cost Estimating Relationships

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1.0 INTRODUCTION AND SUMMARY

1.1 STUDY OBJECTIVES

In undertaking the Cost Model Study, the basic objective was the development of a mathematical model programmed for the IBM 7094; this model was to be designed to develop, on a timely basis, improved cost estimates of advanced manned spacecraft. More specifically the objective of the study was defined as the development of a model with the following characteristics:

1. The model was to have the capability of generating total costs attributable to NASA's Manned Spacecraft Center; these costs were to be divisible into research and development, recurring, and facilities costs.

2. The model was to be used to generate and to output costs in varying levels of detail ranging from total program costs down to costs of an individual spacecraft subsystem.

3. In addition to a pure costing capability, the model was to provide other data which is required in the evaluation of MSC plans; this "other data" was to include current and future spacecraft funding requirements over time (annual and semiannual increments), MSC resource requirements, and cost effectiveness measures.

Concurrent with the Cost Model Study, MSC also established a supporting Cost Analysis Study which was to be conducted by another contractor. In this Cost Analysis Study, cost data was collected and analyzed and subsequently used to develop cost estimating relationships for the Manned Spacecraft Cost Model. The work performed in the Cost Analysis Study is described in the final reports of that study.

It should be noted that the initial results obtained from the operation of the Cost Model are influenced by the data inputs from the Cost Analysis Study.

1.2 SUMMARY OF STUDY ACCOMPLISHMENTS

In conducting the Cost Model Study, the Fort Worth Division of General Dynamics was able to demonstrate the achievement of all of the study objectives. Major accomplishments are summarized below:

1. A comprehensive set of cost categories and corresponding model structure was established. The structure and categories account for all significant elements of spacecraft cost and are sufficiently generalized as to be applicable to all types of spacecraft. Both recurring and non-recurring costs are accounted for, and it is possible to collect various levels of cost aggregations from subsystems through programs.

2. A separate and independent model, which may be used to evaluate up to eight program contingencies, was programmed and delivered to MSC early in the study.

3. Cost estimating relationships were developed in terms of the following advanced technologies: nuclear power, nuclear propulsion, large liquid propulsion, and advanced service module structures.

4. Procedures were incorporated which can be used to modify or manipulate basic costs to reflect special costing situations such as design changes, multiple learning curves, and inflation.

5. Provisions were made to accommodate cost estimating relationships that reflect different subsystem technologies and/or varying levels of input availability.

6. Special subroutines were developed to account for situations unique to spacecraft costing. These special provisions include a reusability subroutine that can be used to estimate the cost of reusing spacecraft; in the subroutine, such factors as turnaround time, number of reuses, and probability of reuse are taken into consideration. Another subroutine is designed to deal with the problem

of computation and allocation of joint costs associated with mission planning and control.

7. Growth potential has been provided in a manner such that, without reprogramming the model, the level of computation of costs may be changed, and cost estimating relationships may be updated as new data becomes available.

8. Two unique submodels were developed: the Printout Submodel (in which unusual flexibility in printout options is offered) and a Center Planning Submodel (in which MSC personnel and funding requirements are generated).

9. An improved method of generating funding or spreading costs over time was developed; this method provides for funding at two different levels, is completely generalized, and requires an absolute minimum in terms of amount of inputs.

10. A multiple spacecraft costing capability was provided by means of which it is possible to compute and display the costs of up to 16 different spacecraft in a single problem run.

11. A concept was developed which can be used to minimize required inputs for a given problem run.

12. The model has been validated by a comprehensive series of check problems. Model logic has been checked out by hand computation, subroutine machine computation, and by integrated machine computation. In this latter step, consideration was given to all costing situations that can reasonably be expected to be encountered.

13. The model has been used in a series of actual costing exercises. In these exercises, the model's sensitivity to various design, performance, and mission parameters has been demonstrated. In addition the model has proved to be a valuable tool in mission analyses by assisting in the determination of optimum mission modes and in the evaluation of competing missions.

14. The model has been implemented and is fully operational at the Manned Spacecraft Center.

2.0 COST MODEL CHARACTERISTICS

A cost model is essentially a systematic procedure which is used to predict costs. The basic tasks undertaken in developing and operating a spacecraft are considered by the model in a logical and orderly manner. Cost model characteristics are depicted in Figure 2-1. These basic tasks are further divided into subtasks that are related to the characteristics of the spacecraft, the modules of the spacecraft, and the subsystems associated with the modules. The cost implications of various spacecraft technologies, such as batteries vs fuel cells, should be considered in the case of each subtask.

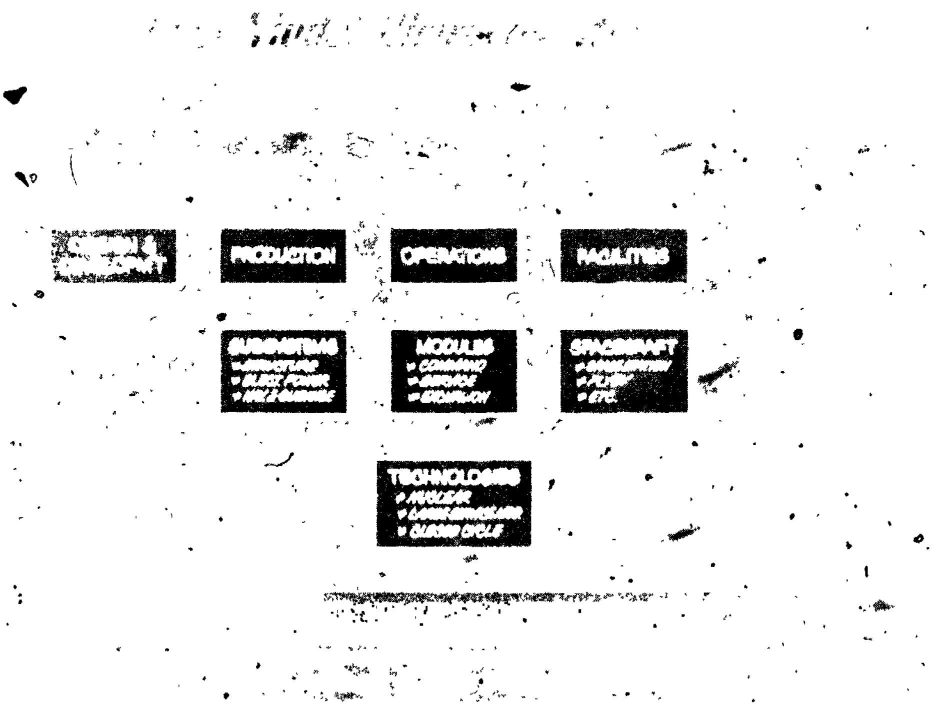


Figure 2-1

A properly constructed model can be used to generate complete costs because it provides an orderly and logical procedure for considering all pertinent cost-sensitive factors. Cost estimates from other sources are often inadequate, not because the costs presented are inaccurate, but because the cost is incomplete. Cost model estimates are also consistent because, by the use of equations, a given variable is always treated as an identical value. In addition, the methodology assumes that a consistent set of procedures will be applied to every costing problem.

Although the model could be used to generate costs by hand computations, a quantum increase in computational speed can be obtained by programming the model for use with a computer. A rapid computational speed means that a very rapid assessment can be made of the cost implications of potential variations in spacecraft design, schedule, and program considerations.

3.0 MANNED SPACECRAFT COST MODEL CONCEPT

The Manned Spacecraft Cost Model provides the user with an analytical tool that combines numerous complex costing techniques with the accuracy, speed, and convenience of modern digital computers and programming techniques. These analytical elements have been combined into a generalized model (refer to Figure 3-1) which is capable of successfully handling most problems encountered in costing conceptual spacecraft. These computational capabilities have grown out of the model concept depicted in the adjacent figure. The major elements of this concept are the outputs, basic model structure, inputs, and a Contingency Planning Model.

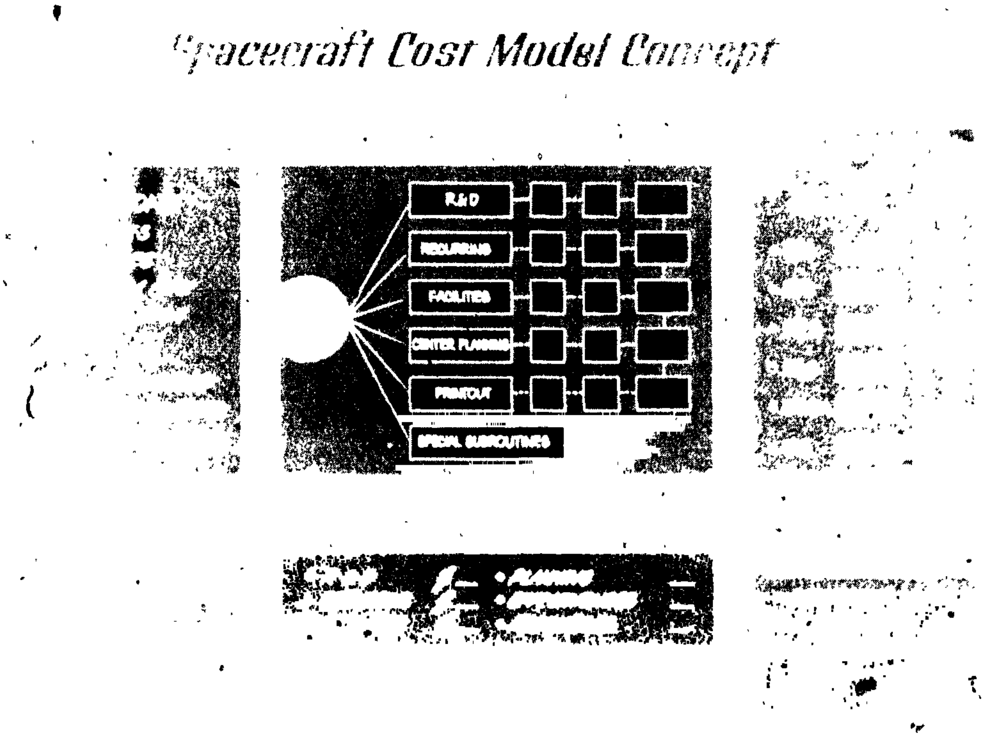


Figure 3-1

3.1 OUTPUTS

Model outputs range all the way from total program cost down to the cost of major development tasks for individual subsystems. Cost outputs are available by subsystem, module, and spacecraft for each program element within three main subdivisions: Research and Development, Recurring, and Facilities. These costs can be obtained in either totals or spread over time to indicate funding requirements.

