# THE DYNAMICS OF R & D PROJECT MANAGEMENT

by

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Submitted to the Alfred P. Sloan School of Management on May 15, 1970, in partial fulfillment of the requirements for the degree of Master of Science in Management.

## ABSTRACT

A simulation model is developed which is capable of representing the dynamic behavior of large, high technology R & D projects, such as are found in the aerospace industry. The model is based upon the Industrial Dynamics techniques developed by Prof. Jay Forrester, and builds directly upon an unpublished M.I.T. Master's thesis by Joe N. Nay, which in turn was based upon a book by Prof. Edward B. Roberts. It represents an overview of project operations, and their interactions with other areas of the firm, and with sub-contractors and the customer agency.

A single project model is created initially, and is verified by: (1) Examination of each of its functional elements against observed operational patterns; (2) Reproduction by the model of historical data from an actual R & D program, when given the real program's initial inputs; and (3) Demonstration of qualitatively reasonable response by the model to inputs lying outside the range of common experience. The model accurately reproduces the past history of an actual program over a seven year timespan, and provides useful insight into basic program dynamics.

The model suggests that a built-in critical period exists on all such programs, resulting from initial underestimation of program scope, and from early over-estimation of program progress, which is gradually corrected. Management response which attributes this critical period to lack of effectiveness of project personnel tends to act in a manner to aggravate the problems. The model also shows the extremely important nature of the scheduling decisions which are made during the project's first year, and which determine its future progress.

The single project model is used to investigate a number of management variables. The management's firmness in adhering to published schedules is shown to be a major factor in attaining good performance. Customer funding criteria and performance, and initial facility availability are also quite important. The performance

ABSTRACT (CON'D.)

of the project, however, is surprisingly insensitive to delays in many of the information channels.

The model is then expanded to handle two projects. Verification is again demonstrated by reproducing the past history on the actual spacecraft project, which was the baseline for the single project verification, and a contemporary aircraft development project. The two project model is then used to examine the effect of certain management variables. It is shown that efficient limits exist for both the maximum allowable overtime on the projects, and the firm's maximum rate of hiring personnel. Little effect on project performance results from increasing the allowable overhead within the firm. The system is shown to be tolerant of serious underestimation of project scope by the firm, but improved estimation of scope by the firm must be accompanied by a corresponding increase in perception of project value by the customer, or else project performance suffers. The customer's control of the project is shown to be slow to implement project cancellations, but is relatively insensitive to externally-applied pressure for budget cuts.

It is concluded that the dynamic simulation technique has value in providing project management with insight regarding the functional interactions which occur within the project, and between the project and its environment. The model presented herein can be used to assess overall effects of basic changes in project, firm, and customer management policies. It can be modified as required to address specific questions of interest to managers and planners.


Thesis Supervisor: Edward B. Roberts
Title: Associate Professor of Management

# ACKNOWLEDGEMENTS

This thesis would not have been possible without the help and encouragement of the following people:

Prof. Edward B. Roberts, who initially aroused my interest in the technique of Industrial Dynamics management simulation modeling, and who provided guidance and useful suggestions throughout the performance of the work; A.L. (Jack) Pugh III, who spent much time and effort educating me on the intricacies of Dynamo programming, and who intervened directly on several occasions to de-bug the model; Prof. Jay L. Galbraith, who performed a useful critique of the draft. Thomas McKessey and Joseph Stalk provided the actual project data which were used to verify the model, and aided me in interpreting these data in terms of the simulation model. Joseph N. Nay wrote the thesis which I used as a starting point for my work, and generously provided his model's computer card deck, which I used to create my first model file. The computer calculations were performed on the IBM System 360/67 operated by the M.I.T. Information Processing Center, and their efficiency and cooperation were most helpful. The thesis was typed by Sandra Lounsbury.

My sincere thanks are extended to all who helped with this thesis, the preparation of which I have found to be a useful educational experience. To my wife Joan, whose patience and understanding supported this effort, as all my endeavors, this volume is dedicated with love.

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# CHAPTER I -- INTRODUCTION AND SUMMARY

## A. HYPOTHESIS

The hypothesis of this work is that a useful Industrial Dynamics management model of large research and development (R&D) projects can be constructed. Such a model can also be used to improve the effectiveness of management, in the method described by Forrester[1], but demonstration of this use is outside the scope of the current thesis effort.

## B. PROBLEM STATEMENT

The problem is to investigate management policies which influence the success or failure of large research and development (R&D) projects, such as are commonly found in the aerospace and electronics industries. The type of management variables to be investigated include the following:

1. Manpower policies and controls: Hiring and firing policies, useage of overtime, procedures for corporate control of project manpower requests and for assignment of resources to projects.

2. Information utilization: Delays and inaccuracies in

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1. Jay W. Forrester, Industrial Dynamics, Cambridge, M.I.T. Press, 1961, pp. 1-46.

information channels used in decision-making; primarily in the estimation and reporting of progress on the project, perception of project scope and value.

3. Management attitudes affecting policy: Firmness in adhering to official schedules, interpretation of progress information in terms of the effectiveness of the project team, policies regarding company-funding of project effort.

4. Subcontractor management: Delays in placing subcontracts, funding policies for subcontractors, subcontractor performance and effectiveness.

5. Facilities: Delays in acquisition, procedures for allocation to projects, effect on project performance.

6. Customer policies: Project funding criteria, delays in funding, criteria for project cancellation or restriction, evaluation of project ultimate cost and value.

7. Project interactions: Effect of one project on another within the company, in terms of project performance (cost, schedule, manpower utilization).

To approach this rather broad range of management policy variables, I shall adopt the viewpoint of the R&D project manager within the prime contractor firm. Hence, the primary focus is on the performance of the project: its cost, schedule, manpower utilization, customer satisfaction, productivity, etc. The way in which the management policies listed above interact to affect project performance is of great interest. Since the project cannot exist by itself, however, but is a part of the total firm, the overall health of the firm is also important. Hence, total employment and sales for the firm are examined as a consequence of different situation of multi-project operations.

The problem statement then becomes: From the viewpoint of an R&D project manager, determine which management policies are most likely to be effective, in terms of project performance and corporate stability.

## C. APPROACH

The approach to be taken in this thesis is as follows:

1. Build upon existing work wherever possible, and avoid "re-inventing the wheel".

2. Create an updated model of the management of large R&D projects. The model should be capable of expansion to cover multi-project operation, thus representing the situation in a typical aerospace company.

3. Verify the model by observing its ability to reproduce past history of a real project whose details are well-known to the author.

4. Investigate the effect of parameter changes and of management policy variables on the performance of the modeled project.

5. Expand the model to cover two projects, occuring either simultaneously or sequentially.

6. Examine the effect of various parameter and management policy changes on the company's operations with two active projects.

7. Based upon this investigation, recommend means for making this model a useful tool to test and aid the selecttion of management improvements in practice.

## D. SUMMARY DESCRIPTION OF MODEL

The simulation model which has been constructed to investigate R&D project management problems is an Industrial Dynamics model of the type developed by Prof.'s Forrester,[2] Pugh[3], and Roberts[4]. The particular model is directly built

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2. Jay W. Forrester, Industrial Dynamics, op.cit.

3. Alexander L. Pugh, III; Dynamo Users Manual, Cambridge, M.I.T. Press 1963, second edition, with Chapter 2 replaced by M.I.T. Sloan School of Management Memo D-1000-3 "Reference Manual", dated June, 1969.

4. Edward B. Roberts, The Dynamics of Research and Development, New York, Harper & Row, 1964.

upon a similar model developed for a thesis by J. N. Nay[5]. The workings and construction of the model are explained in progressively greater detail in the text and the Appendix of this thesis; at this point the reader is given a general orientation and a top-level overview of the model.

In keeping with the Industrial Dynamics type of model, this representation of R&D projects focuses on the primary decision points within the project organization. The decision points are then examined with respect to: What is being controlled; upon what information is the control decision based; what decision criteria are imposed upon the information; how much delay and perception error exists in the information used for the decision process? Decision points are represented in the model as flow rates; quantities being controlled are levels; and information is generally represented by auxiliary variables. The model is constructed by viewing the actual workings of the project organization in the above terms, and establishing which variables exist in cause/effect or feedback relationships by virtue of experience with the functioning of the real organization.

The model aggregates a stream of transactions and events over time as a continuous flow process. Hence, it neces-

5. Joe N. Nay, "Choice and Allocation in Multiple Markets; a Research and Development Systems Analysis", unpublished Master of Science Thesis, M.I.T. Sloan School of Management, June, 1965.

sarily takes a "big-picture", overall view of the project management process. The model deals in terms of gross variables of interest to the project manager, of which the following brief list is a partial example:

Input variables: Intrinsic value (IVPT), Initial schedule completion (SCOP), Initial manpower on project (TMOP), Initial available facilities (APCE), initial estimated cost (ECCP).

Output variables: Perceived required effort (PREP), Customer's cost (CSCP), Firm's cost (FSCP), Total men on project (TMOP), Subcontractors' men on project (SMAP), Overtime used on project (OTUP), Scheduled completion (SCOP), Percent completion (PCC), Perceived technical effectiveness (TEAM).

The model is divided into the following major sections:

Central Sector (Wholly within the firm)

Normal Operating Section

Independent R&D Section

Project Sector - Lying with the firm

Project Sector - Lying with the customer

Value Sector - Joint firm/customer

Subcontract section - Joint firm/subcontractors

Each of these sectors is in turn broken down into a series of inter-related functions, called macro functions. There are 22 macro functions in the complete model, and together they describe mathematically the workings of all the above listed sectors. Fig. A-1 in Appendix A shows all the macros which comprise the model, and their principal inter-relations. The inter-relationships are indicated by the connecting lines and arrows, with the mnemonic names assigned to the inter-connecting variables indicated above the line. The variable names are defined in Appendix B, Detailed Description of Single-Project Model, together with a line-by-line explanation of the entire model printout.

As shown in Fig. A-1, the macro functions carry names which indicate variables of significance to project management, such as: Progress, Project Manpower, Schedule, Firm's Cost, Desired Manpower, etc. In typical Industrial Dynamics style, the variables and the macro functions are given descriptive names meaningful to practical managers, which portray semantically the functions which the variables perform. Thus, the judgement of experienced managers can be used to evaluate the validity of the model from the detailed description given subsequently, since the model is described in familiar terms.

Two basic versions of the model are presented: A single project model, in which the contractor firm's operations consist of a single R&D project; and a two-project model, where two projects exist within the firm. The two-project model exists in both a simultaneous version, where both projects begin together, and a sequential version, where the second project begins after the first has been underway for some time.

The model assumes that the projects are highly developmental, and hence, the true scope and cost is unknown intially, but is gradually revealed as work progresses. Close cooperation and information exchange between customer and contractor is assumed, and except for information delays and distortions due to perception, both customer and contractor are completely open and honest with one another.

An area of considerable interest to the project manager is the employment stability of his firm. This area is treated in detail in the model, and covers the following aspects of manpower utilization: The hiring process, the routine of manpower assignment within the firm, on-the-job training once men are assigned to the projects, and the process by which men are turned back from the projects into a central manpower pool, for reassignment to other projects or to company-funded R&D, or else to layoff from the company. When two projects are involved, the interactions between the projects and the firm's central manpower pool can be examined. The time lags and costs associated with all the above functions can also be determined.

The model uses a summary, aggregate treatment of the scheduling process throughout, which is adequate for studying overall management policies like those considered herein, but would not be satisfactory for examination of more detailed scheduling rules. The model does show good agreement with the officially-published schedules for the completion of the program, but it makes no attempt to consider intermediate milestones. For closer examination of scheduling rules, a different modeling technique would be required, which would allow consideration of discrete events, rather than an aggregate stream of activity flow, as in the current model.

For example, the present model does not consider the disruptive effects which slippage of one intermediate schedule milestone may have upon another milestone, which depend upon the output of the first event. In R&D projects, inter-relation between scheduled events is usually very close due to meshing of a myriad of program activities and events. Hence, the treatment of the present model is superficial in this area.

The model also assumes that no trade-off exists between schedule and product quality. This is a reasonable assumption for aerospace projects, where the highest quality level is necessary regardless of the required schedule. Product quality is controlled by large numbers of government and contractor inspectors, and quality requirements are generally not relaxed due to schedule delivery pressures. This situation may not always be true, however, and wherever it is different the possibility of a schedule vs. quality trade-off should be added to the model.

The model provides sufficient detail to allow treatment of the management policy variations given in the problem statement, but summarizes the resulting effects such that overall performance of the projects, and of the contractor firm, can be readily determined. Further description of the model, in progressively greater detail is given in Chapters II and IV and in the Appendices.

## E. SUMMARY OF RESULTS -- SINGLE PROJECT MODEL

### 1. Model Created and Verified

The model thus constrcuted has been verified by comparison with a large aerospace development project with which the author is intimately familiar. The reference project involved the design, development, production, and test of a large, complex manned spacecraft, which was intended to perform a unique and previously impossible mission of space exploration. Excellent agreement has been obtained between the performance of the model, given the input condition at the start of the reference program, and the historical data on the same variables as measured throughout the history of the real program. This agreement has been verified over a seven-year project time period. The model has also shown excellent stability of operation, in that it is not easily distorted by minor changes in the input parameters. Various sensitivity analyses have shown that the model behaves in an explainable and understandable fashion, as various parameters are modified.

The results of the verification runs are summarized in Figures 1 - 6, which compare model versus historical performance for the following principal variables: Total men on project, subcontractors' expenditures, customer's sunk costs, perceived required effort on project, scheduled completion of project, available facilities and capital equipment. The agreement is seen to be excellent, in that the trends are accurately reproduced in every case, and that in most cases, the absolute values of the parameters are correct within plus or minus ten percent. Forrester considers quantitative agreement to be excellent if it is within the factor of two.[6]

## 2. Management Variables Investigated

The project management model contains approximately 600 variable functions and specified constants, many of which represent management policies, or items under management control. During this investigation, it was possible to investigate only a relatively small number of these items, in the process of answering the broad question posed in the problem statement. 32 variables or constants were subjected to sensitivity analysis prior to validating the model. After model validation, the types of variables mentioned in the problem statement were reviewed, and certain of these were selected for more detailed investigation.

The management policies or variables which were studied are listed in Table 1, which also summarizes the results of each in briefest form. In most cases, the policy variables under study were changed while all other functions and constants were held fixed. The policies studied and the

6. Jay W. Forrester, Industrial Dynamics, op.cit., pages 115-129

TABLE 1

SUMMARY OF STUDY AND RESULTS -- SINGLE PROJECT MODEL

| POLICY | EFFECT ON PROJECT PERFORMANCE* | | | EFFECT ON CUSTOMER ATTITUDE |
|---|---|---|---|---|
| | COST | SCHEDULE | PEAK MANPOWER | |
| Manpower Control | 15% Higher | 22% Longer | 56% Lower | Unfavorable |
| Schedule Firmness | Slightly Lower | 23% Shorter | Much Higher | Favorable |
| Initial Perception of Scope | All Effort Lost | Project Cancelled | Much Lower | Very Unfavorable |
| Improved Perception of Progress (Improper M'G'M'T. response) | Higher | Much Longer | 52% Lower | Unfavorable |
| Perfect Perception of Progress (Proper M'G'M'T. response) | 2% Lower | Slightly Shorter | 19% Lower | Favorable |
| Initial Manpower | Negligible | Negligible | 5% Lower | Negligible |
| Initial Facilities | 8% Lower | 9% Shorter | 4% Lower | Favorable |
| Customer Funding Criteria | All Effort Lost | Project Cancelled | Much Lower | Very Unfavorable |

* Effect of increasing the variable over the range investigated, with other factors fixed.

Figure 1

Verification Results

Total Men on Project

Run 067V

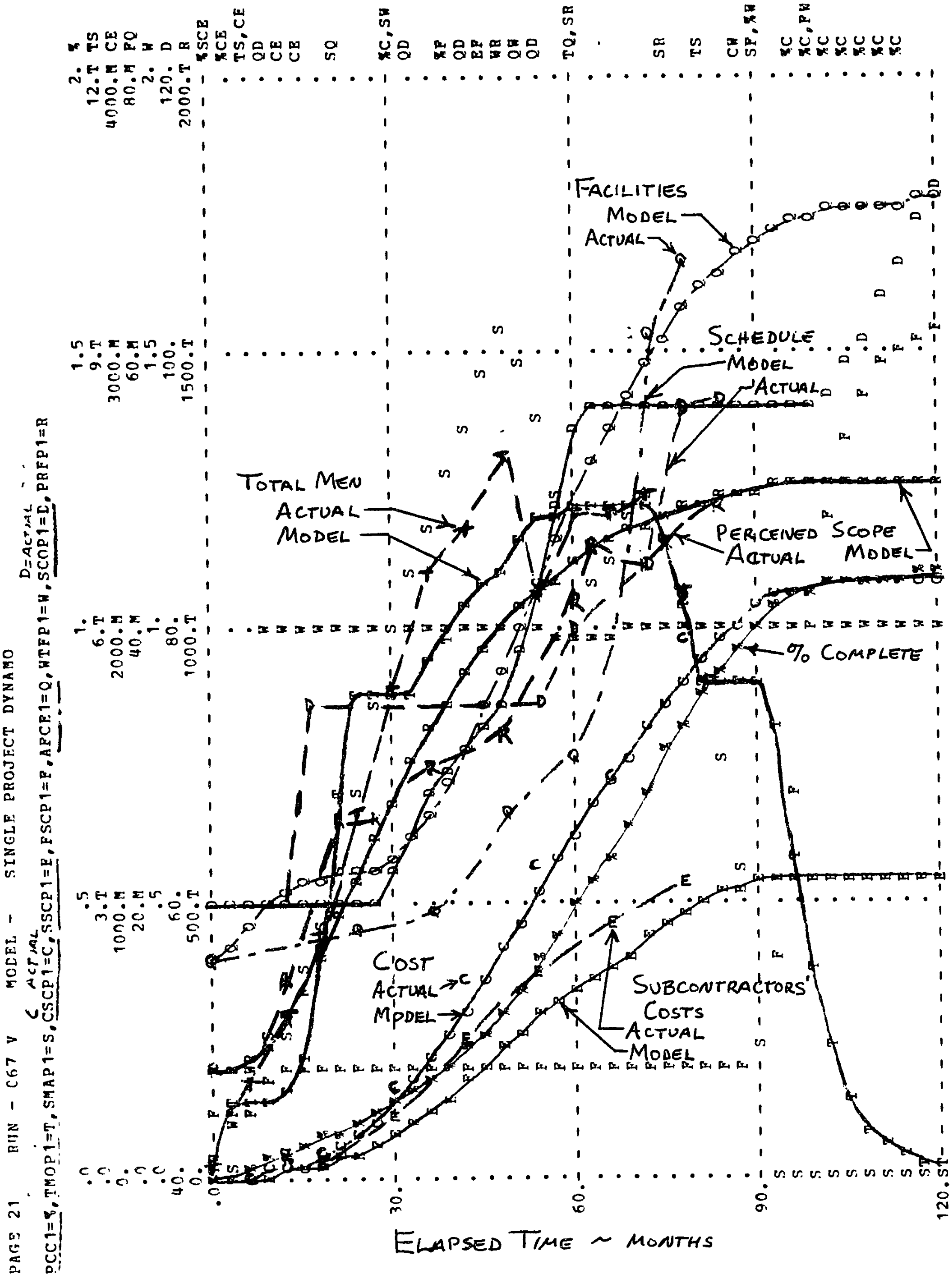


Figure 2
Verification Results
Scheduled Completion Date

Run 067V

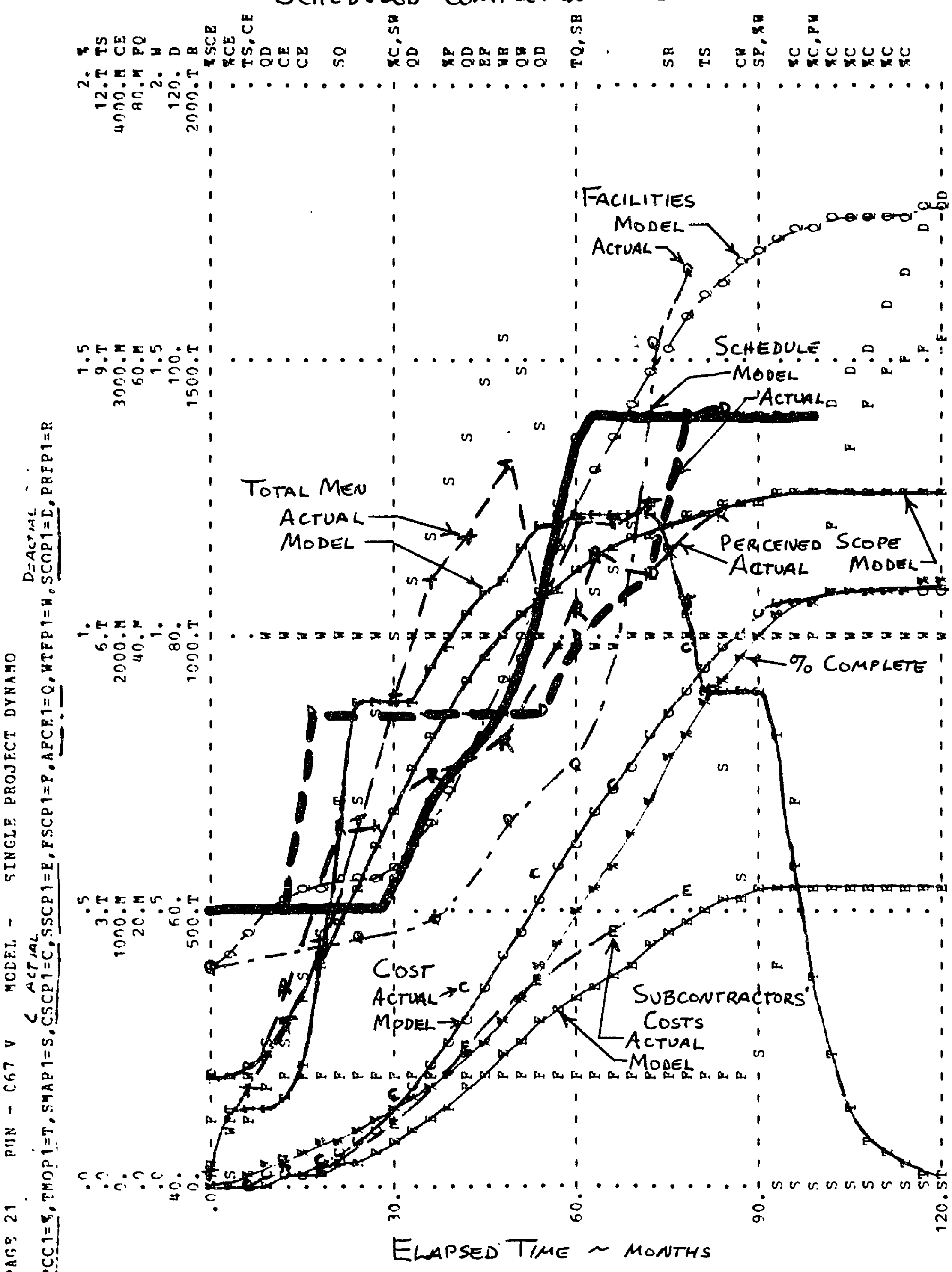
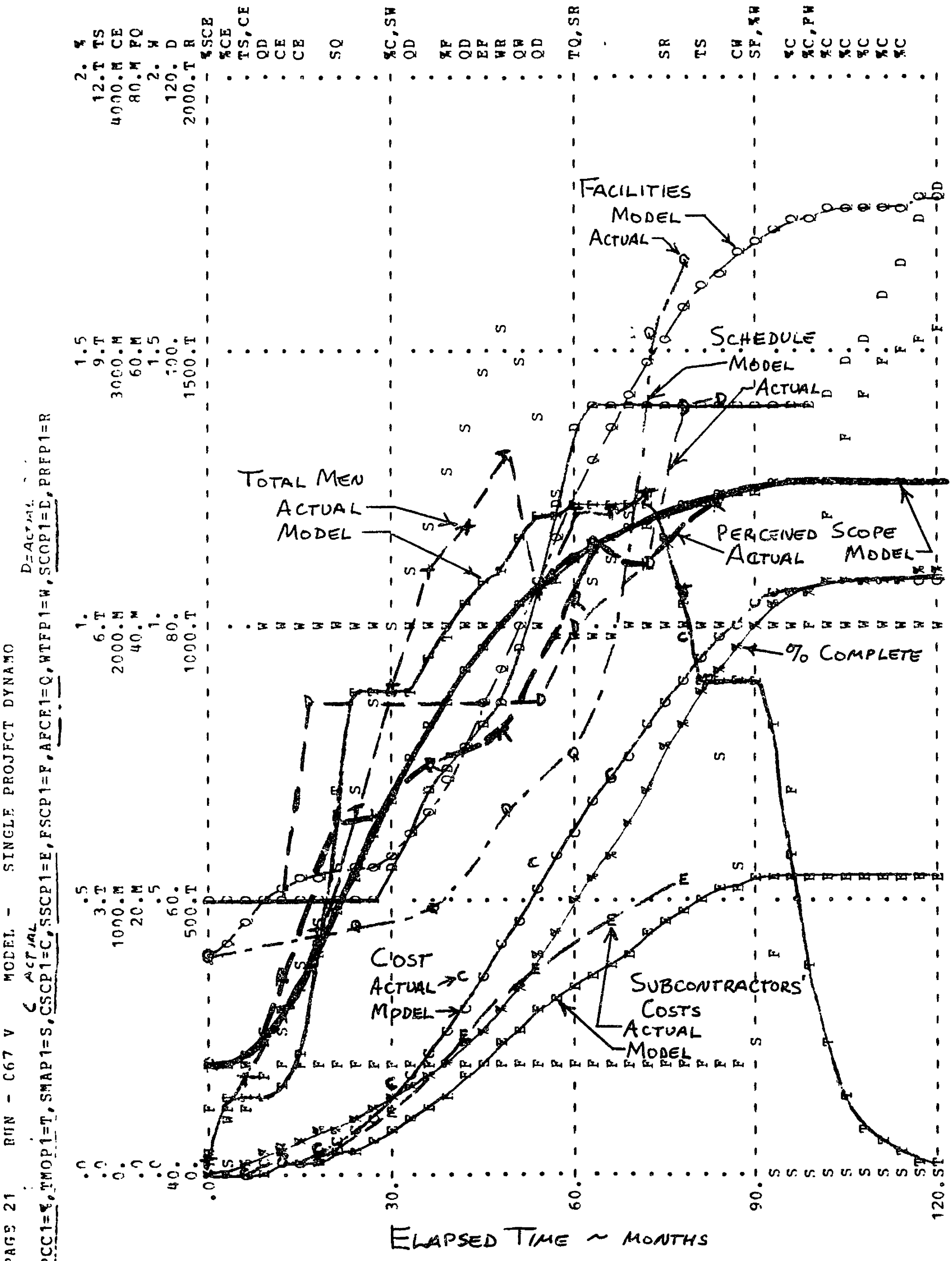


Figure 3
Verification Results
Perceived Required Effort Run 067V



# Figure 4
## Verification Results
## Customer's Sunk Costs

Run 067V

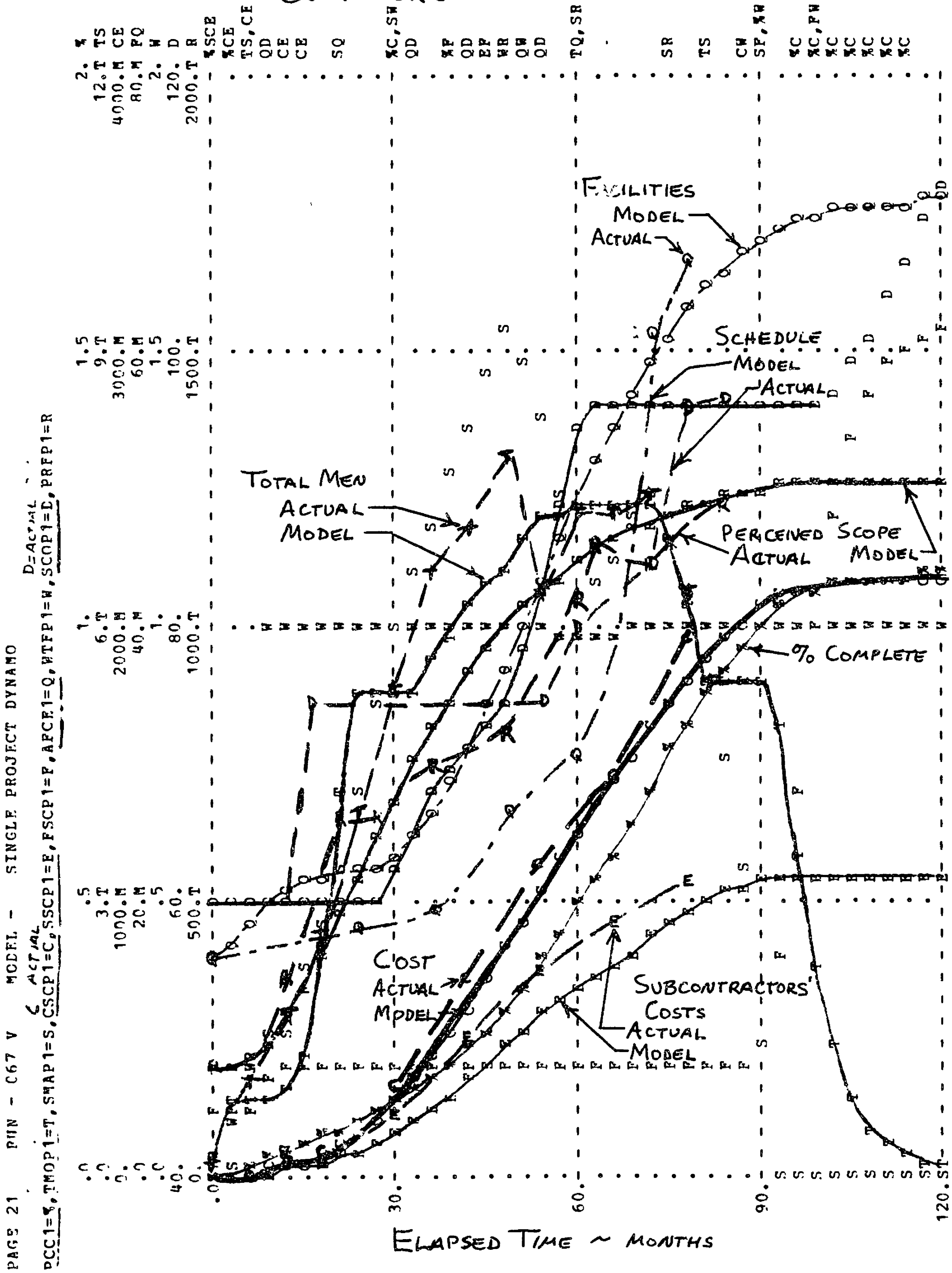


Figure 5

Verification Results

Subcontractors' Expenditures Run 067V

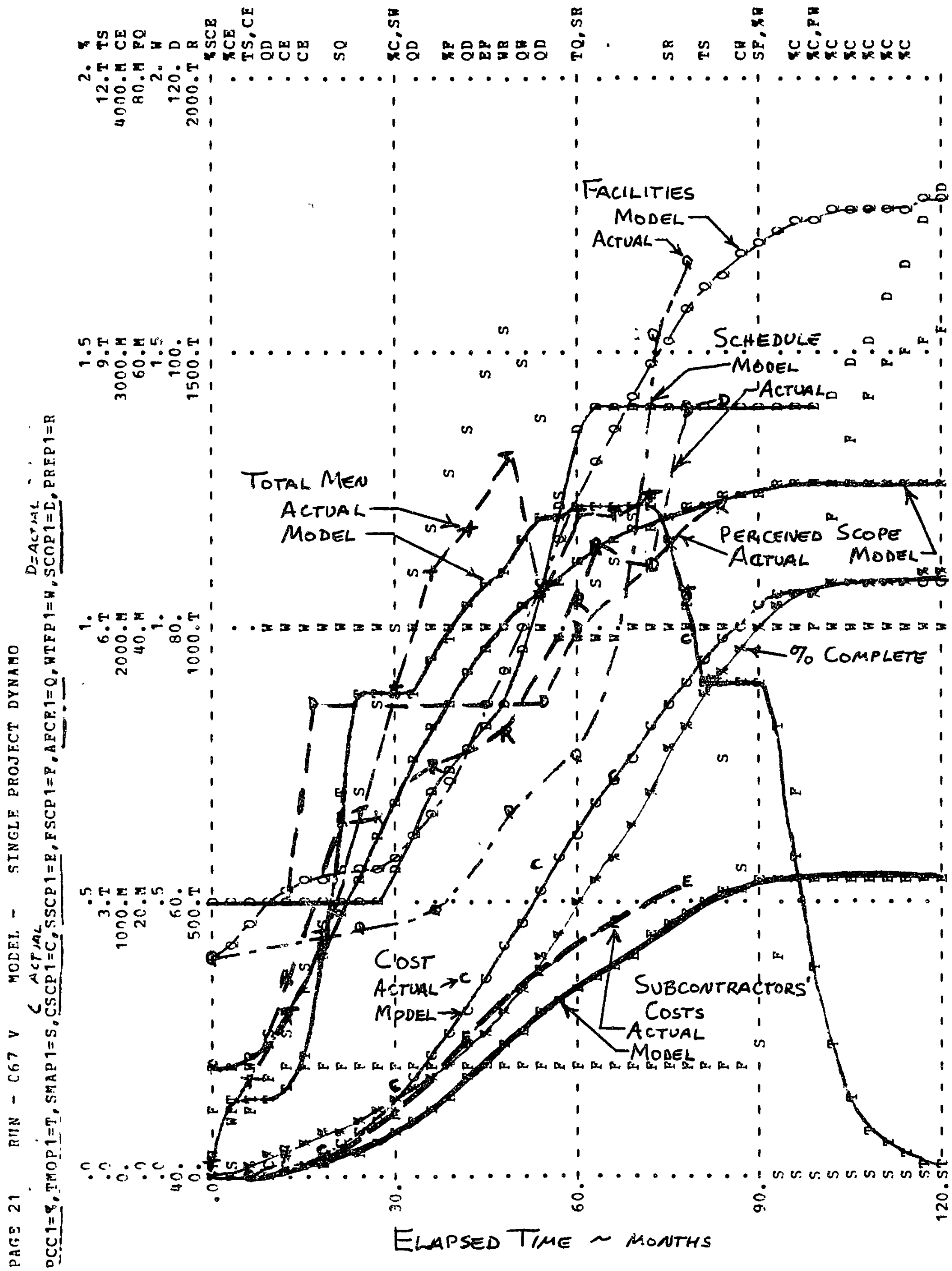
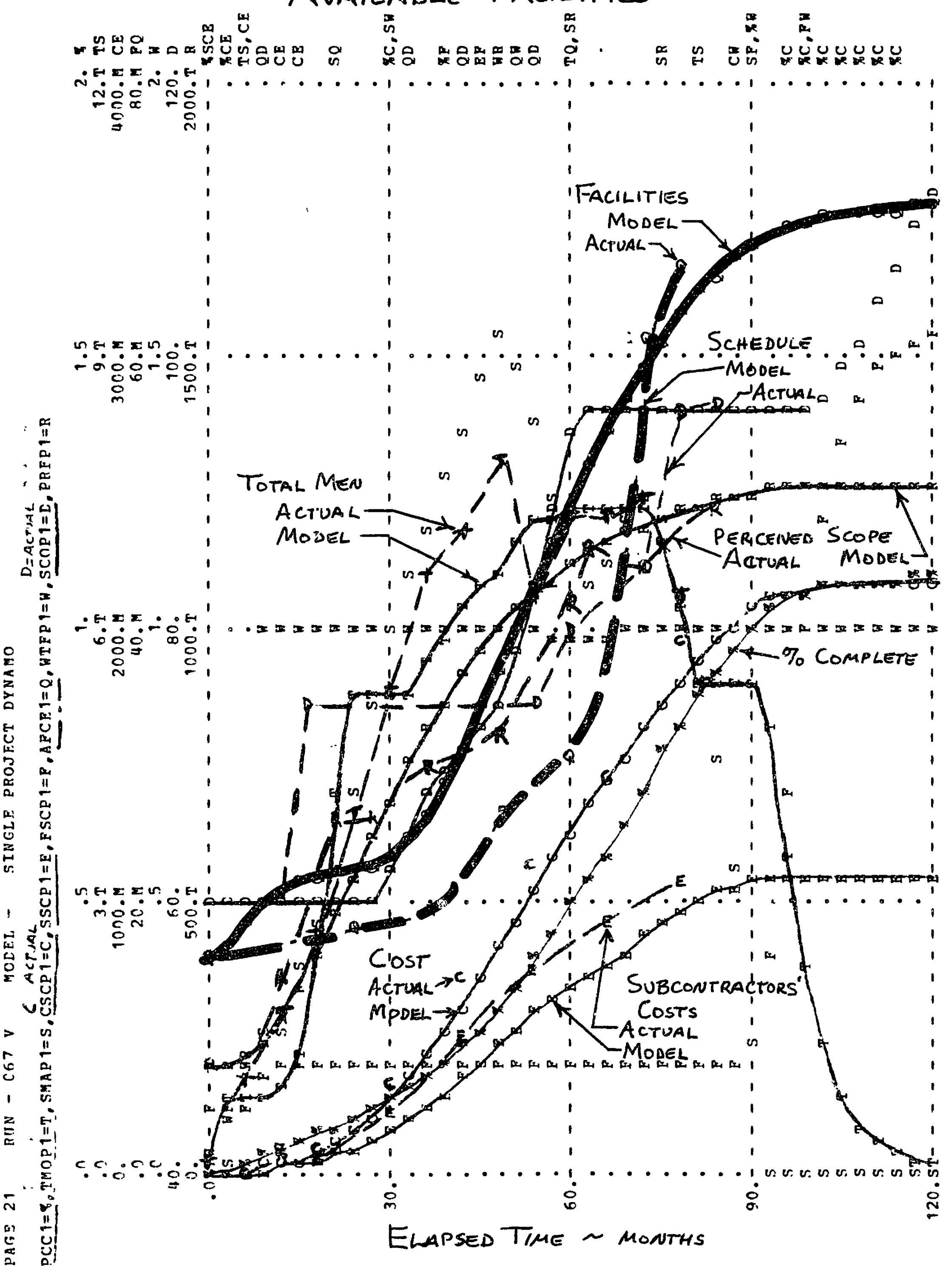


Figure 6

Verification Results

Available Facilities

Run 067 V



results obtained are described briefly in the remainder of this Introduction, and are presented in more detail in Cahpters III and V.

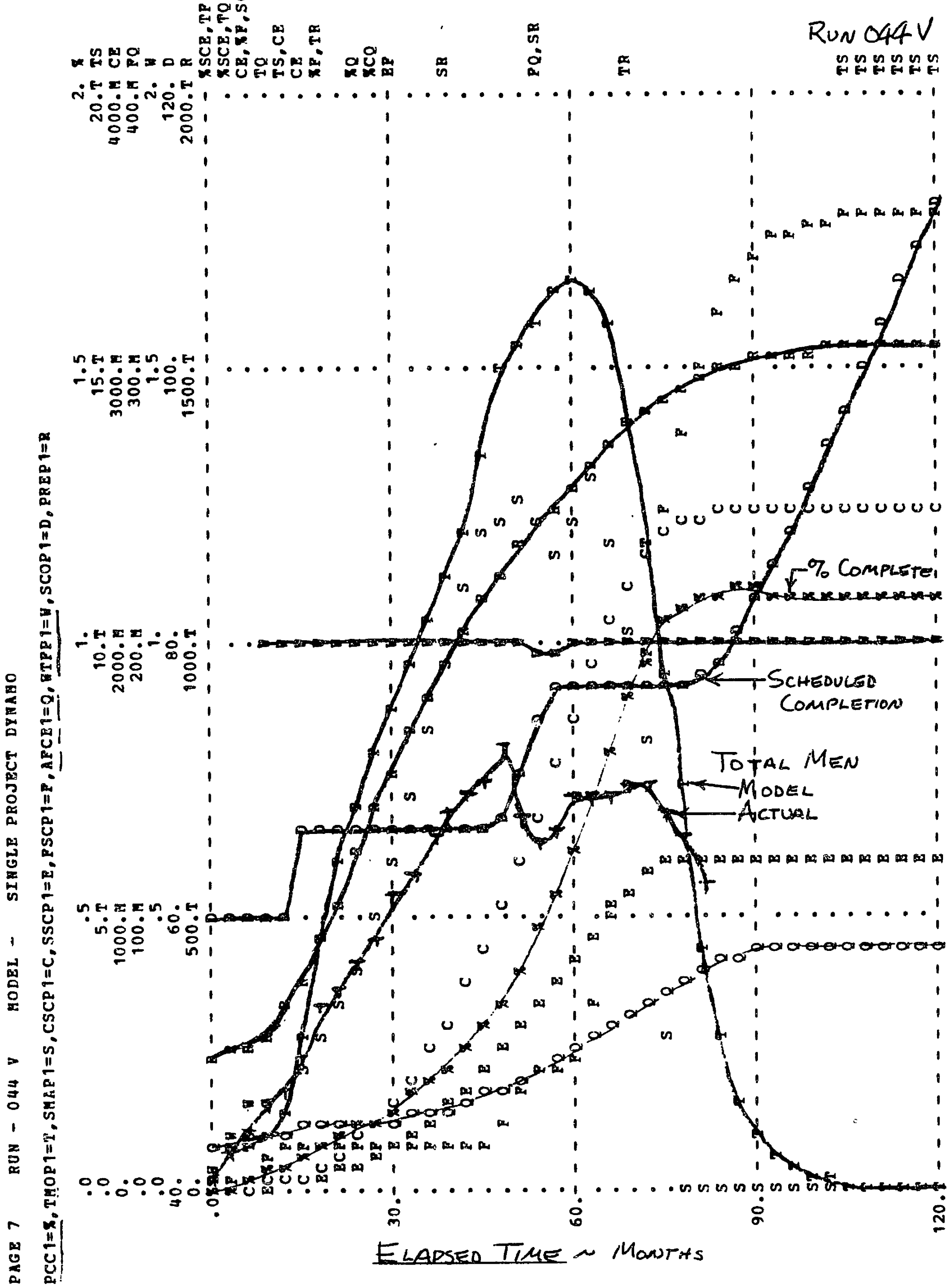
3. Results of Management Policy Studies

a. Manpower Control - A persistent problem during early runs of the model was that the model tended to produce a shorter, sharper peak of manpower applied to the project at the prime contractor's firm than was actually experienced in practice. Figure 7 shows a characteristic manpower curve for the prime contractor during these initial runs. A comparison with real project history shows that peak manpower is almost 100% too high. Numerous parameters were varied in an attempt to reduce the peak and flatten the manpower curve to agree more with real history. Such parameters primarily involve hiring policy and the delays in the hiring loop. None of these was effective in changing the basic shape of the manpower history curve. At this point, the model was carefully re-examined, and the author realized that a fundamental control function which existed in the modeled company had been omitted from the model.

The model basically assumed that when the project had contractual authorization to add manpower, these men were

Figure 7

Performance w/o Corp. Manpower Control



ultimately available, although some hiring delays intervened. This assumption neglected the corporate manpower control function in the modeled company; which acts to delay and minimize any sudden build-up in personnel. The manpower control function operates in two basic ways--it questions the project's need for additional people, and negotiates with the project the amount of additional people which shall be approved for hiring. Thus, the project never really gets all the people it thinks it requires. This manpower control function attempts to project manpower needs ahead into the future, and if the projected peak manpower requirement is of relatively short duration, e.g., six months or less, then manpower control will refuse to authorize additional men for such short-term build-up.

When a manpower control function, incorporating both of those features, was included in the model, a fundamental change in the shape of the manpower curve against time was observed. By adjusting the parameters, the very close match with past history, as shown in Figure 1, was obtained. This is a good example of the manner in which the Industrial Dynamics simulation model forces one to examine clearly the real functions which are operating within an organization.

b. Schedule Firmness

A constant dilemma facing both contractor and customer management on large development projects is the question of how firmly they should adhere to the officially published schedules, in the light of previously unknown technical problems and increases in the scope of the work which appears to render the original schedule unattainable. Several variations in schedule policy have been investigated with the aid of the model. The answer is always the same; Overall performance is enhanced, project completion occurs sooner, customer costs are less, and customer satisfaction is greater, whenever the greatest degree of firmness regarding the official schedule is maintained.

Table 2 summarizes the results of several runs in which schedule policy was varied. The variable Threshold For Changing Schedule (TFCS) is the ratio of the expected schedule slippage, as perceived at any moment in times, divided by the schedule time remaining to completion of the project. The greater this ratio, the more obvious it becomes to management that the official completion date will not be achieved. Values of TFCS=.333, .5 and .667 were investigated. In addition, the customer's relectance to change officially published schedules, represented by the parameter Delay in

TABLE 2

EFFECT OF SCHEDULE FIRMNESS ON PROJECT PERFORMANCE

| | Run # | Threshold for Changing Schedule | Delay in Changing Schedule-MO's. | Project Completion -Months | Cost at Completion -$millions |
|---|---|---|---|---|---|
| Compare | 048 | .5 | 6 | 86 | 2034 |
| | 049 | .667 | 6 | 79 | 2011 |
| compare | 067 | .25 | 6 | 90 | 2073 |
| | 078 | .25 | 12 | 78 | 2046 |
| compare | 062 | .5 | 6 | 74 | 2116 |
| | 063 | .333 | 6 | 96 | 2039 |

Changing Schedule (DICS), was also varied. As shown in Table 2, project performance is significantly enhanced by manintaining a consistently high value of the schedule threshold, and also by retaining a large delay in the cutomer's willingness to change officially published schedules. Note that the data from the real program, most closely corresponds to TFCS=.25, which is a relatively low value. This suggests that some improvement in the conduct of the real program could have been achieved if contractor and customer management had stood even more firmly against schedule slippages than they actually did. In view of the many real pressures which existed on schedule and the conduct of the program, such a statement is far easier to make than to carry out.

c. Perception of the Scope of the Job and of Progress

One of the changes introduced in the model was to recognize that the real scope of a large development program is unknown to the participants at the start of the program. Only as work progresses does the real dimension of the job gradually emerge. This is treated in the model by considering the Real Total Cost to Complete (RTCC), as an unknown fixed quantity. The initial Fraction of the Real Effort which is Recognized at the start of the program (FRER) indicates the percentage of the unknown RTCC which is recognized by the contractor and the customer as being the scope of the job at the time of contract award. This parameter (FRER) was varied, obtaining some interesting results.