The model can be used to output a number of items other than costs: hardware purchased in the R&D and Recurring phases; MSC personnel requirements; and inputs and estimating relationships used in a given problem.

All of the model outputs discussed above are optional features; any one option, any combination of the options, or all options may be exercised at the discretion of the analyst to fulfill the requirements of any given study. The exercising of these options is accomplished by means of appropriate inputs and by use of the Printout Submodel which is located within the basic model structure.

3.2 BASIC MODEL STRUCTURE

Five submodels are included in the basic model structure. The principal characteristics of these submodels and subroutines are discussed in the subsequent paragraphs. A general knowledge of the hierarchy used in computing and printing out cost is a prerequisite to obtaining a good understanding of the specific techniques used in these submodels. A discussion of the fundamentals of this required knowledge is provided in the following paragraphs.

The model can be used to compute, accumulate, and print out several different levels of cost. These levels correspond to hardware components of a mission: subsystem, module, spacecraft, and program. The different levels of model computation are in Figure 3-2.

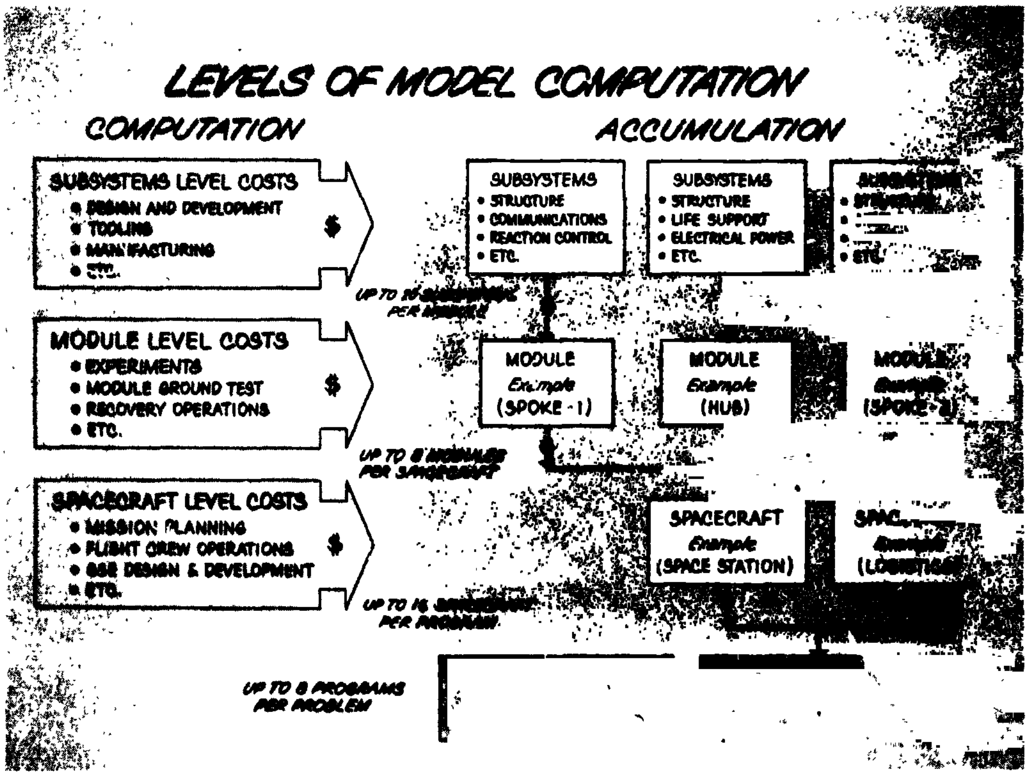


Figure 3-2

The subsystem level is the most detailed level at which costs are computed. Thirteen different subsystem types may be considered by use of the model:

Structure
Propulsion
Environmental Control
Crew Systems
Stabilization
Reaction Control
Navigation and Guidance
Electrical Power
Communication
Instrumentation
Launch Escape
Recovery
Adapter

The model may be used, also, to compute costs for secondary units of any of the foregoing subsystems provided the total number of primary and secondary subsystems in any one module does not exceed 20.

The module level is the next higher level of cost computation within the model. A module is considered to be a set of subsystems separate and, for costing purposes, severable from some other set of subsystems which belong to the same spacecraft. The module level was established primarily to account for costs which cannot be allocated to specific subsystems and which may occur more than once for a given spacecraft.

Some costs are not attributable to either subsystems or modules; the spacecraft level was established to account for such unallocated costs. A spacecraft is defined as a collection of modules capable of flight or operation independent of some other set of modules.

There is also a program level computation; computation at this level, however, is restricted essentially to estimating the operating costs for the Mission Control Center.

In addition to computing at these levels, the model may be used also to accumulate the costs at each level. Thus, all subsystem costs for a given module are attributable to that module, all module costs for a given spacecraft are attributable to that spacecraft, etc.

3.2.1 Research and Development Submodel

The objective of this submodel is to generate estimates of all costs incurred during development of a spacecraft; facilities costs are excepted. During the course of the study, development costs have been generally defined as a non-recurring cost or as those costs incurred in the program up to production of man-rated spacecraft. The model logic, however, is sufficiently flexible to accommodate other definitions of R&D costs such as those costs incurred in the program through completion of manned development flights.

The R&D Submodel initiates the computational sequence of the Spacecraft Cost Model. The analyst may by-pass R&D if recurring and/or facilities costs are of singular interest.

Within the Submodel, costs are estimated at three independent levels and are categorized for printout as shown on the following list.

Subsystem Level

Design and Development

Inplant Testing

Sustaining Engineering - R&D

Tooling

Boilerplate Hardware

Manufacturing - R&D

Module Level

Systems Integration - R&D

Module Ground Testing

Experiments - R&D

Site Activation - R&D

Module Level (Cont'd)

Residual - R&D

Systems Installation R&D

Flight Test - R&D

Recovery Operations - R&D

Non-Flight Test Recurring - R&D

Flight Test Recurring - R&D

Spacecraft Level

Mission Planning and Analysis

Mission Control

Design and Development of Checkout Equipment and Other GSE

Manufacture and Installation of Checkout Equipment and Other GSE

Total GSE Cost

Flight Crew Operations - R&D

Total Spacecraft - Related R&D

The summation of costs accumulated in the above categories is "total spacecraft R&D cost." The summation of these costs in terms of all spacecraft on a program gives "total program R&D cost."

The computational sequence is depicted in Figure 3-3. An examination of the figure will disclose that the model user must identify all elements of the problem: the programs, spacecraft,

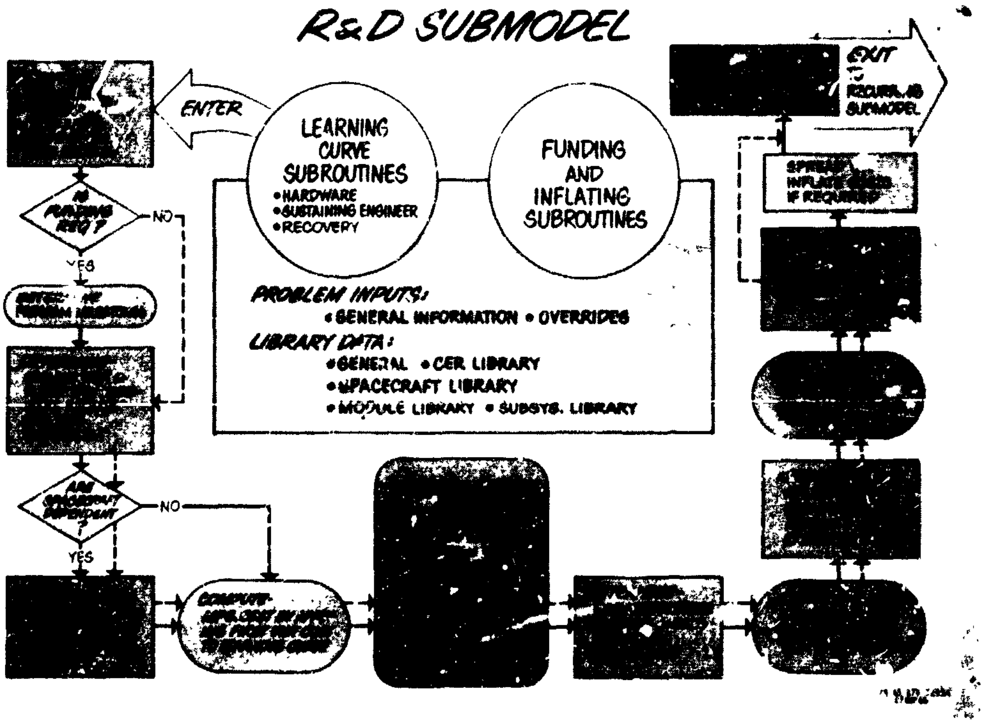


Figure 3-3

modules, and subsystems. On the basis of the identified elements, the submodel then determines if funding is to be computed. If funding is required, milestones and cost spreading parameters will be extracted from libraries for each category listed. The computational sequence begins at the subsystem level where hardware requirements for ground and flight testing and spares are determined. If spacecraft are dependent (i.e., spacecraft use common subsystems), the program searches all spacecraft in a problem to find where common subsystems are used.

Hardware requirements for each type system are totaled. From this total, Manufacturing and Sustaining Engineering costs are computed on given learning curves, and the costs then allocated among the participating spacecraft. Spares are computed and then added to Manufacturing to be printed out. From this point onward, the submodel computes Design and Development, Initial Tooling, and Boilerplate Hardware Costs.

When all subsystems in a problem have been evaluated, module level costs are computed on the basis of each category listed above for each module defined in the problem. Systems Installation cost is computed in the same manner used to compute Manufacturing and Sustaining Engineering costs. Recovery Operations is also computed on a learning curve and is added into total cost for every flight test.

When module level costs have been computed the program determines spacecraft related costs. On the basis of mission and planning duration inputs, the model computes total costs accruing to the Mission Control Center for Planning and Control; these total costs are then allocated evenly over each time interval and are spread among the spacecraft simultaneously occupying the control center. All other spacecraft-related costs are computed and the program is transferred to an accumulation process. All R&D cost for each time period are summed and retained in storage for use in the cost-effectiveness subroutine which may be activated at the end of all other model computations.

When all R&D costs are determined, the model program reads in operational requirements and begins computation of Recurring Costs.

3.2.2 Recurring Submodel

Costs computed in this section of the Spacecraft Cost Model are (1) those costs associated with the manufacture and maintenance of man-rated or operational spacecraft and (2) those costs associated with mission planning, control, and recovery-related activities incurred from the initial planning of the first manned mission through the last interval of the final mission scheduled for a spacecraft.

The Recurring Submodel is an optional feature and may be bypassed. If the submodel is activated, the program follows a set pattern and computes the following costs:

Subsystem Level

Sustaining Engineering-Recurring

Manufacturing-Recurring

Spares-Recurring

Module Level

Systems Integration-Recurring

Systems Installation-Recurring

Acceptance Testing

Launch Site Support

Recovery-Recurring

Reconditioning

Experiments-Recurring

Residual-Recurring

Spacecraft Level

Flight Crew Operations-Recurring

GSE Spares and Maintenance

Mission Planning and Analysis & Mission Control Cost-Recurring

The computational sequence for this submodel is summarized in Figure 3-4. Those costs computed on the basis of a learning curve in the R&D submodel, continue to be computed in this manner in the Recurring Submodel although a different curve slope may be used for operational hardware; the use of the different curve slope is described under the special subroutine discussion. In the Recurring Submodel, the learning curve is entered after the unit number which is the sum of module ground tests plus flight tests.

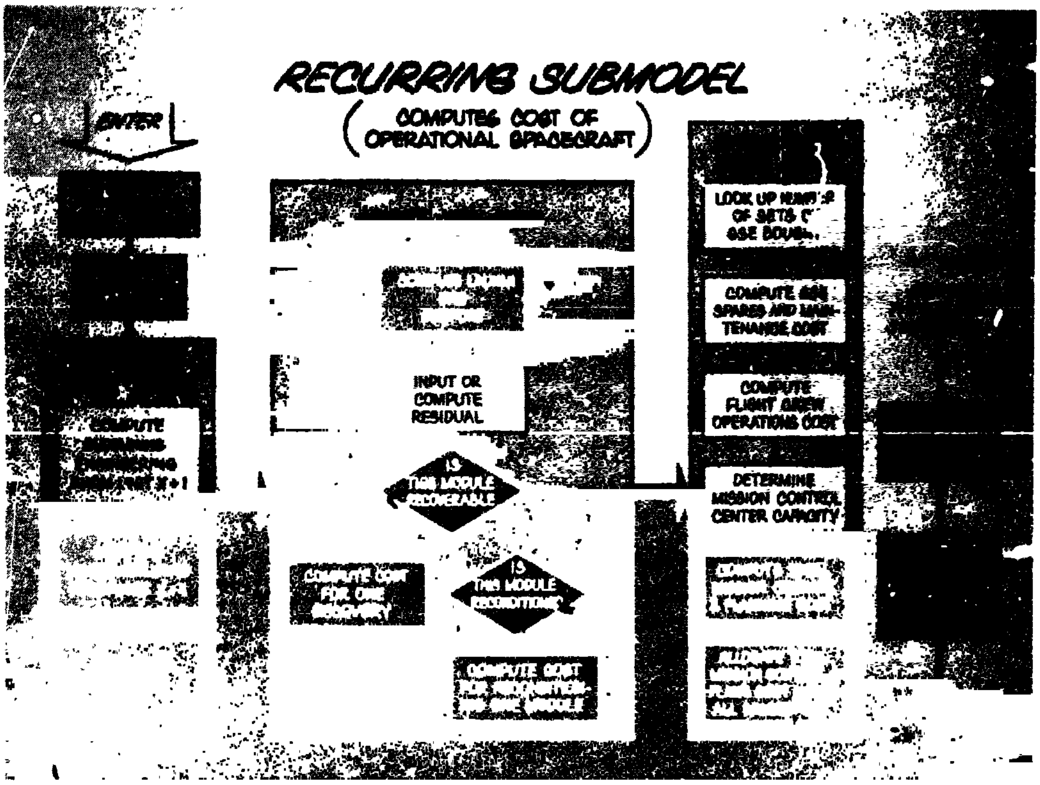


Figure 3-4

This continuity between the two program phases is maintained even in those cases when R&D is not computed. The exception to this interface of learning curves occurs in the instance of refurbishing cost which is computed only in the Recurring Submodel. If refurbishment cost should reflect learning, the computation begins with the first man-rated spacecraft recovered.

There are other differences between the two submodels in terms of the calculation of spares and experiments costs. Recurring spares include all backup units plus a percentage of manufacturing cost. Sustaining engineering is calculated on a per production unit basis which includes back-up units (spare subsystem units). Recurring experiments cost is computed for each flight and is summed for printout.

If non-funded recurring costs are requested, the model calculates funded costs but prints only the totals; such a calculation and printout requires the inputting of beginning and ending dates but facilitates the computation of hardware requirements and refurbishing cost. It also results in more valid mission control and planning costs especially when missions are of long duration.

Upon completion of the recurring phase for all spacecraft and programs included in a problem, the model begins computation of facilities costs.

3.2.3 Facilities Submodel

At the time the Cost Model Study was made, spacecraft facilities had accounted for a relatively small portion of total spacecraft program costs. With the exception of manufacturing facilities, the majority of the facilities used in current spacecraft programs are located at MSC and, presumably, will be available for use in future programs. In general, facilities requirements and costs are highly dependent upon the particular program under consideration. Considerations affecting facilities costs include

(1) mission requirements and design characteristics of the spacecraft in question and (2) the availability and applicability of existing facilities.

Because of its relatively low cost significance and formidable estimating problems, facilities costing has received only cursory attention in past and present studies.

As a result of the foregoing considerations, emphasis in the formulation of the Facilities Submodel has been placed upon simplicity and flexibility. Provisions have been made to consider a variety of facility types with the expectation that only a few types may be costed in a given problem. As has been indicated in Figure 3-5 the submodel sums and prints costs in the following categories:

Total Subsystem Facilities
Total Module Facilities
Total Spacecraft Facilities
    Flight Operations Facilities
    Other Spacecraft Facilities

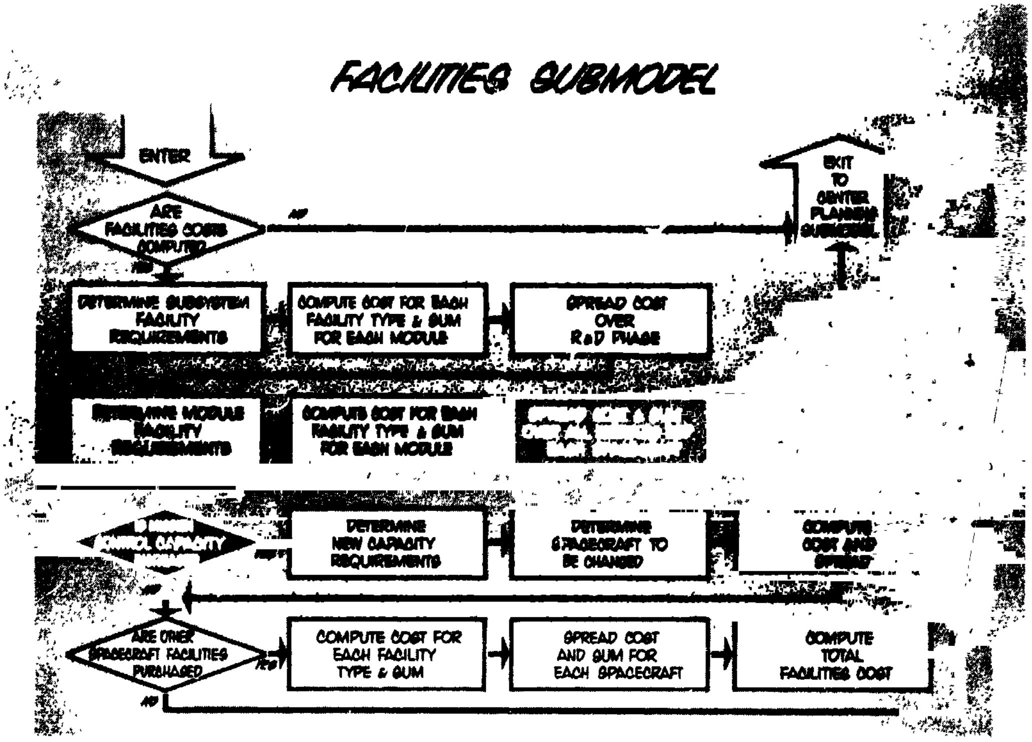


Figure 3-5

For all 13 subsystems considered in the cost model, the capability exists to compute at least one type of facilities cost. Funding of subsystems facilities has been tied to R&D milestones because requirements for these facilities will be generated mainly during subsystem development.