The real project shown in Figures 1-6 had an initial Fraction of Real Effort Recognized (FRER)=.16. With this value, the model yields the curve of perceived required effort shown in Figure 3. Values of FRER=.4, .6 and .8 were also investigated. These results are summarized in Table 3. It is seen that project performance becomes progressively worse as the initial perception of the scope of the job improves. With FRER=.6 and .8, performance becomes so unsatisfactory that the project is cancelled by the customer before completion. The reason for this behavior of the model is similiar to that described by Roberts[7]. The reason for the reduced performance as the Perception of the Required Effort on the project improves at the beginning can be found by observing the slower build-up of the customer's Willingness to Fund the Project (WTFP). The customer's view of the intrinsic value of the project does not build up rapidly

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7. Edward B. Roberts, Dynamics of Research and Development, op.cit., pages 264-269.

TABLE 3

EFFECT OF INITIAL PERCEPTION OF SCOPE

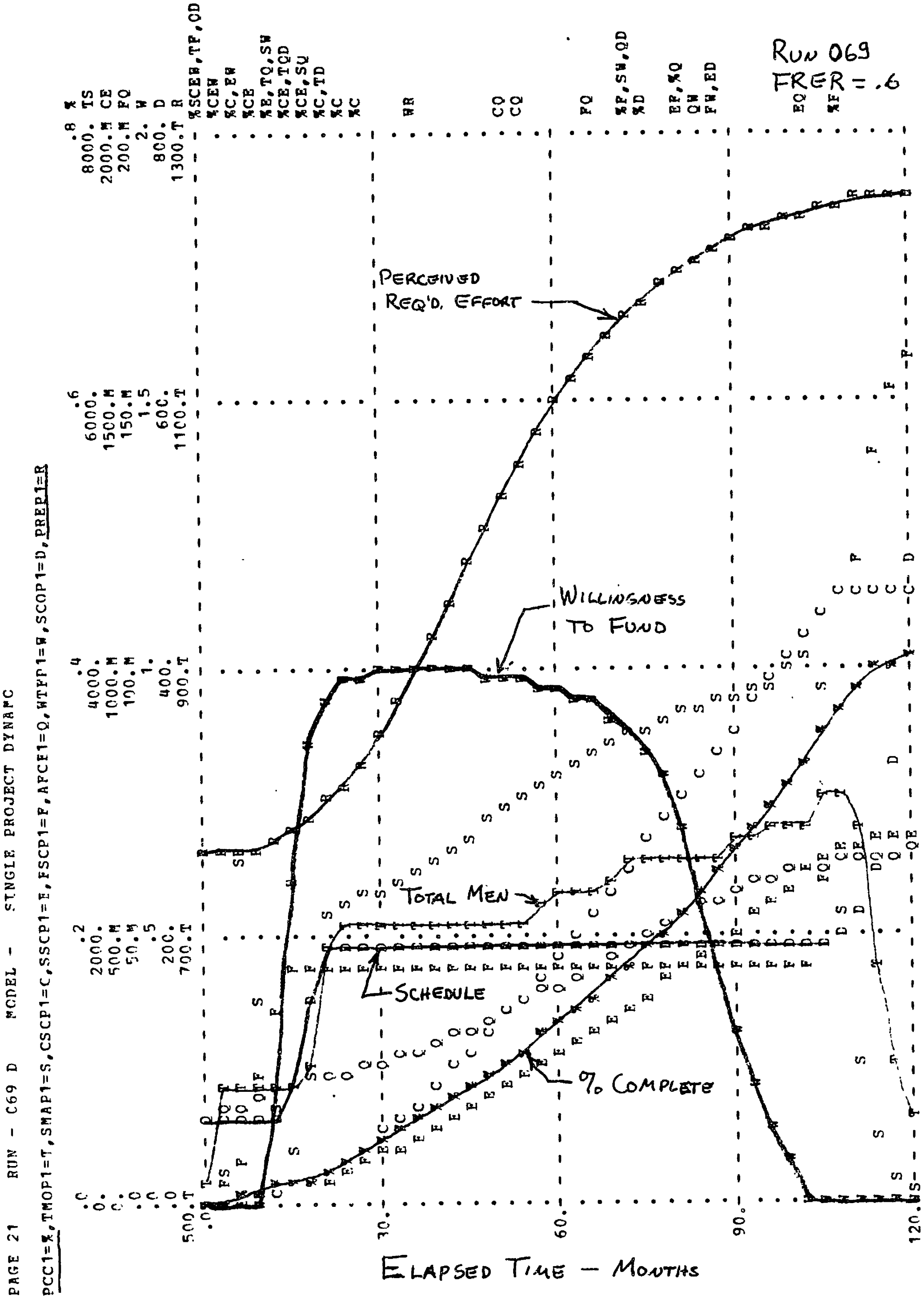
ON PROJECT PERFORMANCE

| RUN # | FRACTION OF REQ'D EFFORT RECOGNIZED | TIME OF PROJECT COMPLETION (C) OR SHUTDOWN (S) -Months | COST AT COMPLETION OR SHUTDOWN-$MILLION |
|---|---|---|---|
| 067 | .16 | 90 (C) | 2073 |
| 068 | .40 | 117 (C) | 2084 |
| 069 | .60 | 102 (S) | 1069 |
| 070 | .80 | 91 (S) | 437 |

enough in the early stages to offset a completely all-seeing perception of the total ultimate scope of the job. Thus the customer initially considers the value to cost ratio to be unacceptably low even after contract award, in those cases, where the perception of the total scope of the job is very accurate. He therefore delays committing himself heavily to funding and starves the project for manpower in the critical early stages where key schedule decisions are being made. This results in a long stretch-out of the schedule which the firm considers obtainable, and growing customer dissatisfaction which increases throughout the life of the program. These trends can be noted by following the variable WTFP for the case presented in Figure 8.

It can be argued that this effect is a real possibility, and that the lack of accurate value perception early in the program will result in such adverse effects on the project, if it encounters usually accurate perception of the required scope and cost of the program. Such a conclusion is rather unsatisfying, however, since this implies that all the effort devoted toward accurate precontractual cost estimation may ultimately work against the best interests of the project. It would probably be more accurate to say that additional effort is simultaneously required in working with the

Figure 8
Effect of Improved Initial Perception of Scope



customer to determine the real value of the program as early as possible, such that the customer may form accurate value to cost ratios even in the very early stages of the program.

Another variable which was investigated was the perception of progress as the project advances. The baserun (Figures 1-6) assumes a progress perception function which results in relatively poor perception of real progress early in the project. Not until the project is fifty percent or so complete does the perception of progress begin to approach the true progress. This is specifically shown by comparing Perceived Progress (PRP) with Cumulative Real Progress (CRP) on Figure 15. This situation appears to reproduce the behavior of the real project very well. The time at which perception of progress coincides with real progress occurs about five years from go ahead, and this corresponds to the first required spacecraft delivery in the real project. This was a hard milestone, readily identifiable, which made real progress visible to all.

Two variations in the representation of perception of progress were investigated. In the first, perception and reporting of progress were greatly improved by changing the function Fraction of Error Recognized (TFER) to provide earlier recognition of a greater fraction of the error in real progress. The delay in reporting real progress was also reduced to one week.

The results of these changes are shown in Figure 9. Although, real, perceived, and reported progress essentially coincide, the overall project performance is greatly reduced. Time of completion is stretched out to 164 months from go ahead, compared with 90 months for the baseline run. The reason is that the early perception of true progress, which is much slower than perceived progress would otherwise have been, causes early sharp reduction in management assessment of the Technical Effectiveness of the Average Man on a project (TEAM). This low value of TEAM persists throughout the life of the project, only gradually improving as real progress is noted, as shown on Figure 10. This is a completely different characteristic than that noted in all other runs, where the believed TEAM remains high until the perception of progress begins to agree with real progress somewhere in the middle of the program.

Since in this case the firm loses faith in the effectiveness of its own men, it sets much more generous schedule targets for itself and does not man up sufficiently to perform the project in a reasonable time period.

FIGURE 9

IMPROVED PERCEPTION OF PROGRESS

RUN 077D

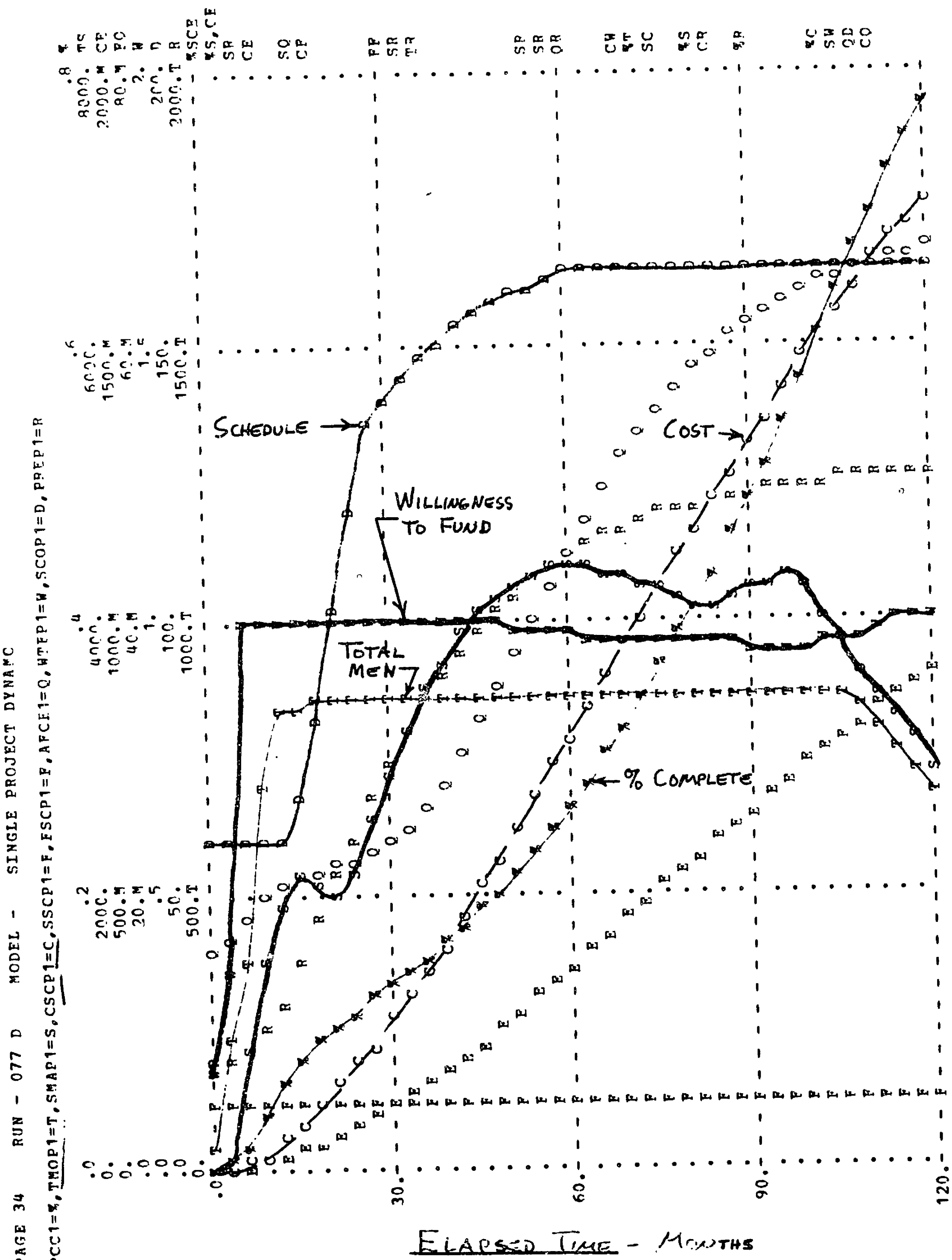
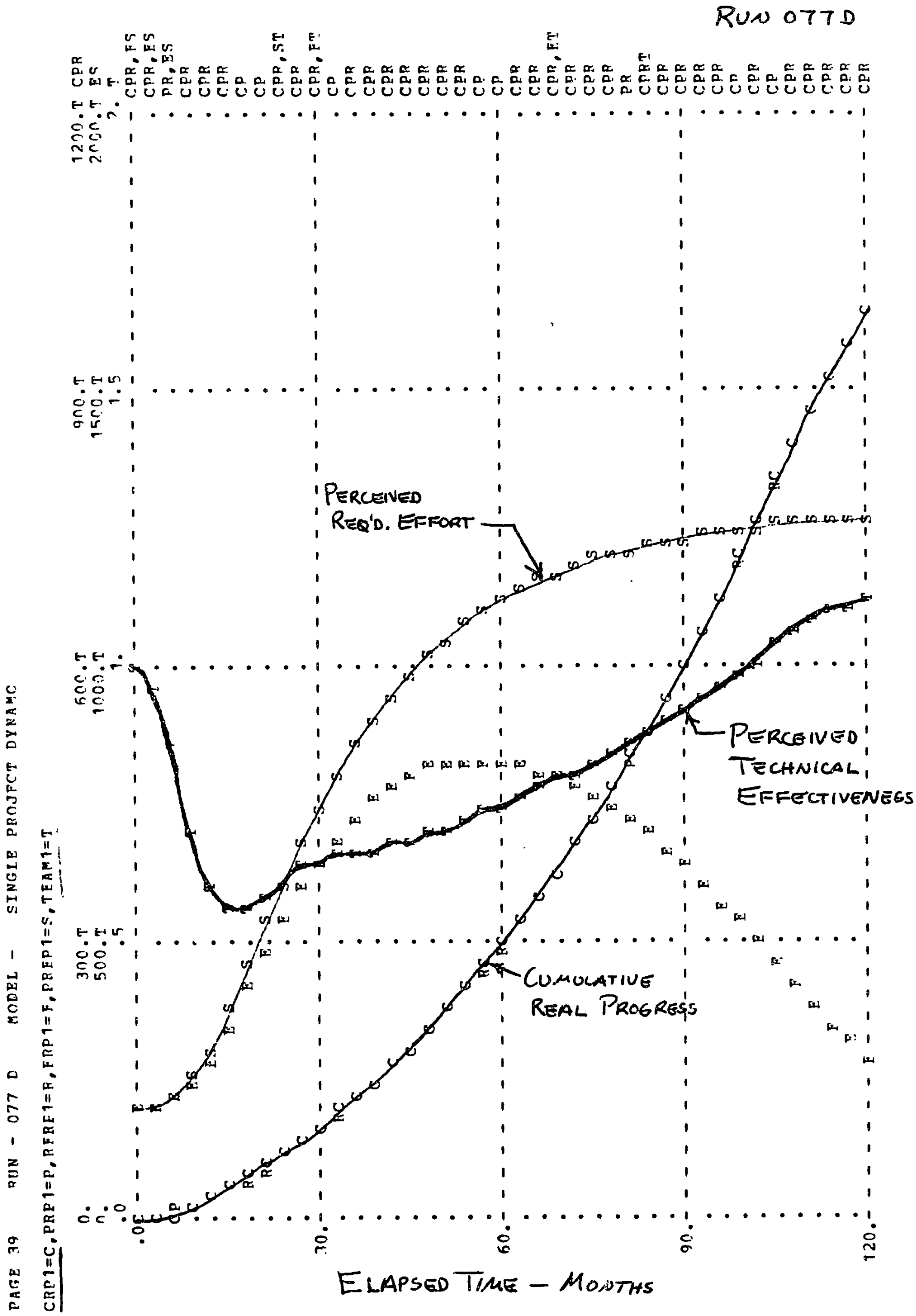


Figure 10
Improved Perception of Progress



In the next run, the model was changed to assure perfect perception and reporting of progress. That is, cumulative real progress equals perceived real progress equals reported progress (CRP=PRP=RERP). In addition, the TEAM function is held constant at 1.0. This represents a case in which the management, while observing accurately the slow initial rate of progress on the project, regards this as a normal situation and does not attribute it to unique lack of effectiveness of its project personnel. With this assumption the project performs very well; slightly better than the baseline run. In comparison with the baseline, the project is completed one month earlier and customer costs are reduced about two percent. This then gives us the value of perfect progress perception properly interpreted by management. However, the hazards of improper interpretation are clearly shown by the preceding results. Also note that the value of perfect progress information is small relative to the value of firmness in holding officially published schedules.

d. Initial Manpower and Facilities Available

The criticality of the level of manpower and of facilities initiall available was investigated and the results are summarized in Table 4. It appears that initial manpower level is not particularly critical, since a fourfold

TABLE 4

EFFECT OF INITIAL MANPOWER AND FACILITIES

| RUN # | INITIAL MANPOWER | INITIAL FACILITIES -$MILLION | PROJECT COMPLETION -MONTHS | COST AT COMPLETION -$MILLION | PRIME'S PEAK MANPOWER | FACILITIES AT COMPLETION -$MILLION |
|---|---|---|---|---|---|---|
| 067 | 160 | 15.7 | 90 | 2073 | 7270 | 68.2 |
| 073 | 640 | 15.7 | 89.5 | 2065 | 6943 | 68.2 |
| 074 | 160 | 31.4 | 82 | 1912 | 7000 | 65.3 |

increase resulted in little change in project performance. This probably results from the generous supervisory ratio (SR=40), which was assumed for the project consistent with the requirement of a crash manpower build-up.

The effect of doubling facilities is considerably more significant. Facilities influence the effectiveness of worker output through a Facilities Productivity Multiplying Factor (FPMF), which is a table function built into the model. Basically, this function says that management pays the penalty for being grossly under-facilitated. The magnitude of this penalty is a subjective judgement in most cases, particularly those involving office work; therefore the conclusion regarding the importance of early facility availability is only as good as the assumed value of this subjective function.

e. Customer Funding Criteria

The basic customer funding criteria assumed in the baseline run is a Return On Investment Criteria (ROIC=1.5). This number is used to divide the customer's perceived value/cost ratio for the project to determine the Suitability of the Project for Investment (SPIC). An index of one or greater means that the customer considers the project suitable for investment with the constraint of ROIC.

The results of varying ROIC are shown in Table 5. It appears that a value of 1.5 is reasonably optimum. For ROIC=1.0, the customer fails to express his displeasure with the slow progress of the project in terms of his willingness to fund the project (WTFP). As a result, the contractor does not take maximum corrective action when he perceives his real progress situation. The result is that with ROIC=1.0, schedule completion occurs three months later than the base-line, although cost to the customer is the same.

A higher value of ROIC=2.25 is disastrous. In this case, the intrinsic value of the project is never high enough to satisfy the customer's desired criteria, and a fairly early shutdown of the project occurs. Thus, it is seen that the customer must be quite careful regarding the goals he sets for his project in terms of required value to cost ratio, particularly in view of his woeful lack of accurate estimates for either value or cost early in the life of the program.

## 4.Other Factors Noted

### a. Built-in "time of troubles" at fifth year

One characteristic consistently shown by the model over a wide-range of input parameters is the existence of the built-in "time of troubles", which usually shows up about

TABLE 5

EFFECT OF CUSTOMER'S RETURN ON INVESTMENT CRITERIA (ROIC)

| | RUN # | ROIC | TIME OF PROJECT COMPLETION (C) OR SHUTDOWN (S) -MONTHS | COST AT COMPLETION OR SHUTDOWN -$MILLION | % COMPLETE AT SHUTDOWN |
|---|---|---|---|---|---|
| compare | 017 | 1.5 | 90 (C) | 2709 | --- |
| | 028 | 2.25 | 66 (S) | 685 | 12.6 |
| compare | 067 | 1.5 | 90 (C) | 2073 | --- |
| | 075 | 1.0 | 93 (C) | 2073 | --- |

sixty months from go ahead. In the case of the real project, this was a meaningful date since it corresponded to the first major hardware milestone, the delivery of the first flight spacecraft. However, in terms of the model the time of troubles results from the gradually improved perception of the scope of the job and the real state of progress on the job. Initially, management overestimates progress on the job. However, perception of progress gradually improves until in about the fifty year, faced with unmistakable hardware milestones, the real state of progress becomes known. Management tends to attribute the difference between its new perception of progress and its previous perception to a lack of effectiveness of the people on the project. This leads to the familiar call for more manpower during a critical schedule milestone period. It does in fact result in some increase in manning within the restrictions imposed by corporate manpower control. However, this crucial manpower period is really the darkness before dawn, since at this point the total scope of the program is quite well known. Subsequent increases in the Perceived Required Effort on the Project (PREP) tend to be small, therefore, the percentage complete increases at a much faster rate. (See, for example, Fig. 3.)

Coincident with the contractor management's loss of faith in the effectiveness of its own people, the customer is similarly losing faith in the desirability of the project. This is shown by observing the dip in the Willingness to Fund the Project (WTFP) function. As modeled, this is a very steep function, and customer behavior is quite sensitive at this critical time to the amount of reported progress on the project. In cases such as the baseline, the dip in WTFP recovers because of the high rate of reported progress which is visible to the customer. This function is very sensitive however, and with less progress the dip may continue to grow until the project is completely shut off, as for example in Fig. 8.

It is interesting for management to be aware that a crucial "time of troubles" is built-in to the typical large development project at birth due to the dynamics of the various functions we have discussed. By understanding the source of some of these pressures management can become more aware of effective means of dealing with them.

b. Criticality of Initial Scheduling Decisions

Another general characteristic of model behavior is the criticality of initial scheduling decisions within one year after contract go ahead. The model assumes that the firm and the customer do not undertake serious reevaluation of their project schedule commitments until about one year after contract go-ahead. This year of grace is a shakedown time in which the contractor and the customer get the job started and jointly grow in their understanding of the scope and requirements of the program. After about a year, however, they begin to review and critically question the schedule commitments which were established at the beginning of the program. They compare their perceived scope of effort remaining with the manpower on hand and approved or considered available. They then make estimates of their ability to complete the program within the required schedule, and begin to compute unofficial schedule discrepancies which are then evaluated against the Threshold For Changing Schedule (TFCS) previously mentioned. This activity is performed quite seriously at the start of the second year from go ahead. If the project has not been adequately supported and manned up to that time, or if the firm's perceived technical effectiveness of the average man (TEAM) is low; then the contractor may decide that the original schedule is unachievable and he may set a much more relaxed schedule as being his best possible effort.

Once a more relaxed schedule is set, it is never subsequently retightened; this is an empirical observation which has been built into the model. Hence the first year's operations have a profound effect on the whole subsequent shape of the program. For example, if the contractor has been unsuccessful in obtaining the manpower he considers necessary during the project's first year, either due to hiring difficulties or due to funding limitations imposed by the customer, he will retain a very pessimistic view of his ability to obtain additional manpower in the future. This view will directly influence his projections of attainable schedule performance. Hence a poor first year may lead firm and customer to set relatively relaxed schedules for the remainder of the program which will guarantee poor performance on the overall program. This is exactly what has happened in the case of impoved initial perception of the scope of the job shown in Fig. 8. Poor first year performance, in this case attributable to initial customer funding limitations, is used as a basis to project a very stretched out schedule as being the best obtainable.

The caution here for management is that the schedule reassesment period early in the program is of the greatest importance to the subsequent performance on the project. In general, the tighter the attainable schedules can be held, the better will be subsequent project performance, in terms of schedule, costs, and customer satisfaction.

c. Characteristics of Subcontractors' Efforts

The addition of an aggregated representation of all project subcontractors has significantly improved the model with respect to matching real program behavior. Subcontractors, taken as an aggregated whole, have three principal characteristics when compared with the prime contractor: (1) They get started on the job later, because the prime must define their tasks and go through a source selection process; (2) They have more freedom in manpower addition and deletion since, in general, the subcontractors have many smaller projects compared to the few large projects at the prime contractor; and (3) They are more expensive per man hour because of the greater specialization, plus the loading of their general overhead on top of their basic cost to the prime contractor. As shown in Fig. 5 the baseline model representation of total subcontractor cost on the project agrees quite well with real history. If anything, the model shows slightly more lag in subcontractor cost build-up than occurred in the real world. However, the great flexibility of subcontractor manpower addition and deletion is a most valuable adjunct to the representation of the prime contractor, who is less flexible in terms of adding and removing people from the job.

## F. SUMMARY OF RESULTS - TWO PROJECT MODEL

The basic single project model was later expanded to a two-project version. The expansion was obtained by simply duplicating the macro functional equations for the second project, and making appropriate changes in the manner of introducing initial conditions. Two versions of the two-project model were created: a simultaneous version, where both projects begin together, and a sequential version, where the second project begins after the first has been underway for some time.

In all cases, Project 1 represented the spacecraft program previously described. Project 2 was given inputs which represented two different aircraft development programs at the modeled company. For the simultaneous case, an aircraft program was chosen which actually began within two months of the real spacecraft program, or about 7½ years ago. The modeled company was a major subcontractor on this military weapons system development, and was responsible for a value of effort equal to about ¼ that of the spacecraft program. The initial required completion date for Project 2 was 80 months from go-ahead, as against 60 months for Project 1. The general shape of the intrinsic value function was similiar for both projects, although the peak level for Project 2 was about 1/3 that of Project 1.

For the sequential case, Project 2 was given inputs representing another aircraft development program which began under contract about 6 years after the start of Project 1, or about 1½ years ago. In this program the modeled company is the prime contractor, responsible for a total program value approximately equal to that of Project 1. The initial scheduled completion date was 90 months from the start of Project 2. The intrinsic value function was again similar qualitatively to that of Project 1, but the peak level was about 40% higher.

Both versions of the two-project model were verified by inserting the initial conditions of the real projects, and then comparing model performance over time with that of the actual projects. In both cases, excellent duplication of the real history of the spacecraft program (Project 1) was obtained. In the simultaneous project case, the duplication of the aircraft program (Project 2) was also quite good, over the full 7 years of available real data. In the sequential project case, the duplication of actual Project 2 performance was not very close, probably due to the lack of inclusion in the model of other actual projects within the real company. This is discussed further in Chapter V. In any case, the observed verification appears adequate for investigation of the management policy variables given in the problem statement.

Military aircraft development programs are commonly divided into lot 1 and lot 2 procurement phases, in which Lot 1 covers development, tooling, and flight demonstration of prototype aircraft, which Lot 2 is the production follow-on. For this study, the two phases have been combined into a single overall program, to make them comparable to the single phase procurement of the spacecraft program. This approach results in a somewhat broader degree of approximation for the aircraft programs, compared with the spacecraft program.

The management policies which were studied with the two-project model are listed in Table 6, which also gives a brief summary of results. The results are further discussed in the remainder of this section, and in more detail in Chapter V.

1. Effect of Overtime

For a limited range of maximum allowable overtime between 1.15 and 1.25, it was found that significant improvements in project performance resulted from reducing the maximum allowable overtime. Such reduction would reflect a policy decision on the part of the firm. This result occurs for

TABLE 6

SUMMARY OF STUDY AND RESULTS -- TWO PROJECT MODEL

| VARIABLE | EFFECT ON PROJECT PERFORMANCE* COST | SCHEDULE | PEAK MANPOWER | EFFECT ON CUSTOMER ATTITUDE |
|---|---|---|---|---|
| Overtime | 5-9% Higher | 5% Longer | 0-10% Lower | Unfavorable |
| Hiring Rate | Negligible (± 1%) | 5% Longer | 8-25% Lower | Favorable |
| Real Cost and Value | Doubled (Given) | 8% Longer | More than Doubled | Very Favorable |
| Early Shutdown | 28% Lower at Shutdown | Project Shutdown | No Change | Very Unfavorable |
| Arbitrary Budget Cuts | No Change | 3% Longer | 2% Higher | Unfavorable |

* Effect of increasing the variable over the range investigated, with other factors fixed.

two reasons: The reduced maximum allowable overtime encourages the project to take on more full time men; and, their productivity increases as the amount of overtime is reduced. This latter effect is a rather subjective judgment and results will vary significantly with the particular function assumed for overtime effect on productivity.

The effect of overtime on performance is summarized in Table 7.

2. Hiring Policy

The results of investigation of corporation hiring policy using the two project model are summarized in Table 8. Major improvements are noted in project performance and in reduction of project cost. Significantly improved efficiency of the firm's central sector operation was also observed. These beneficial effects are traceable to the lag which develops between approved manpower and total men on the project, when the Maximum Attainable Hiring Rate (MAHR) is cut in half, from 700 to 350 men/month. The gap between total men on the job and total men approved by the corporate manpower control office results in a smooth, orderly buildup of project manpower, and minimizes the existence of hiring/ firing cycles during the life of the project.

TABLE 7

EFFECT OF OVERTIME ON PERFORMANCE

| RUN # | PROJECT # | PROJECT COMPLETION -MONTHS | COST AT COMPLETION -$MILLION | MAX. ALLOWABLE OVERTIME (MAOT) | PEAK MANPOWER ON PROJECT |
|---|---|---|---|---|---|
| 099 | 1 | 86 | 2062 | 1.25 | 7032 |
| | 2 | 82 | 529 | 1.20 | 2577 |
| 100 | 1 | 81 | 1885 | 1.20 | 7842 |
| | 2 | 78 | 505 | 1.15 | 2547 |

TABLE 8

EFFECT OF CONSERVATIVE HIRING POLICY

| RUN # | PROJ. # | MAX. ATTAINABLE HIRING RATE -MEN/MONTH | DESIRED STABILITY LEVEL-MO'S. | PROJECT COMPLETION -MONTHS | COST AT COMPLETION -$MILLION | PEAK NO. OF MEN ON PROJECT |
|---|---|---|---|---|---|---|
| 099 | 1 | | | 86 | 2062 | 7032 |
| | 2 | | | 82 | 529 | 2577 |
| | Firm | 700 | 18 | | | |
| 101 | 1 | | | 81 | 2039 | 9440 |
| | 2 | | | 78 | 535 | 2796 |
| | Firm | 350 | 36 | | | |

It thus appears that one practical application of this model is as a tool to management to aid in determining approximately what level of maximum attainable hiring level would result in increased internal manpower efficiency without loss of performance on the firm's projects.

3. Doubling Project Costs and Value

In this experiment, the real total cost to complete (RTCC) of Project 2 was doubled, while the fraction of real effort recognized (FRER) was halved. Thus the initial perception of the size of the job remained the same as before, but the actual size of the job was twice as large. This represents a relatively lower perception of the scope of the project by the contractor. Two simulation runs were then made with this change included; in one of these the intrinsic value of the project (IVPT) was also doubled, while in the other run IVP was left unchanged. In the former case, (Run 110D), the cost and peak manpower on Project 2 was approximately doubled and the time to complete the project was increased by thirteen months. The longer schedule resulted from a longer time required to build up to peak manpower, given a fixed maximum hiring rate limit. However, project performance was normal and the customer's willingness to fund the project (WTFP) remained high throughout.

In the second case however, (Run 113D), the project comes very close to being cancelled by the customer. In fact, WTFP reached the lowest level from which subsequent recovery has ever been achieved in the simulations. Recovery was achieved in this case because of good progress on the job resulting from very high peak manning on Project 2. The customer unhappiness and consequent funding restrictions resulted in even greater effort by the prime contractor, and the project finished two months earlier than in the former case and cost the customer about two percent less. However, the firm's costs increased by a factor of six, so the total cost of the program was actually increased under these circumstances. These results are summarized in Table 9.

4. Early Project Cutoff

A case was simulated in which Project 2 was cutoff by the customer after the completion of Lot 1 development phase (Run 111D). This run is interesting because it shows some of the lags inherent in the customer's control system. The customer's perceived project value was reduced sharply after completion of Lot 1 (T=120). But this did not result in cutoff of new funds until one year later, and did not cause removal of men from the project until one year after that.

TABLE 9

EFFECT OF DOUBLING REAL COST AND VALUE

| RUN # | PROJECT 2 REAL TOTAL COST TO COMPLETE $10^6$\$ | PROJECT 2 INTRINSIC VALUE Peak - $10^6$\$ | PROJECT 2 COMPLETION DATE - MONTHS | PROJECT 2 PEAK MANPOWER -MEN | PROJECT 2 MIN. CUSTOMER SATISFACTION (WTFP) |
|---|---|---|---|---|---|
| 113D | 4600 | 3500 | 178 | 18250 | .237 |
| 110D | 4600 | 7000 | 180 | 15161 | .982 |
| 107V | 2300 | 3500 | 167 | 8010 | 1.000 |

This case does not represent an abrupt project termination, but does suggest a situation in which the customer disillusionment with the value of the project is acute, but the inherent delays in the management control systems are allowed to operate before final action to terminate the project is taken. These results are summarized in Table 10.

5. Susceptibility to Budget Cuts

A sequential two-project simulation was performed in which the Susceptibility to Budget Cuts function (SBC) was enabled, with a random noise input representing random political pressure for budget cuts. Some random budget cutting did take place on Project 1 which delayed the project by 3 months and increased the firm's cost by $3 million dollars. This budget cutting occurred early in the project buildup phase where it could be effective in inhibiting the buildup rate for a short period of time. These results are summarized in Table 11.

TABLE 10

PROJECT 2 SHUTDOWN DELAYS

| RUN # | TIME OF FUND CUTOFF-MO'S. | TIME OF MANPOWER DECREASE-MO'S. | TIME OF PROJECT COMPLETION-MO'S. | CUSTOMER COST AT COMPL. OR SHUTDOWN | FIRM COST AT COMPLETION OR SHUTDOWN-$M |
|---|---|---|---|---|---|
| 111D | 132 | 144 | --- | 1435 | 246 |
| 107V | --- | --- | 167 | 1995 | 4.7 |

TABLE 11

EFFECT OF ARBITRARY BUDGET CUTS

| RUN # | BUDGET CUT FUNCTION | PROJECT # | SCHEDULE COMPLETION -MONTHS | COST AT COMPLETION -$MILLION | PEAK MANPOWER -MEN |
|---|---|---|---|---|---|
| 107V | Inactive | 1 | 90 | 1970 | 7647 |
| | | 2 | 167 | 1995 | 8010 |
| 112D | Active | 1 | 93 | 1970 | 7763 |
| | | 2 | 167 | 1925 | 7659 |

# CHAPTER II -- DESCRIPTION OF SINGLE PROJECT MODEL

## A. REVIEW OF J. N. NAY'S MODEL

### 1. Approach and Emphasis

In reviewing the extensive work in industrial dynamics modeling performed at M. I. T. over the past ten years, by Forrester, Roberts, and several Sloan Fellows and other graduate students, the author determined not to "re-invent the wheel" in performing a thesis in this area. Rather it was decided to build upon the existing work to create a useful model of large research and development projects, which can be readily adapted and used within the author's aerospace company. After reviewing much of the excellent work in this area, J. N. Nay's thesis was selected as most closely conforming to these requirements for a starting point. In Nay's own words, "The goal of this theis in the project area is the producting of a model conceptually simple, yet rich enough to be realistic." This is exactly what was desired by the author. Further, Nay's model has the advantage of being expandable to handle several projects simultaneously. Such multiple project operation of the model makes possible the representation of the major operations of an aerospace corporation, which typically involves several large development programs running simultaneously at various stages of completion.

The author was attracted to Nay's definition of his projects as "a high quality project effort."[1] Both the contractor and the customer are working in an atmosphere of "mutual trust, confidence, and knowledge of the project", and each is being perfectly honest with the other. In the author's experience this is the way most major development projects are really run, and the additions of contractor/customer "game playing" appeared to be an unnecessary complication in some models.

Nay's model considers the firm's handling of manpower in some detail. This was considered attractive because the control and utilization of manpower is one of the most basic problems facing aerospace management, due to the labor-intensive nature of the industry. The model was judged to represent a reasonable degree of complexity in this area.

One area of emphasis in Nay's model which differs somewhat from the author's interests is that Nay, like Roberts, is quite interested in the total life cycle of a development project from its earliest beginnings as a one or

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1. Joe N. Nay, Op.cit., page 5

two engineer effort in some contractor's plant. Both the Nay and Roberts models therefore include considerable detail in the contractor-funded research and development overhead area. This is essential to considering precontractual activities on the project, since the funding for such activities must ultimately come from some R & D overhead pool. These features of the model have been accepted as a probably unnessary but harmless complexity for the author's purposes of concentrating on the post contract award implementation phase of the program.

### 2. Project Sector Description

It is not possible adequately to describe Nay's model without repeating the bulk of his thesis, which does not seem appropriate. A detailed description of the model, including both Nay's sections and the author's, is included in Appendix B & C. These will be useful for the reader who desires details on the construction of the model.

In general terms, Nay's model consisted of a project sector and a central sector. The project sector was further sub-divided into the portion lying within the firm (or prime contractor), and the portion lying within the customer.

These basic sectors are visible in the flow diagram of Appendix A.

a. Project Sector Within the Firm

The project sector within the firm in Nay's original model contained the following primary functions:

1.) Progress -- This function evaluates real progress on the project resulting from the effort of all those working on the job invarious stages of training and project integration. It also includes perceived and reported progress and the firm's management assesment of the technical effectiveness of the average man (TEAM), as derived from the corrections in perception of progress.

2.) Project Manpower -- This function covers the total men on the project (TMOP) and subdivides these men into internal, externally acquired, or fully integrated men, with appropriate time lags for training newly acquired men to greater skill levels. Functions relating to the productivity of men at various training levels, in terms of know how available at the project and schedule pressures felt by the workers, are also included in this section.

3.) Schedule -- This function models the process by which the firm establishes its own estimates of required schedule completion dates. Based upon the manpower currently available and approved, and with a projection of the time required to build up to peak manning, the firm continually reassesses its ability to accomplish the required schedule. It treats this information as unofficial until the discrepancy grows to the point where it exceeds some maximum Threshold for Changing Schedules (TFCS) which is taken as the ratio of the schedule discrepancy to the schedule time remaining. When this threshold is exceeded the contractor will forward through official channels to the customer a revised forecast of his ability to complete the project.

4.) Firm's Costs -- This function calculates the instantaneous spending rate at the project, adding together all sources of expenses. It also includes the rate of company funding, which is resorted to where the necessary spending rate exceeds the maximum allowed by the customer, and also totals the firm's sunk cost on the project. Effort remaining on the project is also calculated as a difference between perceived required effort and the reported progress on the job.

5.) Desired Manpower -- This is a rather complex function in which the project management's desires regarding men to be added or removed from the program are established. In general, the project management operates to remain within a Funded Manpower Level Limit (FMLL) established by the customer's Maximum Allowable Spending Rate (MARC). In addition, the project continually evaluates how many men it needs to complete the job within the required schedule. The project generally requests the smaller of needed versus funded men, although it does exhibit some tendency to hoard manpower when funding is far in excess of needs. However, pressures are exerted against hoarding by the requirements of other projects within the firm.

b. Project Sector Within the Customer

The project sector within the customer consists of the following functions:

1.) Customer Funding -- This function models the means by which the customer budgets funds for the project. The customer begins by deriving his own estimate of the cost to complete the job and compares this with his perception of the value of the program. Using his return on investment criteria (ROIC) as a guide, he determines the suitability of the project for investment. This is reflected in his willingness to fund the project (WTFP) which consists of two separate table functions; one representing initial willingness to fund, and the other representing willingness to fund the project underway. Once the project is well underway, the customer is far more inclined to continue funding it, in comparison with the situation which exists when the project is just starting up. This function also includes delays within the customer organization in making estimates of cost to complete, and delays in the budgeting process. It also contains safeguards to prevent the customer from totally depleting available funds.

2.) Customer Spending and Allocation -- In this function, the customer pays his bills as they are presented by the contractor, with allowance for suitable delays, He also establishes a maximum allowable spending rate which is based on his funds remaining uncommitted through his budget planning horizon which is taken as a fiscal year. Provision is made for issuing project cancellation notices as available funds are depleted. The maximum allowable spending rate depends on available funds, which of course depends upon the customer's funding behavior in the previous function.

3.) Customer Scheduling -- In this function, the customer takes the contractor's forecast completion date, and by applying his own reluctance to change officially published schedules, eventually makes adjustments in the scheduled completion of the project.

c. Value Sector

The value sector is considered a joint project activity of the firm and the customer. In this function, the intrinsic value of the project, which is unknown to the principals at the time, becomes gradually revealed through their rate of perception of value, which in turn depends upon progress in completing the job. It is assumed that contractor and customer share a common estimate of the value of the project.

## 3. Central Sector Description

The central sector lies entirely within the firm. In Nay's model it was subdivided into two parts: The normal operation, and the independent R & D portion.

a. Central Section -- Normal Operation

This portion of the model contains the following functions:

1) Firm's Manpower Allocation -- This function represents the process by which the firm assigns manpower from its central manpower pools to each of several projects. It tests for increases and decreases required by the projects. Increases to the projects are preferentially handled from the internal manpower pool first; then from the new hire pool. Decreases are handled in opposite order; new hires

are let go first where necessary, and internal, experienced personnel later. Functions are included which represent normal attition both of internal experienced personnel and of new hires. This attrition is made a function of the employment stability index of the firm, which in turn is related to the visible backlog of firm work.

2) Firm's Internal Manpower Pool -- This is an integrating function which keeps track of all additions to and removals from the central pool of internal experienced manpower. Additions may come from men returned from project, while removals consist of either men removed from projects or leaving the company.

3) Firm's New Hire Pool -- This is a similar integrating function for the new hire pool. In this case, provision is included for allocating new hires among competing projects in a balanced fashion. Also the delays in the hiring process are included and a limit is placed on the maximum obtainable hiring rate. Several significant changes were made in this portion of the model as will be discussed subsequently.

b. Central Sector -- Independent R & D

This sector consists of the following functions:

1) R & D Allocation -- In this function, an internal R & D budget is established based upon a fixed percentage of

the rate of billings against contracted work. This conforms to the practice prevalent in many defense industries in which a specified percentage of independent R & D is allowed as a charge against existing contract work.

2) Division of R & D -- This function divides up the available internal R & D money among the various projects on the basis of need. Those projects which are fully funded by the customer get no support from internal company R & D, whereas those lacking customer funding may be fully supported in the early stages. This function is essential for adequate representation of the precontract award phases of the project, but plays little part in subsequent activities after contract award has been received.

3) Summation of R & D -- This function merely sums the division indices by which internal R & D funds are allocated among the project.

## B. CHANGES REQUIRED IN THE MODEL

### 1. Emphases

As previously mentioned, the author's interests lie mainly with the implementation of large projects after the contract award from the customer has been received. This is only a portion of the normal project life cycle, and does not include the extensive precontract award effort which is largely supported by independent R & D funds. After reviewing Nay's model, it was decided to retain the independent R & D sections to provide greater flexibility for subsequent usages of the model, even though it is not directly applicable to the present problem. In effect, the presence of the independent R & D functions makes no difference once a contract award is received, since the function allocates internal funds solely on the basis of need as determined by lack of funding from other sources. Hence, when customer funding is available no independent R & D is allocated to the project.

2. Detail in Representing Firm's Operation

It was felt that Nay's model, although considerably detailed in its handling of the firm's manpower, was much less so in handling overall project operation. The Nay model assumed that all work is done within the firm, and presumably by engineering manpower. No mention is made of the ability to use overtime to handle short term manpower peak requirements, nor is any consideration given to the requirement for facilities and capital equipment in order to perform the job. Therefore, the model was modified to add three basic sections aimed at providing greater operational detail. These sections are subcontractors, overtime, and facilities.

3. Greater Fidelity in Representing Some Functions

Certain areas of Nay's model were regarded by the author as not sufficiently true to life. Since, as Forrester says, "During the course of an Industrial Dynamics study, the defense of any model rests primarily on the defense of the details of its design",[2] the author has tried to make the model represent project behavior as he has observed it in the real world. For this reason, the modifications outlined below were made.

a. Perception of Effort

In Nay's original model the required effort on the project was a given known constant. This appeared unrealistic, since in a real development project the participants learned the scope of the job as the job itself progresses. There is no commonly understood size or scope of the job which endures for the life of the program. Hence, perceived required effort on the project (PREP) has been modeled as a function which varies with time starting from some initial perceived scope and proceeding to ultimately reach an initially unknown real total cost to complete (RTCC).

2. Jay W. Forrester, op.cit., page 117

b. Scheduling

Some of Nay's underlying assumptions in scheduling seemed unrealistic, notably one in which the contractor continues to promise to achieve the official schedule until that date is actually passed. Experience indicates that considerable anticipation of missed schedule dates is achieved in highly visible projects, and that the decision to declare a schedule slippage is based upon a projection of current position and performance intoo the future.

c. Manpower Control

As mentioned in the summary, it was necessary to get quite specific in representing the internal manpower control policies of the performing corporation in order to achieve verication of the model against the history of the real project. This function was not included in Nay's model and, indeed, should not be included in a model of any corporation which, as a matter of policy, will hire whatever number are required to fulfill contractual commitments, without regard for the possiblity of subsequent layoffs when the work is completed in the reasonably short term.

## 4. Added Feature -- Susceptibility to Budget Cuts

One extraneous feature has been added to the model, i.e.

a function called Susceptibility to Budget Cuts. It basically represents the fact that if a project is behind schedule, and/or over target cost, it then becomes vulnerable to possible arbitrary budget cuts if its customer agency is put in a difficult position by outside political pressures. This assumes that when faced with a directive to reduce expenditures, the customer agency will objectively cull through its projects, and focus its attention on those which have exhibited poor performance. This appears to be a reasonable assumption for the behavior of well-run agencies. By looking at the combined effect of their performance to date, the company can obtain some indication as to their degree of susceptibility to arbitrary cut backs or stretch outs in the future of each project.

5. Mathematical Updating

Two principal forms of mathematical updating were required. The first was a change in detailed equation format to conform to Dynamo II. In general, this is a simplication of the original rigid format requirements to which Dynamo equations previously had to conform. In addition to some changes in symbology (for example, asterisks instead of parentheses for multiplication), the requirement for specification of equation type numbers was also deleted. Instead of specifying a number and letter equation type, only the letter type designation is now required. For example, an equation formerly identified as type 46L now becomes simply L in Dynamo II format. This format change, which has the unexpected result of making it possible to tell which equations in the model are J. N. Nay's and which ones are the author's (See Appendix B), was readily accomplished by means of a format conversion package prepared by A. L. Pugh, III.

The second mathematical updating was more fundamental. The format of the model was changed to utilize the newly available features, of the user created macros, developed by A. L. Pugh.[3]

The macro technique allowed me to divide the entire model up into some twenty-two macro functions. These functions, many of which interact with one another, represent some of the most significant variables in the model. A flow diagram showing the overall relationship of these macro functions is given in Appendix A, Fig. A-1.