At the module level an estimating capability has been provided for 10 different facility types. Because the costs for some of these facility types, such as additional manufacturing facilities or recovery and reconditioning facilities, may be incurred after development has been completed, funding is based upon milestone inputs in real time.

At the spacecraft level, the costs for flight operations facilities used in mission planning and control are estimated. The cost for this facility category are derived from requirements generated in the R&D and Recurring submodels. Provisions have been made for computing the cost of eight other types of spacecraft related facilities. As with module facilities, funding is based on real time inputs.

Because facilities costs are so highly problem-dependent, the selection of facilities to be costed is treated as a problem input.

3.2.4 Printout Submodel

The Printout Submodel allows the model user to choose the amount of information to be printed on a given program. For cursory analyses, summary reports to total R&D, Recurring, and Facilities costs at the spacecraft, module, and subsystem level can be obtained. In the more detailed analysis, semi-annual costs for all cost categories at all levels can be made available as a printout. Numerous intermediate levels of printout are available The existence of the Printout Submodel makes it possible to retain all problem runs on magnetic tape for reuse and removes the requirements for storage of printouts which are not actually necessary to the immediate task.

3.2.5 Center Planning Submodel

Another submodel within the basic model structure, the Center Planning Submodel, also can operate off of magnetic output tape. In this submodel, inputs used are the cost data generated by the Research and Development and Recurring Submodels. The Center Planning Submodel computes the center personnel requirements at MSC by major center function (e.g., Program office, Flight Crew Operation, R&D Personnel, etc.); these personnel requirements are expressed in terms of civil service personnel and contractor support personnel.

3.3 SPECIAL SUBROUTINES

The operation of the special subroutines is described in the following section. Most of these subroutines are used to service the R&D, Recurring, and Facilities submodels. When certain model options are exercised, the subroutines alter or manipulate the costs generated by these three submodels. The following is a description of the more important subroutines within the model.

3.3.1 Funding Subroutine

One of the major options within the model is the estimation of spacecraft funding requirements. This is accomplished by spreading or distributing cost estimates generated by the model over time. By variation in inputs and library data, various measures of funding (such as expenditures or new obligational authority) can be generated on an annual or semiannual basis.

The development of procedures that are flexible, easily input, and capable of generating realistic funding distributions has been a formidable problem in cost modeling. Until the Spacecraft Cost Model, this problem had never been entirely solved.

The major ingredients of the solution proffered by the Manned Spacecraft Cost Model are the library concept and the PEPTS (Proportion Expenditure - Proportion Time Spent) concept. The library data, in combination with problem inputs, determines the time over which costs are to be spread. The PEPTS concept is used to determine the distribution of the costs over this time span.

In more detail, the funding process is as follows: Within the general library are contained spreading parameters and lags for all cost categories and beginning and ending milestones for categories which cannot be logically tied to some other event in the program. Milestones are input or used for spreading in several different ways. Each module is required to have two major inputs indicating the start and finish of R&D activity for that module.

These two inputs are entered as actual years. Other milestones for subsystem and module cost categories are input as percentages of the module R&D time completed. A set of inputs generally applicable to each level is input once. Additional inputs are required only for special funding cases that deviate from the average program activity. For spacecraft level costs, the milestone inputs are percentages of the time completed from the beginning R&D milestone of the earliest module to the ending R&D milestone of the last module on the spacecraft.

After a cost has been computed in the model and has been located in time by the respective milestone, the program will spread the cost on the basis of a predetermined funding distribution which approximates obligational authority grants and expenditures of funds or other funding measures. The model will first determine the number of intervals prior to the use of a hardware or facility item or prior to the initiation of an operation (such as ground testing, acceptance testing or a flight) for which obligational authority is granted. From this point, the model determines the value of parameters which are input to the model and which are used to spread the cost by the following equation.

$$E\left[P, q\ (T)\right] = \frac{\int_0^T X^{P-1}(1-X)^{q-1}\,dX}{\int_0^1 X^{P-1}(1-X)^{q-1}\,dX}$$

where: X is the definite variable of integration (assuming values from 0 through 1).

T represents the proportion of time which has elapsed for the program.

$E\left[p, q\ (T)\right]$ represents the cumulative percent of cost expended through T.

To obtain the cost associated with each interval, the cumulative curve for (T-1) is subtracted from the cumulative curve to T for each interval associated with the cost being computed.

The symbols p and q are used to define inputs which determine the point of inflection for the cumulative expenditure curve; p and q can be values from .1 through 10.0. For a normal density function, p and q are both 2. In other non-cumulative curves, for example, the larger p becomes, the more skewed is the curve to the left; the larger q becomes, the more rapidly the curve approaches very low values for each progressive time interval.

3.3.2 Learning Curve and Design Change Subroutines

The capability to apply learning to Research and Development costs is available at four separate points in the computational process of the R&D Submodel. The individual costs in which the learning concept appears are Manufacturing and Sustaining Engineering at the subsystem level and Systems Installation and Recovery at the module level. In the Recurring Submodel, this subroutine is applied to Sustaining Systems Installation, Sustaining Engineering, Manufacturing, and Recovery costs. The computation of the learning process is basically the same for all costs against which it is applied. The learning curve procedure used is based upon the modified Wright theory and is discussed more fully below. There are three possible slopes for each curve, and an optional capability is provided for increasing cost as a result of a design change which covers a block of hardware units.

To calculate cost with either positive or negative learning, the model uses the integral of $y = aX^b$ where y is cost at unit X, a is cost at unit 1, and b is the ratio of ln m/ln 2 (m being the slope of the learning curve). The resulting equation is shown below.

$$\text{Cost of block of units between } X_1 \text{ and } X_2 = \frac{a}{b+1}\left[(X_2+.5)^{b+1} - (X_1+.5)^{b+1} \right].$$

This equation is valid when applied to units on a learning curve with one slope. For multiple slope learning curves, the equation is applied to the number of units on each learning curve. In this case, the total hardware cost is the sum calculated in terms of each learning curve.

If a design change occurs and is of such magnitude as to be reflected in cost values, the cost of the block of units over which this change is noticeable is multiplied by (1 + DCF).

DCF is the percent of cumulative average unit cost that the design change is estimated to increase. The design change feature is provided for use in manufacturing, sustaining engineering, and system installation computation.

The model also provides the capability to calculate the cost of subsystems used in common by different modules, spacecraft, and programs. When commonality is considered, data on spacecraft are provided as input in the order in which the spacecraft are developed. The common subsystem requirements for all spacecraft and programs for each time period in the problem are then summed before cost is computed. After manufacturing cost has been computed for each interval, the cost is then allocated to the appropriate spacecraft and programs.

3.3.3 Recovery Subroutine

In the Spacecraft Cost Model, reconditioning cost is computed for each mission in which a reusable module is involved. The recovery subroutine is used to determine (1) the amount of and the time when new hardware should be purchased for recoverable modules and (2) the number of modules to be refurbished in each interval. The procedure begins at the first interval of the operational phase with the computation of minimum inventory in time t for the first reusable module occurring in the program.

$$NI(t) = \frac{\lambda[OPL(t)]}{TU(52)}$$

where

λ = module turnaround time

OPL(t) = number of operational flights in t

TU = computing interval (.5 = 6 months, 1.0 = annually).

This computation is repeated after each time interval and retained in storage for further use.

As minimum inventory is computed for each interval, the model also computes an estimated number of non-reusable modules based on reliability magnitude and growth parameter inputs. This computation is retained in storage for each time period and as a total for the program. The model then computes average probability of reuse for the module based on the following:

$$P(Rec) = 1 - \frac{NR}{OPL(t)}$$

where

NR = estimated number of non-reusables.

On the basis of the above computations and an input value for average number of reuses, the total number of wear-outs is computed and allocated over the program. The model then determines at what interval in the program wear-outs begin occurring. The maximum number of modules needed to meet the schedule requirements (without carrying any forward from interval to interval) is computed as the sum of the minimum inventory, the number of non-reusables, and the number of wear-outs. The summation is retained in storage for each time period for use in the following computations.

In the next step, the model computes the number of modules required in each interval when inventory carry-overs are considered. To do this computation, the model determines if the number of modules brought forward from the previous interval is greater than the number required. If it is greater, the number carried to the next interval is the number brought forward plus what is needed for use in this interval. If the number is less than that required, the model carries forward only the minimum inventory computed earlier and computes and retains a new value for what is required in this interval but could not be obtained from inventory. This new value is then compared with the minimum production rate input (MPR) to determine the number of modules to be purchased in time t. If the number required is equal to or greater than MPR, the model indicates that MPR modules should be bought; if the number required is less than the MPR figure, the model indicates that only the number actually required should be bought.

In the final computation, the number of modules to be refurbished in each time interval is produced. This number is the number of flights less the non-reusables less the wear-outs.

3.4 INPUTS

During the formulation of the model, particular care was taken with input organization and procedures. General Dynamics' prior experience with large generalized models suggested that the utility of a model is determined as much by the ease with which it may be input as by the validity of its results. In the case of the spacecraft cost model, potential input problems were aggravated by the requirement that all major spacecraft subsystems were to be considered explicitly in the costing processes; this means that, in a costing exercise such as a Mars landing, data must be input not only for the 5 spacecraft and 10 modules performing the mission but also for the 52 separate subsystems installed.