The use of the macro functions has two principal values:

1. It makes the model more understandable by subdividing it

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3. Alexander L. Pugh, III, "User-defined Macros" Industrial Dynamics Research Memo D-1268 (unpublished), M. I. T. School of Management, December, 1969.

into pieces, each of which is directed toward a specific functional objective. This can be seen by looking at Fig. A-1 and the computer printout of the model in Appendix C. Note that the computer printout is divided into macro functions with understandable titles, such as Subcontractors, Overtime, Facilities, etc.

2. The second advantage of the macro representation is that it readily allows expansion of the model into multi-project operation. Nay's approach was to duplicate completely the project sector of the model for each successive project. In the present case, only the macro functional equations (see Appendix C), which apply the macro functions to specific projects, need to be duplicated in order to expand the model for multi-project operation.

The conversion of the model to the macro format was not easily accomplished, since it required a great deal of hand editing of the model files. However, it appears to be worthwhile from the standpoint of enhancing model intelligibility and simplifying the task of expanding the model for multi-project operation.

## C. DESCRIPTION OF CHANGES AND ADDITIONS

Below are described in summary form the principal changes and additions which were made to Nay's original model. Details of these sections are to be found in the appendices. Other changes were made in the course of de-bugging and verifying the model, which will be mentioned in the discussion of run results.

1. .Subcontractors

A new section covering the aggregation of all subcontractors was added to the model. Since the subcontractors represent a reflection of the prime contractor himself, considerable simplification of this sector was employed to avoid complicating the overall model. The subcontractor function begins with the assignement of men within the prime contractor organization to handle the tasks of getting subcontract effort defined and underway. The assignment of prime contractor men to subcontracting is modeled as a first order delay. It then results in the processing of subcontracts, and then the budgeting of funds to subcontractors for which purchase orders have been assigned. A third order delay is used to represent this process.

Once funds are available, the subcontractors' begin to assign men to the program. They are careful to remain within funding limits at all times. In addition, the sector models the maximum rate at which the subcontractors, taken as a whole, are capable of increasing manpower as related to the prime contractor's maximum rate of manpower buildup. Because the subcontractors represent a collection of many firms, their ability to add people collectively should be greater than that of any one firm, such as the prime contractor. Therefore, the model includes a subcontractor aggregation hiring multipier (SAHM=2) to represent the increased ability of subcontractors to hire compared to the prime. This multiplier, however, is related to the prime's maximum effective hiring rate, since there is some degree of connection of prime and subcontractors through the overall economic conditions and manpower situation existing in the country.

Once subcontractors' men are assigned to the project, they begin the same process of on-the-job training and integration into the project which has been taking place at the prime contractor's plant. In this case, the model was simplified by assuming that the subcontractors are ultimately capable of the same degree of integration of personnel through in-house training as is the prime contractor. They will, however, lag the prime contractor in time since they are starting later. Therefore, a first-order smoothing of the ratio of effective integrated men to total men for the prime contractor was modeled and applied to the subcontractor. A six month smoothing time was adopted which produces an equivalent lag in the buildup of the subcontractors' manpower effectiveness ratio.

With men assigned to the project and progress being made, the subcontractor is also spending money. This depletes the available budgeted funds and adds to the subcontractors' spent costs on the project (SSCP). Subcontractor costs are added into the total project spending, which is monitored within the prime contractor's spending function.

The balance of spending between prime contractor and subcontractor is established through a parameter called Percent of Job Subcontracted (PJSC). This assigned constant is applied to maximum spending limits established by the customer and to estimates of effort remaining, to obtain the percentage of effort remaining which is attributable to subcontractors. The original source of estimates of PJSC would be the prime contractor himself.

2. Overtime

An overtime function was added to permit the project to cope with manpower deficiencies and short term peaks. This function assumes that overtime is turned on in response to a combination of manpower deficiency and behind schedule position. Manpower deficiency is represented as an index of the project's requested men into the project (DMIP) divided by the Total Men On the Project (TMOP). The schedule situation is represented by the unofficial ratio of forecast to scheduled completion date. The unofficial ratio, which exists before it is compared with the Threshold For Changing Schedules to determine whether the customer will be informed, is used rather than the official schedule, since the project management is closely aware of the schedule situation and responds directly to the unofficial schedule position.

The function includes a limitation on the maximum achievable overtime, thus representing past history on a high-presure program, as well as budgetary policy limits. In addition, a minimum practical overtime limit is specified due to the nature of the work, which involves, e.g., certain tests which cannot be interrupted until completed; dealings with a nationwide network of subcontractors, many of whom are in different time zones, etc; which set a practical lower limit to the amount of overtime with which the project can operate.

### 3. Facilities

Facilities requirements are based upon two factors: capital equipment requirements which are a function of the total dollar volume of the contract to be performed, and floor space requirements, which are a function of the estimated total manpower to be applied to the job. Empirical values for both of these functions were obtained from data within the author's company. These two sources result in a Perceived Facility Requirement. This is compared with Available Facilities and Capital Equipment (AFCE) and the project then establishes the additional facilities which are required. Assuming a desired operational date, the project then establishes an intended rate of facility spending which starts the placing of facilities orders. The model represents the processing of facilities orders and the placing of facilities orders as two cascaded third order delays, which ultimately result in additions to available facilities and capital equipment. Due to prepayments, botn portions of the delay feed into the spending rate for facilities.

The available facilities are compared with the perceived facility requirements to obtain a Facility Availability Ratio (FAR), which in turn determines the Facilities Productivity Multiplying Factor (FPMF), which is applied to all integrated man-months spent on the project. This multiplying factor is a non-linear table function which penalizes productivity significantly for major deficiencies in facilities, but provides very little extra benefit for having adequate or close to adequate facilities.

4. Perceived Required Effort on Project

This function is modeled as a first order integration in which Perceived Required Effort on Project (PREP) is continually corrected towards an unknown Real Total Cost to Complete (RTCC), through a function called Fraction of Error Recognized, which depends upon the percent of the job complete, and also through a delay in changing estimates to complete. This results in a gradual unfolding of the perception of the scope of the project as shown in Fig. 5. The initial Fraction of Real Effort Recognized (FRER) is an important parameter for determining subsequent performance on the project.

5. Scheduling

It was desired to be more realistic in the representation of the scheduling process. However, limitations in Dynamo equation format still require a rather crude approximation of the real technique of schedule projection.

For example, the projected time remaining on the project is obtained at any given time by taking the currently perceived effort remaining on the project, and assuming that the project will go from its current manpower to its currently approved maximum manpower at a rate limited by the maximum ability to hire. This is a crude approximation of the real process, in which a curve against time of project manpower requirements will be compared with a similar curve of manpower availability, and the difference in area under the two curves would be tacked on to the end of the schedule as trial incremental time remaining.

With the trial time remaining computed in this fashion, the forecast completion date is then derived by adding current time to the time remaining. A Schedule Discrepancy Index is then obtained by noting the discrepancy between the expected completion date and the schedule completion of the project. This Schedule Discrepancy Index is then compared with the Threshold For Changing Schedule (TFCS) to determine whether or not the firm will declare the new slipped schedule as its best effort capability, or will rather retain the current officially published schedule. The unofficial ratio of forecast to scheduled completion, however, is used for turning on overtime, because it represents the unfiltered opinion of the project management as to where they stand with respect to schedule.

The Threshold For Changing the Schedule is the ratio of the expected schedule discrepancy to the schedule time remaining. Reasonable agreement with past history on a real program was achieved (see Fig. 4) by using TFCS=.25. Despite the rather surprisingly low value of TFCS, it appears that the modeled process fairly well represents the means by which the real firm determines whether it can indeed achieve the required project schedule.

## 6. Corporate Manpower Control

The object of the firm's corporate manpower control is to minimize short term increases in manpower, in an effect to achieve employment stability. Thus internally it acts as an agency to which the project must justify the real need for any manpower additions which it requests. The corporate manpower control office has the authority to approve or disapprove such requests regardless of whether the project can show that these requests are covered by contractual funding.

The corporate manpower control office uses two principal tactics to accomplish its objectives. The first is a straightforward process of negotiation with the project, by adopting a critical "show me" attitude. Corporate manpower control forces the project to justify the need for every requested increment in manpower. Frequently, the manpower control office will counter-attack by pointing out alleged instances of inefficiencies within the project which, if they were corrected, would result in manpower reductions rather than increases. By means of such bargaining, corporate manpower control negotiates a lower number then the increment originally desired by the project and agrees to submit this to higher management for approval.

The other tactic which is employed is to project the short-term manpower needs of the project over some fairly limited horizon, usually less than one year. If it appears that at the end of this Manpower Planning Horizon (MPH) the project will require no more men than are currently on board, then any desired manpower request will be denied on the grounds that it is too short a period. Of course, this approach ignores the inevitable growth in the required scope of the job which will take place within the span of the MPH, but it is often used as a delaying tactic to defer granting project manpower increments.

The project's requests, thus suitably reduced and rounded off, are then sent into a management manpower approval loop, incurring further delays before authorized manpower is available. On the other hand, negative increments in approved manpower are linked directly to the project's funded level of manpower, such that men will be removed from the project as soon as funding is no longer available, with a minimum of intervening delays.

As represented in the model, the firm's corporate manpower control function can be modified by adjusting three basic parameters: 1.) The Manpower Planning Horizon (MPH), 2.) The table function, Fraction of Manpower Increment Approved (TFMR), which represents the outcome of the manpower negotiation process, and 3.) The Delay for Corporate Manpower Approval (DCMA). Each of these parameters was varied, and the resulting effects on project manpower were observed. Long values of the MPH tended to produce a marked stepwise shape of the project manpower vs. time curve, while large values of DCMA shifted the whole curve downstream in time. The combination of values which were selected (MPH=6 months, DCMA=2 months, TFMR varying from .5 or .6 to 1.0) result in a good fit of the actual data for the spacecraft program (Project 1), and are all within a reasonable range as far as qualitative observations of the workings of the real organization are concerned.

The inclusion of this function in the model resulted in a marked change in appearance of the project manning line, which made it much more closely represent the actual history on the project.

## 7. Susceptibility to Budget Cuts

The project's susceptibility to budget cuts was assumed to be the result of equal weighting of three factors:

1. Customer's Willingness to Fund the Project (WTFP), which represents overall customer satisfaction with the progress on the program.

2. Rate of Schedule Adjustment, which represents the rate at which the customer has been forced to recognize schedule slippages on the program, and,

3. Fund Availability Index, which compares the customer's

estimate of the cost to complete with his available uncommitted funds.

This function assumes that if customer satisfaction is low and/or if schedule slippages have been occurring at a significant rate, or if the estimated costs to complete are greatly exceeding the remaining uncommitted funds; then a combination of these factors results in the project being susceptible to budget cuts. However, before any arbitrary budget cuts take place an additional factor must be present: Outside political pressure must be brough to bear on the customer agency for an overall reduction in expenditures.

The model can be represented as this outside political pressure by any desired function. Currently, both a sineware representation and a random noise representation are included. Selection and limiting constants are included, which allow either formulation of political pressure to be selected, and which permit locking out the entire Susceptibility to Budget Cut function when desired.

8. Value

The original Nay model had a value perception function in which unknown Intrinsic Value of the Project was gradually recognized through a Rate of Value Recognition variable, which in turn depended upon a variable Delay in Recognizing Value.

The existing recognized value was then projected into the future, using a projection horizon, to arrive at an Accepted Common Value of the Program.

During early runs with this value function, I found it to be quite unstable because the projection of the current recognized level of value into the future caused a great amplification of the trend of the present level of value. When value was increasing, projection to the future greatly overestimated intrinsic value, and the reverse occured when value was declining. It appears that a simplier value recognition function will suffice, in which the Accepted Common Value of the Project (ACVP) merely represents an integration, through a variable Rate of Value Recognition, of the unknown Intrinsic Value of the Project. This produces a function which behaves much like the Perceived Required Effort on the Program previously described. Since it is difficult to verify the value of a given program, it can only be said that the values currently used in the model seem to give good correlation with past historical performance of a real program. The variable Intrinsic Value of the Project has been based on budget requests submitted by the agency to Congress for the real program, in advance of the agency knowing in detail what the spending requirements would be. Thus considered as a projection of future spending, it also represents the agency's assessment of the value of completing the program as a function of time. This yields a curve, shown in Fig. 11, which is very similar in shape to the value curves used by both Roberts[4] and Nay[5].

9. Hiring

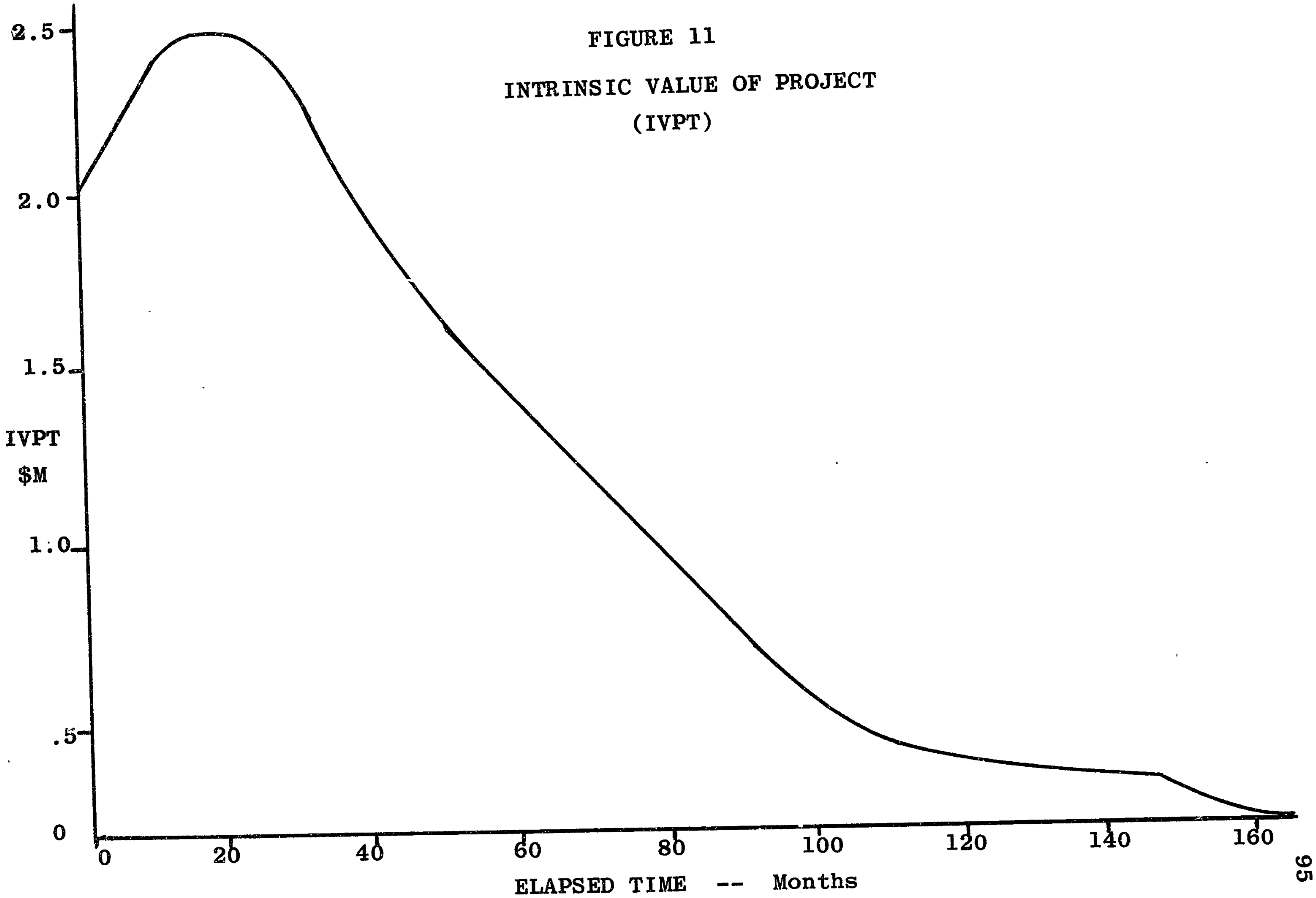
A number of significant changes were made in the hiring loop within the firm's new hire pool. These changes were the results of early runs on the model, which showed a rapid-acting loop in which new hirees were being stuffed into the hiring delay with one hand, while the firm was laying men off the project with the other. A hiring feedback function was therefore added which abruptly shuts off firm hiring whenever layoffs from the project are in progress. This is consistent with actual practice in which the hiring "valve" tends to be turned on and off abruptly from full-open to full-closed, and this cycle is repeated in a saw-tooth pattern.

The desired hiring index was modified by multiplying the Firm's Stability Index (an indication of backlog) by the Fraction of Spending Allowed Internally (FSAI). FSAI is the balance allowed for internal spending once the prime contractor has satisfied subcontractor and facilities spending. A maximum attainable hiring rate (MAHR=700 men per month) was used as empirical data on the real project. This maximum

4. Edward B. Roberts, op.cit., page 23
5. Joe N. Nay, op,cit., pages 47 and 76

FIGURE 11

INTRINSIC VALUE OF PROJECT
(IVPT)



attainable hiring rate is established by the size of the personnel recruiting department and the general economic and labor conditions prevailing at the time of the manpower buildup.

# CHAPTER III. -- RESULTS OF SINGLE PROJECT MODEL SIMULATION

## A. MODEL VERIFICATION

### 1. Description of Verification Baseline -- Run 067V

The most significant quantitative verification of the single project model has been presented in Fig. 1-6 and discussed briefly in the Introduction. Additional data, including variables which cannot be verified directly with past history, are given in Figs. 12-15. Even in the case of variables which cannot be quantitatively verified, the general characteristic shapes appear to agree with the author's perception of real project history. Some differences do exist, as for example the usage of overtime, (Fig. 12). The model does not show the large amount of week to week fluctuation which is present in the real use of overtime. Since the overtime usage depends in part upon individuals' personal availability, a more accurate modeling would probably include a noise factor in the ability to use overtime.

From Fig. 12, it also is seen that the model under-rates the extent to which progress is over-estimated, but the general agreement is good.

Some difficulty was encountered in adjusting the real project data to conform to a constant definition of the scope of the job. In broadest terms, I have defined one hundred

FIGURE 12
VERIFICATION RESULTS — PERCEIVED PROGRESS & OT

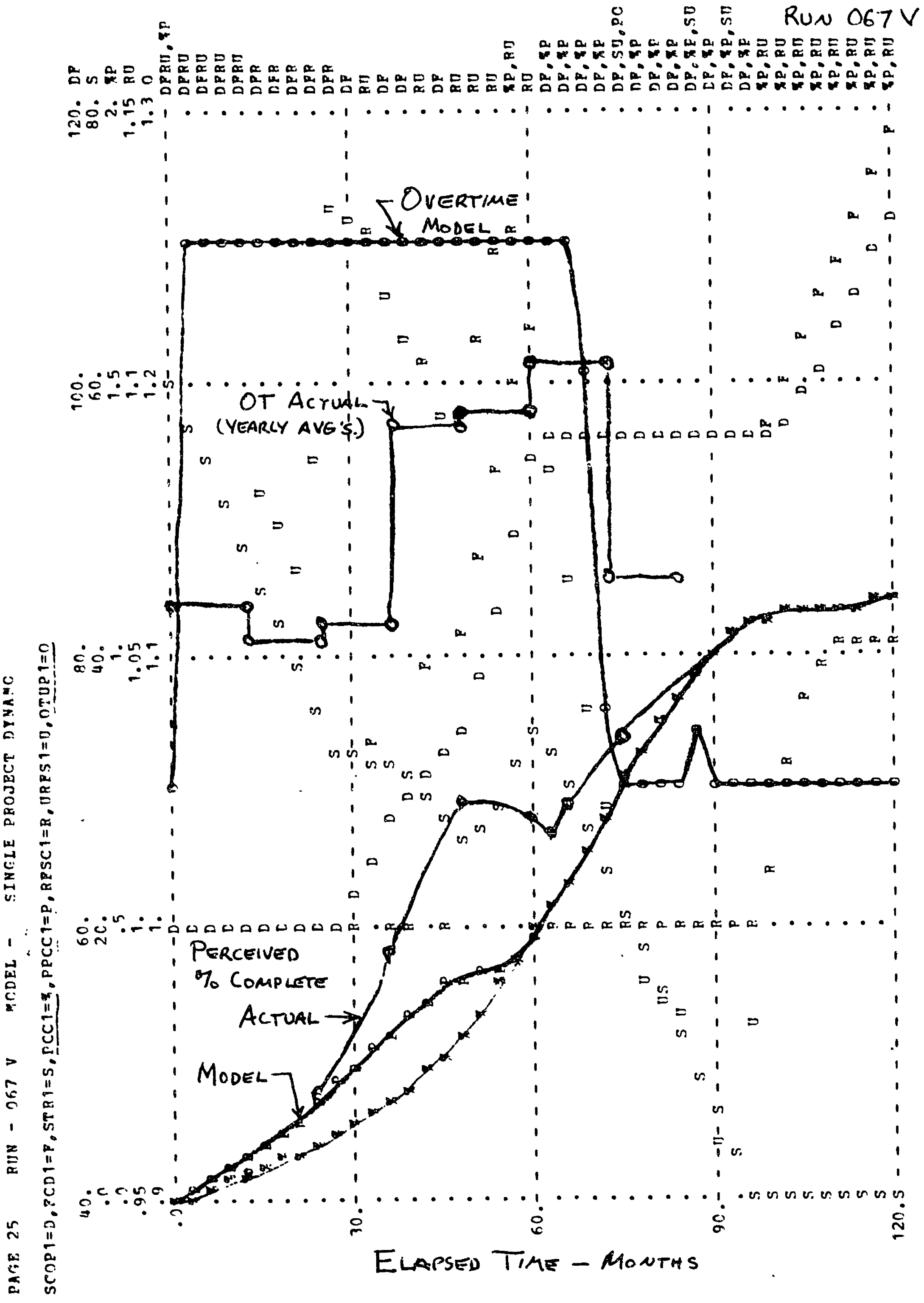


Figure 13
Verification Results – Value and Spending
Run 067V

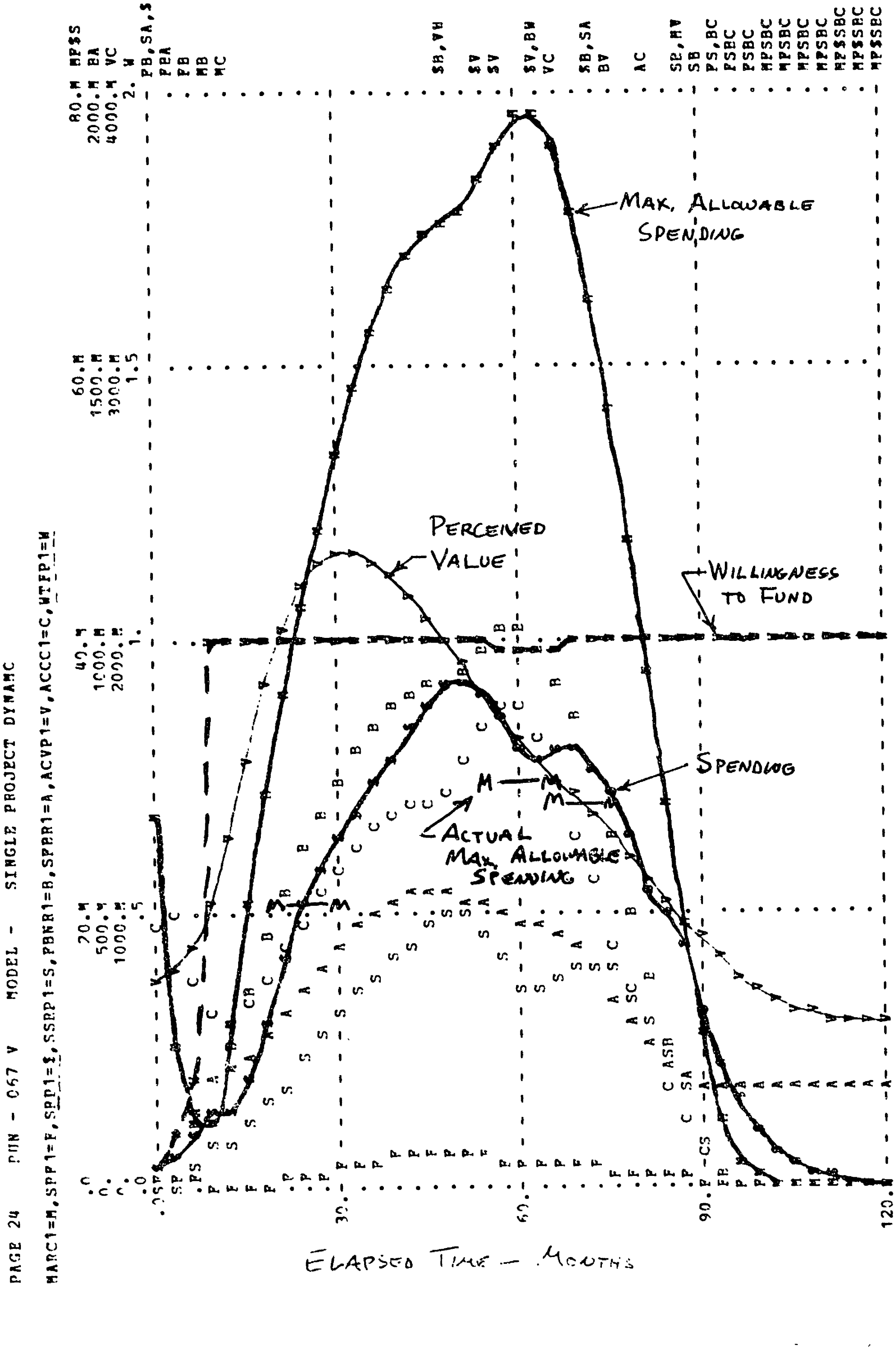


Figure 14

Verification Results - Manpower Run 067 V

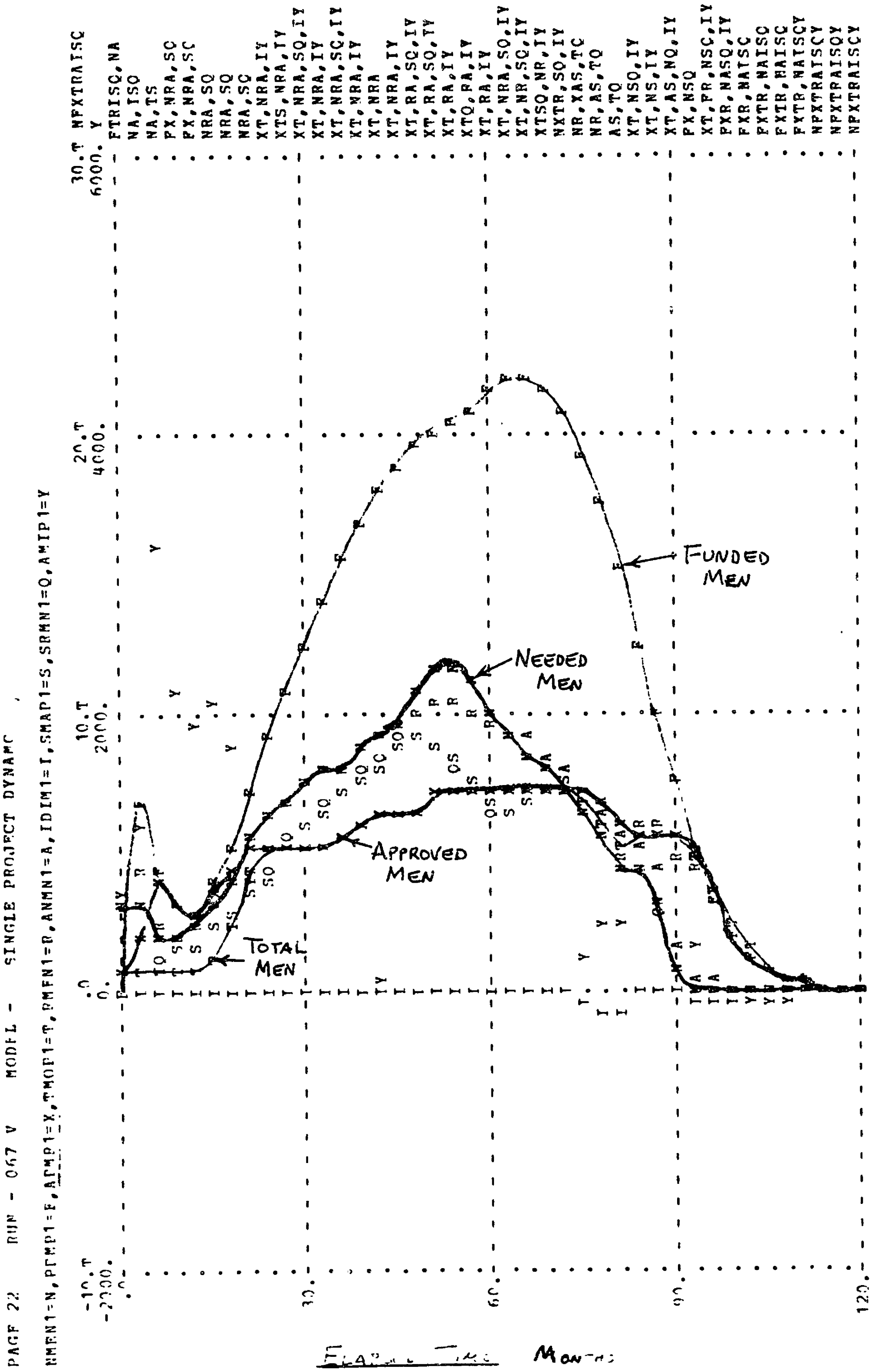
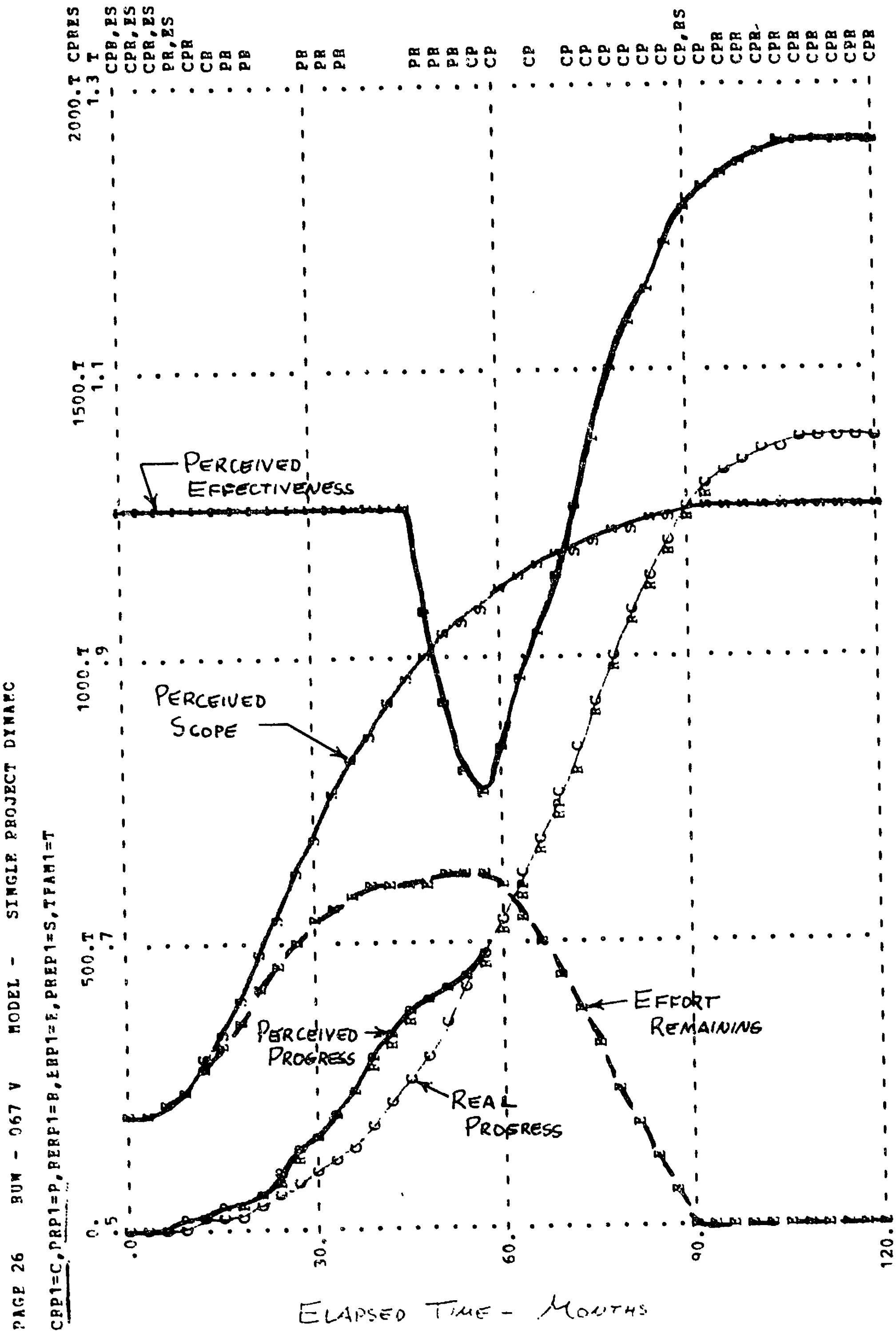


Figure 15

Verification Results – Progress and Effectiveness

Run 067V



percent completion of the project as consisting of the delivery of that number of spacecraft which was originally contracted for, even though the contracted number has been modified somewhat since. Additionally, the completion of the project assumes that the program objective is to achieve completion as soon as possible, and neglects the effect of deliberately directed schedule stretchouts,

The source of some of the data for table functions included in the model has been described. Some of the initial conditions are also worth mentioning. The real total cost to complete (RTCC) is taken from the January, 1970 estimate of the real completion cost of the project, adjusted to a constant number of deliverable spacecraft. The fraction of real effort recognized initially (FRER=.16) comes from the negotiated contract value at the time of contract go-ahead. This was a jointly agreed-upon value which represented the contractor and customer's best estimate of the total cost of the program.

Some of the details of project manpower behavior can be seen in Fig. 14 which shows the total manpower on the program, approved manpower, needed and requested manpower, and finally the manpower permitted by allowable funding limitations. Considering the funding limitations, we see that this governs the manpower during the early buildup stages for about the first year, and also during the project shut down stage after about month 93. In between that time interval, the customer is willing to fund considerably more manpower than the project applies. Total manpower during this period is limited by the Approved Project Manpower Requests (APMR), which is the parameter established by the manpower control function previously discussed. We can see from the shape of the plot how the process of negotiating and leveling off requested peaks in manpower results in a rather flattened manpower curve, which is consistent with actual behavior on the project.

During the critical time of troubles between month 48 and 66, the project's perception of needed manpower hits a peak, as shown by the NMEN line. However, project management limits this peak to the requested value as shown by RMEN, which reflects their Approved Needed Manpower (ANMN). Project management does not approve the full requested needed manpower, as perceived by its first line supervision, because the project management interprets this manpower as being required to make up for deficiencies in effectiveness of the project's personnel, as indicated by the function Technical Effectiveness of the Average Man (TEAM).

Fig. 15 shows the variation of the TEAM function in comparison with the perceived and cumulative real progress. The drop in TEAM, which occurs between months 45 and 57, results when the overestimation of perceived progress gradually becomes apparent to project mmanagement. Project management initially ascribes the relative lack of progress during this time period to a reduced technical effectiveness of its own personnel. Typical management actions during this period include reorganization, efficiency drives, bringing in of new management personnel, etc. All these factors were observed on the real project, and lend qualitative support to the general tendency indicated by the model. Eventually, however, management confidence in its people is restored due to the steady progress which is observable on the job. This progress is more impressive after month 60 because of the gradual reduction in the rate at which the size of the job is perceived to be growing; hence, the real progress becomes more significant because it is not swamped by the discovery of additional required effort. Note, also, that the Effort Remaining curve shows a steady decrease, starting with about month 57. This also results in improved contractor management and customer satisfaction with the progress on the job beyond that time.

Other data not presented herein have been reviewed in connection with the baseline run of the model, and all appear to be qualitatively reasonable. Since this is a single project representation of the firm, the new hiring and integrated manpower pools only function during periods when the project is laying off people. During such times these pools become holding areas up to the maximum percentage allowed, and then become staging areas for personnel layoffs. Performance of this portion of the model appears quite reasonable for the single project model.

Fig. 13 compares the various spending rates on the project, along with estimates of the cost to complete and the estimated project value. As previously stated, the project value function was derived from budget requests for the manned space program which were submitted to the Congress, and the model reproduces this function faithfully. The maximum allowable spending rate by the customer is difficult to compare with actual historical data since the customer did not set regular monthly spending limits, although he did impose total spending targets for certain fiscal years, as shown in Fig. 13. It appears that these fiscal year limits were simply based upon the current level of project spending, rather than being derived from the factors used in the model.

### 2. Chronology Leading Up to Model Verification

#### a. Additional Model Problems

67 computer runs were required before the model verification proviously presented was obtained. The first 17 runs were used in debugging the model and in stabilizing output to the point where the model would run the project to completion.

The initial problems resulted from sweeping interactions between the original section of J.N. Nay's model and the new sections added. Certain sign errors were found in key subcontracting equations which initially prevented subcontractors from ever being employed. Also the use of schedule time remaining in the maximum allowable customer spending rate (MARC) equation made this loop very unstable. Here a constant was substituted representing fiscal year budgeting, which is the budget horizon normally used by the customer. Certain of the integrating functions, such as Fully Integrated Men (FIM), required limiting equations to prevent them from going negative. And finally, the initial model equation started with a very low value of TEAM. This was changed to start with TEAM assumed to be 1.0, that is, 100% effectiveness.

Several other equation errors were discovered in the perceived required effort on the project function (PREP). The initial conditions were improperly specified such that PREP did not buildup normally. This was corrected by redefining the initial conditions. Equation errors were also found in the firm's desired manpower function and in certain of the equations within the subcontractor macro.

A fundamental problem which was discovered was that the addition of subcontractors and facilities spending to the basic prime contractor's spending created a competition for available funds, without having a clear priority rule established as to where the funds should go. This is no doubt a realistic situation, but does not allow consistent operation of the model. It was therefore necessary to add a series of spending controls, which basically divide the allowable contractor spending into fractions for internal spending, subcontractor spending, and facility spending. All money is divided into approximately this proportion for each spending period.

The next area of corrective action required was the hiring loop. Here in addition to correcting some equation errors, it was necessary to add the hiring feedback controls previously mentioned to prevent excessive hiring and firing by the firm, and also to add a limiting maximum hiring rate. The value simplification previously mentioned was also made at this point. An investigation was made into the difference of DT (simulation interval) = 0.5 months vs. 0.25 months. Relatively little difference was found, but 0.25 was retained since it resulted in somewhat improved model stability with relatively little increase in computation time. Several other corrections to the hiring equations were required before finally, in run 017T, the first full length run was achieved whereby the project was satisfactorily completed.

b. Sensitivity Runs

A matrix was then prepared of principal constants, as shown in Table 12, and used to generate a series of sensitivity runs, to obtain some insight into the sensitivity of model performance to the value of these parameters. In the

TABLE 12

SENSITIVITY RUNS MATRIX

| PARAMETER | BASE 017 | SENSITIVITY RUN NUMBER 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fraction Spending for Facilities | 0.1 | .2 | | | | | | | | | | | |
| Desired Facility Order Delay | 12 | | 24 | | | | | | | | | | |
| Delay Placing Facility Orders | 5 | | 10 | | | | | | | | | | |
| Delay in Facility Availability | 15 | | 30 | | | | | | | | | | |
| Facility Productivity Mult. Fact. | .6-1.05 | | | .8- | | | | | | | | | |
| Fraction Error Recognized in Cost Est. | N | | Hi. | | | | | | | | | | |
| Fraction Real Effort Recognized | .16 | .32 | | | | | | | | | | | |
| Delay Changing Schedule Dates | 2 | | | 4 | | | | | | | | | |
| Delay Startup of Planning | 12 | | | 24 | | | | | | | | | |
| % of Job subcontracted | 0.5 | | | | .6 | | | | | | | | |
| Delay S/C Funding Authorization | 3 | | 6 | | | | | | | | | | |
| Delay Placing Subcontracts | 2 | 6 | | | | | | | | | | | |
| Delay Assigning Funding Limits | 3 | | | | 6 | | | | | | | | |
| Delay in Obtaining New Hires | 4 | | | | | 8 | | | | | | | |
| Delay in Evaluating Personnel Rqsts. | 1 | | | | | 2 | | | | | | | |
| Supervisory Ratio | 40 | | | | | | | 20 | | | | | |
| Desired Stability Level | 18 | | | | | | 36 | | | | | | |
| Willingness to Fund Project | N | | | | | | | Hi | | | | | |
| Return on Investment Criteria | 1.5 | | | | | | | | 2.25 | | | | |
| Delay Accepting Cost to Complete | 3 | | | | | | | | | 6 | | | |
| Fixed Delay in Budgeting Funds | 6 | | | | | | | | | 12 | | | |
| Variable Delay in Budgeting Funds | 12 | | | | | | | | | 24 | | | |
| Susceptibility to Budget Cuts--selection | 0 | | | | | 1 | | | | | | | |
| Susceptibility to Budget Cuts--limit | 0 | | | | 1 | 1 | | | | | | | |
| % R & D Charges Allowable | .04 | | | | .06 | .08 | | | | | | | |
| Delay Reporting Real Progress | 1 | | | | | | | 3 | 6 | | | | |
| Fraction Error in Progress Recognized | N | | | | | | | | | | Hi | | |
| Max. Allowable Overtime | 1.4 | | | | | | | | | | | 1.2 | |
| Delay in Clearing Manpower Pool | N | | | | | | | | | | | Lo | |
| Delay in Changing Schedule | 4 | | | | | 8 | | | | | | | |
| Delay in Processing Manpower Rqsts. | N | | | | | | | | 3 | | | | |
| Schedule Productivity Multiplier | N | | | | | | | | | | | | Hi |

interest of economizing on the number of runs, occasionally variables were entered in different portions of the model where it was thought the interaction would be relatively low. For example, variation in the facilities' macro constants were run simultaneously with variations affecting the schedule macro, because the interaction between these two was considered to be small. In this manner a total of 13 sensitivity runs were made as outlined in the Table 12. The results of these runs were then compared with the real program data, and values for the constants were selected which tended to give the best match with real performance, wherever these values were also felt to be reasonable from a subjective standpoint.

Following the selection of constants, the only additional significant model modification required to obtain verification was the addition of the firm's corporate manpower control function as previously described. With this total summation of changes and adjustments the degree of verification with real history demonstrated herein was obtained.

## B. EXPERIMENTATION WITH MODEL

### 1. Manpower Control

The characteristic shape of the total project manpower curve before the addition of the corporate manpower control function is shown in Fig. 7. These data, taken from run 044V, contain all the refinements to the manpower and hiring functions with the exception of the firm's corporate manpower control. Notice the relatively short, sharp peak in total men on the project, which exceeds 16,500. This compares with actual project peak manning in the neighborhood of 7400. Schedule performance is much better than on the real project, in that schedule completion is obtained by month 72, compared with month 90 for the baseline run. However, costs to the customer at completion are also significantly higher ($2.39 billion vs. $2.07 billion). Hence, the effect of the firm's corporate manpower control function is to greatly reduce and flatten the peak manning on the project, which satisfies its primary objective of increasing the stability of the firm's employment. However, it prevents the project from completing the job in the fastest possible time and in this respect operates counter to the customer's desires. Depending upon the value of early schedule completion to the customer, his best interests may or may not be served by the schedule stretchout which the firm's manpower control function imposes upon him. This schedule stretchout is accompanied however, by an absolute cost saving to the customer, and therefore the schedule delay may be considered worth the saving in cost. From the firm's standpoint, there is no question that the corporate manpower control greatly improves its employment stability picture and therefore makes practical operations in the community much more feasible.

2. Schedule Firmness

Consistent indications have been shown in many runs that schedule completion is significantly enhanced, and ultimate cost to completion is minimized, if the firm and the customer adopt a policy of unyielding firmness in retaining published project schedules as long as possible. For best results it appears that schedules should be retained until almost the day before the event is due, at which point its impossibility of accomplishment becomes obvious to all. In practice there is always considerable anticipation of slippage of schedule dates on any closely-managed project. This anticipation is represented in the model as a function of the expected discrepancies and the schedule time remaining, as previously explained.

To see the value of schedule firmness in quantitative terms, it is necessary to compare selection runs in pairs because many other parameters were being varied also. A summary of the effect of schedule firmness is given in Table 2, which shows the most significant performance factors relating to schedule completion and cost. In the first pair of runs, 048 and 049V, the threshold for changing schedules (TFSC) is changed from .5 to .667 as shown in Figs. 16 and 17.

Figure 16
Effect of Schedule Firmness

TFCS = .5 Run 048 V

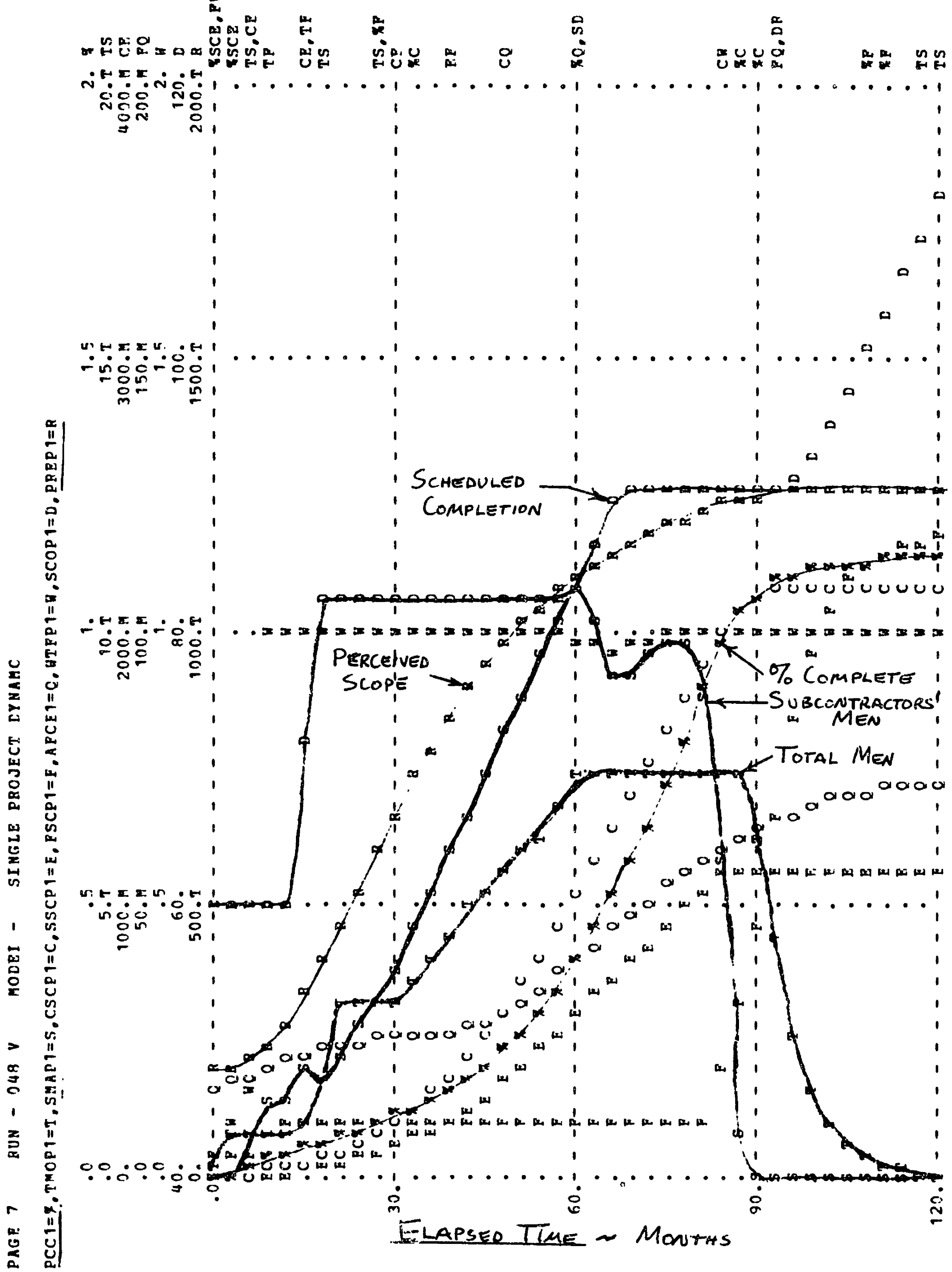
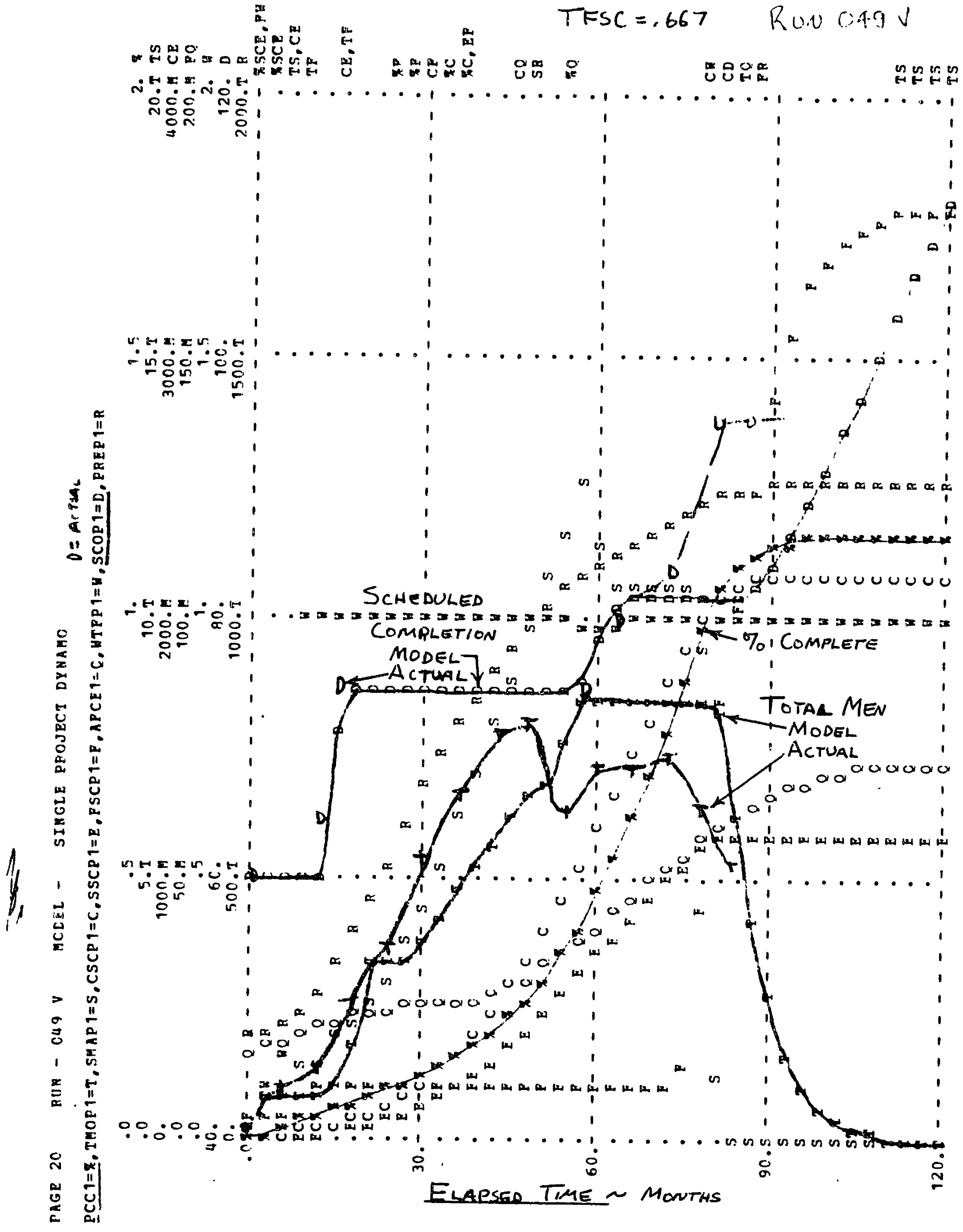


Figure 17

EFFECT OF SCHEDULE FIRMNESS



Schedule performance improves and customer costs are reduced as a result of the increase in this hurdle which must be passed before the firm admits to an official schedule slippage. The same trend is borne out by the pair of runs 062 and 063, whose results are summarized in Fig. 18. Here TFSC=.5 vs. .333, and again superior performance is obtained with a higher schedule hurdle, although cost at completion is higher in this case due to higher peak manning. Several other parameters, principally the corporate manpower control function, were changed between this pair of runs and the previous pair, which is the reason the absolute values of the results are not directly comparable from pair to pair. Finally, in Fig. 19, runs 067 and 078V are compared. In both of these runs, TFSC=.25, but the customer's delays in changing his officially published schedules (DICS) is changed from 6 months to 12 months. This increased customer "foot dragging", before accepting a pessimistic schedule prediction from the contractor, again results in improved performance and reduced costs. Once again these results are not directly comparable to the previous pairs because of other intervening parameter changes.

The general conclusion of studying these variables is to support a hard-boiled, "stick-to-the-schedules" policy on the part of contractor management and customer management.

# Figure 18

## Effect of Schedule Firmness

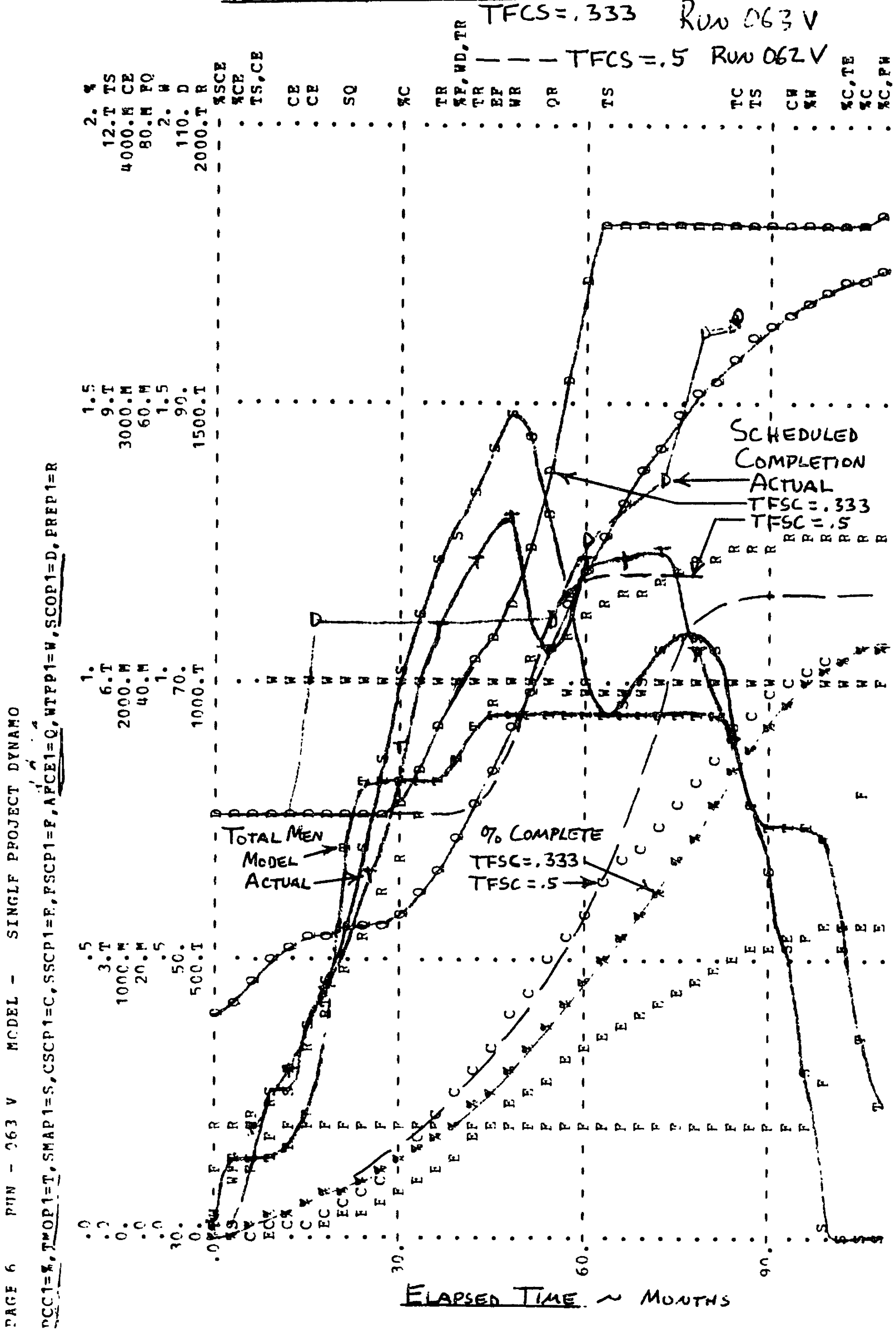
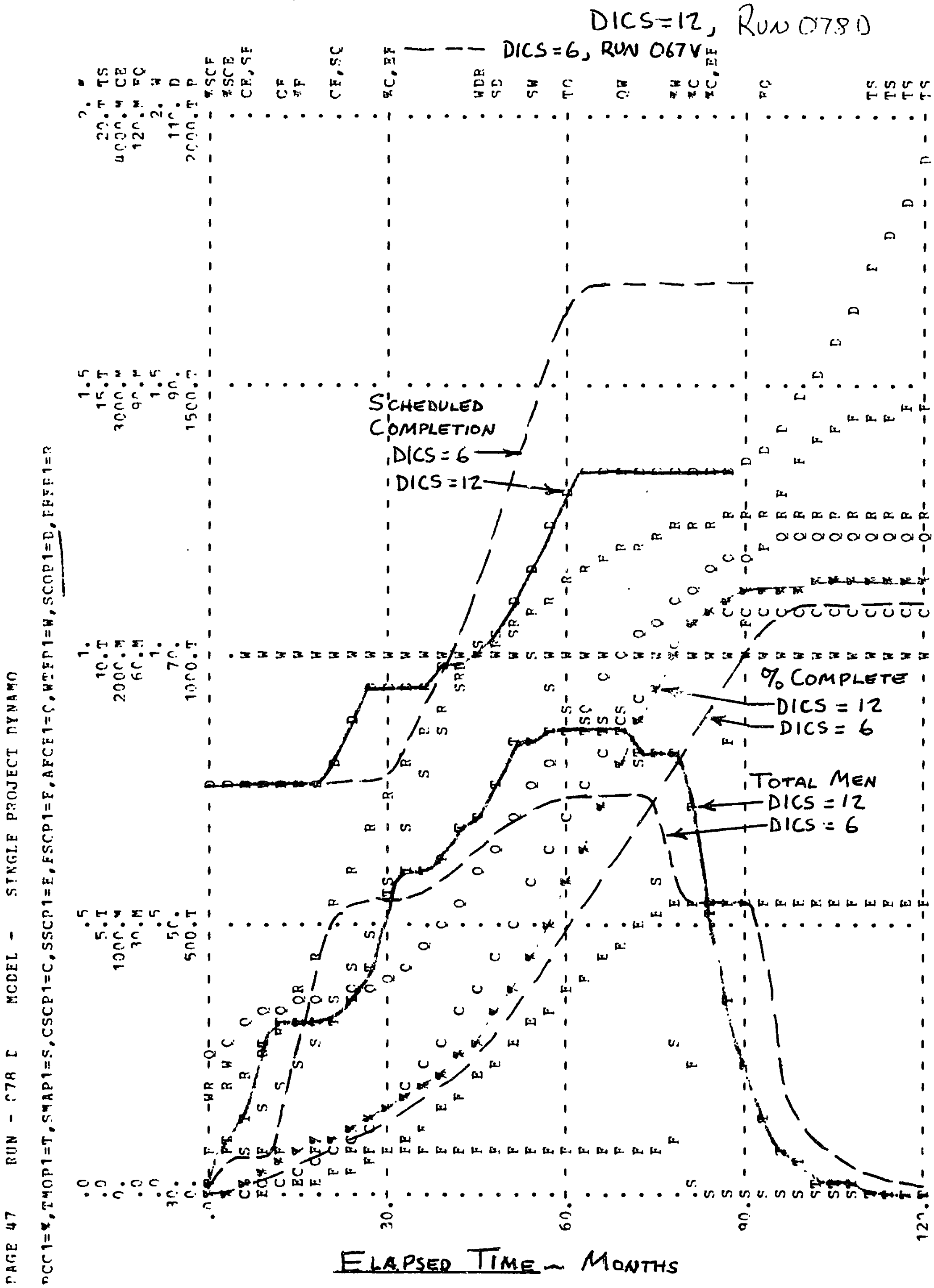


FIGURE 19

EFFECT OF SCHEDULE FIRMNESS



3. Perception of Scope of the Job, and of Progress

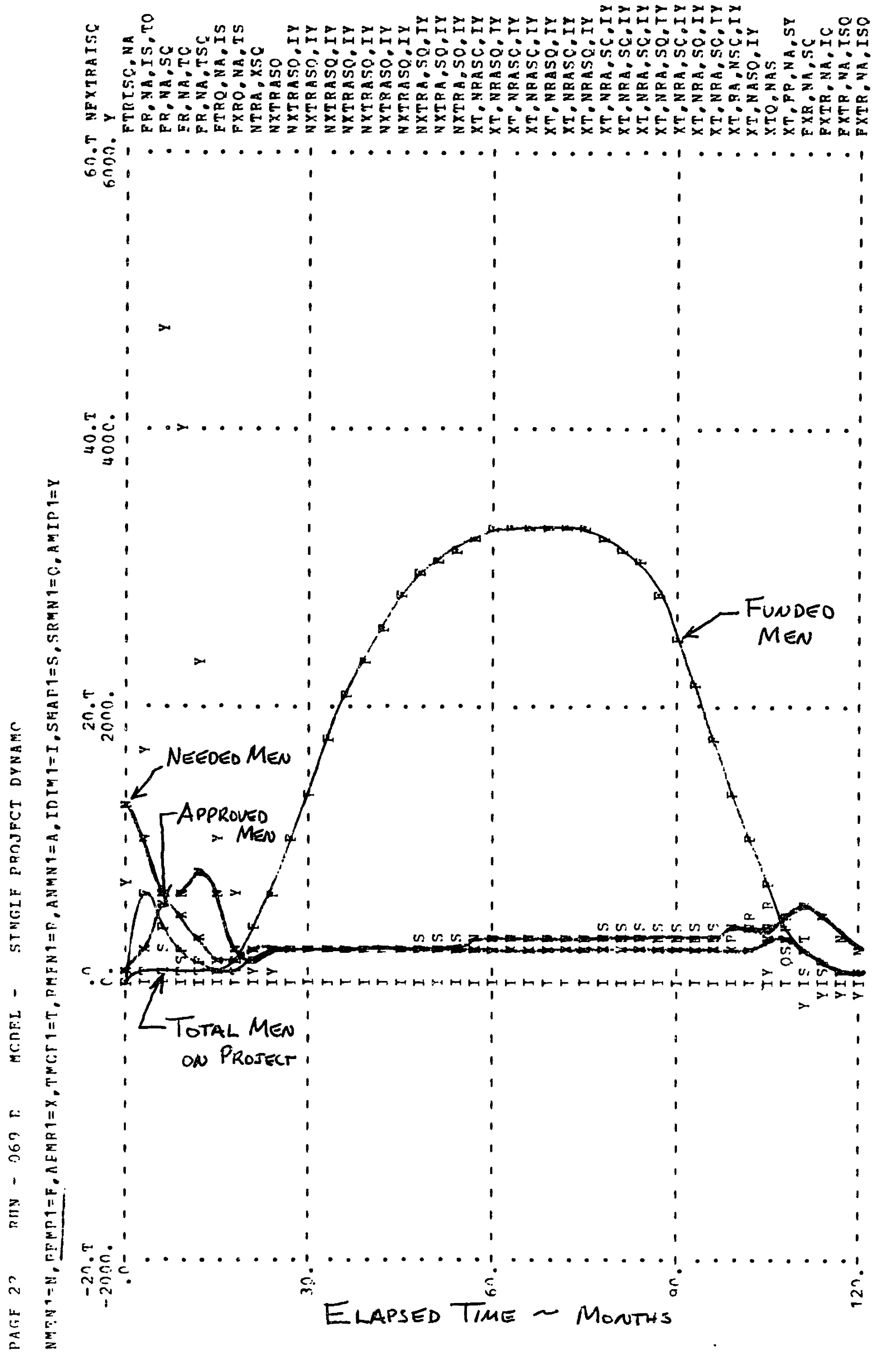
These effects are summarized in Table 3. In order to examine the effects of initial perception of the scope of the job, we must compare the baseline run 067V with runs 068 through 070D.

From Table 3, we see a steady trend towards proper project performance and even early project shutdown as the initial Fraction of Required Effort Recognized (FRER) is increased. With FRER=.4 in run 068, the project is able to struggle to a belated completion. In the other two runs with FRER=.6 and .8, project shutdown occurs. To understand the reason for this behavior, we must examine more closely the manpower and customer willingness to fund the project, as shown in Fig. 8 and 20 for the typical case of run 069D.

In Fig. 8, compared to the baseline run 067 shown in Fig. 13, we see that the customer's willingness to fund the project (WTFP) is slow in buildup. The customer is unable to reconcile the high initial cost estimate for the program with his relatively low early perception of project value. Therefore he drags his feet on funding, and as Fig. 20 shows, the funded manpower limit remains quite low through the first 18 months, of the project. Unfortunately this means that the numbers of men available and approved at the end of the critical first year, when searching schedule decisions are

# Figure 20

## Improved Initial Perception of Slope – Manpower Effects



being made, is very low. Therefore, the contractor feels impelled, based upon his first year's experience in difficulties with obtaining funding, to quote the very pessimistic schedule predictions shown in Fig. 8, that is, schedule completion by the 192nd month. Once having made such a pessimistic schedule prediction, the contractor is then under relatively little pressure to achieve a high manpower limit, and this, together with his internal manpower control system, results in a very low level of manning. The customer gradually becomes unhappy with the project's slow rate of progress, and a steady deterioration in Willingness to Fund the Project occurs, which accelerates sharply by month 78 and eventually results in total shutdown of the project by the customer.

As previously referenced, this behavior by my model seems to be the same as that encountered by both Roberts and Nay. Whether such behavior would occur in the real world depends greatly upon the source of the value function used by the customer. If the customer has performed extensive in-house studies of the system under development and has a thorough understanding of its potential usefulness, then he may have a high initial perception of the program value. The more unknown and risky the development project is, the less likely it is that the either the value or the cost will be adequately accounted for in the early stages of development. Therefore, the conclusion of this investigation is not that a firm should strive any less diligently to understand the total scope and the toal cost of a proposed development program, but rather that it should simultaneously work closely with the customer to make sure that the understanding of the potential usefulness and value of the system is at an equally high level as the understanding of its costs.

The effect on performance of changes in perceived progress as compared to real progress are summarized in Table 13. The reason for these effects have previously been explained in conjunction with Figs. 9 and 10, and will be be repeated here.

Similar results in which improved perception of progress due to increased fraction of error in progress recognized, which resulted in significantly poorer project performance was also noted during sensitivity run 030V, as shown in Table 13.

4. Initial Manpower and Facilities Available

The following comments are added to the results previously presented in Table 4. It appears that the reason why initial manpower level has a negligible effect on project performance is due to the assumed supervisory ratio (SR)=40. This assumes that a crash manpower buildup is occuring, and that the firm is willing to put as many as forty men under one supervisor, in the process of increasing project staffing. With such a high value of supervisory ratio the manpower buildup is not

TABLE 13

EFFECT OF IMPROVED PERCEPTION OF PROGRESS

| | RUN # | PERCEIVED PROGRESS -MAN-MONTHS | DELAY IN REPORTING PROGRESS-MO'S. | PROJECT COMPLETION -MONTHS | COST AT COMPLETION -$MILLION |
|---|---|---|---|---|---|
| compare | 067 | Normal | 1 | 90 | 2073 |
| | 079 | Perfect (=Real Progress) | 0 | 89 | 2030 |
| compare | 075 | Normal | 1 | 93 | 2073 |
| | 077 | Improved (Fraction of Error Recognized is higher) | 0.25 | 164 (est.) | 1763 (at T=120) |
| compare | 017 | Normal | 1 | 90 | 2709 |
| | 030 | Improved (Fraction of Error Recognized is higher) | 1 | 145 (est.) | 2579 (at T=120) |

limited significantly by lack of supervisors, since the training cycle is short enough that new integrated personnel are available sufficiently rapidly to keep up with the maximum attainable hiring rate. In one of the early sensitivity runs, this parameter was reduced to 20, and it still did not represent a limiting factor on the maximum rate of manpower addition. Experience suggests that SR between 20 and 40 is perfectly reasonable for a project in a rapid stage of build-up, particularly where highly experienced personnel are being hired in many categories. These experienced supervisors can be placed in a supervisory role themselves with a minimum of training and indoctrination, and thus can very rapidly serve to direct the efforts of others, resulting in an effectively low supervisory ratio as defined by the model.

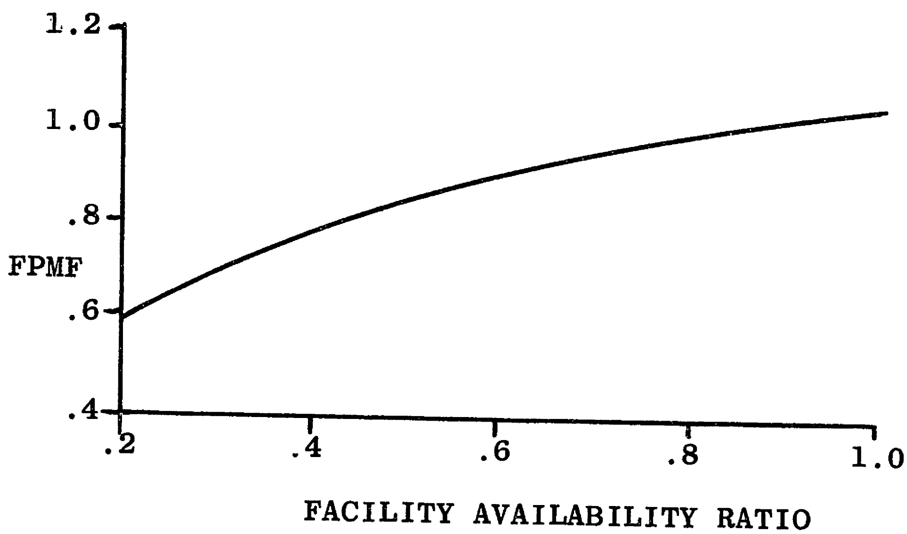
Since findings regarding the importance of early availability of facilities so depend upon the subjective assumed function Facilities Productivity Multiplying Factor (FPMF), this function is shown in Fig. 21. Unfortunately, no direct was exists to check this against past performance, so it will have to remain a subjective input into the model.

5. Customer Funding Criteria and Performance

As would be expected, the progress of the project is quite sensitive to the criteria which the customer sets for project funding, and to the delays which are encountered in his budgeting and funding process. The significance of these

FIGURE 21

FACILITIES PRODUCTIVITY MULTIPLIER
(FPMF)



factors on resulting performance are summarized in Tables 5 and 14. In the early sensitivity runs, it was found that doubling the delay in budgeting funds from 6 months to 12 months for the fixed delay, and from 12 months to 24 months for the variable delay was sufficient to cause premature shutdown of the project, as shown in Table 14. This is reasonable when it is considered that the various delays in the customer's loop for adding manpower and for billing and collecting his funds lie outside the first assumed set of delays, but inside the second.

The other principal variable that was investigated was the return on investment criteria (ROIC). Increasing ROIC to 2.25 from 1.5 was sufficient to cause project shutdown in the early sensitivity runs, as shown in Table 5.

Early project shutdown in this case is straight-forward; with a high value of ROIC, the customer's perceived value to cost ratio soon falls below the criteria level which he considers suitable for investment. As the project progresses, even though the estimated cost to completion begins to decrease, value is also decreasing, and the ratio is such that the customer's Willingness to Fund the Project never recovers.

The baseline Run 067V was made with ROIC=1.5. This was compared with ROIC=1.0 in Run 075, and some slight decrease in performance was noted. The project took 3 months longer to complete even though customer costs remained the same.

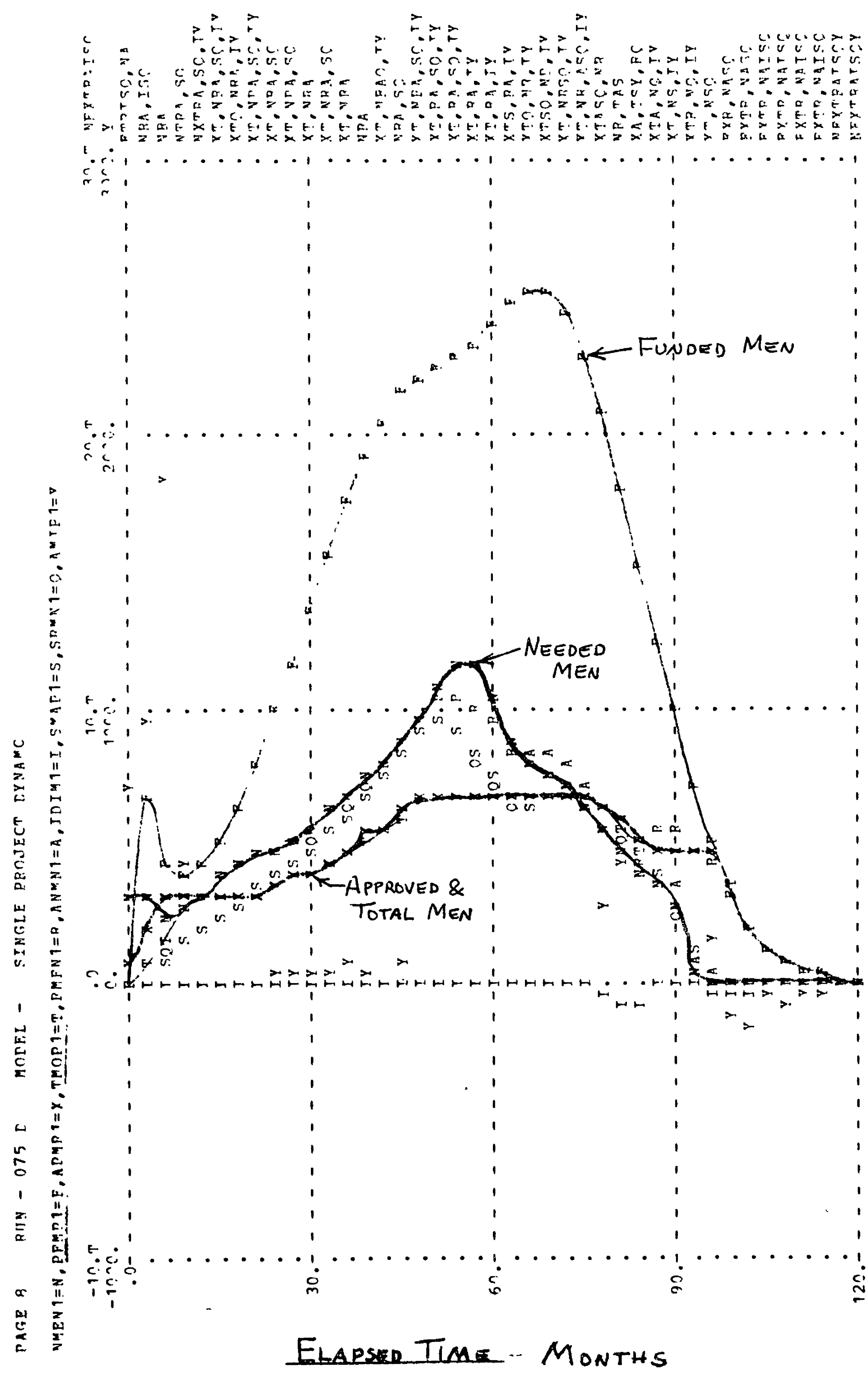
TABLE 14

EFFECT OF CUSTOMER FUNDING PERFORMANCE

| RUN # | FIXED DELAY IN BUDGETING -MONTHS | VARIABLE DELAY IN BUDGETING -MONTHS | DELAY IN ACCP'T'G COST ESTIMATES -MONTHS | TIME OF PROJ. COMPLETION (C) OR SHUTDOWN (S) -MONTHS | COST AT COMPLETION OR SHUTDOWN (% COMPLETE) (AT SHUTDOWN) -$MILLION |
|---|---|---|---|---|---|
| 017 | 6 | 12 | 3 | 90 (C) | 2709 |
| 029 | 12 | 24 | 6 | 96 (S) | (67%) |

In this case, the reason appears quite subtle, and is related to the behavior of the firm's manpower control function. Comparing Figure 22 for Run 075 with Figure 14 for the baseline run, we see that in the former case the funded manpower limit is significantly higher early in the program. This is what we would expect would result from a lower ROIC; the customer Willingness to Fund the Project increases more rapidly during the first few months of operation. The reason this appears to effect overall performance adversely is that the Approved Project Manpower Requirement (APMR), established by the firm's corporate manpower control section, also rises to a somewhat higher level in the first year of the project. However, at this point the test of peak manpower round-off cannot be passed, whereas the same test was passed in the baseline run. Hence, a plateau in manpower results from months 6 through 21 in Run 075, while the baseline run reaches a higher plateau only at month 21. Thus it appears that the slight worsening of project performance results from a rather subtle difference in the behavior of the firm's corporate manpower control function, which may or may not be justifiable in real terms. It is safe to say that there is relatively little difference in overall performance, whether the customer's Return on Investment Criteria is set at 1.0 or 1.5.

Figure 22
Effect of Reduced ROIC on Manpower
ROIC = 1.0 Run 075D



# CHAPTER IV. -- DESCRIPTION OF TWO-PROJECT MODEL

## A. FACILITIES ALLOCATION

The only functional change which was necessary to convert the single project model as previously described to two-project operation, was that of providing for release and reallocation of facilities when the project no longer needs them. The single project model had provision only for the acquisition of facilities by the project, and did not concern itself with facility release and reassignment. This feature was added by providing a facilities reallocation function. This function is based upon an assessment of the excess general-purpose facilities which become available as the project nears completion. The excess facilities are computed by comparing the perceived facility requirement with the facilities available or in the procurement process. When this difference becomes negative, there are excess facilities which can be released. Not all of these facilities are general-purpose, however. Some of them are special-purpose which are of value only to the project for which they were initially obtained.

Excess facilities are turned-in to the corporation by the individual projects, and are reallocated to new projects on the basis of the projects' approved manpower increment, taken as a fraction of the total of all approved manpower increments for all projects within the company.

Details of this functional change are discussed in Appendix D, and are shown in the equation printout for the two-project model in Appendix E.

## B. TECHNIQUE OF MODEL EXPANSION

The single project model was expanded by simply repeating the macro functional equation for Project 2, in addition to Project 1. The first expansion was to a two-project model, and initially this model was given inputs corresponding to the spacecraft project previously discussed, and to an aircraft project which was performed simultaneously in the author's company. The aircraft project was later changed to represent a second aircraft project which began after the spacecraft project had been underway for six years, as described in Chapter I, Section F.

## C. OTHER CHANGES

### 1. Initial Conditions

Some minor modifications were required for two-project operations, where different initial conditions must be specified for each project. It was no longer possible to use a single initial condition equation. In most cases, the initial condition equation inside the macro function was set equal to a constant. This constant was defined separately for Projects 1 and 2, thus specifying different initial conditions for each project. Details of this technique are shown in the equation printout of Appendix E.

### 2. Inputs Varying with the Project

It was also found that certain input constants and table functions, which had previously been considered to be universal for all projects, required different values for spacecraft programs as compared with aircraft programs. The primary differences arose in the macro Perceived Required Effort on Project, (PREP).

The PREP macro function represents the perceived scope of the job. However, perception of scope requires a different definition for spacecraft and aircraft programs, because of the different manner in which these programs are handled contractually. The large spacecraft program represented in the model was handled as a single contract covering all hardware deliveries. Thus a constant overall scope of work was intended originally, and this is represented by the PREP function. Increases in PREP result from increased knowledge of the scope of the job.

The aircraft programs, however, are commonly contracted in two lots: Lot 1 covers design, development, and production of a limited number of deliverable aircraft, usually six or less. Lot 2 represents the production follow-on which may cover several hundred additional production aircraft deliveries. The initial perception of the scope of the job covers Lot 1, but the perception grows rapidly when approval to advance into Lot 2 is given. In this case, the growth in perception is a matter of contractual definition rather than limited knowledge of the scope of the job.

To handle this difference between the two program types, the table function Fraction of Error Recognized (TFRC) was made different for the spacecraft and the aircraft projects. In the case of the latter, there is a very rapid increase in fraction of error recognized after the first 10% of the job is completed, because approval of the Lot 2 follow-on generally occurs after between 10% to 20% of the total project effort has been completed. When this approval is obtained, the firm's perception of the total scope of the job changes rapidly. Also the Delay in Changing Perceived Effort (DCPE) was reduced for the aircraft project to ½ the delay used in spacecraft, because the unknowns in technology in the aircraft projects are less, and the delay is more a function of contractual approval than of technological discovery.

## D. SEQUENTIAL PROJECT OPERATION

The following changes were required in order to achieve satisfactory model operation for two sequential projects. The principal difference in sequential project operation is that the second project does not begin until a considerable time period has elapsed. Hence, initial conditions cannot be used as a means of triggering the start of Project 2. Project 2 start-up is achieved by the timing of the intrinsic value function IVPT, from which the remainder of the project functions are activated.

### 1. Scheduling Startup Keyed to Percent Completion

The previous versions of the model inhibited the startup of the scheduling functions as a function of elapsed time, to a value set by the constant Delay in Startup of Planning (DSUP). This is not satisfactory for sequential operation, since the exact startup time of Project 2 cannot be established as accurately as for Project 1. It is equally reasonable to consider that the delay in startup of planning is a function of percent real completion of the job. This delay was therefore changed to be a function of Percent Complete (PCC), with a threshold value of PCC=.05 as the point at which the scheduling functions are activated. Results of this change appear quite reasonable; in fact, the comparison with the schedule history of Project 1 shows even better agreement with this version of the scheduling function than with the previous version.

## 2. Perceived Required Effort Inhibited by % Completion

A problem for sequential project operation resulted from the nature of the function for Perceived Required Effort on Project (PREP) at low values of Percent Completion (PCC). A small rate of increased perception of required effort was calculated in the model, and then integrated to produce the level of PREP. For a sequential project, the integration of this small rate resulted in a large build-up in PREP during the time interval before the project actually starts. This is not realistic since no real progress is being made on the project during this time period. The PREP equations were therefore modified to eliminate any rate of increased perception of PREP until PCC exceeds a minimum value, set at .02.

# CHAPTER V: -- RESULTS OF TWO-PROJECT SIMULATION

## A. MODEL VERIFICATION -- TWO PROJECT MODEL

### 1. Description of Verification Baseline -- Run 099V

A summary of results of verification baseline runs of the project model is shown in Fig. 23 through 27. For this run the two-project model had the inputs of the large spacecraft project (Project 1) and the simultaneous large aircraft development project (Project 2).

Considering Figs. 23 and 24, we see that an excellent verification of Project 1 was again obtained. In comparison with actual quantities, the model results are very close to the values given inthe single project verification, Run 067V. The only discrepancy is that in the two-project case, Project 1 is completed four months earlier than the single project model run, and approximately four months earlier than the actual project. The earlier completion of the project appears to result from somewhat higher productivity of fully integrated men during the first three years when Project 1 is building up. This in turn appears traceable to somewhat higher facilities availability, particularly between the second and third year. The increase in facilities is attributable to reallocation of facilities from Project 2, which takes place inadvertently during the early phases of Project 2. This represents somewhat unrealistic behavior, since Project 2 would not generally release facilities in its early buildup phase if they were to be required subsequently. Thus for

Figure 23
Two Project Verification Results

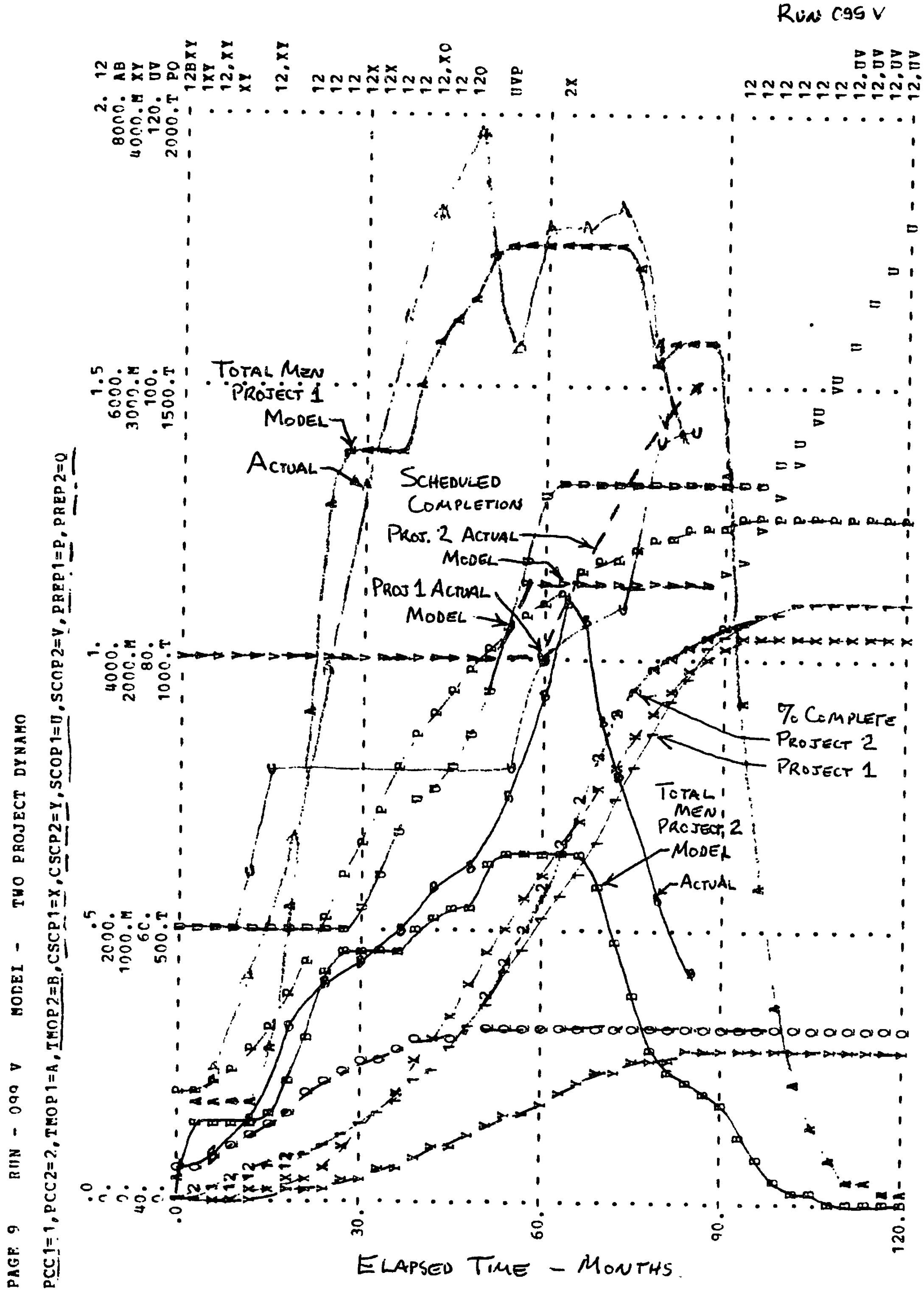
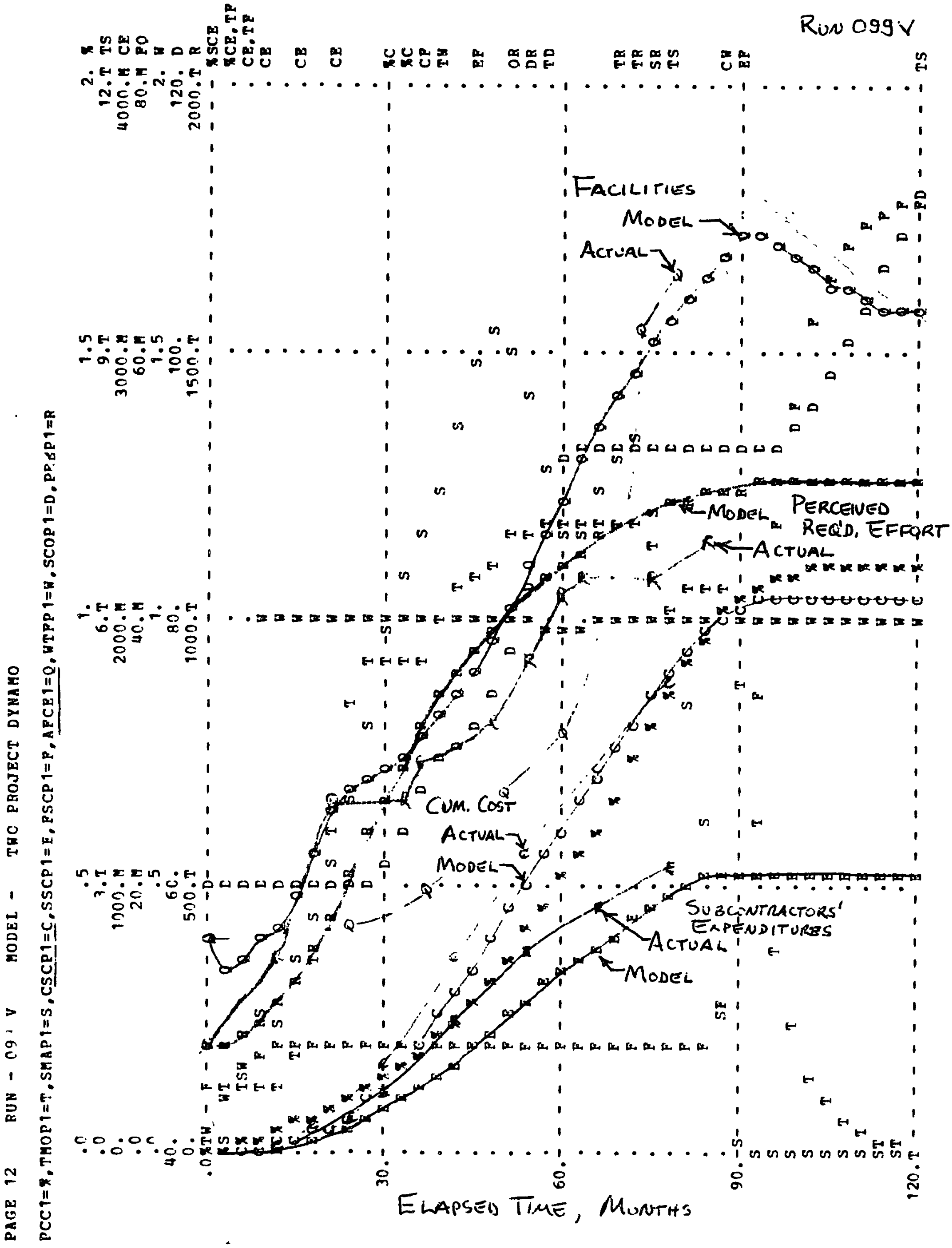


FIGURE 24

TWO PROJECT VERIFICATION – RESULTS FOR PROJECT 1



all practical purposes, it appears that the verification of Project 1 in the two project model is equivalent to that previously obtained with the single project model.

Verification results for Project 2 are shown in Figs. 23, 25 and 26. From Fig. 23 it is seen that the verification of Project 2 is not as good as that obtained on Project 1. Total Men On the Project (TMOP), particularly, is poorly represented by the model. The actual project data show a very sharp peak in men on the project between the fifth and sixth year from go-ahead. The appearance of this curve is similar to that obtained without the corporate manpower control function operative. However, in this case we know that corporate manpower control was functioning to some degree on both Projects 1 and 2 at all times. Also Project 2 is completed earlier than it should be, and the drop-off in total manpower occurs about 9 months too early.