In anticipation of these multiple input problems, input procedures were streamlined (1) through the use of multipurpose inputs, (2) by extensive use of inputs that are either "0" or "1", and (3) by adoption of the namelist procedure. This latter procedure frees the user from the usual requirements (and the associated errors) of entering inputs in a predetermined order and in narrow specified fields.

An equal or greater contribution to the solution of the input problem was provided, however, in the organization of the input data. Inputs required for computation are divided into two categories:

library data and problem data. Library data is input as required and then is retained for use on subsequent problems. Problem data, on the otherhand, must be input for each problem run.

Problem data is further subdivided between problem-required and problem-option inputs. Problem-required data has been reduced to the absolute minimum number of instructions necessary to activate the model. Problem-required data is composed of less than 10 items and is restricted to such items as the names of the programs and spacecraft to be costed, whether or not common usage subsystems are involved, and the number of spacecraft for which problem data is required.

Problem-optional data is quite voluminous because of the large number of functions performed by the model and the numerous optional methods of accomplishing these functions. Problem options include over 75 different items; however, only a few of these are normally exercised on any given problem. In general, problem options fall into three classes: computational options, library overrides, and cost inputs. Computational options include instructions to compute such items as cost effectiveness, inflation, reconditioning cost, and funding requirements. Library overrides were incorporated to permit temporary variations in libraries such as modification of design or performance data for a baseline spacecraft. In addition to the computational options and library overrides, it is possible to input certain aggregate measures of cost such as research and development cost for a specific spacecraft.

Most of the inputs required for use in a problem will be contained within libraries. There is a significant advantage to this approach to the input problem: once the values of parameters are entered into libraries, the values will be available for use in future problems. The necessity for re-inputting this data for each problem run is eliminated. On the otherhand, the alteration of infrequently changing data can be accomplished expeditiously by incorporating the static data into libraries rather than building it into the program.

Library data is divided into two major groups: general library data and specific library data. Each of these groups in turn is subdivided into subsystem data, module, and spacecraft data.

The general library was established as a means of retaining large groups of data that are relatively independent of the design and performance characteristics of the spacecraft being costed. Consequently, this type of data is input infrequently and is input only as a result of periodic updating or to reflect special costing situations. In general, the following categories of information are contained in the general library:

1. Mission control center parameters
2. Policy and structural coefficients used in the Center Planning submodel
3. Learning curve slopes
4. Spares factors
5. Funding milestones and shaping parameters.

Specific library data applies to some specified design or mission configuration. This type of information is entered the first time a new design is to be costed and is then retained and made available for use in each subsequent problem in which that particular design is called for. Specific library data for the spacecraft includes program milestones, the names of the modules used by the spacecraft, and spacecraft-related design and performance parameters. These parameters are used in the cost estimating relationships and include such data as spacecraft crew complement, weights, and number of flights.

Module level data includes a list and count of subsystems installed in the module, refurbishment parameters (if reuse of the module is being considered), program milestones, cost throughputs, and design and performance parameters. Design and performance parameters currently used in the CER's include such information as weights, dimensions, volumes, mission duration, thrust, and attitude change rates.

Subsystem level library data is generally similar in nature to the library data listed for modules and spacecraft.

3.5 COST ESTIMATING RELATIONSHIP LIBRARY

Most cost generation accomplished by means of the model is a result of the use of cost estimating relationships. The cost estimating relationship (CER) is an equation which represents the relationship of the cost of a particular spacecraft hardware element or activity to design, performance, and/or mission parameters.

In the Spacecraft Cost Model, all cost estimating relationships are contained within a library rather than made an integral part of the computer program. This feature, which was pioneered by General Dynamics in a companion study for NASA/MSFC, provides enormous advantages over any previous cost model concept. By use of the library concept, CER's are always available for use and yet may be improved or altered without the requirement of modifying the program.

Each CER in the library is described on one to five cards. The description identifies the CER and contains a Fortran statement of the equation. Each CER is identified with respect to four factors:

1. Computation level (subsystem, module, etc.)
2. Subsystem type (structure, propulsion, etc.)
3. Cost category (manufacturing, flight test, etc.)
4. Technology (current, nuclear, etc.)

The Fortran statement of the equation indicates the variables used in the equation, and the operations to be performed on the variables. The operations include addition, subtraction, multiplication, division, exponentiation (including negative and fractional exponents), and conversion to natural logrithms. During the operation of the model, the computer program calls for a particular CER when it is required, decodes the CER, executes the equations described by the Fortran statement, and stores the cost yielded by the relationship. Application of the library concept to CER's not only permits updating of an individual CER in minutes but also provides the capacity for using virtually an unlimited number of CER's. Up to 99 different CER's may be stored for an individual cost category. This storage feature not only makes it possible to consider all foreseeable technologies but also provides a capability to select CER's based on the availability of input data. By using this concept, it would be possible to select a complex and presumably highly accurate CER when the design of a spacecraft under consideration is well-defined or to use a very gross estimating relationship when the spacecraft to be costed is sketchily defined.

Another major advantage of the use of a cost estimating relationship library is that use of the library allowed model development to proceed concurrently with and separately from the development of CER's. This parallel development effort enabled MSC to obtain a working cost model considerably earlier than would have otherwise been possible. Accordingly, it was decided to give the Cost Analysis Study contractor the responsibility for developing most of the estimating relationships currently being used in the model.

Because of specialized knowledge and prior experience, General Dynamics, however, was charged with development of estimating relationships for the certain advanced technologies. These technologies include nuclear isotope electrical power systems, nuclear reactor electric power systems, nuclear and liquid pump-fed propulsion systems, and large service modules.

3.6 CONTINGENCY PLANNINC MODEL

The cost estimating relationships contained in models (such as the Spacecraft Cost Model) are formulated from historical data which normally represent a wide spectrum of programs. Some of these programs have been accelerated and others "stretched-out" during the program lifetime. The effects of acceleration or "stretch-out" on program cost are difficult to isolate and are, therefore, included in the cost data used to derive the cost estimating relationships. If the long range planner wishes to postulate contingencies, such as program acceleration or stretch-outs, it is often difficult to assess the cost impact of these contingencies.

A procedure to explore the effects of contingencies on launch vehicle costs had been developed for NASA-MSFC. Early in the study MSC asked that this still-experimental procedure be modified so that its feasibility as a predictor of spacecraft contingency costs might be explored. This modified procedure, the Contingency Planning Model, operates independently of the rest of the Spacecraft Cost Model.

In its final form, the Contingency Planning Model assesses the influences of eight major contingencies:

Technological Stretch-out
Budget Constraint
Cost Sharing
Cancellation
Technological Recovery
Acceleration
Parallel Systems
Fixed Cost

Additional details concerning the Contingency Planning Model may be found in the Contingency Planning Model Programmer and User's Manual (published in November 1965) and in General Dynamics/Fort Worth report number FZM-4247 (published in June 1965).

4.0 MODEL APPLICATIONS

A discussion of possible model applications is contained in the following section. Of all the results of the study, those results of paramount interest and importance are the potential applications of the model. It is believed that these applications can best be illustrated by example problems. These problems represent a wide range of spacecraft types and costing problems and were used to validate the model logic, library data, and estimating relationships. These representative problems, taken together, are not an exhaustive list of applications but were selected to typify the problems that will be encountered most frequently. Included are typical problems related to absolute cost analysis, cost sensitivity, budget planning, and other special factors.

The costs presented herein should not necessarily be construed as the actual or ultimate costs of the spacecraft programs or of the program components used as examples. The Manned Spacecraft Cost Model was designed to be sensitive to variations in design parameters, mission parameters, and program variables such as quantities and timing. In the following sections, it will be shown that the ultimate cost of a mission or spacecraft, can vary markedly depending on the choice of parameters and variables. Therefore, the costs presented herein can be considered to be accurate in light of the assumptions made concerning mission parameters and program variables.

4.1 ABSOLUTE COSTS

The model will be used most frequently to obtain the absolute costs of a given spacecraft configuration, thus allowing NASA to verify the reliability and completeness of estimates obtained from external sources. The model also provides a common or standard measure for evaluating costs of competing design concepts. In addition to evaluating external estimates, the model complements NASA's internal spacecraft design capability by providing the means for producing a quick assessment of the costs of a given design; this assessment can be made prior to disclosure of the design outside NASA.

Examples of the type of absolute costs that can be obtained with the model are presented in Figure 4-1. The costs and model inputs