Schedule verification for both projects is only fair as shown in Fig. 23. Here again verification is better for Project 1 than Project 2, since Project 2 slips to a smaller value of completion time than occurred on the actual program. In both cases, however, the general shape of the curve and the approximate location of significant schedule slips are similar to that experienced on the actula projects. In Fig. 25, we see rather good verification of cost and perceived required effort on Project 2. The facilities and subcontracting curves also look qualitatively good, although specific historical data to verify them are not available.

Fig. 26 also shows good agreement between the model and actual perception of percent complete on Project 2. For this parameter the agreement is actually better than

FIGURE 25

TWO PROJECT VERIFICATION – RESULTS FOR PROJECT 2

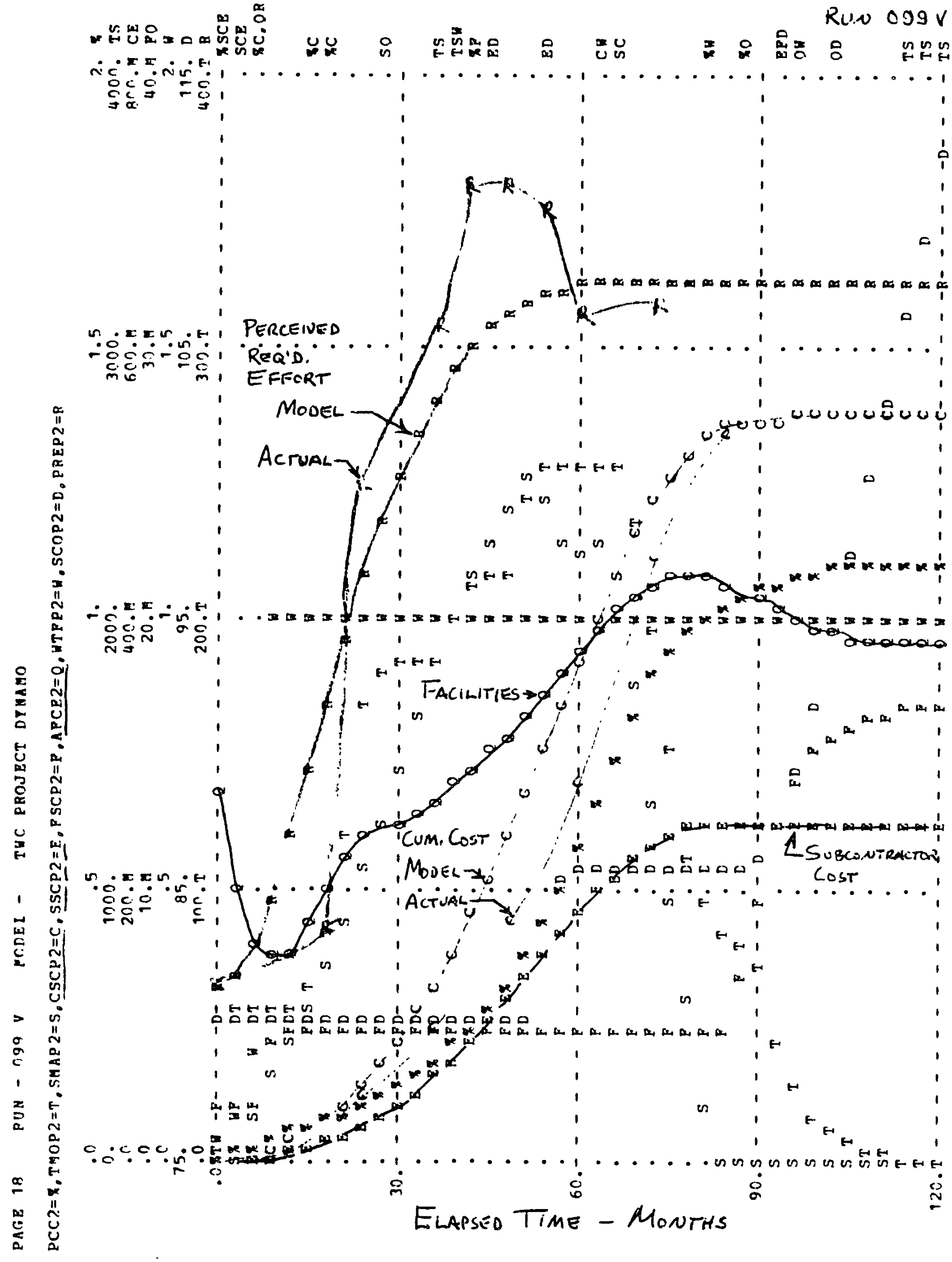
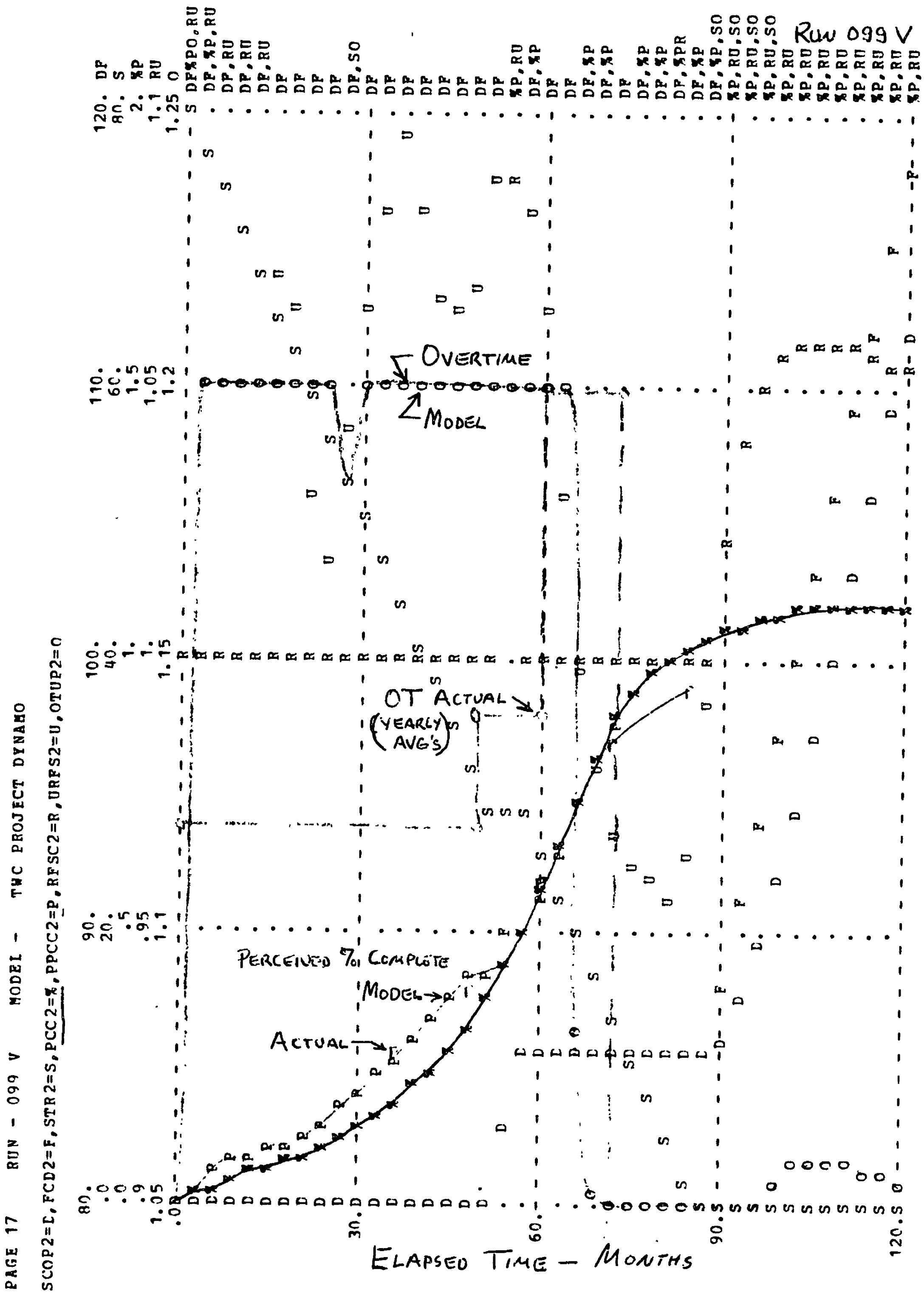


FIGURE 26

TWO PROJECT VERIFICATION – RESULTS FOR PROJECT 2



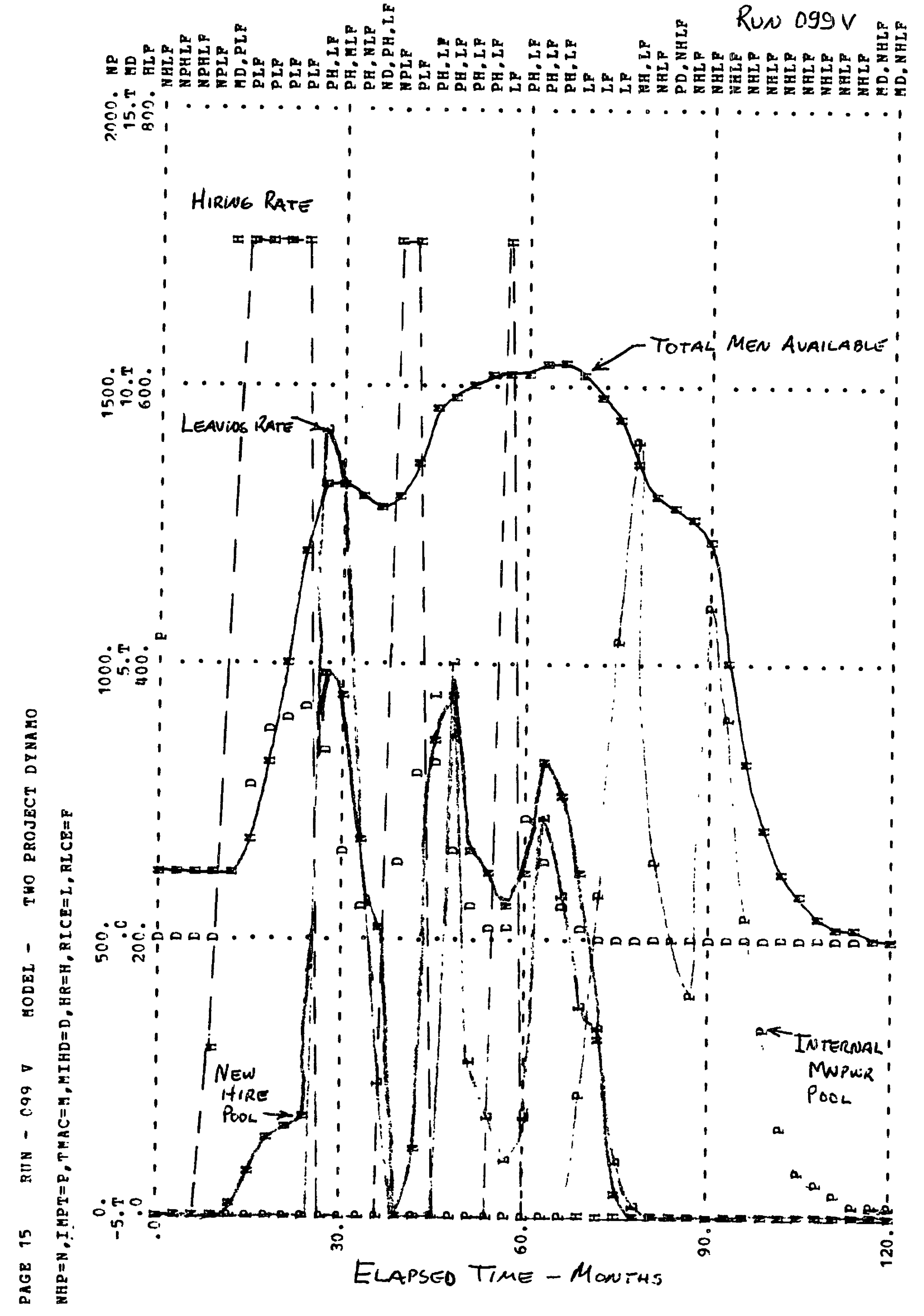
that obtained on Project 1. The model is tending to overestimate the usage of overtime on both projects. This effect is shown for Project 2 in Fig. 26. It appears that the addition of a budgetary factor as a restriction on the use of overtime would be desirable, particularly in the case of aircraft programs.

In general, however, the verification of Project 2 is quite acceptable. Both projects display the same qualitative characteristics in all of the variables studied, and both have behaved quite stably through a large number of computer runs with different input conditions.

Fig. 27 shows the results of the verification run for the central sector of the prime contractor's firm. We see a characteristic sawtooth shape of the hiring rate as it alternates between zero and the maximum allowable limit. The rate of leaving the company is an alternating sawtooth with the leaving rate peaking when the hiring rate is zero. A new hire pool builds up after the second year and is periodically exhausted by shutting off the hiring and drawing the men from the new hire pool into the projects, which are then in their build-up stage. When the projects' requirements for manpower decrease after the fifth year, a pool of experienced internal men then becomes available, and builds up to the peak limit before employees are discharged. Review of this central sector data gives confidence that the model is acting reasonably with respect to the various manpower functions, since cycles of alternate hiring and firing similar to these were observed in the actual case.

FIGURE 27

TWO PROJECT VERIFICATION — RESULTS FOR CENTRAL SECTOR



## 2. Chronology of Two-Project Model Verification

### a. Corporate Manpower Control Function

In reviewing the actual manpower data on Project 2, the shape of the total men vs. time curve looked very much as though no internal corporate manpower control was effectively functioning for Project 2, whereas the historical curve of Project 1 shows a strong influence of corporate manpower control. Knowledge of the firm's actual operation suggests that some degree of corporate manpower control was indeed exercised on all projects, and therefore this difference is unexplained.

One possibility to explain the difference in manpower curves between Project 1 and Project 2 is that the corporate manpower function may be oversimplified by treating all classes of manpower the same. It is possible that differing policies were applied to different skill categories of manpower. For example, some of the skill categories may have been in great demand for aircraft projects and not needed by the spacecraft project, as for example, aerodynamic engineers, while in other cases the reverse would be true. In cases of corporate oversupply of a certain skill, the corporate manpower control function would tend to deal more leniently with the projects' requests for manpower. However, no evidence is available that such differentiation by skill in fact existed for Project 2 during the period under consideration.

To further test this possibility, different values were tried for the function which represents the corporate manpower control's negotiations with the projects. In some cases, the corporate manpower control agency was assumed to be considerably more lenient in its negotiations with Project 2 than with Project 1, and the input function

(TFMR) was varied accordingly. Such differentiation did result in a higher value of peak manpower for Project 2, but did not produce the shape characteristic of the historical data. Such a shape could only be produced by totally removing the corporate manpower function from control of Project 2, which does not appear reasonable in view of the actual operations of the firm. A slightly higher value of TFMR than that originally used in the single project model appeared to give slightly better results for Project 2, in terms of a higher value of peak manpower, without significantly changing the shape and value of the manpower curve for Project 1. Therefore, a slightly increased value for TFMR was finally adopted and applied equally to both projects. This represents an input change to Project 1 compared with the single project model. The difference in TFMR changed the minimum value of the fraction of manpower submitted for approval by the corporate manpower control function from 0.5 to 0.6.

b. Overtime

Somewhat counter-intuitive results were found regarding the use of overtime. It appears that for overtime values near the maximum permitted (1.25 to 1.15), there is a definite advantage in project performance if the maximum allowable overtime limit is lowered. This result applied to both projects. In reviewing actual historical data regarding the use of overtime, it appears that the average use of overtime on Project 2 was between .10 and .05 less than on Project 1. Therefore, the constant for Maximum Allowable Overtime (MAOT) was made different for Projects 1 and 2. This somewhat improves the simulation of Project 2 by delaying the project completion by about 3 months.

c. Percent of Job Subcontracted

During some of the early verification runs, the model was overshooting the desired percentage of job subcontracted by about .02 at completion of the project. This effect appeared consistent through several runs. It was also noted that the rate of internal manpower buildup was fairly sensitive to the specific values used for Percent of Job Subcontracted. Since the aircraft program of Project 2 used a somewhat lower percentage of job subcontracted, this value was adjusted by the .02 overshoot to obtain the maximum reasonable manpower buildup from the model. It is also quite possible that the percentage of jobs subcontracted on Project 2 may have been significantly lower than the value used during the first two years of the simulated project. This results from the Lot 1/Lot 2 procurement technique used in aircraft projects. In general, the prime contractor subcontracts out significantly less of the job during the initial Lot 1 development than he will for the production follow-on. Accurate data are not available on this effect for Project 2. However, to the extent that it did occur, it would tend somewhat to explain the reason why the prime contractor's actual manpower so far exceeded that predicted by the model.

3. Description of Sequential Two-Project Baseline

The results of a sequential two-project baseline (Run 107V), in which the second project started approximately six years after the first, are shown in Figs. 28 through 30. Figure 28 shows the overall performance of the two projects. Project 1, the spacecraft development program used in the earlier simulations, is completed by T= 90, and men are being removed from the program rapidly at that time. Project 2, representing a large aircraft development program, begins with in-house effort at T=60

FIGURE 28

TWO SEQUENTIAL PROJECTS — BASELINE RESULTS

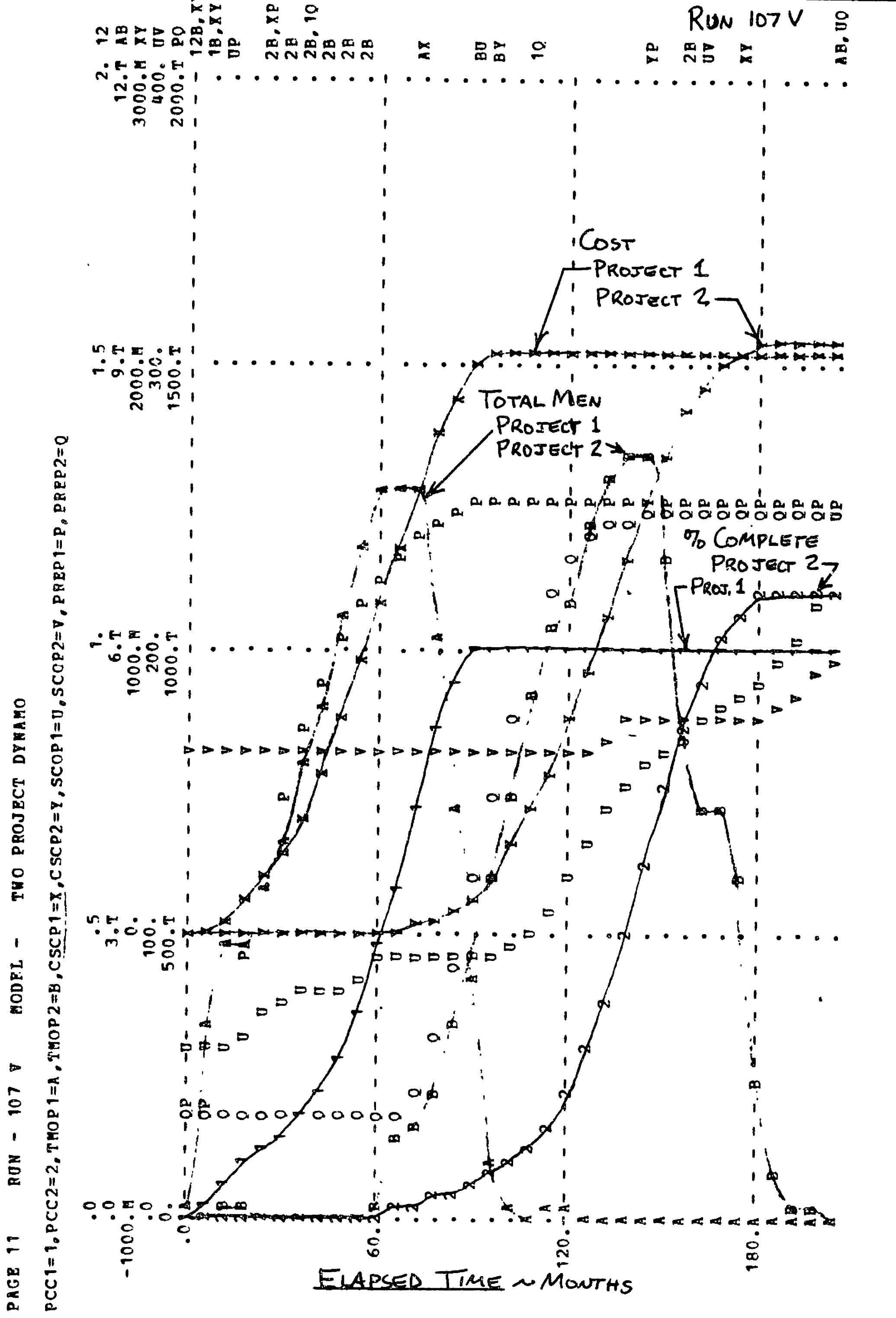
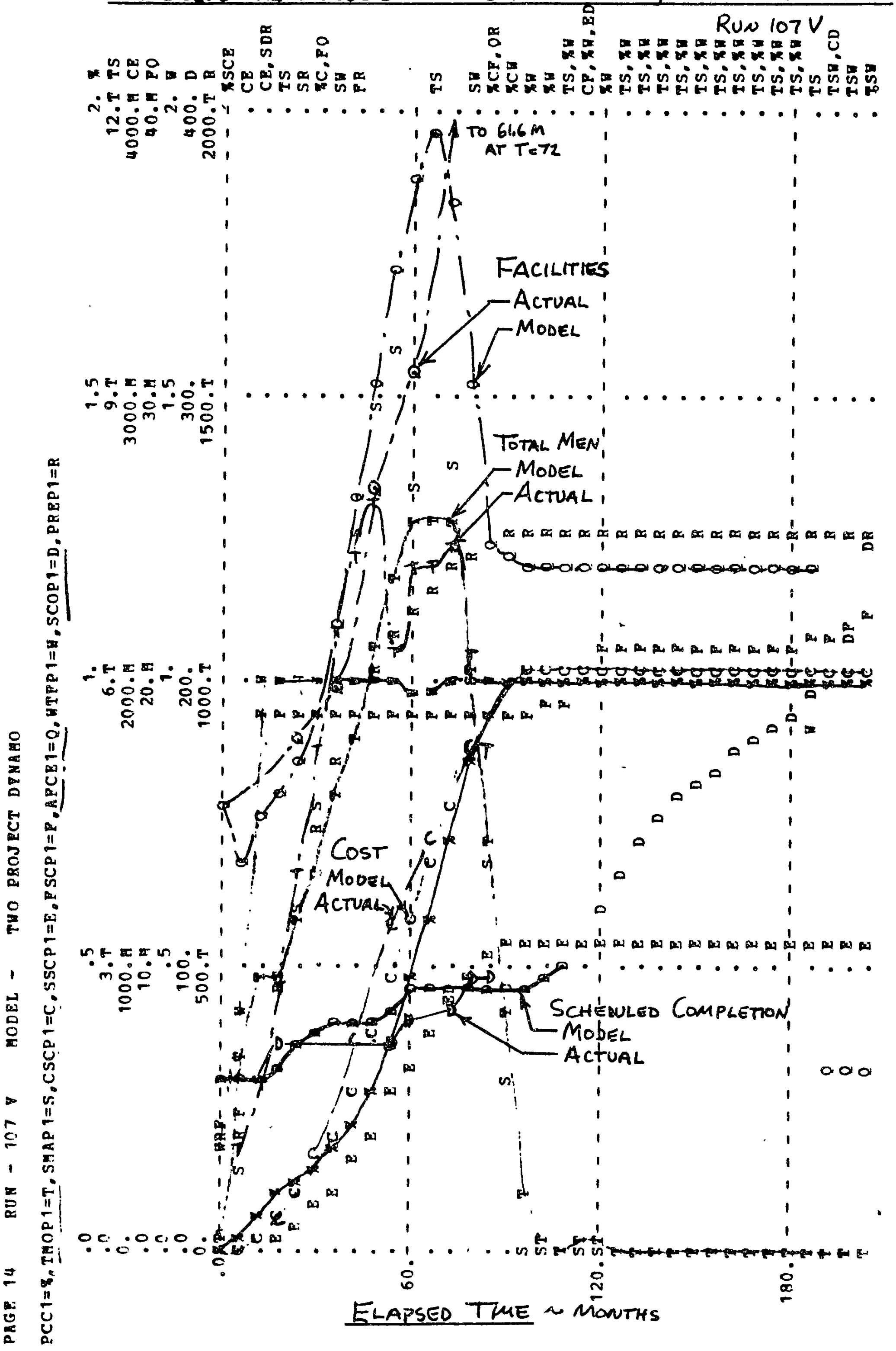


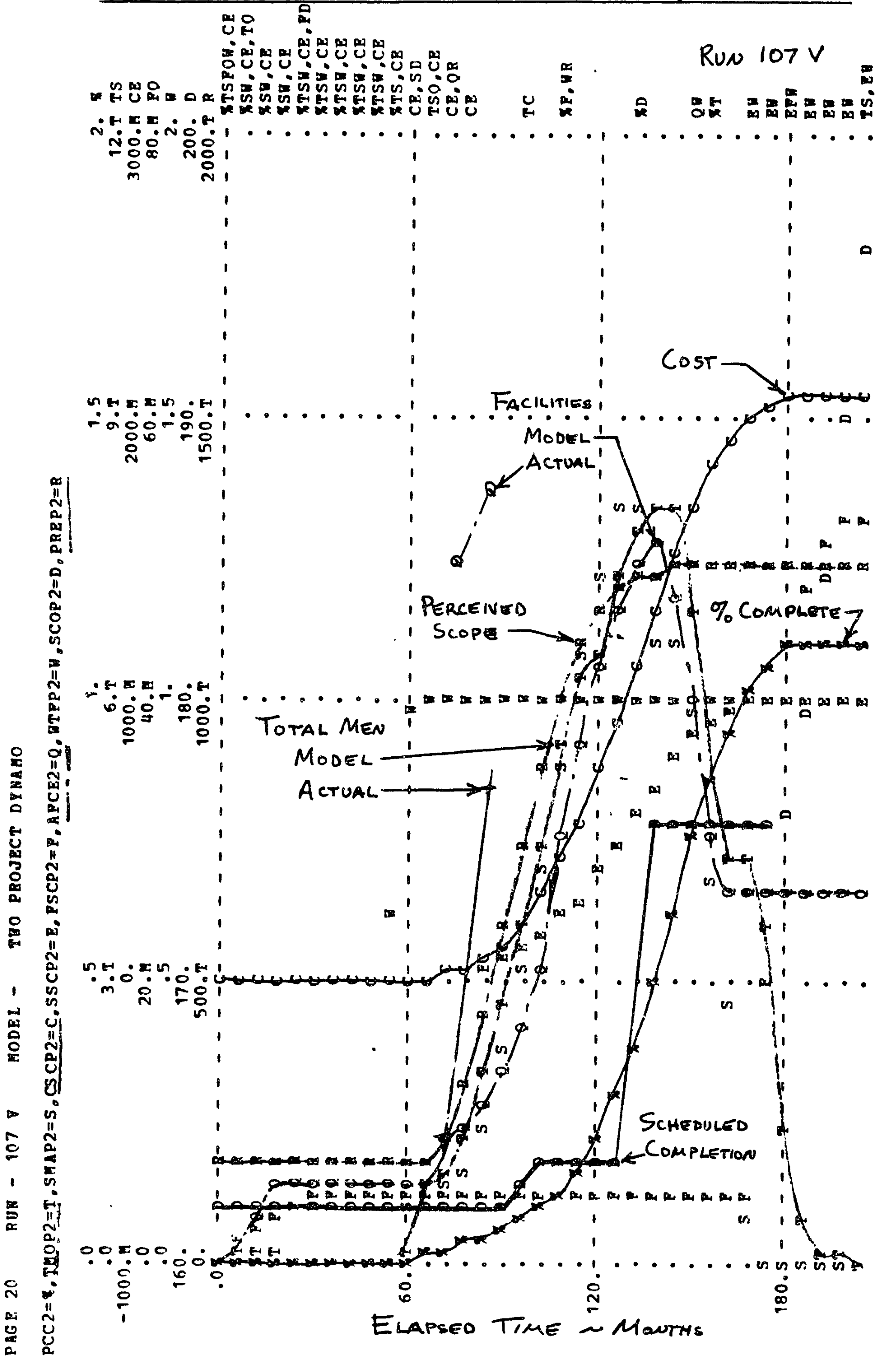
FIGURE 29

TWO SEQUENTIAL PROJECTS — BASELINE RESULTS, PROJECT 1



# Figure 30

## Two Sequential Projects — Baseline Results, Project 2



and becomes customer-funded by T=72. Project 2 is completed at T=167, and the general shape of the cost and manpower curves are very similar.

Figure 29 shows that excellent verification with actual history on Project 1 has been preserved. The agreement between model and actual manpower and cost is similar to that obtained previously, while the agreement on schedule is actually improved. This improvement results from the change in the scheduling logic discussed previously. The facilities curve is no longer directly comparable with the actual data, since the model has been modified to release general-purpose facilities from one project to another, while the actual data reflect the cumulative acquisition of facilities by the project. Hence, the facilities curve should be compared with actual data only during its increasing portion, and for this portion of the curve the agreement with actual history is very good.

The performance of Project 2 is shown in Fig. 30. Project 2 has actually been underway for only a little more than one year, and therefore not much actual data are available for comparison with the model predictions. The Figure does show a one-year comparison between the model and actual data for total men in the prime contractor's project, and for prime contractor facilities. In both cases, the model greatly underestimates the rate of buildup of manpower and facilities, and in the case of facilities, these are misplaced in time. It is believed that this poor correlation between model and actual history results from the somewhat limited scope of the model. In the actual company, there are several other large projects underway simultaneously with Project 2, and in the real case, all of the other company projects were rapidly decreasing at the time Project 2 was increasing. Therefore, the available manpower and facilities pool for Project 2 was considerably greater in the real world than that shown by the model, since the model considered only those men and facilities released from Project 1. This effect was particularly important for Project 2, since it was unique in building-up while the remainder of the company was decreasing. In comparison, Project 1 and the simultaneous Project 2 discussed earlier (Run 099V) were both building-up in manpower and facilities at a time when the remainder of the firm was neither increasing nor decreasing. In this case, the influence of the remainder of the firm not covered by the model is less significant, since this protion of the firm was remaining static, and hence was not available to Projects 1 and 2 as a source of manpower and facilities. This lack of fidelity will be reduced as the model is expanded to handle a greater number of projects.

In all other respects, Run 107V appears to be a good baseline for sequential project operation, The behavior of the central sector is similar to that observed in previous simulations. The Maximum Attainable Hiring Rate (MAHR=700 men/month) results in periodic overhiring, which causes intermittent layoffs. This process is repeated during the build-up period for both Projects 1 and 2. The total men available at the company shows two peaks separated in time by five years, representing the peak manpower requirements of the two projects.

## B. EXPERIMENTATION WITH TWO-PROJECT MODEL

### 1. Effect of Overtime

The effect of overtime on the two-project model is summarized in Table 7. For the limited range of overtime usage investigated, reduction in overtime was very beneficial to project performance. Significant reduction in project completion time and costs resulted from lowering the maximum allowable overtime by .05, from initial values of 1.25 and 1.20 for Projects 1 and 2 respectively. This improvement is traceable to two effects. First, the corporate manpower control function tends to use the equivalent manpower utilization on the project, considering all overtime, as its baseline in determining whether proposed manpower increments are sufficiently long-term to justify approval. Thus the more overtime the project uses, the greater its equivalent manpower level, and the less likely it is to obtain approval for further increments of full-time men. Thus we obtain the result that with the maximum allowable overtime limited by company policy and budgetary restrictions, the corporate manpower control function is more amenable to allowing additions to the full-time project staff. This effect is consistent with that observed in practice.

The other principal effect of overtime is more subjective. An overtime productivity multiplier (OTPM) was used which relates the productivity of all workers on the project to the average overtime utilization. For prolonged periods of high overtime, the productivity is lowered due to fatigue and inefficiency. Unfortunately, this is a rather subjective curve, and therefore the significance of this portion of the effect is only as good as one's faith in the estimation of overtime effect on productivity. The representation used for OTPM reached a minimum value of .88 when average overtime equaled 1.25.

## 2. Effect of Hiring Policy

The two-project model was used to investigate the effect of a more conservative hiring policy. In Run 101D, the Desired Stability Level (DSL) was set equal to 36 months, compared with 18 months in the two-project baseline, Run 099V. The Maximum Attainable Hiring Rate (MAHR) was cut in half, from 700 men/month for the baseline, to 350 men/month for Run 101D. Of these two changes, the reduction in MAHR was by far the more significant, since the firm still operated in the characteristic fashion of either hiring at the maximum rate or not hiring at all. Apparently the DSL levels chosen have not yet approached the value at which the firm's stability index poses a serious restraint to hiring.

The reduction in MAHR could result from a deliberate management policy, or merely from a failure to expand the personnel recruitment activities to a sufficiently high level to achieve greater hiring rates. In this case, it seems that the reduction was a deliberate management policy, since the past history of the author's firm shows that a rate of 700 men/month was actually achieved over a prolonged period.

The effect of this policy change on performance is shown in Table 8, and in Fig. 31, which should be compared with Fig. 23 for the two-project baseline. We see that project performance is significantly improved by the more conservative hiring policy. Completion of both projects occurs sooner; five months sooner for Project 1 and four months sooner for Project 2. Cost of the programs is reduced by about 1½% on Project 1 but increases slightly for Project 2. We also note a marked change in the shape of the prime's total manpower vs. time curve for both projects. Each project attains a higher level of total manpower and reaches that maximum level as a result of a steady increase, rather than the step-wise progress shown in Fig. 23.

Fig. 32 shows the manpower situation in more detail

FIGURE 31

CONSERVATIVE HIRING POLICY – EFFECT ON PERFORMANCE

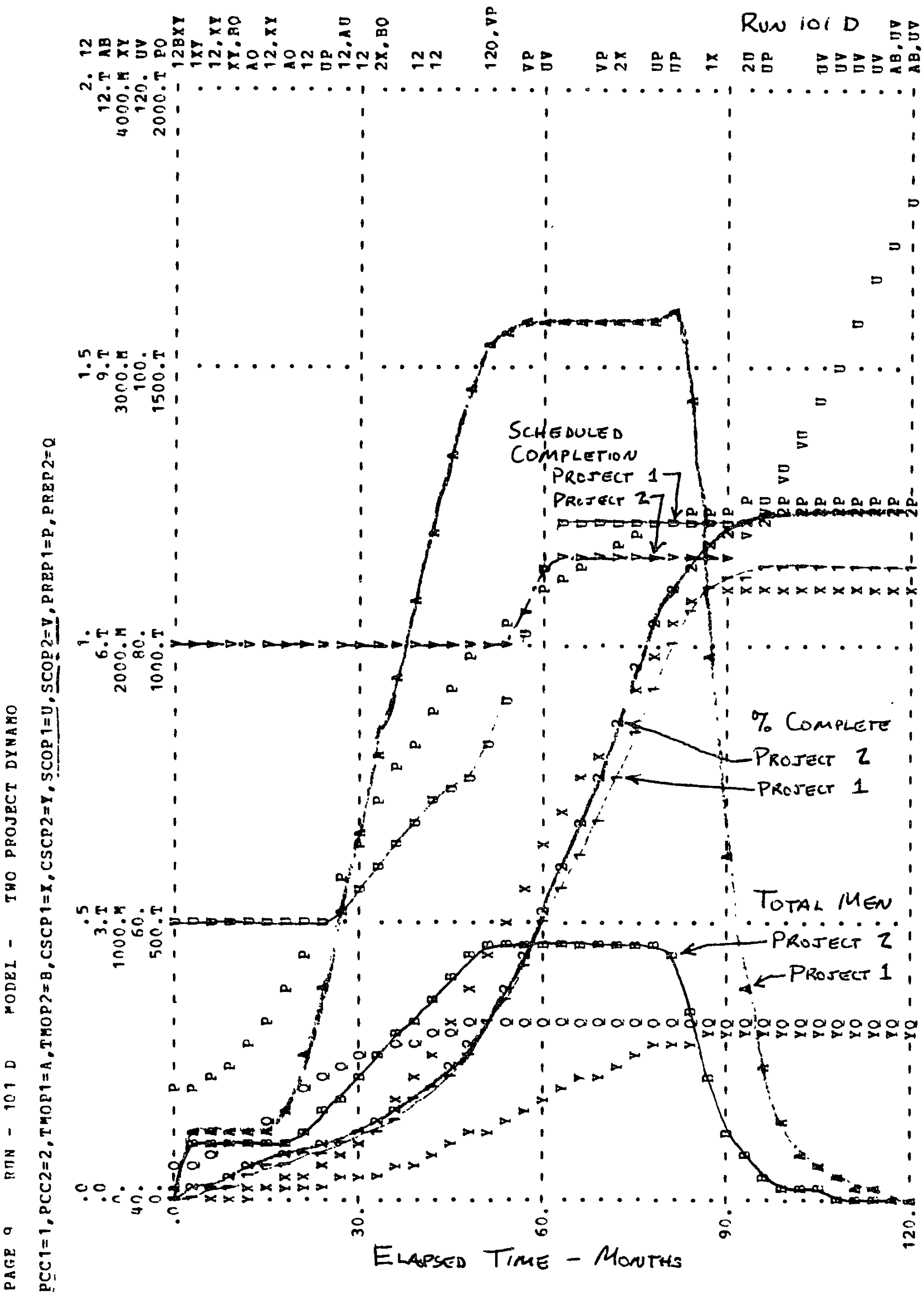
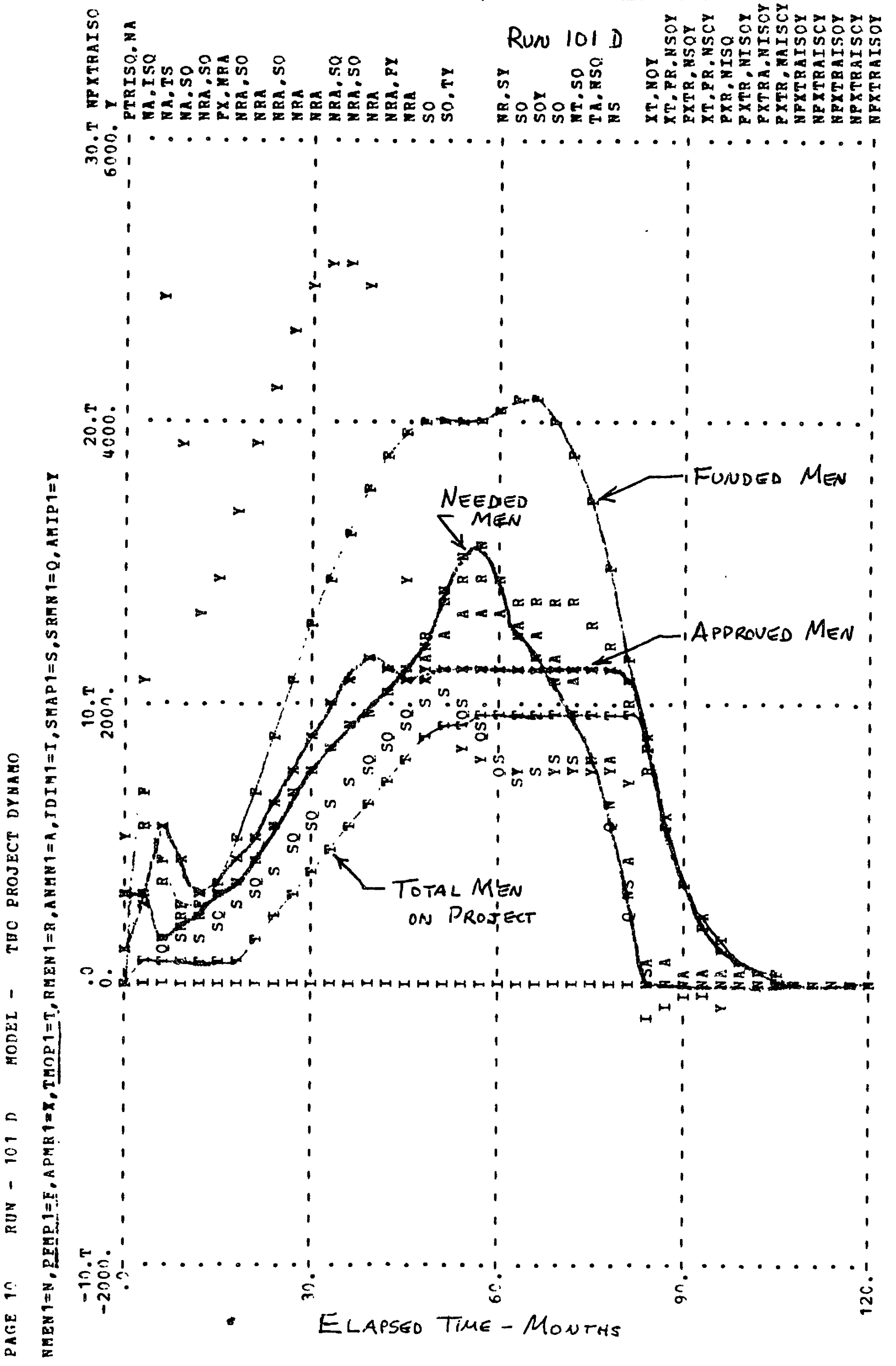


Figure 32

Conservative Hiring Policy – Effect on Proj. 1 Manpower



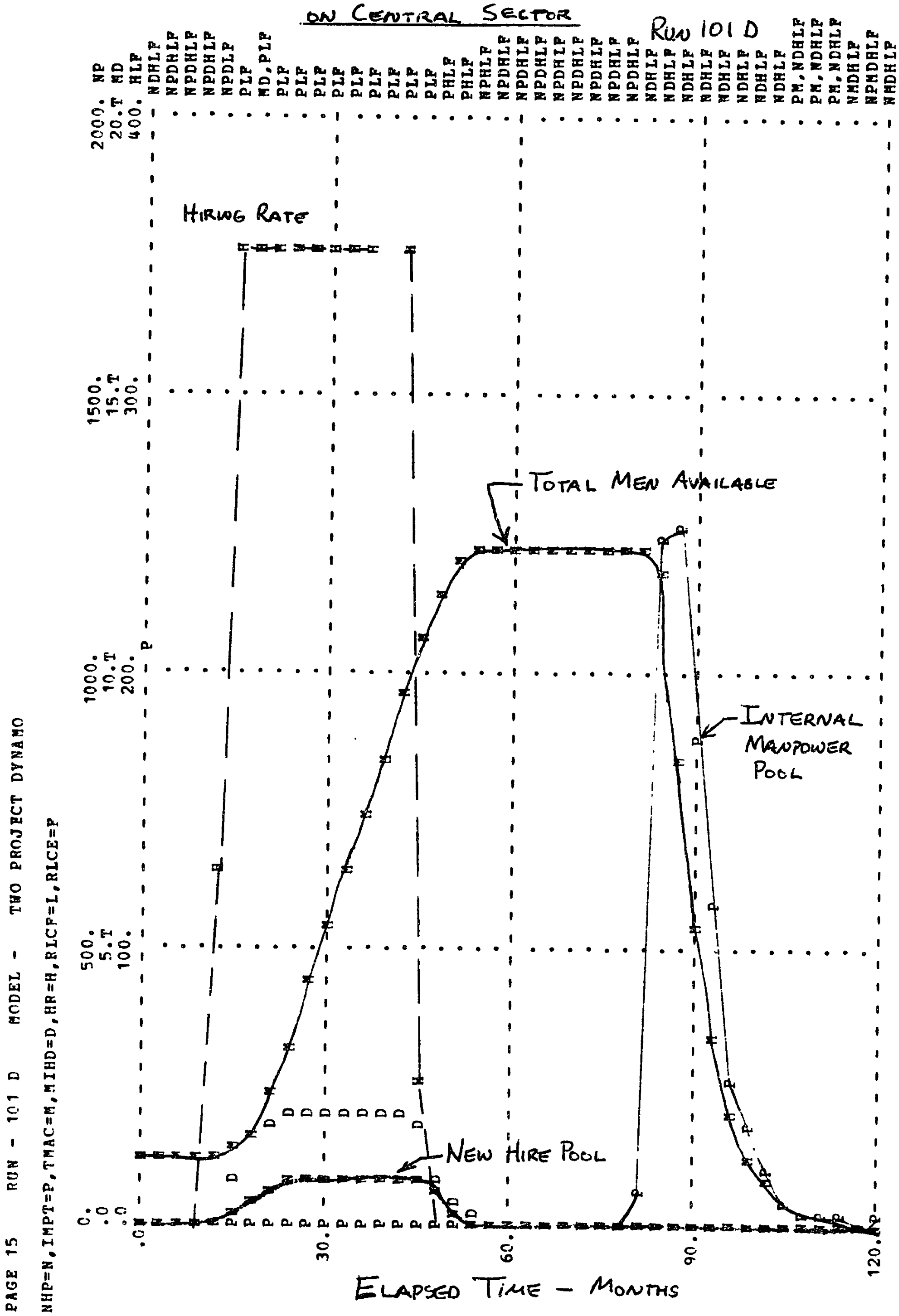
for Project 1. This should be compared with Fig. 14, which gives almost identical results to the two-project baseline. The curve of approved men vs. time again reflects a steady build-up to a peak level, rather than step-wise increases as in Fig. 14. Total men on the project significantly lags the approval of manpower, whereas with the more aggressive hiring policy, the total manpower coincides with approved manpower from time T=24 months onward. This shows that the reduced maximum hiring rate is unable to keep up with the rate of manpower approvals within the firm.

The reason for this fundamental difference in project manning can be seen by comparing Fig. 32 with Fig. 14 in the region of time T= 24 months. In this time region, comparison of the approved manpower curve with that for total manpower on the project is significant. At this point, the level of manning on the project is sufficiently high that the project can no longer justify to corporate manpower control the long-term nature of the required manpower increase, and therefore corporate manpower control turns off further approvals for almost a year, during which time the perceived scope of the job increases to the point where long term manpower increases can again be justified. With the conservative manpower hiring practices, however, total men on the project never reaches the approved level and the project is therefore able to justify the long-term nature of their required manpower increments. This results in the smooth growth in both approved men and total project manning.