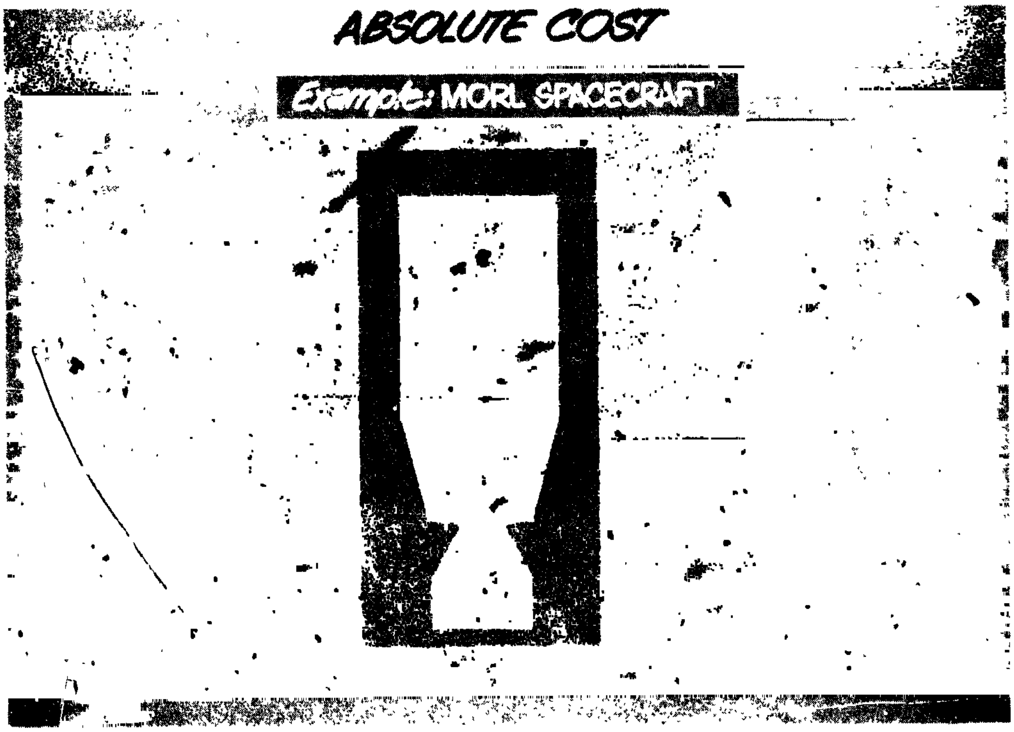
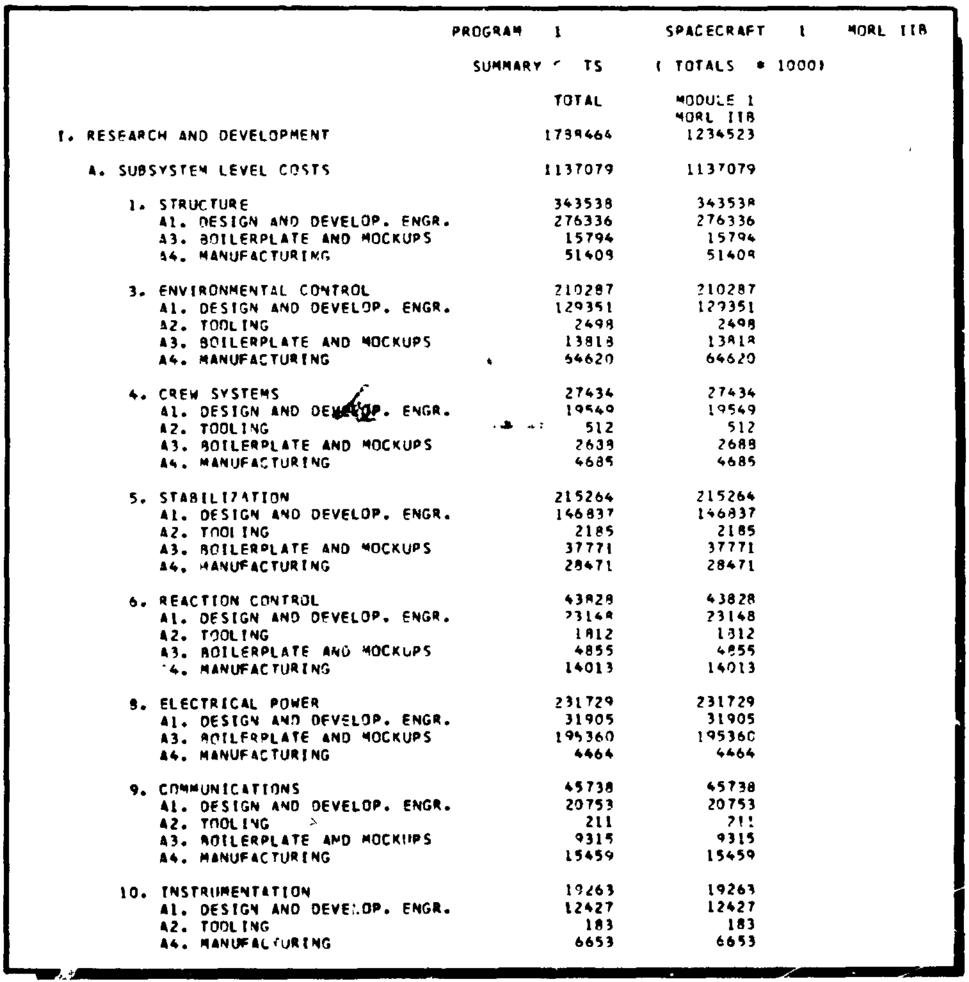


Figure 4-1

contained in the figure were extracted from a model check problem in which a MORL-type of space station is used as the example; an examination of the figure will disclose that the largest single component of these costs is subsystem-level R&D costs.

The composition of the space station subsystem R&D costs are shown in Figure 4-2 which is, in actuality, a reproduction of a computer output sheet. The figure illustrates the amount of data generated by the model. These include not only the cost of each subsystem installed in this particular space station but also estimates for the major subsystem development tasks (such as design and development, test articles, etc.).



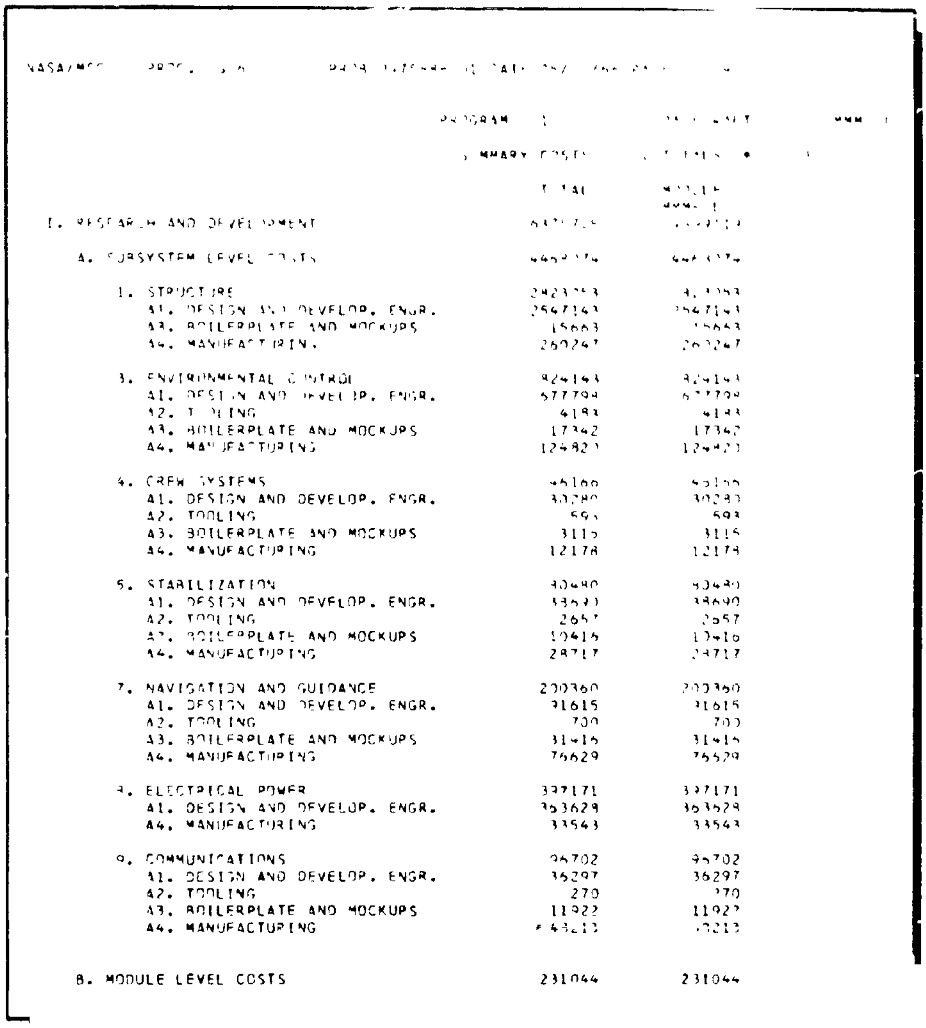
```
                                            PROGRAM   1          SPACECRAFT   1    MORL IIB

                                             SUMMARY COSTS      ( TOTALS  * 1000)

                                                    TOTAL        MODULE 1
                                                                 MORL IIB
  I. RESEARCH AND DEVELOPMENT                     1739464       1234523

     A. SUBSYSTEM LEVEL COSTS                     1137079       1137079

        1. STRUCTURE                               343538        343538
           A1. DESIGN AND DEVELOP. ENGR.           276336        276336
           A3. BOILERPLATE AND MOCKUPS              15794         15794
           A4. MANUFACTURING                        51409         51409

        3. ENVIRONMENTAL CONTROL                   210287        210287
           A1. DESIGN AND DEVELOP. ENGR.           129351        129351
           A2. TOOLING                               2498          2498
           A3. BOILERPLATE AND MOCKUPS              13818         13818
           A4. MANUFACTURING                        64620         64620

        4. CREW SYSTEMS                             27434         27434
           A1. DESIGN AND DEVELOP. ENGR.            19549         19549
           A2. TOOLING                                512           512
           A3. BOILERPLATE AND MOCKUPS               2688          2688
           A4. MANUFACTURING                         4685          4685

        5. STABILIZATION                           215264        215264
           A1. DESIGN AND DEVELOP. ENGR.           146837        146837
           A2. TOOLING                               2185          2185
           A3. BOILERPLATE AND MOCKUPS              37771         37771
           A4. MANUFACTURING                        28471         28471

        6. REACTION CONTROL                         43828         43828
           A1. DESIGN AND DEVELOP. ENGR.            23148         23148
           A2. TOOLING                               1812          1812
           A3. BOILERPLATE AND MOCKUPS               4855          4855
           A4. MANUFACTURING                        14013         14013

        8. ELECTRICAL POWER                        231729        231729
           A1. DESIGN AND DEVELOP. ENGR.            31905         31905
           A3. BOILERPLATE AND MOCKUPS             195360        195360
           A4. MANUFACTURING                         4464          4464

        9. COMMUNICATIONS                           45738         45738
           A1. DESIGN AND DEVELOP. ENGR.            20753         20753
           A2. TOOLING                                211           211
           A3. BOILERPLATE AND MOCKUPS               9315          9315
           A4. MANUFACTURING                        15459         15459

       10. INSTRUMENTATION                          19263         19263
           A1. DESIGN AND DEVELOP. ENGR.            12427         12427
           A2. TOOLING                                183           183
           A4. MANUFACTURING                         6653          6653
```

Figure 4-2

4.2 COST SENSITIVITY

By use of the model, it is possible to assess the sensitivity of absolute costs to variations in program considerations. The model was deliberately designed to be sensitive to changes in design, schedule, quantities, development philosophy, and technology. It is precisely these factors about which there is the greatest uncertainty at the start of a new spacecraft program and during the latter stages of existing programs. The model structure, and its associated estimating relationships, permit the identification of those factors which are most cost sensitive and which allow reasonable bounds to be set upon spacecraft program cost.

The sensitivity of the model to design and performance considerations is illustrated if the subsystem level R&D costs for a Mars mission module (in Figure 4-3) are compared with those costs previously presented for the MORL. Total subsystem level R&D for MORL is $1.137 billion as compared with $4.468 billion for Mars mission module. This differential results from the differences in design which are a product of the more stringent demands placed on the mission module. The mission module must provide support for eight men for 420 days under deep space conditions without any possibility of resupply or outside help. In contrast, the MORL supports six men for 90 days with the possibility that the crew



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NASA/M[illegible]

                                                PROGRAM [illegible]

                                                SUMMARY COSTS [illegible]

                                                  TOTAL       MODULE
                                                              [illegible]
I. RESEARCH AND DEVELOPMENT                    [illegible]  [illegible]

   A. SUBSYSTEM LEVEL COSTS                    [illegible]  [illegible]

      1. STRUCTURE                                2823053      2823053
         A1. DESIGN AND DEVELOP. ENGR.            2547143      2547143
         A3. BOILERPLATE AND MOCKUPS                15663        15663
         A4. MANUFACTURING                         260247       260247

      3. ENVIRONMENTAL CONTROL                     824143       824143
         A1. DESIGN AND DEVELOP. ENGR.             677798       677798
         A2. TOOLING                                 4183         4183
         A3. BOILERPLATE AND MOCKUPS                17342        17342
         A4. MANUFACTURING                         124820       124820

      4. CREW SYSTEMS                               46166        46166
         A1. DESIGN AND DEVELOP. ENGR.              30280        30280
         A2. TOOLING                                  593          593
         A3. BOILERPLATE AND MOCKUPS                 3115         3115
         A4. MANUFACTURING                          12178        12178

      5. STABILIZATION                              80480        80480
         A1. DESIGN AND DEVELOP. ENGR.              38690        38690
         A2. TOOLING                                 2657         2657
         A3. BOILERPLATE AND MOCKUPS                10416        10416
         A4. MANUFACTURING                          28717        28717

      7. NAVIGATION AND GUIDANCE                   200360       200360
         A1. DESIGN AND DEVELOP. ENGR.              91615        91615
         A2. TOOLING                                  700          700
         A3. BOILERPLATE AND MOCKUPS                31416        31416
         A4. MANUFACTURING                          76629        76629

      8. ELECTRICAL POWER                          397171       397171
         A1. DESIGN AND DEVELOP. ENGR.             363628       363628
         A4. MANUFACTURING                          33543        33543

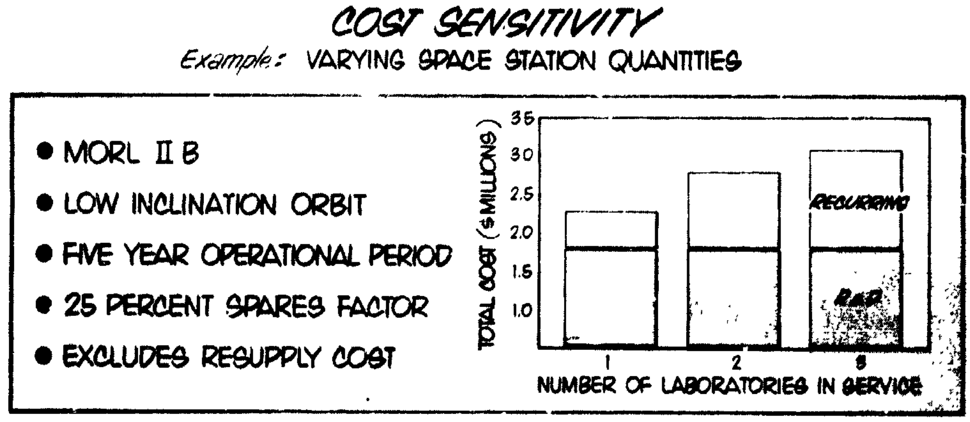
      9. COMMUNICATIONS                             96702        96702
         A1. DESIGN AND DEVELOP. ENGR.              36297        36297
         A2. TOOLING                                  270          270
         A3. BOILERPLATE AND MOCKUPS                11922        11922
         A4. MANUFACTURING                          48213        48213