The conservative hiring policy also results in far more efficient operation of the central sector of the firm. This can be seen by comparing Fig. 27 with Fig. 33. For the conservative hiring policy, we see far less hiring and

FIGURE 33

EFFECT OF CONSERVATIVE HIRING POLICY ON CENTRAL SECTOR



firing, but rather a single sustained period of hiring during which a steady build-up of total men in the company occurs, and then a long steady period in which no hiring occurs, but during which the men who have been hired are absorbed into the projects. The result is a considerably more efficient operation, since less effort is wasted on hiring and training men who are then released during the successive hiring/firing cycles shown in Fig. 27. This effect partly accounts for the lower cost to the customer of Project 1 with the conservative hiring policy.

In summary, it appears that a conservative hiring policy offers significant advantages both in terms of project performance and the efficiency of the firm's internal operation. By means of a model such as this one, the firm could experiment with various hiring rate levels to determine what is the most efficient threshold at which to set the maximum hiring limit, for any given set of project requirements.

### 3. Effect of Increased Allowable Overhead

A run was made (Run 102D) in which the percent of internally-funded research and development expense allowable as overhead (PCAO), and the percent of men allowed in the internal manpower pools (PAIP) were both increased by 50%, to .06 and .08 respectively. No significant differences from the baseline (Run 099V) were observed for either of the two projects. Comparison of the detailed performance of the central sector of the firm indicates that the manpower pools, both the new hire pool and the internal experienced manpower pool, rise to somewhat higher levels at their peaks. However, the overall shape of central sector performance is almost identical to that shown in Fig. 27. Therefore, it appears that where we are considering only projects which are proceeding in implementation under contract, there is little effect on firm or project performance of increases in the allowable overhead charges. A different result would be expected if we were considering projects which were still in the unfunded precontractual stage.

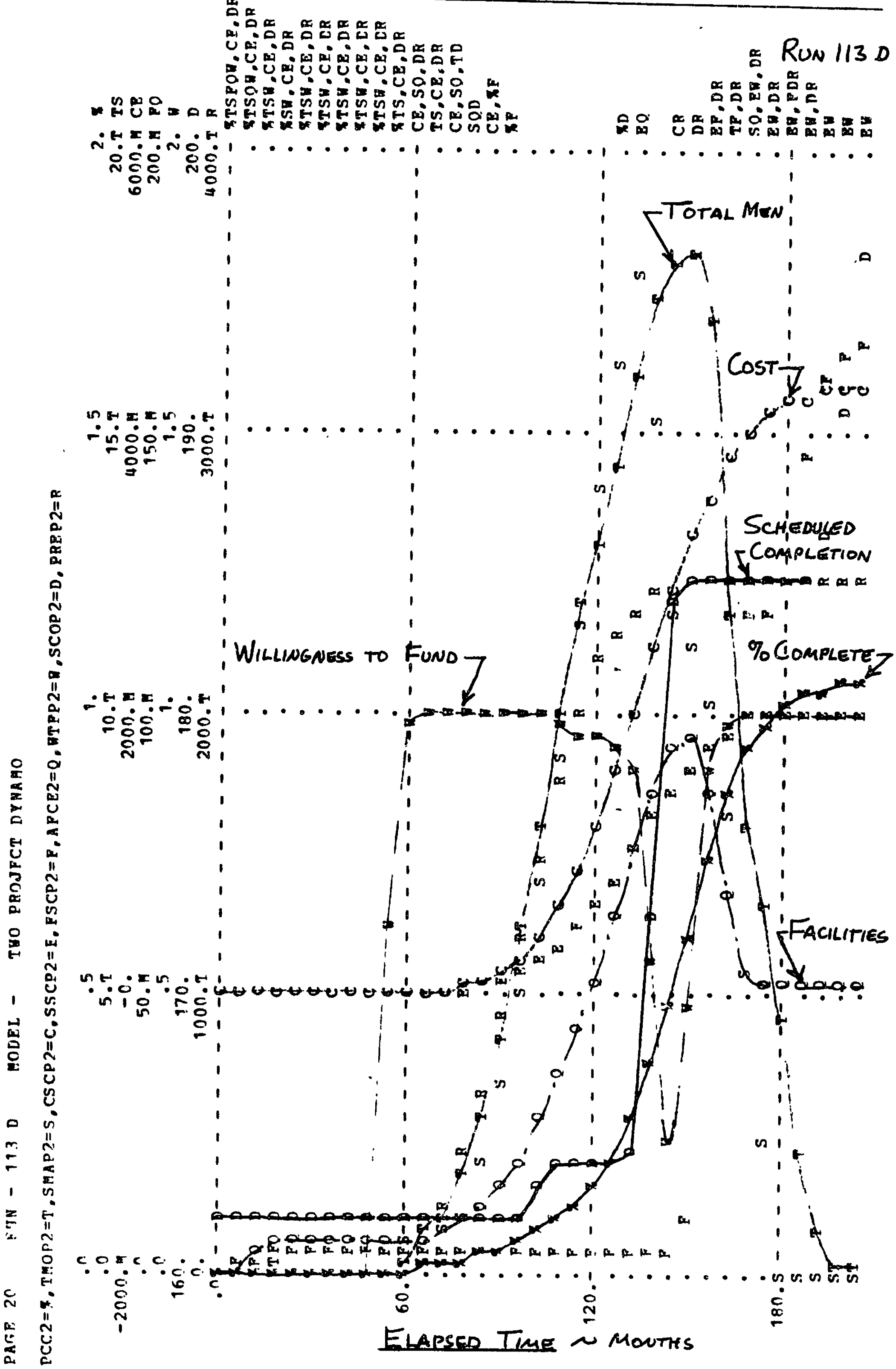
4. Doubling Project 2 Cost and Value

Some interesting effects were observed when the Real Total Cost to Complete (RTCC) was doubled, and the Fraction of Real Effort Recognized (FRER) was halved, for Project 2. As mentioned in the Introduction, this effect was investigated with the original intrinsic value of the project (IVPT), and then with IVPT doubled. The results are given in Table 9 and Fig. 34.

The simulations in which both costs and value were doubled (Run 110D) produced no unusual results. Total manpower and costs approximately doubled, and the schedule slipped thirteen months due to the longer time required to reach peak manpower. However, when costs were doubled without increasing value, the project barely avoided cancellation, as shown in Fig. 34. With RTCC doubled and FRER halved, the initial perceived scope of the job is the same as that used in the baseline run. Hence there is no inhibiting effect on early customer funding. However, as costs continue to grow towards the much higher ultimate value, the customer's willingness to fund the project rapidly decreases, because the estimated project cost exceeds his perception of project value. The Willingness To Fund curve in Fig. 34 is seen to decrease sharply at T=132 and reaches a minimum of .237 at T=144. This is the lowest value of WTFP from which recovery has subsequently been achieved in a simulation. As Fig. 34 shows, the

FIGURE 34

DOUBLED REAL COST — EFFECT ON PROJECT 2



total manpower level is very high (over 18,000 men) when the customer's willingness to fund is lowest, and rapid progress is being achieved on the project, as seen from the slope of the percent complete curve. The customer perceives this rapid progress just in time and this causes a rapid increase in his willingness to fund the project, resulting in successful project completion. As seen from Table 9, the pressure applied by the customer in the form of funding limitations encourages the project to man-up to a higher level, resulting in two months earlier schedule completion and a slight decrease in cost to the customer. However, the firm itself bears considerably higher costs as a result of its selection of higher manning levels, and hence the total cost of the project is increased, for this case where the project size was doubled without doubling the customer's perceived value.

Doubling RTCC while halving FRER represents the real case in which the ultimate size of the project is being underestimated by an additional factor of two, over and above the sizable initial underestimation of scope. Hence it is seen that the system is quite tolerant of serious underestimation of project scope by the firm. From the previous results it has been shown that any improvement in the firm's perception of scope must be accompanied by a corresponding increase in perception of project value by the customer, or else project performance suffers.

5. Early Cutoff of Project 2

This case is interesting because it gives some insight into the delays inherent in the funding and manpower control system. The Intrinsic Value of Project 2 (IVPT 2) was sharply reduced at the completion of the Lot 1 development phase, T=120. This would correspond to a case where the customer is dissatisfied with the results obtained in the aircraft development program, but does not translate this dissatisfaction into immediate project cancellation. As shown in Fig. 35, willingness to fund decreases from T=120 onward, and has shut off most new funding by T=132. Thus a one year delay ensues in the process of recognizing the reduced value of the project and taking action. However, progress on the project is so rapid at the time of funding cutoff that the firm elects to keep going at its own expense, in the hope that the project termination can be reversed. In our two-project model, of course, the firm is driven to this course of action because it has no other work available for its employees, a situation which hopefully is not represented in the real world. The firm, therefore, retains men on the job for an additional year, and incurs very heavy costs in so doing. At T=144 however, with no revival of customer interest, the firm gives up and rapidly removes men from the project and from the company. A summary of these delays and the costs incurred thereby is given in Table 10.

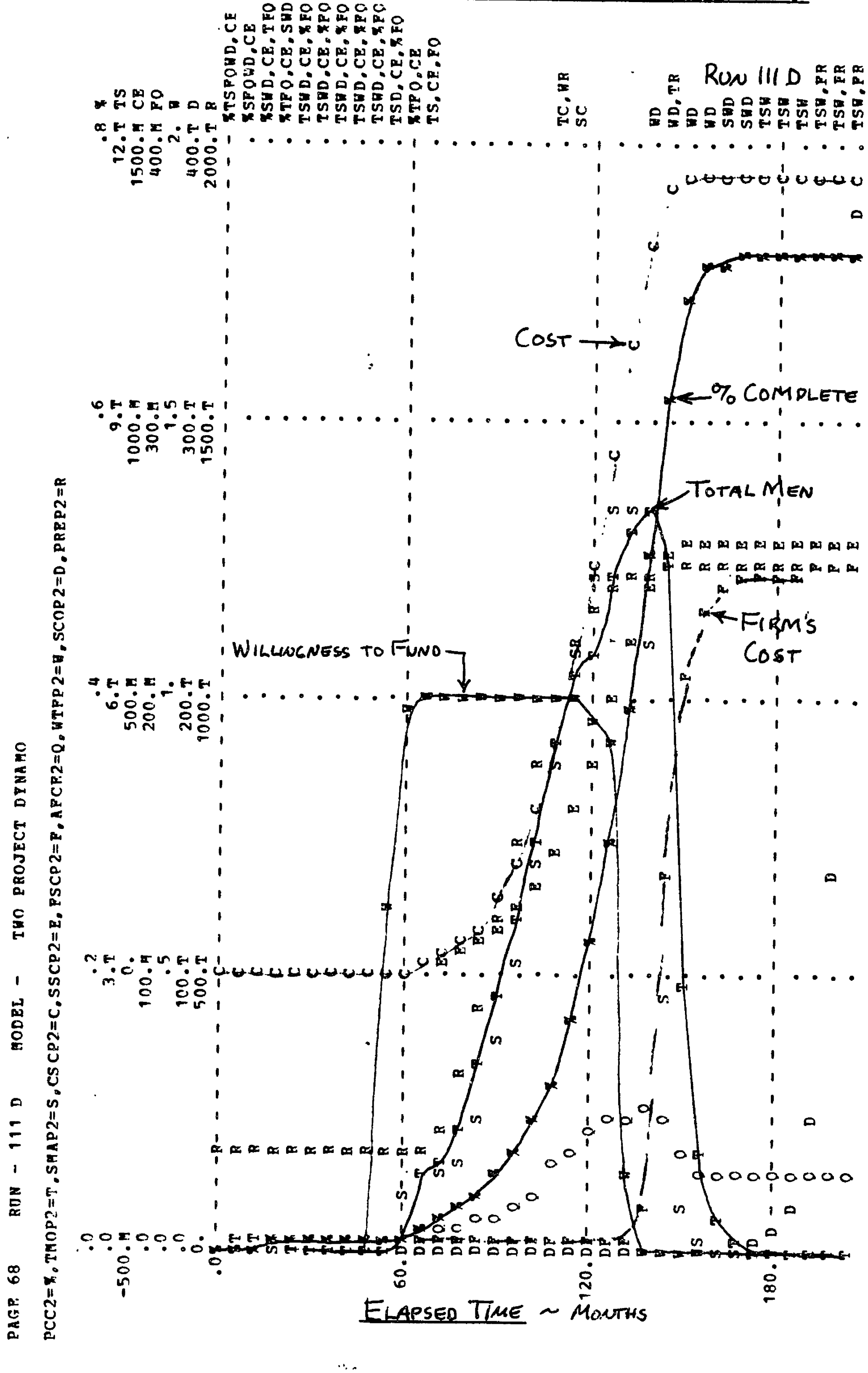
This case represents a situation which could occur in the real world, if the firm had no other source of employment for its people, and if it perceived a possibility that the decision of the customer agency to terminate the program might be reversed in the face of continued excellent progress on the job. The risks of such a course of action are apparent, however, in the heavy cost burden borne by the firm in this case.

### 6. Susceptibility to Budget Cuts

The Susceptibility to Budget Cuts function, which has been previously described, was uncaged in Run 112D, with political pressure for budget cuts represented by random

FIGURE 35

PROJECT 2 TERMINATION AFTER LOT 1 COMPLETION



noise. As noted in the Introduction and summarized in Table 11, some arbitrary budget-cutting did occur which resulted in a 3-month schedule stretch-out of Project 1, and a $3 million increase in firm's costs, with no increase in customer costs. No clear evidence of budget cuts on Project 2 exists from the run, although peak manning was somewhat different, which suggests that some effect not recorded in the run output may have occurred. A 15% arbitrary budget cut did occur in Project 1 at T=12. This is a critical time for manpower build-up, in which the funded manpower is limiting the project approved manpower, and hence some effect was noted on overall project performance.

In general, it appears that the Susceptibility to Budget Cuts function would require repeated simulations to establish the degree of vulnerability of a particular project to random, politically-inspired budget cutting. Such simulation would be of value only when project management is concerned that the margin for success in a project is sufficiently narrow that such arbitrary behavior could have serious consequences.

# CHAPTER VI. -- CONCLUSIONS AND RECOMMENDATIONS

The broad conclusion is that the hypothesis has been satisfied by the creation of a model of large research and development projects which can be useful as a management tool. This conclusion is based on the fact that the model satisfies Forrester's basic criteria: (1.) Each element of the model can be justified in terms of knowledgeable qualitative observations by managers working on projects of this nature. Also values of parameters were used that can either be traced to real cases, or appear qualitatively reasonable in terms of real world situations. (2.) The model has been able to reproduce quite well the actual performance of a real program over a seven-year time span. This achievement gives confidence in the basic structure of the model, and its ability to function in a representative fashion. (3.) The model behaves in a reasonable and explainable manner when given inputs beyond the scope of normal experience.

Investigations with the single project version of the model have shown that one of the most important management policy variables is that of firmness in adhering to the officially-published schedules. A policy of firmness ultimately results in lower costs and faster project completion. Any vacillation therefore is to be avoided, as it has directly the opposite effect.

Some interesting and perverse effects by which improved perception of the scope of effort required at the start of the job may actually impede progress on the job are predicted by the model. It appears that such behavior is a real possibility. However, it becomes an objective for customer and contractor to work together to better understand the true value of their system, so that this type of erroneous evaluation can be avoided.

It was also found that an internal corporate manpower control function has a very powerful effect on overall project behavior. It tends to retard on-schedule performance of the project, but acts to reduce costs and greatly stabilizes the firm's employment level. On balance it would appear that this function serves a quite useful purpose.

Other factors are discussed from the single project runs which are of relatively lesser importance. It is significant to note that the model is quite stable throughout all its operations, and that it does respond reasonably to changes in key decision criteria or key information streams wherever these exist throughout the project.

The model is a valuable training aid for program managers, since it allows them to investigate the interactions between the various project, corporate, and customer activities. For example, the model forecasts a built-in "time of troubles" for all large R & D projects, and shows how the program manager can improve or worsen the situation by his resulting actions.

Experimentation with the two-project model has shown that significant improvement in project performance, cost reduction, and internal operating efficiency can be achieved by limiting both the maximum allowable overtime, and the maximum attainable hiring rate. It appears that this model will be particularly valuable in permitting investigation of these effects, and in allowing management to establish approximate values which promise to yield the most effecient overall results.

## A. SUMMARY ANSWER TO PROBLEM STATEMENT

Referring to the Problem Statement given in Chapter 1, Section B, the following summary answer is given:

The R & D project manager will find that the following management policies are most likely to be effective, in terms of project performance and corporate stability:

### 1. Manpower Policies and Controls

Limit maximum allowable hiring rate and overtime usage for greatest efficiency. Provide feedback procedure to prevent corporate hiring when projects are laying men off. Basic manpower control procedures are adequate as modeled.

### 2. Information Utilization

Moderate delays in progress reporting and perception have relatively little effect. Improvements in the firm's estimation of project scope must be accompanied by increased perception by the customer of value, or the project will suffer.

### 3. Management Attitudes Affecting Policy

Such attitudes are very important. Firmness by management in supporting official schedules is essential. Management should avoid interpreting the initial overestimation of progress on the project as evidence of lack of project team effectiveness, or it will take improper corrective actions which may harm the project. Company funding policies regarding R & D do not significantly affect performance on projects under contract, but other studies have shown their importance in obtaining contracts in the first place.[1,2]

4. Subcontractor Management

Subcontractor performance greatly aids the project, and even with normal delays in the system, the subcontractors reach their peak effectiveness before the prime contractor. The present procedures therefore appear quite satisfactory regarding subcontractors.

5. Facilities

Initial level of facilities is very important to project performance. No other variations were studied in this area.

6. Customer Policies

The customer's return on investment criteria for projects is very important, and shows an optimum value of 1.5. Too high an investment hurdle will cause project shutdown. Progress on the project is also sensitive to delays in the customer's funding procedures. If funds are not made available in a timely manner, performance suffers.

7. Project Interactions

No detrimental interactions were noted in the limited two-project simulations which were performed, and hence the current procedures for allocating men and facilities to projects appear to have no major problems.

1. Edward B. Roberts, op.cit., pp. 251-269.
2. Joe N. Nay, op.cit., pp. 39-45

## B. RECOMMENDATIONS

Obviously the capability of this model has not been fully exercised in the time available for this study. The following areas of major interest are recommended for further work:

### 1. Schedule Stretchout Capability

The model has recently been modified to be capable of introducing arbitrary stretch-outs into the project schedules, accompanied by an increase in the estimated overall cost of the project. Such stretch-outs are commonplace today, when the aerospace industry is in a period of retrenchment. The customer directs a schedule stretch-out to reduce current expenditiures, while recognizing that the overall cost to completion will be increased because of less efficient utilization of resources.

Because of the current interest in this situation, the schedule stretch-out capability should be exercised for various relative project phasings, on the two-project model.

### 2. Model Expansion

The model should be further expanded to handle four projects, with any desired relative phasing. This can be done with relatively minor modifications to the sequential version of the two-project model.

### 3. Application to Problem Statement

With a four-project model, greater attention could be given to those portions of the Problem Statement which were least thoroughly treated in the current work.

Emphasis should be given to management policies in the areas of project interactions, facilities, and subcontractor management, since these received the least specific treatment herein.

# CHAPTER VII. -- BIBLIOGRAPHY

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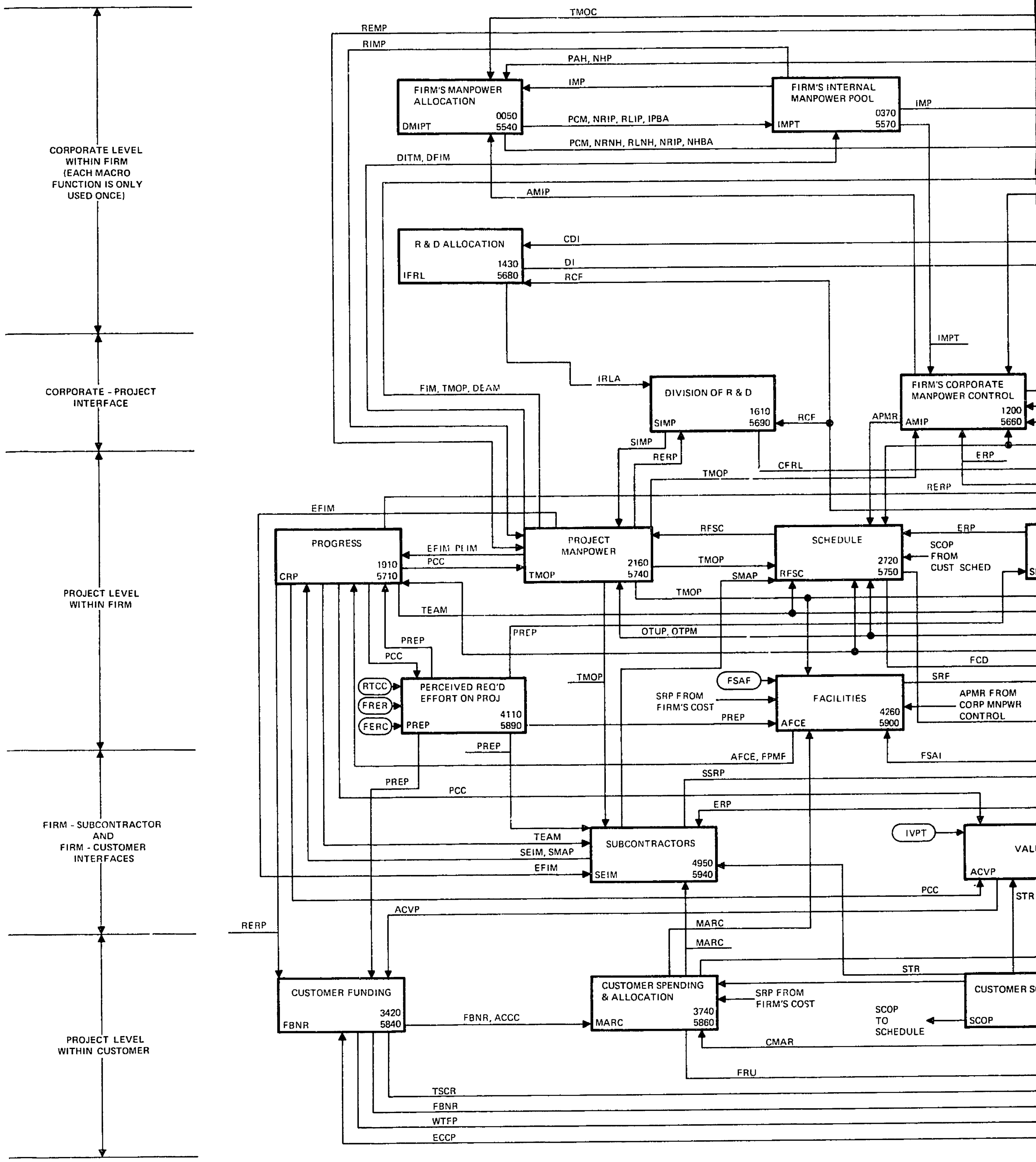
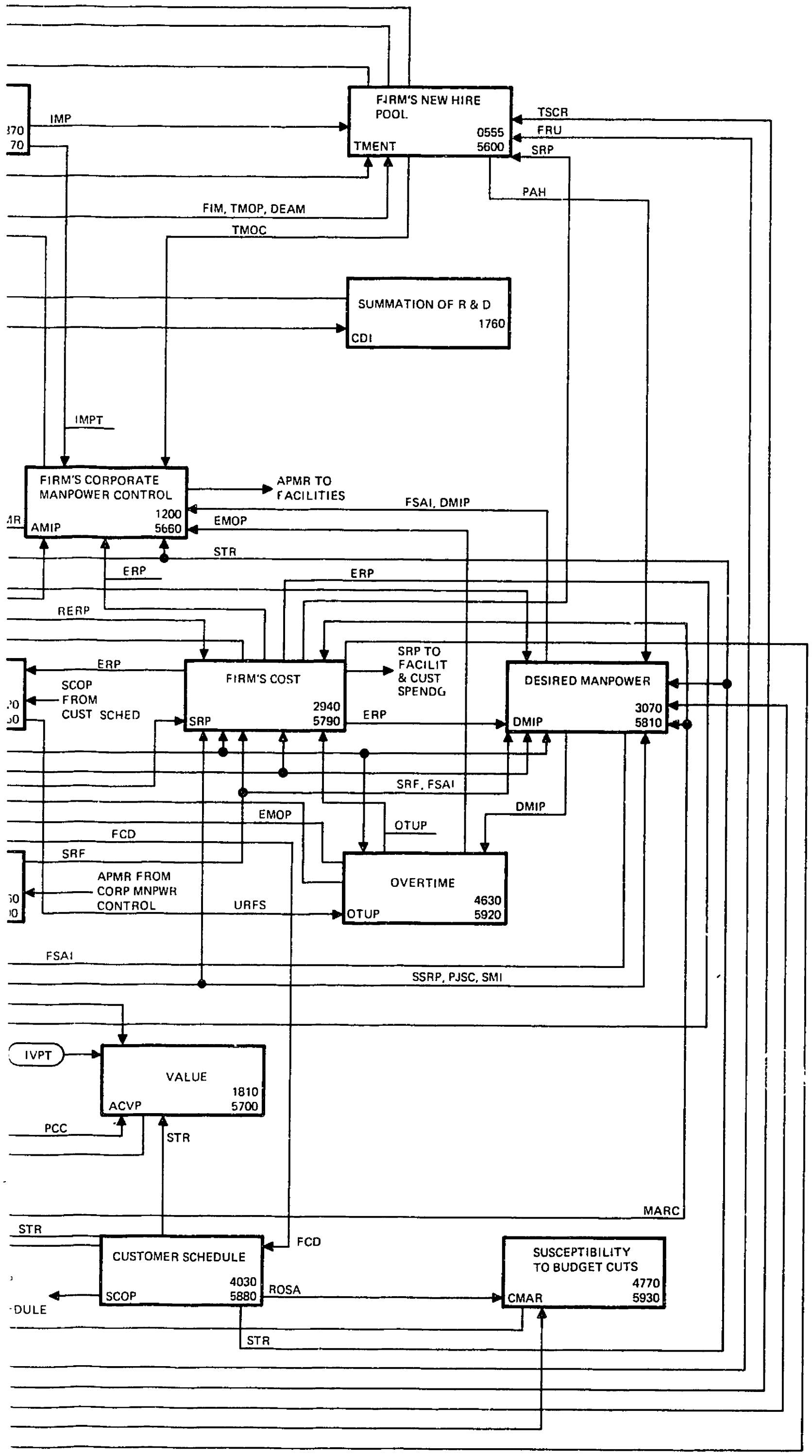
# APPENDIX A

## MODEL FLOW DIAGRAM

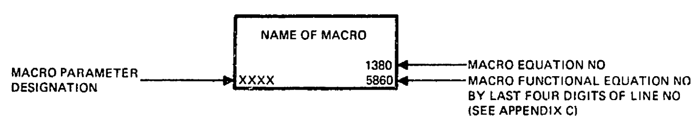


CORPORATE LEVEL WITHIN FIRM (EACH MACRO FUNCTION IS ONLY USED ONCE)
CORPORATE - PROJECT INTERFACE
PROJECT LEVEL WITHIN FIRM
FIRM - SUBCONTRACTOR AND FIRM - CUSTOMER INTERFACES
PROJECT LEVEL WITHIN CUSTOMER
FIRM'S MANPOWER ALLOCATION 0050 5540 DMIPT
FIRM'S INTERNAL MANPOWER POOL 0370 5570 IMPT
R & D ALLOCATION 1430 5680 IFRL
DIVISION OF R & D 1610 5690 SIMP
FIRM'S CORPORATE MANPOWER CONTROL 1200 5660 AMIP
PROGRESS 1910 5710 CRP
PROJECT MANPOWER 2160 5740 TMOP
SCHEDULE 2720 5750 RFSC
PERCEIVED REQ'D EFFORT ON PROJ 4110 5890 PREP
FACILITIES 4260 5900 AFCE
SUBCONTRACTORS 4950 5940 SEIM
CUSTOMER FUNDING 3420 5840 FBNR
CUSTOMER SPENDING & ALLOCATION 3740 5860 MARC
TMOC
REMP
RIMP
PAH, NHP
IMP
PCM, NRIP, RLIP, IPBA
PCM, NRNH, RLNH, NRIP, NHBA
DITM, DFIM
AMIP
CDI
DI
RCF
IMPT
IRLA
FIM, TMOP, DEAM
SIMP
RERP
CFRL
APMR
ERP
TMOP
EFIM
RFSC
EFIM PEIM
PCC
SMAP
SCOP FROM CUST SCHED
TEAM
PREP
OTUP, OTPM
FCD
SRF
RTCC
FRER
FERC
FSAF
SRP FROM FIRM'S COST
APMR FROM CORP MNPWR CONTROL
FSAI
AFCE, FPMF
SSRP
IVPT
VALU
ACVP
SEIM, SMAP
STR
MARC
CUSTOMER SC
SCOP
SCOP TO SCHEDULE
FBNR, ACCC
CMAR
FRU
TSCR
FBNR
WTFP
ECCP

# MULTI-PROJECT DYNAMIC MODEL
# OVERALL MODEL STRUCTURE
# SHOWING MACRO FUNCTIONS AND PRINCIPAL INTER-RELATIONS
# FIGURE A-1




NOTES
1. ONLY MOST IMPORTANT INTERACTIONS ARE SHOWN FOR CLARITY
2. ALL MACRO FUNCTIONS ARE REPEATED FOR EACH PROJECT, EXCEPT AT CORPORATE LEVEL
3. KEY TO SYMBOLS



# APPENDIX B

## DETAILED DESCRIPTION OF SINGLE PROJECT MODEL

This Appendix describes the single project model in detail and references the specific equations presented in Appendix C--Equation Printout--Single Project Model.

As referenced earlier, my mathematical model of large research and development programs has been constructed by building upon the work previously done by J. N. Nay[1]. I have added directly several sections to Nay's model, and have also modified specific equations wherever necessary. In describing my model in this Appendix, I shall include some descriptive material which was included by J. Nay in his thesis, since portions of his model are essentially unchanged in my model. It would be unduly cumbersome to specifically quote or reference every sentence of J. Nay's description which I have included in the

[1]Joe Neal Nay, Choice and Allocation in Multiple Markets, a research and development systems analysis (unpublished master of science thesis, M. I. T. School of Industrial Management May, 1965).

write-up herein. Therefore, I will make the following general delineation of the source of this material:

The sections of the model dealing with subcontractors, overtime, facilities, perceived effort required on project, scheduling, manpower control and susceptibility to budget cuts were new additions to the model which I provided exclusively. I also significantly modified the value and the personnel hiring sections, the latter being included within the macro Firm's New Hire Pool. I also reformatted the entire model to conform to Dynamo 2 equations format requirements and added the concept of macro functions, as an aid to subdividing the model into understandable and readily expandable segments.

Other changes were made in specific equations as required throughout the development of my model. Due to format changes which have occurred since J. Nay prepared his original model equations, it is possible to tell which equations are in their original unmodified form and which equations have been modified to some degree by me. The difference is in the equations format as follows: The original unmodified Nay equations have more than two spaces following the equation type designator letter. In contrast, the equations which I have either added or modified have exactly two spaces between the equation type identifier letter and the beginning of the equation.

For example, if we look at Page 4 of Appendix C Lines 1820 and 1830 are seen to be original Nay equations, as indicated by five spaces which appear between the capital A at the left hand margin of the line and the start of the equation proper. In contrast, line 1840 has been modified by me, as indicated by two spaces which exist between the capital R at the left hand margin and the start of the equation. This correlation with format is not 100% accurate, but it does give a fairly close approximation of the source of the specific equations listed in the Appendix C Equation Printout.

In a similar fashion, the written material in this descriptive appendix derives either from Nay or from myself, depending on whether the section under discussion is largely unchanged from the original Nay model or has either been added or significantly modified by me. Hence, I will not indicate in this appendix with quotation marks wherever I make direct quotations from J. Nay's thesis, but it can be understood that in those sections in which changes to Nay's original are a minimum, I have also repeated his description of the model section directly herein.

Rather than copy over the equations in this descriptive appendix, I shall refer the reader to the appropriate line numbers in Appendix C--Equation Printout for Single Project Model. I shall use the last four digits of the line number as the reference to locate the equation. Thus for example on Page 1 of Appendix C, Line 0080 refers to the following equation: PCM1.K=AMIP1.K/DMIPT.K

In the event that any equation extends over more than one line, as indicated by capital X in the left hand margin of the line (X designates continuation cards), I shall refer to the equation simply by the number of the first line of the equation. Thus, Line 0550 refers to the four line equation including

Lines 0550 through 0580 in Appendix C.

In reviewing Appendix C, the reader will note that many of the variables are preceeded by a dollar sign ($), as for example, $TRII in Equation 0180. The dollar sign is the designator for an internal function, as explained subsequently. It will not be included in the variables identifications in this appendix.

With these acknowledgements and conventions understood, we can now proceed with a detailed description of the Single Project Model, taking it in the same order in which it appears in the Appendix C Equation Printout. The reader is also referred to the descriptive flow diagram of Appendix A which gives a visual presentation of the inter-relations between the various functions in the model. Throughout this Appendix, I shall define the variables and parameters which are used in the Equation Printout of Appendix C.

## CENTRAL SECTOR

The central sector of the model divides most naturally into two parts, a normal operating section and an independent research and development allocation section. They will be discussed in that order. The functions performed encompass collection of information, decisions based on policy, and administration of these decisions. In the Single Project Model, only the equations for Project 1 are active; those for other projects are set equal to zero.

## NORMAL OPERATING SECTION

This section is shown in Figure A--and includes the macro functions for Firm's Manpower Allocation, Firm's Internal Manpower Pool, and Firm's New Hire Pool.

### Firm's Manpower Allocation

The desired manning increases from the projects are considered first. These are summed to obtain the total requirement of the projects for manpower. In the printout, we have subverted modeling practice slightly to avoid a division by zero at a boundary condition.

Equation 0070

DMIPT - Desired manning increases, total all Projects - Men
AMIP1 - Approved manning increases Project 1 - Men
AMIP2 - Approved manning increases Project 2 - Men - etc.

The percentage of men available for allocation who will be assigned to Project 1 is computed as follows:

Equations 0080 through 0110

PCM1 - Percent men to 1 - Dimensionless
PCM2 - Percent men to 2 - Dimensionless - etc.

The total request is first tested to see if it can be filled with internal men and the number of internal personnel to be allocated is chosen to be either the amount of the request or the total number in the pool.

Equations 0180 and 0190

TRII - Test of requested increment against internal pool - Men
DMIPT - Desired manning increase, total all Projects - Men
IMP - Men in internal manpower pool - Men
IPBA - Internal personnel being allocated - Men

If not enough men exist in the internal pool to satisfy the requirements, the remaining requirement is levied against the new hire pool.

Equations 0200 through 0220

RIRQ - Remaining increment requested - Men
TRII - Test of requested increment against internal pool - Men
TRNH - Test of requested against new hire pool - Men
MHP - Men in new hire pool - Men
NHBA - New hires to be allocated - Men

The number of people left in the pools for whom there is no present requirement is found next.

Equations 0230 through 0250

IMER - Internal men remaining in pool - Men
NHMR - Newly hired men remaining in pool - Men
IMP - Internal men in pool - Men
IPBA - Internal personnel being allocated - Men
NHP - New hires in pool - Men
NHBA - New hires being allocated - Men
TMIP - Total men remaining in pool - Men

Since the company only carries a percentage of its total manpower in the pool, excess must be removed.

Equations 0260 and 0270

NOMP - Number over maximum in pools - Men
TMOC - Total men on contract

PAIP - Percent allowed in pool - Dimensionless
NBRP - Number being removed from pool - Men

The number being removed immediately come from the new hire pool until it is exhausted, and then from the internal manpower pool.

Equations 0280 through 0300

TFNH - Test for removing new hires - Men
MRNH - Number removed from new hire pool - Men
NHMR - New hire men remaining - Men
NRIP - Number removed from internal pool - Men

Even among the men not removed, there is attrition through the variable Delay In Clearing the Pool.

Equations 0320 and 0330

RLIP - Rate of leaving from the internal pool - Men/Month
DCIP - Delay in clearing the pool - Months
IMER - Internal men remaining - Men
RLNH - Rate of leaving from new hire pool - Men/Month

The delay in clearing the central pools is dependent upon the firm's stability index.

Equation 0340

TDICP - Table, Delay in Clearing Pool - Months
PAH - Pressure against hoarding - Dimensionless

Firm's Internal Manpower Pool

The rate at which total internal (experienced) men are assigned to each project is computed by multiplying the number of internal personnel being assigned by the percent allocated to each project, and dividing by the time allowed for reassignment. (Assumed = DT.)

Equations 0390 through 0420

RIMP1 - Rate of Internal Men to Project 1 - Men/Month
PCM1 - Percent of men to 1 - Dimensionless

The rate of leaving the company from the internal pool is the sum of the removal and voluntary leaving rates. Men removed are assumed to require about one month's notice.

Equation 0430

RLCI - Rate of leaving company from internal pool - Men/Month
NRIP - Number removed from internal pool - Men (also equal to the removal rate in Men/Month)

The number of men in the internal pool is simply the last level plus the sum of arrivals and departures during the period.

Equation 0470

IMP - Men in the internal manpower pool - Men
RIFP - Rate of internal men from the Projects, Total - Men/Month

The rate of internal men from the projects is created from the decrements at each project as a convenient form to fit the available Dynamo equation format.

Equations 0440 through 0460

DITM1 - Decrement in Internally transferred men Project 1 - Men
DFIM1 - Decrement in fully integrated men Project 1 - Men
RFFT - Rate from First Two - Men/Month
RFST - Rate from Second Two - Men/Month

Firm's New Hire Pool

The rate of externally acquired employees to each project during the next period is dependent upon the portion allocated to that project.

Equations 0590 through 0620

REMP1 - Rate of external (Newly Hired) men to Project 1 - Men/Month
PCM1 - Percent men to 1 - Dimensionless

The rate of people leaving the company from the new hire pool is the sum of the two rates of leaving. The firm's stability index is the present secure funding divided by the desired secure funding, both expressed in months of backlog.

Equations 0630 and 0640

FSI - Firm's Stability Index - Dimensionless
PSF - Present secure funding - Months
DSL - Desired secure funding - Months
RLCE - Rate of leaving company, external men - Men/Month
NRNH - Number removed from new hire pool - Men (also equal to the removal rate in Men/Month)
RLNH - Rate of leaving new hire pool - Men/Month

The present secure funding is based upon a first order smoothing of the backlog and total spending rates.

Equations 0650 through 0670

BKLG - Backlog - Dollars
TMEN - Total men - Men

The backlog of funding used is a combination of projected funding from each project and present backlog.

Equation 0710

TSCR - Test, sign change ratio - Dollars

(TSCR1 is the amount of money that the customer is presently starting through the budgeting delay.)

FRU - Funds remaining uncommitted - Dollars

The total men at the company or expected is used in determining stable funding. This figure is not allowed to fall below one for model convenience.

Equations 0720 through 0740

ZMEN - Actual MEN at company or expected - Men
TMEN - Total MEN - Men
TMOC - Total MEN on contracts - Men
TMOC1 - Total men of Project 1 - Men
DONH - Delay in obtaining new hires - Months

A limit on new hiring results from the maximum number of new hires which can be supervised by each fully integrated man.

Equation 0750

LIM - Limit on hiring - Men
FIMT - Total fully integrated men - Men
SR - Supervisory ratio - Dimensionless

The total available fully integrated men in the company are divided among the project by means of a balance ratio, which is the ratio of that portion of the backlog attributable to a particular project, divided by the total corporate backlog.

Equations 0760 through 0850

BR1 - Balance ratio, Project 1 - Dimensionless
TBR1 - Trial BR1 - Dimensionless
TSCR1 - Market forecast (Test sign change ratio - Dollars
FRU1 - Funds remaining uncommitted - Dollars
BKLG - Backlog - Dollars

The company hires to correct its stability index to the desired level, after correcting the index to cover internal spending only.

Equations 1050, 1060, 1090 and 1100

HINC - Hiring increment desired - Men
FSI - Firm's stability index - Dimensionless
HAA - Hire at all - Men
HR - Hiring rate - Men/Month
DEPR - Delay in processing personnel requisions - Months

When the firm is laying off men, either new hires or internal personnel, the hiring rate is turned off.

Equations 1070 and 1080

RLOM - Rate laying off men - Men/Month

NRIP - Number removed internal pool - Men/Month
NRNH - Number removed new hire pool - Men/Month
HRB - Hiring feedback - Dimensionless

The hiring rate is then established as the minimum of either the trial hiring rate, based upon corrections of the firm's stability index, but limited by available supervisors; or the maximum allowable hiring rate, which is established by the size of the personnel department and the nature of the labor market.

Equations 0860 and 0870

THR - Trial hiring rate - Men/Month
HR - Hiring rate - Men/Month
MAHR - Maximum attainable hiring rate - Men/Month (a constant)

The hiring process is modeled as a third order exponential delay.

Equation 0890

NHA - New hire arrivals - Men/Month

There are generally some men in the hiring delay who are considered as hired but not yet on the payroll.

Equation 0900

MIHD - Men in hiring delay - Men

The rate of return of external men to the new hire pool is constructed from the projects' decrements.

Equation 0920

REFP - Rate of external men from projects - Men/Month
DEAM1 - Decrement of externally acquired men at Project 1 - Men

Since Dynamo levels only allow for six rates, we condense two of the rates out of the new hire pool into one.

Equation 0930

CFR - Convenient form of rate - Men/Month
PCM1 - Percent of men to 1 - Dimensionless
NHBA - New hires being allocated - Men

The number of men in the new hire pool is the last number plus the changes during the period. The pool is constrained to never go negative.

Equations 0940 through 0960

NHP - Men in new hire pool - Men

REFP - Rate of external men from Project - Men/Month
NHA - New hire Arrivals - Men/Month
RLCE - Rate of leaving company from external pool - Men/Month
REMP4 - Rate of external men from Project 4 - Men/Month

The rate of charging against the manpower pool and the accumated total of charges to the pool are calculated for use as supplementary variables.

Equations 0970 and 0980

RCOP - Rate of charging to pool - Dollars/Month
NHP - Number of men in new hire pool - Men
IMPT - Number in internal Manpower pool - Men
MEOH - Men engineering and overhead charge - Dollars/Man Month
COP - Charges to pool - Dollars

A cumulative total is also calculated of the men leaving the company. The men available at the company are calculated as total men minus those in the hiring delay.

Equations 0990 through 1020

MLO - Men laid off - Men
RLCE - Rate of leaving company, external men - Men/Month
RLCI - Rate of leaving company, internal men - Men/Month
TMAC - Total men available to company - Men
TMEN - Total men committed to company - Men

The function Pressures Against Hoarding reflects the ability of the firm's management to prevent project managers from hoarding manpower over and above their minimum need. This internal management pressure is most effective when the firm's stability index is high, indicated by a large backlog of work available. When the backlog becomes scarce, the firm is less effective in convincing projects not to give up men for which they have contractual support but not necessarily a pressing need. This occurs because in times of small backlog there is a reasonable likelihood that men released from the projects may be let go from the company and hence not available again to the project if the need should arrive.

The desired hiring increment is that amount which will reduce the internal spending portion of the firm's stability index to unity.

Equations 1050 & 1040

HINC - Hiring increment desired - Men
FSI - Firm's stability index - Dimensionless
TMEN - Total men - Men
FSAI - Fraction of spending allowed internally - Dimensionless
PAH - Pressure against hoarding - Dimensionless

The requested hiring increment is taken as the lesser of the desired hiring increment as computed above, or the limit established by the availability of supervisory personnel. The hiring increment can never be less than zero, and is further limited by feedback from the projects, which prevents hiring when the projects are laying off men.

Equations 1060 through 1100

THAA - Trial hire at all? - Men
QAAA - Requested hiring increment - Men
RLOM - Rate of laying off men - Men/Month
NRIP - Number removed from internal pool - Men/Month
NRNH - Number removed from new hire pool - Men/Month
HFB - Hiring feedback - Dimensionless

Firm's Corporate Manpower Control

This macro function represents the operation within the corporation which controls and processes manpower requests from the projects, and acts as an agency to which the projects must justify their utilization of manpower. The manpower control function attempts to stabilize the firm's employment, particularly by resisting rapid manpower buildup.

The corporate manpower control office uses two main tactics in acting to stabilize the firm's employment. The first tactic consists of projecting the currently-recognized effort remaining on the project into the future for a limited time period. If at the end of this manpower planning horizon time period, the required project manpower does not exceed the equivalent manpower already available, then the project's request for more men is disapproved on the grounds that the requirement is too short-term. The manpower planning horizon is generally from 6 months to one year. This is primarily a delaying tactic, since the perceived effort remaining on the project is increasing with time during the buildup phase of a project, and hence a projection of manpower requirements which does not account for some increase in project scope is unrealistic.

Equations 1220, 1230, and 1390

PFMN - Projected future manpower needs - Men
ERP - Effort remaining on project - Man-Months
EMOP - Equivalent men on project - Men
MPH - Manpower planning horizon - Months
STR - Scheduled time remaining - Months
NMIP - Negotiated manpower increment - Men
DMIP - Desired manpower increment - Men

The other manpower control tactic is one of negotiation. In this approach, the project is required to justify each man it requests and is encouraged to "split the difference" between its requested incremental manpower and some smaller number. The corporate manpower group exerts maximum pressure when the internal manpower pool is at a low level compared to the allowable number of men in the pool. This reflects a company-wide shortage of manpower and in this case, the corporate manpower control discourages new hiring by negotiating lower manpower increments with the projects. If the company has more men available than it needs, however, the corporate manpower control relaxes its pressure and allows the project to cover these men under project funding.

<u>Equations 1240 through 1270</u>

FMRA - Fraction of manpower request approved - Dimensionless
ILMP - Index of level of manpower in pool - Dimensionless
IMPT - Internal manpower pool, total - Men
TMOC - Total men on contract - Men
PAIP - Percent allowed in pool - Dimensionless
TMSA - Trial manpower increments submitted for approval - Men
MISA - Manpower increments submitted for approval- Men
DCMA - Delay in corporate manpower approval - Months

The rate of approval of manpower increases is a function of the increases submitted for approval, less the difference between the total of approved manpower level and that requested by the project. Total approved manpower level is integrated based upon the rate of approving manpower increments. In the event that funded manpower levels no longer cover the number of men on the project, however, the firm's corporate manpower control function immediately reduces the approved manpower level by that increment. Thus, the internal manpower control offers great resistance to manpower increases by the project, but no resistance to manpower decreases if these are due to lack of contractual funding coverage.