   B. MODULE LEVEL COSTS                           231044       231044
```

Figure 4-3

can safely abort any time and return to earth in a matter of hours. The Mars Mission Module factors, taken together, result in more severe demands being made on structure, electrical power, environmental control, and communications; these are the subsystems that show the greatest cost increase over comparable elements in the MORL.

An example of the sensitivity analyses attainable are portrayed in Figure 4-4. This figure is used to summarize the results obtained from the model when the number of operational space stations is varied. Increasing the number of stations from one to three results in a $700 million increase in total cost. The change in total cost is attributable to (1) higher subsystem level costs which reflect



	ONE LAB	TWO LABS	THREE LABS
Spacecraft Level	$ 852,870	$ 1,070,157	$ 1,287,441
Module Level	101,391	105,338	109,285
Subsystem Level	1,421,538	1,612,175	1,725,624
TOTAL (1000's OF $)	$ 2,375,799	$ 2,787,670	$ 3,122,350

Figure 4-4

increasing manufacturing and sustaining engineering costs, and (2) the increasing spacecraft level cost which is due to greater mission control requirements.

4.3 MISSION ANALYSIS

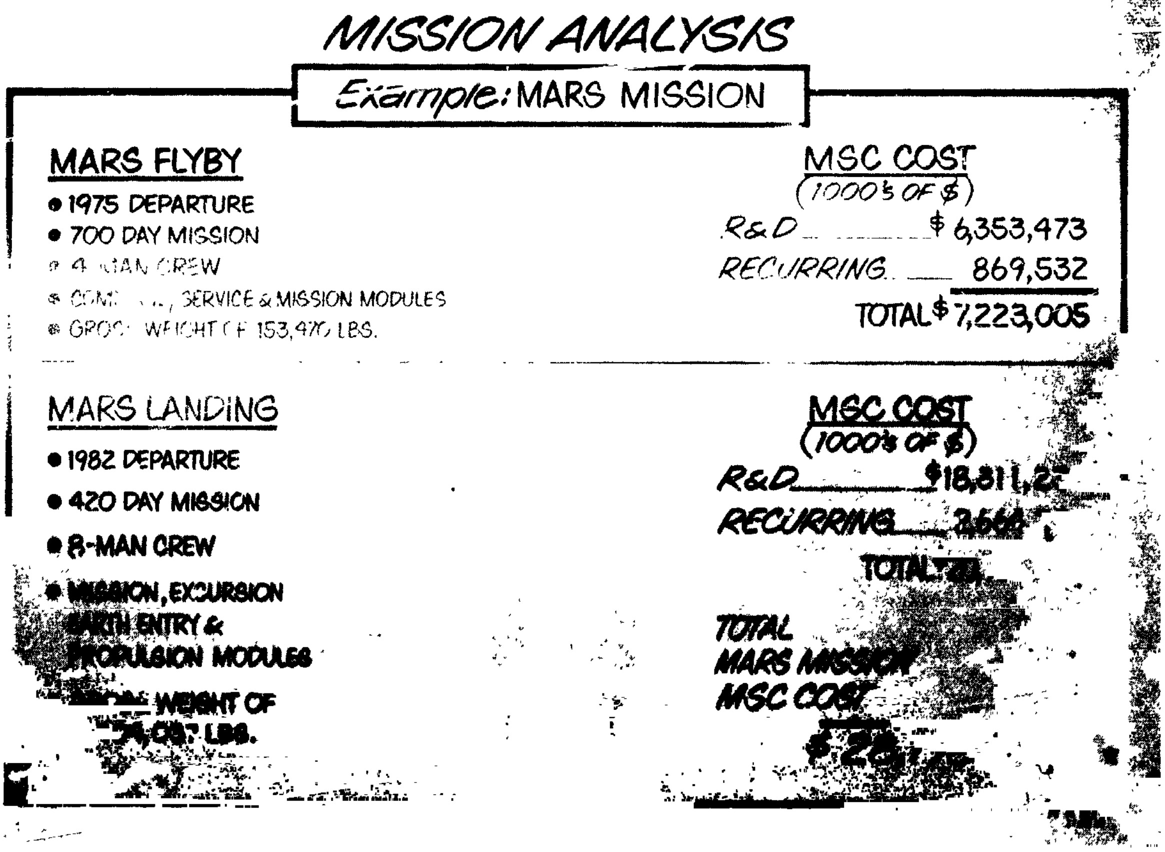
Use of the model can greatly facilitate mission analysis. In this area, the model may be used in the following possible applications:

1. Establishment of the costs of competing missions which are equally attractive on other grounds

2. Assessment of economics resulting from using the "building block approach" to performing a given mission

3. Evaluation of specified mission modes.

An example of the latter application is shown in the next figure. Presented in Figure 4-5 are the results of model estimates of the cost of one approach to performing a manned Mars mission: a Mars flyby which is followed by a Mars landing expedition. Figure 4-6 (reproduction of output of the model) depicts major spacecraft elements and their costs for the landing expedition.



MISSION ANALYSIS

Example: MARS MISSION

MARS FLYBY

- 1975 DEPARTURE
- 700 DAY MISSION
- 4-MAN CREW
- COMMAND, SERVICE & MISSION MODULES
- GROSS WEIGHT OF 153,470 LBS.

MSC COST
(1000's OF $)
R&D .... $ 6,353,473
RECURRING 869,532
TOTAL $ 7,223,005

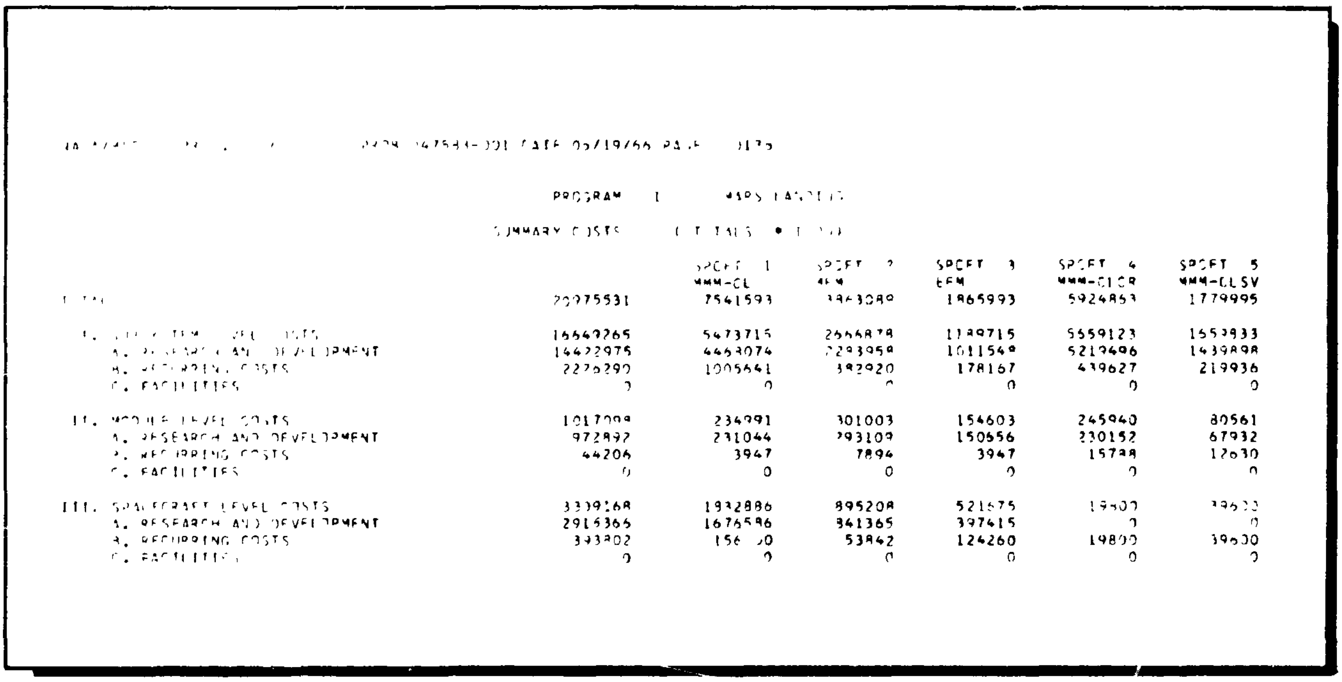
MARS LANDING

- 1982 DEPARTURE
- 420 DAY MISSION
- 8-MAN CREW
- MISSION, EXCURSION EARTH ENTRY & PROPULSION MODULES
- [illegible] WEIGHT OF [illegible] LBS.

MSC COST
(1000's OF $)
R&D .... $18,811,2[illegible]
RECURRING ...... 2,66[illegible]
TOTAL [illegible]

TOTAL
MARS MISSION
MSC COST
$ 28[illegible]

Figure 4-5



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                                        DATE 05/19/66 PAGE   0175

                                   PROGRAM  I        MARS LANDING

                             SUMMARY COSTS      ( TOTALS  •  1966)

                                             SPCFT  1    SPCFT  2    SPCFT  3    SPCFT  4    SPCFT  5
                                             MMM-CL      MEM         EEM         MMM-CLCR    MMM-CLSV
TOTAL                               22975531  7541593     3963089     1865993     5924853     1779995

  I.  SUBSYSTEM LEVEL COSTS         16649265  5473715     2666878     1189715     5559123     1553933
      A. RESEARCH AND DEVELOPMENT   14422975  4463074     2293959     1011549     5219496     1439898
      B. RECURRING COSTS             2226290  1005641      382920      178167      439627      219936
      C. FACILITIES                        0        0           0           0           0           0

 II.  MODULE LEVEL COSTS             1017099   234991      301003      154603      245940       80561
      A. RESEARCH AND DEVELOPMENT     972892   231044      293109      150656      230152       67932
      B. RECURRING COSTS               44206     3947        7894        3947       15788       12630
      C. FACILITIES                        0        0           0           0           0           0

III.  SPACECRAFT LEVEL COSTS         3339168  1932886      895208      521675       19800       39600
      A. RESEARCH AND DEVELOPMENT    2916366  1676596      841365      397415           0           0
      B. RECURRING COSTS              393802   156  0       53842      124260       19800       39600
      C. FACILITIES                        0        0           0           0           0           0
```

Figure 4-6

4.4 CENTER PLANNING

The model also provides NASA with a center planning capability by means of which long range center personnel estimates can be obtained in a fraction of the time required by usual methods. Thus the model permits the rapid estimation of changes in personnel requirements which have come about from changes in either (1) the composition of spacecraft programs managed by MSC or (2) Center policy on both of these factors. The output of the model is characterized as being fitted to functional lines and as being in sufficient detail so that it can be matched with the current MSC organization.

4.5 FUNDING APPLICATIONS

Through the use of the model, consideration can be given to the funding implications of a mix of both current and future programs; thus the model provides a tool for integrating long range technical planning with financial planning. Although the model does not provide the detailed funding data required for program control purposes, it can provide information for use in answering questions that are frequently asked of NASA program control offices. An example of this application is shown in Figure 4-7. In this figure, model outputs of the annual expenditures for a Mars flyby mission have been imposed on Apollo program estimates. As a result of relatively minor changes in inputs, other funding measures (such as new obligational authority or commitments)could be generated on an annual or semiannual basis for the program mix shown in the example.

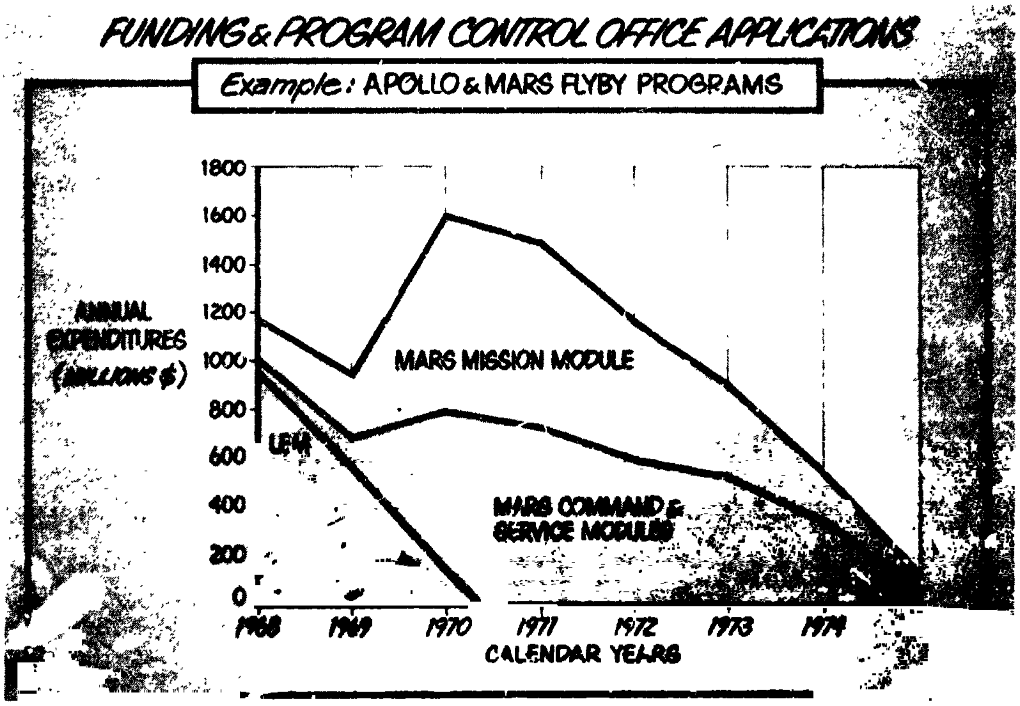

Figure 4-7

5.0 RECOMMENDATIONS FOR FUTURE STUDY

Five months of checkout have verified the fact that the model structure is fundamentally sound. However, preliminary investigations by General Dynamics indicate that additional work on most of the model's estimating relationships seems to be warranted. Although the current relationships are the best available, additional effort could profitably be spent on refining the relationships through the process of further filtering of the data from which the relationships were developed. The following steps should be taken:

1. Continue analysis of the division between variable and non-variable costs.
2. Further analyze module and spacecraft level costs and, in particular, GSE costs.
3. Evaluate all CER's with respect to the implications of advanced technologies.

Although there is convincing evidence that operation of the program is satisfactory, use of the model would be enhanced by making minor alterations to provide additional gross spreading functions and to incorporate a print/plot submodel.