Equations 1280 through 1370

RAMI - Rate of approving manpower increments - Man/Month
DRMU - Difference in required men utilized - Men
DARM - Difference between approved and requested men - Men
TAPR - Trial apprvoed manpower requirements - Men
TRFM - Trial rate of removing funded manpower - Men/Month
RRFM - Rate of removal of funded manpower - Men/Month
PFMP - Project funded manpower level - Men
APMR - Approved project manpower requirements - Men
AMIP - Approved men into project - Men

# INDEPENDENT R AND D SECTION

## R & D Allocation

Initially, the total rate of billing the customer for service at the company is determined. The rates are used in place of a short-term smoothing.

### Equation 1440

ROBT - Total rate of billing the customer - Dollars/Month
ROB1 - Rate of billing on Project 1 - Dollars/Month

This billing rate itself is smoothed over a time. A quarter is used here as the smoothing time.

### Equation 1450

Nominal independent research and dvelopment funding is taken as a percentage of smoothed billing and reduced through engineering and overhead costs to a manpower level.

### Equation 1470

NIFRL - Nominal internally funded research level - Men
PCAO - Percent allowable - Dimensionless
SROB - Smoothed rate of billing - Dollars/Month
MEOH - Mean Engineering and overhead costs - Dollars/Men-Month

This nominal rate becomes the internal limit after a delay involved in allocation and negotiation.

Equation 1480

RIFRL - Rate of IFRL
IFRL - Internally funded research level - Men

Equation 1520

The internal level to be allocated is given a further floor (after Project 1 is funded) of the two men initially used to start Project 1.

Equations 1540 and 1550

IRLA - Internal research level to be allocated - Men
QFRL - Minimum funded research level - Men
IFRL - Internally funded research level - Men
RCF1 - Rate of spending company funds on 1 - Dollars/Month

Summary of R & D

A cumulative division index is obtained by summing the division indexes of each project.

Equation 1760

CDI - Cumulative division index - Dimensionless
DI1 - Division index, Project 1

Division of R & D

The next series of equations are duplicated for each project. The allocation to a project is simply the total amount to be allocated times the percentage that is to go to that project.

Equation 1620

AIFL - Allocation of internally funded level to Project - Men
PRD - Percent of internally funded Research & Development level to project - Dimensionless

The desired change in funded research at the project is that necessary to adjust to the present allocation.

Equation 1630

DCFR - Desired change in funded research - Men/Month
CFRL - Company funded research level at project - Men

This is adjusted immediately both in CFRL (which is simply a record of company funded researchers sent to the project) and at the fully integrated manpower pool. If the change is a reduction, only those researchers not under contract are withdrwawn from the project.

Equations 1650 through 1680

SIMP2 - Simple method of inserting IR&D in project 2 - Men/Month
CRM2 - Company funded men at 2 - Dollars/Month
RCF2 - Rate of spending company funds at 2 - Dollars/Men-Month
MECH - Mean engineering and overhead costs - Dollars/Men-Month

The percentage to each project is formed (in a manner similiar to that used in the last section) from the division indices for each project. Those indices expresses both a fraction desired for that project initially and a decrease in pressure for independent research and development funding as contractual coverage increases.

Equations 1690 through 1730

PRD - Percent of R&D to project - Dimensionless
DI - Division index for project - Dimensionless
FRD - Fraction of R&D initially intended for project - Dimensionless
DUI - Development unnecessary index for project - Dimensionless
IUI - Interim unnecessary index for project - Dimensionless
MARC - Maximum allowable rate, customer (250000 represents allowable coverage)
FDU - Funded development unnecessary - Dimensionless

## PROJECT SECTOR

The project sector represents the project operations both within the contractor and the customer. All of the project's equations herein would be repeated for each project in the case of a multiple project model, by means of separate macro functional equations for each project.

For the single project they are only used once as Project 1. The value section is a portion of the project sector but represents an interface between the customer and the contractor, since they both must recognize and agree upon the value of the project at the outset.

### Value

The intrinsic value of Project 1 is given by a table function. This table function was derived for the single project model from the NASA budget requests for manned spaceflight, and can be considered an exogenous variable. The table, IVPT1, tabulates the variation in value over time for Project 1.

Equation 1820

IVP - Intrinsic value of project - Dollars
IVPT1 - Table of IVP for Project 1 - Dollars
TIME - Time base for Dynamo - Months

The delay in recognizing value is another table function with high-low limits, and gives the delay in recognizing value as a function of the percentage of the project actually completed. This reflects the long delay in intially recognizing project value.

Equation 1830

DRV - Delay in recognizing value of project - Months
PCC1 - Percent complete at project - Dimensionless

The rate at which value is recognized is given by the error in recognized value divided by the delay in recognizing it.

Equation 1840

RVRC - Rate of value recognition at project - Dollars/Month
DRV - Delay in recognizing value - Months
IVP - Intrinsic value of project - Dollars
RLVC - Recognized level of value, current at project - Dollars

The realized level of value is simply the last level plus the amount recognized in the next solution interval.

Equation 1850

The accepted value is gradually adjusted towards the current recognized level.

Equation 1870

ACVP - Accepted common value for project - Dollars
DAVC - Delay in accepting value, common - Months

PROJECT SECTION LYING WITHIN THE FIRM

Considered next is that portion of the project sector that lies within the firm. The term project in the following material refers to that portion of the project sector pertaining to the contractor.

Progress

Cunulative real progress is accumulated as a level by adding the rate of progress times time over each interval to the last level of progress.

Equation 1930

CRP - Cumulative real progress - Effective Man/Months
RPR - Real progress rate - Effective Man-Months/Month

The real rate of progress is the product of the number of equivalent fully integrated men and the productivity of one fully integrated man, times a facilities productivity multiplying factor.

Equation 1950

FPMF - Facilities Productivity multiplying factor - Dimensionless
RPR - Real progress rate - Effective Man-Month/Month
PFIM - Productivity of fully integrated man - Effective Months/Month
EFIM - Equivalent fully integrated men - Men
SEIM - Subcontractors' equivalent integrated men - Men

The actual percentage of the job complete is calculated as an auxiliary function.

Equation 1960

PCC - Percent complete - Dimensionless
CRP - Cumulative real progress - Effective Man/Months
PREP - Perceived required effort on project - Effective Man-Months

On the other hand the perceived real progress equals the accumulation of perceived rate of progress plus the corrections of recognized errors.

Equation 1970

PRP - Perceived real progress - Effective Man-Months

PERP - Perceived rate of progress - Effective Man-Months/Month
PECR - Perceived error correction rate - Effective Man-Months/Month

The perceived error correction rate is dependent on the recognized error, which is in turn dependent upon the amount of error existing and the fraction recognized.

Equation 1990

PECR - Perceived error correction rate - Men
ERRP - Error recognized on Project - Effective Man-Months

Equations 2000 and 2010

EPP - Error in perception of progress - Effective Man-Months
CRP - Cumulative real progress - Effective Man-Months
PRP - Perceived real progress - Effective Man-Months

Equation 2040

FER - Fraction of the error recognized - Dimensionless
TFER - Table, fraction of error recognized - Dimensionless
PREP - Required effective effort on project - Effective Man-Months

The fraction of the error recognized at the project is a function of either the believed %

complete or the actual % complete, whichever is larger.

Equation 2030

DPCC - Dominant percent complete - Dimensionless
PPCC - Perceived percent complete - Dimensionless
PCC - Percent complete - Dimensionless

There is some delay at the project before perceived progress, good or bad, is reported.

Equation 2050

RERP - Reported real progress - Effective Man-Months
DRRP - Delay in reporting real progress - Months
PRP - Perceived real progress - Effective Man-Months

The rate of correcting technical effectiveness expresses the thought that the project director looks for a fixed value of effectiveness which is valid for the past work of his team. In other words, he tends to think of errors in progress discovered and corrected as being caused by an error in the effectiveness estimate used on all work previously accomplished.

Equations 2070 through 2100

RCT - Rate of correcting TEAM - Effective Months/Month

ERRP - Error recognized on project - Effective
Man/Months
MMET - Man-Months expended, Total - Man-Months
TEAM - Technical effectiveness of the average man -
Effective Months/Month
TREAM - Trial technical effectiveness of average
man - Effective Month/Month

The total man-months expended is the accumulation of that spent in each increment, by both prime and subcontractors.

Equation 2110

EMOP - Equivalent men on project - Men
SMAP - Subcontractor's men assigned to project - Men

The project director's perception of technical effectiveness determines his perceived rate of progress.

Equation 2130

PERP - Perceived rate of progress - Effective
Man-Months/Months
TEAM - Technical effectiveness of average men -
Effective Months/Months
TMOP - Total men on project - Men

Project Manpower

The total men on the project at the prime contractor's facilities is the sum of his experienced internally acquired men, his fully integrated men, his externally acquired men, and his internal men assigned to subcontracting.

Equation 2180

EAMP - Externally acquired men on Project - Men
ITMP - Internally acquired men on Project - Men
FIM - Fully integrated men on Project - Men

For the following sections of the model, the levels and rates of flows will be covered first. The method of applying rates out of the project will be outlined and finally the method of accounting for unsupervised and supervised men in tallying effectiveness will be discussed. The latter also determine normal rates of flow between the three levels of externally acquired, internally transferred and fully integrated men. Consider the level of fully integrated men.

Equations 2190 and 2230

RIIM - Rate of integrating internal men - Men/Month
RRIM - Rate of removing integrated men - Men/Month
SIMP - Simple method of indicating internally funded work by originators - Men/Month
RASC - Rate of assigning men to subcontracting - Men/Month

The rate at which men move from internally transferred men to fully integrated men is calculated by changing the effective number of internal back into equivalent supervised men and dividing by the delay in integrating internal men. This models the training rate for men who know the company well, but not the project.

Equation 2240

EITM - Effective internally transferred men - Effective Men
DIIM - Delay in integrating internal men - Months
PRIT - Productivity of internally transferred men - Effective Men/Men

The number of internally transferred men is the cumulant of the rates in and out plus the past level.

Equation 2250

ITMP - Internally transferred men on project - Men
RIMP - Rate of internal men to project - Men/Month
REIM - Rate of conversion of external to internal men - Men/Month
RIIM - Rate of integrating internal men - Men/Month
RWIT - Rate of withdrawal of internally transferred men - Men/Month

Similarly, the rate of conversion of external to internal men is based on the equivalent number of supervised externally acquired men. Some further explanation is given below.

Equation 2310

EEAM - Effective externally acquired men - Effective Men
DEIM - Delay in converting externally acquired to internal men - Months
PREA - Productivity of externally acquired men - Effective Men/Months

In the same manner as internal men, externally acquired men is a level determined from the previous level and the entry and exit rates.

Equation 2320

EAMP - Externally acquired men on project - Men
REMP - Rate of external manpower to project - Men/Months
REIM - Rate of conversion of external to internal men - Men/Months
RWEA - Rate of withdrawal of externally acquired men - Men/Months

When personnel are to be removed from the project, the number to be removed is tested first against external men.

Equation 2340

TDEA - Test decrement in externally acquired men - Men

IDIM - Increment desired in manning - Men
EAMP - Externally acquired men on project - Men

The decrement in externally acquired men is equal to either the total available or IDIM, whichever is less.

Equations 2350 and 2360

DEAM - Decrement in Externally acquired men - Men
EAMP - Externally acquired men - Men
IDIM - Increment desired in manning - Men
RWEA - Rate of withdrawal of externally acquired men - Men/Month

If there are not enough men in EAMP to cover the increment a test is made on ITMP and either all of the men there or the remaining increment required are withdrawn.

Equations 2260 and 2270

RRCM - Remaining required change in manning - Men
TDIM - Test decrement for internal men - Men
ITMP - Internally transferred men on project - Men
DITM - Decrement in internally transferred men - Men
RWIT - Rate of withdrawal of internally transferred men - Men/Month

In the case where a decrement still remains to be satisfied, it must now be withdrawn from fully integrated men.

Equation 2210

RRIM - Rate of removal of integrated men - Men/Month
DRIM - Delay in releasing integrated men - Months

The effectiveness evaluation expresses the following things. Unsupervised men are considered less productive than supervised men in all categories, unsupervised men are absorbed at a much slower rate than supervised (1/2 in the case of external unsupervised, 1/3 in the case of internal unsupervised) in all categories, and lastly, trainers are not as effective as fully integrated men not acting as trainers.

First the two effectivenesses are expressed as the sum of the effectiveness of those supervised and those not supervised.

Equation 2380

EEAM - Effective externally acquired men - Effective Men
PRUM - Productivity of unsupervised men - Effective Men/Month
IMLP - Internal men left on project - Men
PCSU - Percent supervised - Dimensionless
PRIT - Productivity of supervised internally transferred men - Effective Men/Man

An inverted form of the percentage of fully integrated men used as trainers can be found from the suppervision test index (defined below).

Equations 2420 and 2430

IPCT - Inverted form of percent trainers - Dimensionless
TIS - Test Index for supervision - Dimensionless

In the printout it can be seen that a rather crude modeling device has been used to avoid division by zero in the following equation. However, the addition of a small positive constant to the denominator has little effect on the simulation and is economical terms of equations.

Equation 2460

TPT - Total potential trainees - Men
EMLP - External men left on project - Men
IMLP - Internal men left on project - Men

The number of equivalent fully integrated men is found by adding the contribution of trainers and non-trainers. PRFI can be considered a relative productivity index in this equation, and does not equal the absolute level of productivity of fully integrated men (PFIM).

Equation 2440

QFIM - Equivalent fully integrated men - Effective men
PRFI - Productivity of fully integrated men - Effective Men/Man
FIM - Fully integrated men - Men
PCT - Percentage used as trainers - Dimensionless
PRTR - Productivity of trainers - Effective Men/Man

Finally, the number of effective fully integrated men on the project is found by simply summing the contribution of each type of manpower accounted for in the project, and multiplying by overtime usage.

Equation 2370

EFIM - Effective fully integrated men - Effective Men
QFIM - Equivalent fully integrated men - Effective Men
EEAM - Effective externally acquired men - Effective Men
EITM - Effective internally transferred men - Effective Men
OTUP - Overtime used on project.

In all cases when there is a decrement, the number of men to be left in any category is simply the number of men present minus the decrement.

Equations 2470 and 2480

IMLP - Internal men left on project - Men
ITMP - Internal transferred men on project - Men
DITM - Decrement in internally transferred man - Men

EMLP - External men left on project - Men
EAMP - Externally acquired men on project - Men
DEAM - Decrement in externally acquired men on project - Men

The percentage of personnel supervised is 100% if the test index of supervision is greater than one, or it equals the test index of supervision where this is less than one. The total potential trainees, which is a measure of the project's ability to absorb new personnel, is the product of the number of men who can be allocated per trainer times the total fully integrated men available.

Equations 2490 and 2500

PCSU - Percentage supervised - Dimensionless
TIS - Test index, supervision - Dimensionless
TPT - Total potential trainees - Men
FIM - Fully integrated men - Men
NMPT - Number of men per trainer - Men/Man

Next we consider the actual productivity formulation. Productivity is the product of four multipliers due to know-how at the project, the effect of schedule on productivity, an early productivity multiplier, and the effect of overtime on productivity.

The know-how at the project multiplier reflects the improvement in productivity as the work force becomes more experienced. It is therefore represented as a function of percent completion of the job. The effect of schedule on productivity postulates that the greatest productivity is achieved when the project is slightly behind schedule. This provides incentive for maximum effectiveness on the job. If the project is well ahead of schedule, or if it is so far behind as to seem hopeless, then no additional improvement in productivity results. The early productivity multiplier attempts to represent the high productivity of the small core of fully trained personnel who are on the job at the time of go-ahead. Once this core becomes dissipated by the addition of new people, this particular productivity advantage disappears. This factor is therefore represented as a function of total men on the project. The overtime productivity multiplier shows a decrease in productivity as long periods of sustained overtime are used, due to fatigue of the work force.

Equation 2510

PFIM - Productivity of fully integrated men - Effective Months/Month
KHAP - Know-how at the project - Effective Months/ Months
SPRM - Schedule Ratio multiplier, productivity - Dimensionless
EPM - Early productivity multiplier - Dimensionless
OTPM - Overtime productivity multiplier - Dimensionless

Equation 2520

BFFS - Bias for a firm schedule - Dimensionless
SPRM - Schedule ratio productivity multiplier - Dimensionless
TSPM - Table, schedule productivity multiplier - Dimensionless
RFSC - Ratio, forecase to schedule delivery date - Dimensionless

Equation 2540

TEPM - Table, early productivity multiplier - Dimensionless
TMOP - Total men on project - Men

Schedule

The next series of equations produce the forecast time to completion. No forecast time less than the original length of the project is allowed. That figure is used until the expected completion date lags the schedule completion by more than some threshold amount, when compared with schedule time remaining. Of course, the forecast completion date is the forecast time remaining plus the time of the forecast.

The contractor is continuously re-estimating his schedule position. His estimate of trial time remaining on the project consists of two parts: a projected time to attain peak manning and then the time remaining at peak manning. The projected time to attain peak manning assumes that the contractor will proceed to the currently authorized personnel manning requirements (APMR) from his present total manning level at the maximum attainable hiring rate (MAHR). Once he reaches this level, the remaining time at peak manning is calculated by subtracting the effort completed from the current estimate of effort remaining on the project (ERP), and dividing by the total equivalent effective men at prime and subcontractors.

Equations 2730 through 2770

TTRP - Trial time remaining on project - Months
PTPM - Projected time to peak manning - Months
TPPM - Trial projected time to peak manning - Months
APMR - Approved project manning requirements - Men
MAHR - Maximum attainable hiring rate - Men/Month
TMOP - Total men on project - Men
TRPM - Time remaining at peak manning - Month
ERP - Effort remaining on project - Man-Months
OTUP - Overtime used on project - Dimensionless
SMAP - Subcontractors' men assigned to project - Men

In the initial time after contract go-ahead, there is little serious re-evaluation of the schedule situation until the contractor makes some progress on the job and is able to add a substantial number of people to the job, and until his perception of the scope of the project improves. After some period of time, however, assumed to be one year in most cases, the contractor and the customer begin a serious re-evaluation of their schedule situation. This delay in start-up of planning (DSUP) is the time after which the contractor begins to make serious estimates of his schedule situation. Hence, as long as the elapsed time on the project does not exceed the DSUP the contractor will automatically quote the initial schedule time remaining as the official schedule. After the DSUP has elasped, however, he may quote a longer time in accordance with the threshold tests discussed subsequently.

<u>Equation 2780</u>

XTRP - Expected time remaining on project - Months
DSUP - Delay in start-up of planning - Months
STR - Schedule time remaining - Months

The next equations form a schedule discrepancy index, based upon the contractors expected discrepancy in adhering to the official schedule, divided by the schedule time remaining. This schedule discrepancy index is compared with a threshold for changing schedules (TFCS) and when it exceeds this value the contractor will then quote a new forecast completion date which is different from the currently approved schedule. However, the contractor also maintains an unofficial ratio of forecast to schedule completion which does not have the filtering effect of the threshold for changing schedule. This unofficial ratio is the contractors' current belief of his schedule situation, and he uses this in establishing his overtime requirements for the project.

Equations 2790 through 2840

FCD - Forecast completion date - Month
SCOP - Schedule completion of project - Month
TFDS - Threshold for changing schedule - Dimensionless
SDI - Schedule discrepancy index - Dimensionless
URFS - Unofficial ratio of forecast schedule completion - Dimensionless
XCD - Expected completion date - Month
TSDP - Trial schedule discrepancy on project - Month
XSDP - Expected schedule discrepancy - Month

The unofficial ratio of forecast schedule completion reflects the contractors' officially forwarded forecast compared with the customer's current official schedule completion date. The contractor smooths his expected completion date through a reluctance to change schedules, reflected as a delay in changing schedule dates.

Equations 2850 and 2860

RFSC - Ratio of forecast schedule completion - Dimensionless
SXCD - Dmooth expected completion date - Month
DCSD - Delay in changing schedule dates - Month

Firm's Cost

The figure used for effort remaining is based on the project director's reported progress and, of course, cannot be less than zero.

Equations 2960 and 2980

XRP - Experimental value for effort remaining on project - Effective Man-Months
RERP - Required effort to complete project - Effective Man-Months
ERP - Effective effort remaining on project - Effective Man-Months

The project director bases his expected cost to completion at any time of effort remaining, overhead, and the effectiveness of his team.

Equation 2970

ECCP - Expected cost to complete project - Dollars
ERP - Effort believed remaining on project - Effective Man-Months
TEAM - Technical effectivenss of the average man - Effective Months/Months
AMCR - Average manpower conversion rate - Dollars/ Man-Month

The firm's sunk cost into the project are simply the last cost plus those incurred during the latest period.

Equation 2990

FSCP - Firm's sunk costs at project - Dollars
RCF - Rate of spending company funds - Dollars/Month

The next two equations assume that any spending on the project in excess of the allowable rate covered by the customer must be considered a sunk cost at the firm.

Equations 3010 and 3020

RCF - Rate of spending company funds - Dollars/Month
TRCF - Trial rate of spending company funds - Dollars/Month
SRP - Spending rate at the project - Dollars/Month
MARC - Maximum allowable spending rate, customer - Dollars/Month

The spending rate at the project is the sum of charges from all sources. It includes the contractor's internal manpower spending including the overtime premium attached thereto. It also includes the spending rate incurred at the subcontractor's and the spending for facilities.

Equation 2940

TMOP - Total men on project - Men
MEOH - Mean engineering and overhead cost - Dollars/Man-Month
OTUP - Overtime used on project - Dimensionless
OTPR - Overtime premium ratio - Dimensionless
SRF - Spending rate for facilities - Dollars/Month
SSRP - Subcontractor's spending rate on project - Dollars/Month

Desired Manpower

The next four equations show how the present maximum spending rate allowed by the customer in terms of an upper limit on manning at the project, and gives a smoothed rate of change of this limit on funded manning. The project director uses these figures to avoid situations of manning in excess of that contractually covered. Such overages would lead to direct and possibly unrecoverable sunk costs at the firm. The limit on funded manning is simply the previous limit plus any change taking place. In computing allowable internal manning, the fraction of allowable spending earmarked for facilities and for subcontractors must first be deducted.

Equations 2090 through 3150

FMLL - Funded manpower level limit - Men
RFML - Rate of change of funded manpower level limit - Men/Month
MMLL - Maximum manpower loading level - Men
MARC - Maximum allowable rate of spending, customer - Dollars/Month
MEOH - Mean engineering and overhead costs - Dollars/Man-Months
SRFM - Smoothed rate of funding manpower - Men/Month
FSAI - Fraction spending allowed internally - Dimensionless
PJSC - Percent of job subcontracted - Dimensionless
FSAF - Fraction spending allowed for facilities
DSIM - Delay in smoothing internal men - Months

In this model, the requests of the project director for hiring are carried out through evaluation of project backlog position. His requests for actual people are generated internally and are based on both the needed people under the conditions of the project and the number of people supportable by the contract. The number of men needed depends on job size, technical effectiveness and schedule, and upon the subcontractors' effectiveness in manning their portion of the project. Initially the prime contractor views his manpower needs as though he were going to do the whole job internally, but as the subcontractors' manning becomes effective and the job becomes better defined, the prime backs off to manning consistent with his fraction of the effort.

<u>Equations 3170 and 3190</u>

TNMN - Trial needed men - Men
NMEN - Needed MEN - Men
ERP - Effort believed required at project - Effective Man-Months
STR - Scheduled time remaining - Months
TEAM - Technical effectiveness of the average man - Effective Months/Months

One additional constraint is imposed on the project by project management. At times where a portion of the additional manpower requested by the project appears to be compensating for project inefficiency as shown by low values of the technical effectiveness of the average man (TEAM), then in such cases the project management will not approve that portion of the manpower request which is attributable to inefficiency. In other words, project management itself will insist upon correcting the perceived inefficiency rather than making up for it by adding additional people.

Equations 3230 through 3260

TNMI - Trial needed men due to inefficiency - Men
NMNI - Needed men due to inefficiency - Men
ANMI - Allowable needed men due to inefficiency - Men
DRCI - Delay, resistance to compensating for inefficiency - Months
TANM - Trial allowable needed men - Men

The dominant needed men is the minimum of the needed men requested by first line supervision or the approved needed men allowing for the inefficiency considerations, whichever is smaller.

Equation 3200

DNMN - Dominant needed men - Men

The number of supportable men used by the project director is the actual present level unless this level is falling. Since a delay is encountered in removing integrated men from the project, he must project ahead when funding is falling to avoid being caught with unsupported manpower on his project.

Equations 3180 and 3210

SMEN - Supportable men - Men
MMLL - Maximum manpower loading level - Men
PFMP - Projected funded manpower level - Men
DRIM - Delay in removing integrated men - Months

The number of desired men at the project is the minimum of the number needed and approved by project, and the number supportable. (Empire building does not occur in our quality project.)

Equation 3220

DMEN - Desired men - Men
NMEN - Needed men - Men
SMEN - Supportable men - Men

One more factor is seen as affecting the number of men requested. When work is plentiful there are jobs waiting for all internal employees. However, as the backlog at the company shrinks, personnel who are transferred from the company are much more likely to be released from the company. This causes pressure from both management and the engineers to keep as many people on the contract as it will support. This is expressed in the model by a reduced pressure against hoarding.

Equation 3270

RMEN - Requested men - Men
PAH - Pressure against hoarding - Dimensionless
DMEN - Desired men - Men
SMEN - Supportable men - Men

The allowable needed men finally approved by the project also considers the subcontractors' effectiveness in manning the job in the same way the requested needed men was adjusted.

Equation 3280

ANMN - Allowable needed men - Men

Since the prime contractor and the aggregate subcontractors' have different effective average manpower conversion rates, the latter being higher because of the addition of overhead and profit, the overall costs must be obtained through an average manpower conversion rate which converts man-months to dollars.

Equation 3290

AMCR - Average manpower conversion rate - Dollars/ Man-Months

The desired increment in men is found by subtracting the men already present (except for those funded by the company) from the number requested. A positive increment becomes an increase request. The increase requests are smoothed due to a delay in processing manpower requests.

Equation 3300

DIMP - Desired increment in manning, project - Men
SDIM - Smoothed desired increase in men - Men
DPMR - Delay in processing manpower requests - Months

A negative increment becomes a decrease request up to the limit of manning.

Equations 3310 through 3330

TIDE - Trial increment decrease in men - Men

IDIM - Incremental decrease in manning - Men

This is the IDIM that activates the personnel removal structure described earlier.

## PROJECT SECTOR LYING WITHIN THE CUSTOMER

This portion of the project sector describes those activities taking place within the customer for the project. It encompasses evaluation, funding, scheduling, control of spending rate and payment.

### Customer Funding

Our discussion will commence with the funding desired by the customer for the project. This is determined by the expected cost to completion estimated by the project, and the willingness of the customer to fund such costs for this project.

### Equation 3440

FDC - Funding desired by customer - Dollars
ECCP - Expected cost to completion, project - Dollars
WTFP - Willingness to fund project - Dimensionless

For evaluation purposes there is a delay even within the customer in adjusting accepted costs to current estimates.

### Equation 3450

ACCC - Accepted cost to completion at customer - Dollars

DACC - Delay in accepting costs, customer - Months
CECC - Current estimate of completion costs,
customer - Dollars

The current estimate of completion costs is dependent on the inexperience at the project (believed by the customer) in the specific undertaking.

Equations 3470 through 3490

CECC - Current estimate of cost to completion,
customer - Dollars
ECCP - Expected cost to completion, project - Dollars
IMC - Inexperience multiplier, customer -
Dimensionless
TIMC - Table, IMC - Dimensionless
RPC - Reported percent complete, project -
Dimensionless
RERP - Reported real progress - Effective Man-Months
PREP - Perceived required effort on project -
Effective Man-Months

Willingness to fund the project shifts slowly from one curve to another as bias for the project builds up.

Equation 3500

WTFP - Willingness to fund project - Dimensionless
IWTF - Initial willingness to fund - Dimensionless
WFPU - Willingness to fund project underway -
Dimensionless
BEMF - Bias effect multiplier, funding - Dimensionless

The bias for a project underway is simply the bias from the last period plus the bias growth during the period.

Equation 3510

MBPU - Measure of bias for program underway - Units Dimensionless
RBG - Rate of bias growth - Units/Month

Bias for a program underway only begins to build up when the program is fully or nearly acceptable by all criteria and is reporting progress back to the customer.

Equation 3530

TABRB - Table, rate of bias growth - Units/Month
WTFP - Willingness to fund the project - Dimensionless

The bias is nonlinearly associated with the bias multiplier discussed before to determine what funding curve is in use at the customer.

Equation 3540

BEMF - Bias effect multiplier, funding the project - Dimensionless

Both initial willingness to fund and the willingness to fund a project underway are table functions which reflect the initial reluctance to fund, and the later tendency to continue funding a project underway.

Equations 3550 and 3560

IWTF - Initial willingness to fund - Dimensionless
TIWTF - Table, initial willingness to fund - Dimensionless
WFPU - Willingness to fund project underway - Dimensionless
TWFPU - Table, willingness to fund project underway - Dimensionless
SPIC - Suitability of project for investment by customer - Dimensionless

Equations 3570 and 3580

TSPI - Trial suitability for investment - Dimensionless
VCR - Value to cost ratio - Dimensionless
ROIC - Return on investment criteria - Dimensionless

The value to cost ratio is formed from the accepted cost at the customer and his accepted value of the project.

Equations 3590 and 3600

ACVP - Accepted common value for project - Dollars
ACCC - Accepted cost to completion at customer- Dollars

Again in the printout a modification has been made simply to avoid division by zero at the end of the program.

Using the desired funding as established above, the customer will continuously exert budgeting pressure to bring budgeted funds into agreement with desired funding.

Equation 3610

DRCF - Desired rate of change of funds - Dollars/ Month
FDC - Funding desired by customer - Dollars
FBNR - Funds budgeted but not removed - Dollars
DIBF - Delay in budgeting funds - Months

The delay in budgeting funds is not a constant; but depends on both the suitability of the project and whether the desired change is negative or positive.

Equations 3620 through 3640

FDBF - Fixed delay in budgeting funds - Months
VDBF - Variable delay in budgeting funds - Months
ESOD - Effect of suitability on delay - Dimensionless
SPIC - Suitability of project for investment by customer - Dimensionless
TSCR - Test sign change ratio - Dollars

(Note that TSRC at any given time is the increment of money being started through the budgeting delay and is used as such later in determining backlog.)

When the rate of budgeting funds is negative it cannot exceed some absolute value that withdraws all remaining funds.

Equation 3560

RBF - Rate of budgeting funds - Dollars/Month
DRCF - Desired rate of changing funds - Dollars/Month
MRDA - Maximum rate of decreasing funds - Dollars/Month

The funds budgeted and not removed are simply equal to the previous figure plus the amount budgeted minus the amount spent.

Equation 3670

FBNR - Funds budgeted and not removed - Dollars
RBF - Rate of budgeted funds - Dollars/Month
ROS - Rate of spending - Dollars/Month

Customer Spending and Allocation

The rate of spending is ideally the accounts payable divided by the delay in payment. Spending cannot exceed funding, however, and the careful reader will find this safeguard added to the model in the printout.

Equations 3750 through 3770

TROS - Trial rate of spending - Dollars/Month
ROS - Rate of spending - Dollars/Month
APC - Accounts payable at customer - Dollars
RARP - Rate of allowable reduction in project funds - Dollars/Month

The customer's sunk costs are simply the past costs plus the amount spent during the period.

Equation 3780

CSCP - Customer's sunk costs, project - Dollars

Accounts payable at the customer are past accounts payable increased by billings during the period and decreased by payments.

Equation 3800

APC - Accounts payable at customer - Dollars
ROB - Rate of billing - Dollars/Month
ROS - Rate of spending - Dollars/Month

Rate of billing is based on the spending rate at the project; but cannot exceed the maximum rate established by the customer.

Equation 3820

MARC - Maximum allowable rate, customer - Dollars/Month
SRP - Spending rate at project - Dollars/Month

The next series of equations states that the maximum rate becomes zero when the last of the funds are being removed in the period, and that until that time it is based on spreading the uncommitted funds of the customer over the customer's budget planning horizon, usually a fiscal year. The maximum allowable rate is smoothed by the customer's delay in assigning funding limits.

The customer issues a cancellation notice whenever his funds remaining uncommitted are lower than that required to support one integration time period in the model, (DT). However, a smoothing delay is included to account for the natural reluctance of the customer to cancel an on-going project.

<u>Equations 3840 through 3940</u>

DAFL - Delay in assigning funding limits - Months
DICN - Delay in issuing cancellation notices - Months
TMAR - Trial MARC - Dollars/Month
CNO - Cancellation notice - Dimensionless
DRCF - Desired rate of change of funds -Dollars/Months
MRDA - Maximum rate of decreasing allocations - Dollars/Month
FRU - Funds remaining uncommitted - Dollars
FBNR - Funds budgeted and not removed - Dollars
APC - Accounts payable at customer - Dollars
BPHC - Budget planning horizon, customer - Months

SCN - Susceptibility to cancellation - Dollars/Month
SSCN - Smoothed SCN - Dollars/Month

## Customer Schedule

The schedule time remaining is the schedule completion date less the present time. For convenience this time is never allowed to become smaller than DT.

## Equations 4040 and 4050

TTR - Trial time remaining - Months
SCOP - Scheduled completion of the project - Months

Even a firm schedule is subject to adjustment towards the forecasted completion date predicted by the project.

## Equation 4060

ROSA - Rate of schedule adjustment - Months/Month
DICS - Delay in changing schedule - Months
FCD - Forecast completion date - Months

The schedule completion date is, of course, the previously scheduleddate plus any change in it during the period.

## PROJECT SECTOR

Returning to the Project Sector lying within the firm, we shall cover more macro functions added to the original model.

### Perceived Required Effort on Project

On complex development projects, the real scope of work required is never truly visible to those carrying out the program, but only gradually is revealed as the work progresses. The perceived effort is the initial estimate plus recognized changes to the estimate.

### Equation 4120

The unknown real total effort required, and the initial error is estimating total effort, are assumed parameters.

### Equations 4140 and 4150

The fraction of error in the estimated scope of work which is recognized depends upon real progress. Error recognition increases with progress on the job.

Equation 4160

The rate of error recognition depends upon the error in the estimate, and the fraction of error recognized.

Equations 4170 through 4190

PREP - Perceived required effort on project - Effective Man-Months
RCEC - Rate of correction of estimate to complete - Man-Months/Month
IEC - Initial estimate to complete - Effective Man-Months
RREP - Real required effort on project - Effective Man-Months
FREC - Fraction of error recognized in estimate to complete - Dimensionless
TFRC - Table, fraction of error recognized in estimate to complete - Dimensionless
PCC - Percent complete - Dimensionless
RTCC - Real total to complete - Dollars
FRER - Fraction of required effort recognized - Dimensionless

Facilities

An important factor within the firm's operations is the availability of the necessary facilities and capital equipment to carry out the project. Facility availability affects the rate of real progress on the job, and the spending rate. It is characterized by rather long delays in ordering and obtaining new facilities.

The perceived facilities requirements depend upon the firm's estimate of the scope of the job, which establishes facility and capital equipment requirements, and of the maximum manpower required, which establishes office and factory space requirements.

Equations 4270 through 4290

PFR - Perceived facilities requirements - Dollars
ECER - Estimated capital equipment requirements - Dollars
CERR - Capital equipment requirements ratio - Dollars/Man-Month
EFSR - Estimated floor space requirements - Dollars
FSRR - Floor space requirements ratio - Dollars/Man
RMEN - Requested men - Men
APMR - Approved project manpower requirement - Men

The additional facilities requirements are determined by subtracting all on-order or available facilities from the perceived requirements. The additional allocation, of course, can never be negative. The additional facilities allocation is then converted into a trial intended spending rate by considering the desired schedule deadline by which the firm would like to have the additional facilities available.

Equations 4300 through 4320

TAFR - Trial additional facilities required - Dollars
FOP - Facilities orders placed - Dollars
FOIP - Facilities orders in internal processing - Dollars
AFCE - Available facilities and capital equipment - Dollars
AAFR - Allocated additional facilities requirements - Dollars/Month
DPFO - Delay in placing facilities orders - Months

However, several other factors must be considered before the firm can commit to an intended rate of facilities spending. The available funding must be compared with limits set by the customer and with the fraction of total spending which is earmarked for facilities. The maximum allowable spending rate as determined by customer limitations is obtained by multiplying the fraction of spending allowed for facilities (FSAF) times the customer established maximum allowable spending rate for the project. However, this must also be compared with the desired spending rate obtained by observing the actual total project's spending, and multiplying this by the fraction of spending allowed for facilities. The lesser of these two limits is taken as the requested rate of facilities spending, and the intended rate of facilities spending is then taken as the lesser of either the requested rate or the trial rate of facilities spending, which was previously derived from facilities needs.

Equations 4360, 4370, 4490 and 4500

MASF - Maximum allowable spending rate, facilities - Dollars/Month
MARC - Maximum allowable spending rate, customer - Dollars/Month
FSAF - Fraction of spending allowed for facilities - Dimensionless
IRFS - Intended rate of facilities spending - Dollars/Month
DSRF - Desired rate of facilities spending - Dollars/Month
SRP - Spending rate on project - Dollars/Month
RRFS - Requested rate of facilities spending - Dollars/Month

The rate of ordering facilities is modeled as a third-order delay, dependent upon intended rate of facilities spending. The orders then enter a second third-order delay to account for the time required by the facility suppliers to fabricate and install the facilities and equipment. The end result is an available level of facilities at the firm.

Equations 4330 through 4350
4390 through 4460

TOIP - Trial facilities orders in process - Dollars
TOP - Trial facilities orders placed - Dollars
RFA - Rate of facilities availability - Dollars/Month
DFA - Delay in facilities availability - Months

The rate of spending for facilities is a function of the facilities orders placed and in process. Assume that it is proportional to the total of these two levels, since progress payments are frequently made in advance of facility occupancy.

Equation 4470

SRF - Spending rate for facilities - Dollars/Month
DPFB - Delay in paying facilities bills - Months

The spending rate for facilities is included within the overall project spending rate, neglecting the limitations on facility spending which are usually imposed by the customer as a separate budget item. Since the factors which determine the facilities budget tend to be the same items which the customer considers in making up the overall project budget, I shall assume only one overall budget limit is imposed by the customer, rather than subdividing it.

I have also assumed that the availability or nonavailability of facilities has an effect upon the productivity of personnel assigned to the project. I have represented this effect by a facilities productivity multiplying factor (FPMF), which is a dimensionless index indicating the percentage efficiency of operations which are attributable to facilities. The FPMF is a function of a facilities availability ratio, which is simply the ratio of the available facilities and capital equipment, to the perceived facilities requirements. As can be seen from the function in the equation printout in Appendix C, I have assumed a productivity function which penalizes productivity substantially when available facilities drop below 60% of perceived requirements. On the other hand, little advantage is gained by having 100% of facilities requirements.

Equations 4480, 4510, and 4580

FPMF - Facilities productivity multiplying factor - Dimensionless
FAR - Facilities availability ratio - Dimensionless

## Overtime

One of the project manager's most flexible variables is the use of overtime. The decision to use overtime (OT) is based on a need for manpower, as indicated by an outstanding increment request, and a behind schedule position, as indicated by the contractor's unofficial rate of forecast to schedule completion. Overtime is limited to some maximum practical value, however, by factors such as fatigue and morale. Smoothing of OT usage results from a delay in using OT, based upon looking at past requirements. For simplicity, I shall assume that OT authorized is the same as that actually used. A minimum practical OT level also exists due to the nature of the work--for example, tests which must be completed once started.

## Equations 4630 through 4650, 4680

OTUP - Overtime used on project - Dimensionless
IOTR - Index of overtime required - Dimensionless
MAOT - Maximum allowable overtime - Dimensionless
DIMP - Desired increment in manning project - Men
URFS - Unofficial ratio forecast to schedule completion - Dimensionless

SOTR - Smoothed OT requirement - Dimensionless
MPOL - Maximum practical OT level - Dimensionless

The use of OT affects the real progress rate by changing both the equivalent number of integrated men and their effectiveness. The OT productivity multiplier accounts for reduced efficiency due to fatigue with heavy, sustained OT.

Equations 4660 and 4710

OTPM - Overtime productivity multiplier - Dimensionless
TOPM - Table, overtime productivity multiplier - Dimensionless

Overtime also affects program spending rate, both by changing the number of effective men (40-hour week equivalent men) on the job, and by virtue of the overtime premium pay.

Equation 4670

OTUP - Overtime used on project - Dimensionless
EMOP - Equivalent men on project -
TMOP - Total men on project

Those equations in the model which relate to job charges and progress estimation must be based on equivalent men rather than total men (headcount), as for example, Equations 2110 and 2130.

## PROJECT SECTOR LYING WITHIN THE CUSTOMER

### Susceptibility to Budget Cuts

The customer agency of government is also subject to external pressures which influence its operations. In particular, the projects under its control are periodically investigated by other governmental agencies, such as General Accounting Office or Budget Bureau, or else are the target of inquiries by the Congress or by the press. During such periods, the customer has a strong incentive to review the performance of his projects, and to take punitive action against any laggards. The punitive action usually consists of an arbitrary cut in the maximum allowable spending rate for the project.

The factors considered by the customer in examining projects for possible punitive action are the project's technical, cost, and schedule performance, and the availability of funds. In the model, technical, cost, and schedule performance are represented by the customer's willingness to fund the project, his estimate of the cost to complete, and the rate of schedule adjustment; respectively. I have considered exogenous pressure for budget cuts can be cyclical, representing yearly elections and budget reviews, or else random, resulting from unforeseen political effects. Both versions are included, with a switch function to permit selection. This entire effect can also be dropped from the model by means of a limiting constant.

Lacking better insight, I shall assume that the customer weighs technical, cost and schedule performance equally when evaluating project status. The susceptibility to budget cuts is smoothed over by a delay, on the part of the customer, in recognizing such susceptibility.

Equations 4780 through 4870

SBC - Susceptibility to budget cuts - Dimensionless
WTFP - Willingness to fund project - Dimensionless
ROSA - Rate of schedule adjustment - Months/Month
IAAF - Index of Adequacy of available funds - Dimensionless
FAI - Fund availability index - Dimensionless
CECC - Customer's estimate of cost to complete - Dollars
FRU - Funds remaining uncommitted - Dollars
TPBC - Trial pressure for budget cut - Dimensionless
TTBC - Alternate trial pressure for budget cut - Dimensionless
PPP - Period of political pressure - Months
PFBC - Pressure for budget cuts - Dimensionless

LIMC - Limiting constant - Dimensionless (0 or 1)
SELC - Selection constant - Dimensionless (0 or 1)
CMAR - Cut in maximum allowable spending rate - Dimensionless
TCMR - Table, cut in max allowable spending rate - Dimensionless
TMAR - Trial maximum allowable spending rate - Dollars/Month
STR - Schedule time remaining - Months
SSBC - Smoothed susceptibility to budget cuts - Dimensionless
DRSB - Delay in recognizing susceptibility to budget cuts - Months

## SUBCONTRACT SECTION

In large system development projects, a major proportion of the work is subcontracted to subsystems and equivalent manufacturers. Fifty percent of the dollar value of the project may be the typical magnitude of total subcontracting. This large subcontract effort is directed by the prime contractor, who must monitor the technical efforts and progress of the subcontractors, establish their budgets and provide funding, and coordinate the diverse activities of the subcontractors with the prime's own efforts, to produce an orderly flow of system development, fabrication, and testing effort.

A large system development will typically involve several hundred subcontractors, ranging in size from small component suppliers, to multi-million dollar subsystem development subcontractors. For the purpose of constructing the model, the operations of the larger, major subcontractors are considered. These subcontractors typically receive detailed monitoring and control from a subcontract management office within the prime contractor's organization.

Although each of these is handled separately, for model purposes they are all lumped together as one aggregate subcontractor, representing the sum of all subcontract effort on the project. The dollar value of subcontracting used represents the sum of all procurement, which represents minor subcontracts and purchases, in addition to major subcontractors.

To further simplify the model's representation of subcontractors (which otherwise could be as complex as the prime firm), I shall assume that the subcontractors are very much like the prime contractor, and therefore such factors as manpower effectiveness, and maximum manpower build up rates, can be adapted directly from the prime firm's portion of the model. In this way, the essential dynamic features of aggregate subcontractor behavior are represented with a minimum of complexity.

Assume the subcontracted effort is a fixed percentage of the total scope of the project.

Equation 4970

SCRP - Subcontracting required on project - Dollars
PREP - Perceived required effort on project -
Man-Months

PJSC - % of job subcontracted - Dimensionless
SCOH - Subcontractors' mean engineering and overhead rates - Dollars/Man-Month

Integrated men from the prime's project staff are assigned to monitor subcontracting in accordance with a fixed ratio to subcontract value. They may also be removed by the same criteria, and hence the rate may be positive or negative, but the level of men assigned can never be less than zero.

Equations 4990, 5210, and 5220

RASC - Rate of assignment of men to subcontracts - Men/Months
DASC - Delay in assigning men to subcontracting - Months
PMSVR - Project men to subcontract value ratio - Men/Dollars
IMAS - Integrated men assigned to subcontracting - Men

The equations for total men on the project, integrated men on the project, and total potential trainees must be modified to include the men assigned to subcontracting monitoring.

Equations 2180, 2190 and 2500

FIM - Fully integrated men on project

RIIM - Rate of integrated internal men - Men/Month
RRIM - Rate of removing integrated men - Men/Month
SIMP - Simple method of indicating internally-funded work - Men/Month
EAMP - Externally acquired men on project - Men
ITMP - Internally acquired men on project - Men
TPT - Total potential trainees - Men
NMPT - Number of men per trainer - Men/Man

The rate of placing subcontracts depends upon the number of men in the prime contractor's project assigned to subcontracting. The procurement process is represented by a third order delay.

Equations 5000 through 5060

RPSC - Rate of placing subcontracts - Dollars/Month
DSPA - Delay in starting procurement actions - Months
SCIP - Subcontracts in procurement cycle - Dollars/Month
SSRP - Subcontractors spending rate on project - Dollars/Month
SFBR - Subcontractor funds budgeted, not released - Dollars
DSPC - Delay in placing subcontracts - Months

With the subcontracts placed, the subcontractors are then authorized to assign men to a level consistent with the unspent value of the subcontracts. Since the subcontractors have the same factors influencing their ability to add manpower as the prime, I will assume that the maximum rate of adding men follows the prime contractor's experience, with smoothing and delays added to account for the lesser elasped time on the project at the subcontractors' compared to the prime.

Since the subcontractors are really many separate firms, they are able to hire men at a greater overall rate than the prime. (For example, 1000 firms can add 1 Man/Month, for a total hiring rate of 1000 Man/Month.) This agglomeration effect is accounted for by a subcontractors' agglomeration hiring multiplier (SAHM). Similarly, hiring by the subcontractor is not necessarily zero when the prime's hiring is zero, but reaches a minimum hiring rate level (MSHL) established by subcontractors' independent actions.

<u>Equations 5070 through 5110</u>

ATMP - Average total men on project
TMOP - Total men on project
DSTM - Delay in smoothing total men - Months
TMRCM - Trial maximum rate of change of manpower - Dollars/Month
MRCMP - Maximum rate of change of manpower on project - Men/Month
MRASM - Maximum rate of assigning subcontractors manpower - Men/Month
SMAP - Subcontractors' manpower assigned to project - Men
TRASM - Trial rate of assigning subcontractors' men Men/Month

SCAM - Subcontractors' authorized manpower - Man-Months
DASM - Delay in assigning subcontractors' men - Months
RASM - Rate of assigning subcontractors' men - Men/Month
SAHM - Subcontractors' agglomeration hiring multiplier - Dimensionless
MSHL - Minimum subcontractor hiring rate limit - Men/Month

The subcontractors will not always add men at the maximum rate, however, since subcontract management keeps clearly in sight the maximum manpower level supported by firm prime contractor funding. In the model, this is represented as an aggregate function, but it presents the individual actions of the managers of each of the various subcontractors. The subcontractors' maximum manpower limit is obtained from the maximum allowable spending rate on the entire project, established by the customer agency, and the total percentage of the job to be subcontracted. This limit is smoothed by a delay in establishing funding authorization by the prime contractor, to result in a smoothed subcontractor maximum manpower limit. The manpower level which the subcontractor management desires will then be either the lesser of the authorized manpower or the supportable subcontractor manpower limit. The authorized manpower is computed using a budget planning horizon for subcontractors which is the lesser of either the initial schedule of the project or the official schedule time remaining.

Equations 5230 through 5260

SMML - Subcontractor maximum manpower limit - Men
MARC - Maximum allowable spending rate, customer - Dollars/Month
PJSC - Percentage of job subcontracted - Dimensionless
SCOH - Subcontractors' mean engineering and overhead charges - Dollars/Man-Month
SSML - Smoothed subcontractor maximum manpower limit - Men
DSFA - Delay in smoothing funding authorization - Months
SDML - Subcontractors' desired manpower level - Men
BPHS - Budget planning horizon, subcontractor - Months
ISDP - Initial schedule duration of project - Months

The subcontractors also estimate the number of men they need to complete the job in a manner similar to the prime contractor. In the aggregate, they estimate the subcontractor effort remaining on the job as a function of the total project effort remaining times the percentage of the job subcontracted. The subcontractors' needed men is then the subcontractor effort remaining divided by the schedule time remaining, times the technical effectiveness of the average man. The subcontractor then requests a manning level which is either the lesser of the needed men or the desired men based on funding limitations.

Equations 5310 through 5330

SERP - Subcontractor effort remaining on project - Man-Month
ERP - Effort remaining on project - Man/Month
SNMN - Subcontractor needed men - Men
STR - Schedule time remaining - Months
TEAM - Technical effectiveness of the average man - Dimensionless
SRMN - Subcontractor requested men - Men

A trial rate of assigning men in the subcontractors' plants is then formed based upon the subcontractors' requested men and the men already assigned to the project. The final rate of assigning subcontractors' men is established as the minimum of the rate derived from the subcontractors' requested men, or the maximum rate established by comparison with the prime contractors' ability to add manpower.

Equations 5120 and 5130

TRASM - Trial rate of assigning subcontractor men - Men/Month

DASM - Delay in assigning subcontractor men - Months
RASM - Rate of assigning subcontractor men - Men/Month

The number of subcontractor men assigned to the project is then a level function resulting from the integration of the rate of assigning men to the job. This level can never be less than zero, of course.

Equations 5140 through 5160

TSMAP - Trial subcontractor men assigned to project - Men
SMAP - Subcontractor men assigned to project - Men

In order to show the removal of the prime contractor's men assigned to monitor subcontracts as the subcontracts are completed, the following equations are added. The rate of removal is determined by a table function based upon the percentage of completion of subcontract effort. When the subcontract effort is almost done, the prime contractor removes most of his men from monitoring subcontracts.

Equations 5290 and 5300

PSCC - Percentage of subcontracted effort complete - Dimensionless

SSCP - Subcontractors spent cost on project - Dollars
SCRP - Subcontracting required on project - Dollars
RMAS - Removal of men assigned to subcontracting - Dimensionless

The aggregate subcontractors' capability of manning thejob is monitored by the prime contractor. This subcontractor manning index is used as a guide by the prime contractor in establishing his own internal manpower requirements. As the subcontractor manning index approaches unity, the prime contractor is willing to limit his own efforts to the fraction of the job planned for internal performance by the prime contractor.

Equations 5350 through 5370

FSMP - Fraction of subcontractor manning on project - Dimensionless
SMAP - Subcontractor men assigned to project - Men
TSMI - Trial subcontractor manning index - Dimensionless
SMI - Subcontractor manning index - Dimensionless

The subcontractors' men are assumed to be as effective on the average as the prime contractor's men, and hence they are added into the total of effective integrated men that affect real progress, in the same ratio as the prime's effective/total men.

However, since the subcontractors' staff is less mature than the prime's, in terms of duration on the project, the prime's ratio of effective/total men is given a smoothing delay before applying it to the subcontractor.

Equations 5170 through 5190

MER - Manpower effectiveness ratio - Dimensionless
SMER - Smoothed manpower effectiveness ratio - Dimensionless
STME - Smoothing time for manpower effectiveness - Months

The subcontractors' charges are added into the total spending rate, neglecting subcontractors' billing time lags.

Equation 5200

SSRP - Subcontractors' spending rate on project - Dollars/Month

The equation for total spending rate on project, SRP, as modified to include overtime, facilities, and subcontractors' charges, has been previously given. (Equation 2940)

## Macro Function Equations

On the next to the last page of the Equation Printout--Appendix C, a section called Macro Functional Equations appears. These equations (5540 through 5960) are the means by which the macro functions are converted into operating equations within the model. A macro function is a shorthand notation for a function of several variables and equations. To use a simple example, consider the macro function for overtime, Equation 4620. Here we see an equation of the following form:

MACRO OTUP (URFS, SMIP, TMOP, EMOP, OTPM)

This equation defines a macro function OTUP which in turn is a function of the parameters listed beneath it, between the MACRO card and the MEND card (for macro end). The parameters in the parenthesis to the right of the macro represent inputs to or outputs from the macro. These are accessible functions which can be transferred into or out of the macro as required, and for which printed output results can be obtained. However, the macro also contains several internal functions for which no output can be obtained, but which function internally within the macro to determine the values of the output parameters. For example, refer to Equations 4640 and 4650, which define the internal parameters TOTR and IOTR respectively. You will note that all internal macro parameters are prefaced by a dollar sign ($). This symbol is the designator which denotes that these are internal macro parameters for which output cannot be obtained.

Returning now to the macro functional equations, we see in Equation 5920 the macro functional equations for overtime. Since overtime is a project function, an equation for overtime must appear for each project. In the single project model, however, there is only one project, Project 1. Hence, Equation 5920 shows OTUP (URFS 1.K, DMIP1.K TMOP1.K, OTPM1.K)

This designator the macro function as applied to Project one. The .K indicates that this functions varies with time. We can also tell it as an auxilary function from the typed designation in the left margin. Please refer to the Dynamo Users Manual for a more complete description of the equation conventions.

Hence, the macro functional equation for overtime, Equation 5920, creates an operating function for the overtime used on Project 1 which the Dynamo compiler will then solve. If we had additional projects, we would have to supply additional macro functions, for each project as required. Note that some of the macro functions in the central sector occur only once, and therefore will not be duplicated for additional projects. This is true, for example, for the very first macro functional equation, Equation 5540.

## Constants

Universal constants, which apply to all projects, need not be listed as inputs or outputs to a macro function. They can be listed anywhere in the model and will still be able to enter the macro functions. If a constant applies to a particular project only, however, it then must have the number designator of the project, and it must appear in the macro function as an input or output.

In general, I have listed constants where they occur after the macro end (MEND) card for each macro function. However, the last two pages of the Printout also contain a list of miscellaneous constants. These are all universal constants, with the exception of the intrinsic value of the project (IVPT 1), which applies only to Project 1, and therefore is listed as input to the macro functions in which it occurs.

## Additional Equations

This final section of the model follows the requirements listed in the Dyn@mo Users Manual. Here the form of output is specified in terms of both printed and plotted variables. The SPEC card designates the time inteval DT to be used in the model, the length of the model run, and the period of printed and plotted output. The final card is the run number which serves to identify each runs' output.

# APPENDIX C

## EQUATION PRINTOUT -- SINGLE PROJECT MODEL

FILE: MPDM024 DYNAMO P1 MASSACHUSETTS INSTITUTE OF TECHNOLOGY

```
*   SINGLE PROJECT DYNAMO
NOTE                CENTRAL SECTOR
NOTE                       NORMAL    OPERATING    SECTION
NOTE    FIRM'S MANPOWER ALLOCATION
MACRO DMIPT(AMIP1,AMIP2,AMIP3,AMIP4,NHP,THOC,IMP,PAH,PCM1,PCM2,PCM3,PCM4
X   ,IPBA,NHBA,NRNH,RLNH,NRIP,RLIP)
A      DMIPT.K=AMIP1.K+AMIP2.K+AMIP3.K+AMIP4.K+0.1+0
A      PCM1.K=AMIP1.K/DMIPT.K                        ( MEN TO 1
A      PCM2.K=AMIP2.K/DMIPT.K                        ( MEN TO 2
A      PCM3.K=AMIP3.K/DMIPT.K                        ( MEN TO 3
A      PCM4.K=AMIP4.K/DMIPT.K                        ( MEN TO 4
N   PCM2=0
N   PCM3=0
N   PCM4=0
N   AMIP2=0
N   AMIP3=0
N   AMIP4=0
A      $TRII.K=DMIPT.K-IMP.K                          TEST OF REG FOR INT
A      IPBA.K=CLIP(IMP.K,DMIPT.K,$TRII.K,0)           INT PER TO BE ALLOC
A      $RIRQ.K=CLIP($TRII.K,0,$TRII.K,0)               REM INER REQ
A      $TRNH.K=$RIRQ.K-NHP.K                          TEST REQ NEW HIRES
A      NHBA.K=CLIP(NHP.K,$RIRQ.K,$TRNH.K,0)           NEW HIRES BEING ALLOC
A      $IMER.K=IMP.K-IPBA.K                          INT MEN REM POOL
A      $NHMR.K=NHP.K-NHBA.K                          NEW HIRES REM POOL
A      $TMIP.K=$NHMR.K+$IMER.K                          TOT MEN IN POOLS
A      $NOMP.K=$TMIP.K+(-THOC.K)(PAIP)                NO OVER MAX, POOL
A      $NBRP.K=CLIP($NOMP.K,0,$NOMP.K,0)               NO BEING REM FOR POO
A      $TFNH.K=$NBRP.K-$NHMR.K                         TEST FROM NEW HIRES
A      NRNH.K=CLIP($NHMR.K,$NBRP.K,$TFNH.K,0)          NO REM NEW HIRE
A      NRIP.K=CLIP($TFNH.K,0,$TFNH.K,0)               NO REM INT POOL
N   NRIP=0
A      RLIP.K=(1/$DICP.K)($IMER.K-NRIP.K)             RAT LEAV INT POOL
A      RLNH.K=(1/$DICP.K)($NHMR.K-NRNH.K)             RAT LEAV N H POOL
A      $DICP.K=TABHL(TDICP,PAH.K,0,1,0.2)
MEND
NOTE    FIRMS INTERNAL MANPOWER POOL
MACRO IMP(DFIM1,DFIM2,DFIM3,DFIM4,DITM1,DITM2,DITM3,DITM4,PCM1,PCM2,PCM3
X   ,PCM4,IPBA,NRIP,RLIP,RLCI,RIMP1,RIMP2,RIMP3,RIMP4)
R      RIMP1.KL=(IPBA.K)(PCM1.K)/DT                 RAT INT MEN
R      RIMP2.KL=(IPBA.K)(PCM2.K)/DT                 RAT INT MEN
R      RIMP3.KL=(IPBA.K)(PCM3.K)/DT                 RAT INT MEN
R      RIMP4.KL=(IPBA.K)(PCM4.K)/DT                 RAT INT MEN
R      RLCI.KL=RLIP.K+NRIP.K                        RAT LEAV COMP, INT
R      $RIPP.KL=(1/DT)(DITM1.K+DITM2.K+DITM3.K+DITM4.K+$RFFT.K+$RFST.K)
A      $RFFT.K=(1/DRIM)((DT)(DFIM1.K)+(DT)(DFIM2.K))  RATE FR FIRST TWO
A      $RFST.K=(1/DRIM)((DT)(DFIM3.K)+(DT)(DFIM4.K))    RATE FR SEC TWO
L      IMP.K=IMP.J+(DT)($RIPP.JK-RLCI.JK-RIMP1.JK-RIMP2.JK-RIMP3.JK-RIMP4
X   .JK)
N      IMP=720
N   RIMP2=0
N   RIMP3=0
N   RIMP4=0
MEND
NOTE    FIRM'S NEW HIRE POOL
MACRO TMEN(NRNH,RLNH,IMP,PCM1,PCM2,PCM3,PCM4,NHBA,FRU1,FRU2,FRU3,FRU4,TS
```

```
X  CR1,TSCR2,TSCR3,TSCR4,TMOP1,TMOP2,TMOP3,TMOP4,DEAM1,DEAM2,DEAM3,DEAM4MPD00560
X  ,FIM1,FIM2,FIM3,FIM4,NHP,PAH,MIHD,HR,TMOC,RLCE,BKLG,COP,MLO,TMAC,FIMTMPD00570
X  ,REMP1,REMP2,REMP3,REMP4,NRIP,FSAI,SRP1,SRP2,SRP3,SRP4,TPSR)           MPD00580
R     REMP1.KL=(NHBA.K)(PCM1.K)/DT                  RATE EXT MEN          MPD00590
R     REMP2.KL=(NHBA.K)(PCM2.K)/DT                  RATE EXT MEN          MPD00600
R     REMP3.KL=(NHBA.K)(PCM3.K)/DT                  RATE EXT MEN          MPD00610
R     REMP4.KL=(NHBA.K)(PCM4.K)/DT                  RATE EXT MEN          MPD00620
R     RLCE.KL=NRNH.K+RLNH.K                         RAT LEAV CO, EXT      MPD00630
A     $FSI.K=$PSF.K/DSL                             FIRMS SEC IND         MPD00640
A     $TPSF.K=BKLG.K/TPSR.K                   TR PRES SEC FUND            MPD00650
A  $PSF.K=SMOOTH($TPSF.K,DSBK)            PRESNT SEC FUNDG                MPD00660
A  TPSR.K=SRP1.K+SRP2.K+SRP3.K+SRP4.K+1.0      TOT PROJ SPDG              MPD00670
N  SRP2.K=0                                                               MPD00680
N  SRP3.K=0                                                               MPD00690
N  SRP4.K=0                                                               MPD00700
A     BKLG.K=TSCR1.K+TSCR2.K+TSCR3.K+TSCR4.K+FRU1.K+FRU2.K+FRU3.K+FRU4.KMPD00710
A     $ZMEN.K=TMOC.K+MIHD.K+NHP.K+IMPT.K             TOT MEN              MPD00720
A     TMEN.K=MAX($ZMEN.K,1)                                               MPD00730
A     TMOC.K=TMOP1.K+TMOP2.K+TMOP3.K+TMOP4.K                 TOT MEN AC MPD00740
A     $LIM.K=-$ZMEN.K+(FIMT.K)(SR)                                        MPD00750
A     FIMT.K=($BR1.K)(FIM1.K)+($BR2.K)(FIM2.K)+($BR3.K)(FIM3.K)+($BR4.K)MPD00760
X   (FIM4.K)                                                              MPD00770
A     $TBR1.K=(TSCR1.K+FRU1.K+0)/(BKLG.K+1+0)                             MPD00780
A     $BR1.K=MAX($TBR1.K,0)                                               MPD00790
A     $TBR2.K=(TSCR2.K+FRU2.K+0)/(BKLG.K+1+0)                             MPD00800
A     $BR2.K=MAX($TBR2.K,0)                                               MPD00810
A     $TBR3.K=(TSCR3.K+FRU3.K+0)/(BKLG.K+1+0)                             MPD00820
A     $BR3.K=MAX($TBR3.K,0)                                               MPD00830
A     $TBR4.K=(TSCR4.K+FRU4.K+0)/(BKLG.K+1+0)                             MPD00840
A     $BR4.K=MAX($TBR4.K,0)                                               MPD00850
R     $THR.KL=$HAA.K/DEPR   TR HIRING RATE                                MPD00860
R  HR.KL=MIN($THR.KL,MAHR)               HIRING RATE                      MPD00870
N     HR=0                                                                MPD00880
R     $NHA.KL=DELAY3(HR.JK,DCNH)                         HIRING DELAY     MPD00890
L     MIHD.K=MIHD.J+(DT)(HR.JK-$NHA.JK)           MEN IN HIR DEL          MPD00900
N     MIHD=0                                                              MPD00910
R     $REPP.KL=(1/DT)(DEAM1.K+DEAM2.K+DEAM3.K+DEAM4.K+0+0)                MPD00920
R  $CPR.KL=REMP1.KL+REMP2.KL      CON FORM RATE                           MPD00930
L  $TNHP.K=$TNHP.J+(DT)($REPP.JK+$NHA.JK-RLCE.JK-REMP3.JK-REMP4.JK-$CPR.MPD00940
X  JK)                                  TR NEW HIRE POOL                  MPD00950
A  NHP.K=MAX($TNHP.K,0)                 NEW HIRE POOL                     MPD00960
R  $RCOP.KL=(NHP.K+IMPT.K)*MEOH          RATE OF POOL CHG                 MPD00970
L  COP.K=COP.J+DT*$RCOP.JK              CHARGES TO POOL                   MPD00980
L  MLO.K=MLO.J+DT*(RLCE.JK+RLCI.JK)     MEN LVG COMPANY                   MPD00990
N  MLO=0                                                                  MPD01000
N  COP=0                                                                  MPD01010
S  TMAC.K=TMEN.K-MIHD.K                 TOT MEN AVAIL                     MPD01020
N     $TNHP=0                                                             MPD01030
A     PAH.K=CLIP(1,$FSI.K,$FSI.K,1)                  PRESS AGAINST HOARDINMPD01040
A  $HINC.K=($FSI.K-1)*TMEN.K*FSAI     HIRING INCR DES                     MPD01050
A  $THAA.K=MAX($QAAA.K,0)               TR HIRE AT ALL?                   MPD01060
A  $RLOM.K=NRIP.K+NRNH.K                RATE LAYING OFF MEN               MPD01070
A  $HFB.K=SWITCH(1,0,$RLOM.K)           HIRING FEEDBACK                   MPD01080
A  $HAA.K=$THAA.K*$HFB.K                HIRE AT ALL?                      MPD01090
A  $QAAA.K=MIN($HINC.K,$LIM.K)                                            MPD01100
```

```
N   REMP2=0
N   REMP3=0
N   REMP4=0
MEND
C   DSL=18                                         DES STABILITY LVL
C   MAHR=700                                      MAX ATTAIN HIRING RATE
C   DONH=6                                               DLY OBTNG NEW HIRES
C   DSBK=6                                         DLY SMTHG BKLG
NOTE          FIRMS CORPORATE MANPOWER CONTROL
MACRO AMIP(EMOP,TMOP,PSAI,IMPT,TMOC,SRFM,APMR,DMIP,FMRA,MISA,ERP,PFMP,ST
X   R)
A   $PFMN.K=((ERP.K*PSAI)-(EMOP.K*MPH))/STR.K  PROJ FUT MNPWR NDS
A   $NMIP.K=CLIP(DMIP.K,0,$PFMN.K,EMOP.K)     NEGOT MNPWR INCRMNT
A   FMRA.K=TABHL(TFMR,$ILMP.K,0,1.2,.2) FRACT MNPWR RQST APPRVD
A   $ILMP.K=IMPT.K/(TMOC.K*PAIP)         INDX LVL MNPWR IN POOL
A   $TMSA.K=$NMIP.K*FMRA.K                TR MNPWR INCR SUBMTD FOR APPRVL
A   MISA.K=SMOOTH($TMSA.K,DCMA)          MNPWR INCR SUBTD FOR APPRVL
R $RAMI.KL=(MISA.K-$DRMU.K)/DCMA         RATE APPRVG MNPWR INCR
A   $PRTM.K=DMIP.K+TMOP.K                PROJ REQT TOT MEN
A   $DARM.K=APMR.K-$PRTM.K               DIFF APPRVD RWSD MEN
A   $DRMU.K=MAX($DARM.K,0)               DIFF REQ MEN UTILXD
L   $TAPR.K=$TAPR.J+DT*($RAMI.JK+$RRFM.JK)   TR APP MNPWR REQTS
A   APMR.K=MAX($TAPR.K,0)                APPRVD PROJ MNPWR REQTS
A   $TRFM.K=MIN(SRFM.K,0)                TR RATE REMVL FUNDD MNPWR
A   $RRFM.K=CLIP(0,$TRFM.K,PFMP.K,APMR.K)    RATE RMVL FUND MNPWR
A   AMIP.K=APMR.K-TMOP.K                 APPRVD MEN INTO PROJ
N   $TAPR=TMOP+IMPT
MEND
C   MPH=6                                MNPWR PLNNG HORIZ
T   TFMR=.5/.6/.8/.9/.95/.98/1.0     TABL,FRACT MNPWR INCR APPVD
C   DCMA=2                               DLY CORP MNPWR APPRVL
NOTE         R&D ALLOCATION
MACRO IFRL(ROB1,ROB2,ROB3,ROB4,RCF,IRLA,RIFRL)
A       $ROBT.K=ROB1.JK+ROB2.JK+ROB3.JK+ROB4.JK
L       $SROB.K=$SROB.J+(DT)(1/DSRB)($ROBT.J-$SROB.J)
N       $SROB=0
A       $NIFRL.K=(PCAO)($SROB.K)/MEOH                   NEG INT FUND RGS LEV
R       RIFRL.KL=(1/DAIF)($NIFRL.K-IFRL.K)            RAT INT FUND R + S
N   ROB2=0
N   ROB3=0
N   ROB4=0
L       IFRL.K=IFRL.J+(DT)(RIFRL.JK+0)
N       IFRL=0
A       IRLA.K=MAX($QFRL.K,IFRL.K)                      INT MEN TO BE ALLOC
A       $QFRL.K=CLIP(2,0,0,RCF.K)                      MIN LEVEL
MEND
C   DSRB=3                                 DLY SMTHG RATE OF BILLING
C   PCAO=.04                               R&D ALLOWABLE
N   DAIF=DT
NOTE   DIVISION OF R&D
MACRO SIMP(RCF,CDI,RERP,MARC,IRLA,CFRL,DI)
A      $AIFL.K=(IRLA.K)($PRD.K)
A      $DCFR.K=(1/DT)($AIFL.K-CFRL.K)
R       SIMP.KL=MAX(-$CFM.K,$DCFR.K)
N   SIMP=0
```

```
A     $CFM.K=RCF.K/((MEOH)(DT))
L       CFRL.K=CFRL.J+(DT)(SIMP.JK+0)
N       CFRL=0
A     $PRD.K=DI.K/CDI.K
A       DI.K=(FRD)($DUI.K)($FDU.K)
A     $IUI.K=(-MARC.K/.25E6)+1
A       $DUI.K=MAX(0,$IUI.K)
A       $FDU.K=CLIP(0,1,RERP.K,2000)
MEND
NOTE   SUMMATION OF R&D
A  CDI.K=DI1.K+DI2+DI3+DI4+0.1      CUM DIVIS INDEX
N  DI2=0
N  DI3=0
N  DI4=0
NOTE                    VALUE
MACRO  ACVP(BEMF,STR,IVPT,PCC,RLVC)
A       $IVP.K=TABHL(IVPT,TIME.K,0,96,12)          INTR VAL PROJ
A       $DRV.K=TABHL(TDRV,PCC.K,0,0.05,0.01)
R  $RVRC.KL=($IVP.K-RLVC.K)/$DRV.K    RATE VAL REL, CUST
L    RLVC.K=RLVC.J+(DT)($RVRC.JK+0)            REC LEV VAL CUST
N       RLVC=776E6
L  ACVP.K=ACVP.J+(DT/DAVC)*(RLVC.J-ACVP.J)  ACC CUST VAL, PROJ
N       ACVP=776E6
MEND
NOTE                    PROGRESS
MACRO CRP(AFCE,FPMF,EMOP,EFIM,PFIM,PREP,PRP,RERP,TEAM,PCC,PPCC,MMET,RPR,
X  SEIM,PERP,SMAP)
L    CRP.K=CRP.J+(DT)(RPR.JK+0)              CUM REAL PROG
N       CRP=0
R  RPR.KL=FPMF.K*PFIM.K*(EFIM.K+SEIM.K)    RATE REAL PROG
A       PCC.K=CRP.K/PREP.K
L     PRP.K=PRP.J+(DT)(PERP.JK+$PECR.JK)        PER  PROG
N       PRP=0
R       $PECR.KL=$ERRP.K/DT                        PER ERR CORR RATE,PP
A     $ERRP.K=($EPP.K)($FER.K)                   ERR REC PROJ   PER PROG
A       $EPP.K=CRP.K-PRP.K                      ERR PERC P-OG
A       PPCC.K=PRP.K/PREP.K                        PERCENT COMPLETE
A       $DPCC.K=MAX(PPCC.K,PCC.K)
A       $FER.K=TABHL(TFER,$DPCC.K,0,1,0.1)         FRAC ERR PER PROG REC
L  RERP.K=RERP.J+(DT/DRRP)*(PRP.J-RERP.J)    REP REAL PROG
N       RERP=0
R       $RCT.KL=$ERRP.K/((MMET.K)(DT))             RATE CORR TEAM
L     $TREAM.K=$TREAM.J+(DT)($RCT.JK+0)             TR TECH EFF AVG MAN
N       $TREAM=1.0
A  TEAM.K=MAX($TREAM.K,0.1)                   TECH EFF AVG MAN
L  MMET.K=MMET.J+DT*(EMOP.J+SMAP.K)      MAN MOS EXPD
N       MMET=0.1
R  PERP.KL=TEAM.K*(EMOP.K+SMAP.K)      PRCVD RATE PROGRESS
MEND
NOTE          PROJECT MANPOWER
MACRO TMOP(REMP,RWEA,RIMP,IDIM,OTUP,PCC,RFSC,OTPM,SIMP,FIM,RWIT,EAMP,
X  RRIM,EFIM,PFIM,RASC,IMAS,DFIM,DITM,DEAM)
A       TMOP.K=EAMP.K+$ITMP.K+FIM.K+IMAS.K              TOTAL MEN PTOJ
L       $TFIM.K=$TFIM.J+(DT)($RIIM.JK-RRIM.JK+SIMP.JK-RASC.JK)
A       DFIM.K=MAX($TDIM.K,0)                     DECR FULLY INT MEN
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FILE: MPDM024  DYNAMO   P1                 MASSACHUSETTS INSTITUTE OF TECHNOLOGY
R      RRIM.KL=DFIM.K/DRIM                         RATE RED INTEG MEN        MPD02210
N      $TFIM=160                                                             MPD02220
A   FIM.K=MAX($TFIM.K,0)                         FULLY INTEG MEN ON PROJ     MPD02230
R      $RIIM.KL=$EITM.K/((DIIM)(PRIT))              RATE INT. INTERNAL MEN   MPD02240
L      $ITMP.K=$ITMP.J+(DT)(RIMP.JK+$REIM.JK-$RIIM.JK-RWIT.JK)               MPD02250
A      $RRCM.K=MAX($TDEA.K,0)                       REM REQ CHANGE MEN       MPD02260
A      $TDIM.K=$RRCM.K-$ITMP.K                      TEST INCR INT MEN        MPD02270
A     DITM.K=CLIP($ITMP.K,$RRCM.K,$TDIM.K,0)      DECR INT TRANS MR          MPD02280
R      RWIT.KL=DITM.K/DT                           RATE WITH T INT TR MEN    MPD02290
N      $ITMP=0                                                               MPD02300
R      $REIM.KL=$EEAM.K/((DEIM)(PREA))              RATE CONV EXT INT MEN    MPD02310
L      EAMP.K=EAMP.J+(DT)(REMP.JK-$REIM.JK-RWEA.JK+0)                        MPD02320
N      EAMP=0                                                                MPD02330
A      $TDEA.K=-IDIM.K-EAMP.K                      TEST DECR EXT AC MEN      MPD02340
A     DEAM.K=CLIP(EAMP.K,-IDIM.K,$TDEA.K,0)     DECR EXT AC MEN              MPD02350
R      RWEA.KL=DEAM.K/DT                           RATE WUTH EXT ACQ MEN     MPD02360
A   EFIM.K=OTUP.K*($QFIM.K+$EEAM.K+$EITM.K)     EFF INTEG MEN                MPD02370
A     $EEAM.K=(PRUM)($EMLP.K)+(-$PCSU.K)(PRUM)($EMLP.K)+($PCSU.K)(PREA)*     MPD02380
X     ($EMLP.K)                                  EFF EXT ACQ MEN             MPD02390
A     $EITM.K=(PRUM)($IMLP.K)+(-$PCSU.K)(PRUM)($IMLP.K)+($PCSU.K)(PRIT)*     MPD02400
X     ($IMLP.K)                                  EFF INT TRANSF MEN          MPD02410
A     $IPCT.K=CLIP($TIS.K,1,$TIS.K,1)              INVERT PER CENT TR        MPD02420
A      $PCT.K=1/$IPCT.K                             PER CENT TRAINERS        MPD02430
A     $QFIM.K=(PRFI)(FIM.K)+(-$PCT.K)(PRFI)(FIM.K)+($PCT.K)(PRTR)(FIM.K)     MPD02440
NOTE                                               EQV FULL INTEG MEN        MPD02450
A      $TIS.K=$TPT.K/($EMLP.K+$IMLP.K+1)   TEST INDEX, SUPER                 MPD02460
A      $IMLP.K=$ITMP.K-DITM.K                      INT MEN LEFT ON PROJ      MPD02470
A      $EMLP.K=EAMP.K-DEAM.K                       EXT MEN LEFT ON PROJ      MPD02480
A     $PCSU.K=CLIP(1,$TIS.K,$TIS.K,1)              PER CENT SUPERVISED       MPD02490
A   $TPT.K=NMPT*(FIM.K+IMAS.K)       TOT POT TRNEES                          MPD02500
A   PFIM.K=$KHAP.K*$SPRM.K*$EPM.K*OTPM.K   PROD INTEG MEN                    MPD02510
A      $KHAP.K=TABHL(TMDKH,PCC.K,0,1.0,0.2)         KNOW-HOW PROJ            MPD02520
A      $SPRM.K=TABHL(TSPM,RFSC.K,0,2,0.25)          SCH RAT PROD MULT        MPD02530
A      $EPM.K=TABHL(TEPM,TMOP.K,0,350,50)            EAR PROD MULT           MPD02540
MEND                                                                         MPD02550
N  DFIM2=0                                                                   MPD02560
N  DITM2=0                                                                   MPD02570
N  DEAM2=0                                                                   MPD02580
N  DFIM3=0                                                                   MPD02590
N  DITM3=0                                                                   MPD02600
N  DEAM3=0                                                                   MPD02610
N  DITM4=0                                                                   MPD02620
N  DFIM4=0                                                                   MPD02630
N  DEAM4=0                                                                   MPD02640
N  TMOP2=0                                                                   MPD02650
N  TMOP3=0                                                                   MPD02660
N  TMOP4=0                                                                   MPD02670
N  FIM2=0                                                                    MPD02680
N  FIM3=0                                                                    MPD02690
N  FIM4=0                                                                    MPD02700
NOTE        SCHEDULE                                                         MPD02710
MACRO RFSC(EMOP,ERP,TEAM,SCOP,FCD,SMAP,STR,URFS,APMR,TMOP,OTUP)              MPD02720
A   $TTRP.K=$PTPM.K+$TRPM.K                 TR TIME RMNG ON PROJ             MPD02730
A   $PTPM.K=MAX($TPPM.K,0)                  PROJTD TIME TO PEAK MNNG         MPD02740
A   $TPPM.K=(APMR.K-TMOP.K)/MAHR            TR PROJTD TIME TO PEAK MNNG      MPD02750
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FILE: MPDM024   DYNAMO   P1                    MASSACHUSETTS INSTITUTE OF TECHNOLOGY
A   $TRPM.K=((ERP.K-.5*$PTPM.K*(APMR.K-TMOP.K)-TMOP.K*$PTPM.K)              MPD02760
X   /(TEAM.K*(OTUP.K*APMR.K+SMAP.K)))           TIME RMNG AT PEAK MNNG      MPD02770
A   $XTRP.K=CLIP($TTRP.K,STR.K,TIME.K,DSUP)     XPTD TIM REM PROJ           MPD02780
A   FCD.K=CLIP($SXCD.K,SCOP.K,$SDI.K,TFCS)  FOR COMPL DATE                  MPD02790
A   $SDI.K=$XSDP.K/STR.K                  SCH DISCRP INDEX                  MPD02800
A   URFS.K=$SXCD.K/SCOP.K                      UNOFFL RATIO FORE SCH COMP   MPD02810
A   $XCD.K=$XTRP.K+TIME.K          EXPTD COMPL DATE                         MPD02820
A   $TSDP.K=$SXCD.K-SCOP.K            TRIAL SCHD DISCRP                     MPD02830
A   $XSDP.K=MAX($TSDP.K,0)         EXPTD SCHD DISCRP                        MPD02840
A      RFSC.K=FCD.K/SCOP.K                       RATIO FORE SCH COMP        MPD02850
A   $SXCD.K=SMOOTH($XCD.K,DCSD)         SMTHD EXPTD COMPLTN DATE            MPD02860
N   $XCD=SCOP                                                               MPD02870
MEND                                                                        MPD02880
C   DCSD=2                                DLY CHGG SCH DATES                MPD02890
C   TFCS=.25                                TRSHOLD FOR CHGG SCHED          MPD02900
C   DSUP=12                               DLY START UP OF PLNNG             MPD02910
NOTE        FIRM'S COST                                                     MPD02920
MACRO SRP(RERP,PREP,TEAM,MARC,OTUP,SRF,SSRP,TMOP,FSCP,ERP,ECCP,RCF,AMCR)    MPD02930
A   SRP.K=MEOH*TMOP.K+(OTUP.K-1)*TMOP.K*MEOH*OTPR+SRF.JK+SSRP.JK            MPD02940
NOTE     SPDG RATE AT PROJ                                                  MPD02950
A      ERP.K=MAX($XRP.K,0)                                                  MPD02960
A      ECCP.K=(ERP.K)(AMCR)/TEAM.K                                          MPD02970
A   $XRP.K=PREP.K-RERP.K           TRL EFFORT RMNG                          MPD02980
L     FSCP.K=FSCP.J+(DT)(RCF.JK)                FIRM SUNK COST, PROJ        MPD02990
N      FSCP=4.5E6                                                           MPD03000
R      RCF.KL=MAX($TRCF.K,0)                        RATE COM FUND           MPD03010
A      $TRCF.K=SRP.K-MARC.K                        TRIAL RATE CUST FUND     MPD03020
N   RCF=0                                                                   MPD03030
MEND                                                                        MPD03040
N   ECCP1=384E6                                                             MPD03050
NOTE           DESIRED MANPOWER                                             MPD03060
MACRO DMIP(MARC,STR,TEAM,ERP,PAH,CFRL,XMOP,FMLL,MMLL,RMEN,IDIM,DIMP         MPD03070
X   ,NMEN,PFMP,TMOP,SRF,SSRP,FBNR,PJSC,FSAF,FSAI,AMCR,SRFM,ANMN,SMI)        MPD03080
L     FMLL.K=FMLL.J+(DT)($RFML.JK+0)              FUND MEN LEV LIM          MPD03090
N      FMLL=0                                                               MPD03100
R   $RFML.KL=(MMLL.K-FMLL.K)/DT     RAT CHG FUN MAN LEVEL                   MPD03110
L   SRFM.K=SRFM.J+(DT/DSFMR)*($RFML.JK-SRFM.J)   SM RATE FUND MEN           MPD03120
A   $TMMLL.K=(MARC.K*FSAI)/MEOH           TR MAX MNPWR LDG LVL              MPD03130
N   FSAI=1-PJSC-FSAF                      FRACT SPDG ALLOWD INTERNLY        MPD03140
A   MMLL.K=SMOOTH($TMMLL.K,DSIM)          MAX MNPWR LDG LVL                 MPD03150
N      SRFM=0                                                               MPD03160
A      $TNMN.K=ERP.K/((STR.K)(TEAM.K))        TR NEEDED MEN                 MPD03170
A      $SMEN.K=MIN(MMLL.K,PFMP.K)                  SUPP MEN                 MPD03180
A   NMEN.K=($TNMN.K*(1-SMI.K))+($TNMN.K*SMI.K*FSAI)    NEEDED MEN           MPD03190
A   $DNMN.K=MIN(NMEN.K,ANMN.K)            DOMINANT NEEDED MEN               MPD03200
A     PFMP.K=FMLL.K+(SRFM.K)(DRIM)              PROJ FUNDED MAN LEV         MPD03210
A      $DMEN.K=MIN($DNMN.K,$SMEN.K)                  DES MEN                MPD03220
A   $TNMI.K=$TNMN.K-(ERP.K/STR.K)         TR NEEDED MN DUE TO INEFFCY       MPD03230
A   $NMNI.K=MAX($TNMI.K,0)                NEEDED MN DUE TO INNEFFCY         MPD03240
A   $ANMI.K=SMOOTH($NMNI.K,DRCI)          ALLOW NEEDED MN DUE TO INEFFCY    MPD03250
A   $TANM.K=$ANMI.K+(ERP.K/STR.K)         TR ALLOW NEEDED MEN               MPD03260
A     RMEN.K=(PAH.K)($DMEN.K)+($SMEN.K)+(-PAH.K)($SMEN.K)                   MPD03270
A   ANMN.K=($TANM.K*(1-SMI.K))+($TANM.K*SMI.K*FSAI)    ALLOW NEEDED MEN     MPD03280
N   AMCR=((FSAI*MEOH)+(PJSC*SCOH))/(FSAI+PJSC)     AVG MNPWR CONV RATE      MPD03290
A      DIMP.K=RMEN.K-TMOP.K+CFRL.K               DES INER IN MEN            MPD03300
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A       $TIDE.K=MAX(-XMOP.K,$SDIM.K)                    TRIAL INCR DES
A       XMOP.K=TMOP.K-CFRL.K
A    IDIM.K=MIN($TIDE.K,0)                 INCR DES IN MEN
A    DMIP.K=MAX($SDIM.K,0)                 DES MEN INCR
A    $SDIM.K=SMOOTH(DIMP.K,DPMR)             SMTHD DES INCR IN MEN
N    RMEN=5*TMOP
MEND
C    DPMR=1                                DLY PROCESS MNPWR RQSTS
C    DSIM=6                                     DLY SMTHG INT MEN
C    DRCI=12                               DLY RSTNCE TO COMP FR INEFCY
NOTE                          CUSTOMER FUNDING
MACRO FBNR(ECCP,MRDA,RERP,PREP,ACVP,ROS,DRCF,MBPU,CECC,WTFP,RBF,ACCC,BEM
X    F,TSCR)
A       $FDC.K=(ECCP.K)(WTFP.K)                      FUT FUND DES CUST PROJ
L    ACCC.K=ACCC.J+(DT/DACC)*(CECC.J-ACCC.J)         ACC COST CUST
N    ACCC=PREP.K*MEOH*3.0
A       CECC.K=(ECCP.K)($IMC.K)                      CUST EST COST COMP
A         $IMC.K=TABHL(TIMC,$RPC.K,0,0.08,0.01)         INEXP MULT CUST
A         $RPC.K=RERP.K/PREP.K                            REP PERC COMP
A       WTFP.K=(1.0)($IWTF.K)+(-BEMF.K)($IWTF.K)+(BEMF.K)($WFPU.K)
L       MBPU.K=MBPU.J+(DT)($RBG.JK+0)                MEAS BIAS PROJ UNDERWAY
N         MBPU=0
R    $RBG.KL=TABHL(TABRB,$RPC.K,0,1,.2)     RATE BIAS GRWTH
A         BEMF.K=TABHL(TBEMF,MBPU.K,0,8,2)             BIAS EFF MUTL FULL FUND
A         $IWTF.K=TABLE(TIWTF,$SPIC.K,0,1,0.05)          INT WILL FUND
A         $WFPU.K=TABLE(TWFPU,$SPIC.K,0,1,0.05)          WILL FUND PROJ UNDERWA
A         $SPIC.K=MIN($TSPI.K,1.0)                       SUIT PROJ INV, CUST
A         $TSPI.K=$VCR.K/ROIC                            TRIAL $SPIC
A         $VCR.K=ACVP.K/$CCC.K                         VAL COST RATIO
A         $CCC.K=MAX(ACCC.K,1)
A       DRCF.K=(1/$DIBF.K)($FDC.K-FBNR.K)            DES RATE CHG FUND
A    $DIBF.K=FDBF+VDBF*$ESOD.K-$SPIC.K*VDBP*$ESOD.K  DEL BUDG FUNDS
A       $ESOD.K=CLIP(1.0,-0.3,TSCR.K,0)               EFF SUIT DEL
A         TSCR.K=$FDC.K-FBNR.K                        TEST SIGN CHANGE RATIO
R         RBF.KL=MAX(DRCF.K,-MRDA.K)                 RATE BUDG FUNDS
N    RBF=0
L       FBNR.K=FBNR.J+(DT)(RBF.JK-ROS.JK)         FUND BUDG NOT REL
N         FBNR=27E6
MEND
N    TSCR2=0
N    TSCR3=0
N    TSCR4=0
NOTE      CUSTOMER SPENDING AND ALLOCATION
MACRO MARC(SRP,CMAR,FBNR,DRCF,STR,ROS,CSCP,MRDA,FRU,ROB,ACCC)
A         $TROS.K=$APC.K/DPAP                             TRIAL RATE SPEND
R         ROS.KL=MIN($RARP.K,$TROS.K)                   RATE SPEND
A         $RARP.K=FBNR.K/DT
L       CSCP.K=CSCP.J+(DT)(ROS.JK+0)              CUST SUNK COSTS
N         CSCP=0
L       $APC.K=$APC.J+(DT)(ROB.JK-ROS.JK)           ACC PAY, CUST
N         $APC=0
R         ROB.KL=MIN(MARC.K,SRP.K)                  RATE BILL
N         ROB=0
A       $TARC.K=($SMAR.K)($CNO.K)            TR MAX ALLOW RATE, CUST
A    MARC.K=MAX($TARC.K,0)                            MAX ALLOW RATE, CUST
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FILE: MPDM024   DYNAMO   P1                MASSACHUSETTS INSTITUTE OF TECHNOLOGY
A    $CNO.K=CLIP(1,0,$SSCN.K,0)              CANC NOT
A     MRDA.K=FRU.K/DT                             MAX RATE DECR ALLOC
A     FRU.K=FBNR.K-$APC.K                         FUNDS REM UNSPENT
A  $TMAR.K=(FRU.K/BPHC)*CMAR.K   TRIAL,MAX ALLOW RATE
A  $SMAR.K=SMOOTH($TMAR.K,DAFL)          SMTHD MAX ALLOC RATE
N  $TMAR=FBNR
A  $SCN.K=DRCF.K+MRDA.K                  SUSCEPT TO CANCEL
A  $SSCN.K=SMOOTH($SCN.K,DICN)            SMTHD SUSCEPT TO CANCEL
N  $SCN=ACCC
MEND
N  FRU2=0
N  FRU3=0
N  FRU4=0
C  DAFL=3                                DLY ASSG FUNDG LIMITS
C  DICN=6                                DLY ISSUNG CANCEL NOTICE
C  BPHC=12                               BUDGET PLNNG HORIZ, CUST
NOTE      CUSTOMER SCHEDULE
MACRO SCOP(FCD,MBPU,STR,ROSA)
A      $TTR.K=SCOP.K-TIME.K                        SCH TIME REM
A      STR.K=MAX($TTR.K,DT)
A     ROSA.JK=(1/DICS)(FCD.K-SCOP.K)     RATE SCHED ADJUST
L     SCOP.K=SCOP.J+(DT)(ROSA.JK)            SCH COMP PROJ
N      SCOP=60
MEND
NOTE   PERCEIVED REQD EFFORT ON PROJ
MACRO PREP(PCC,RTCC,FERC,FRER,AMCR)
L  PREP.K=PREP.J+DT*$RCEC.JK                PRCVD EFFORT RMNG
N  PREP=$IEC
N  $IEC=$RREP*FRER                            INIT EST OF EFFORT REQD
N  $RREP=RTCC/AMCR     REAL REQD EFFORT
A  FERC.K=TABHL(TFRC,PCC.K,0,1,.1)      FRACT ERROR RECOGZD
A  $EEC.K=$RREP-PREP.K                      ERROR IN EST TO COMP
A  $REEC.K=$EEC.K*FERC.K                 RECOGND ERROR EST COMPL
R  $RCEC.KL=$REEC.K/DCPE                 RATE CORR EST TO COMP
MEND
C  RTCC1=2400E6    REAL TOT COST TO COMPL
C  FRER1=.16                                  FRACT REAL EFF RECOGNZD
T  TFRC=0/.42/.52/.53/.54/.58/.67/.83/.92/.97/1.0
C  DCPE=12                                     DLY CHGG PRCVD EFFORT REQD
NOTE     FACILITIES
MACRO AFCE(PREP,TMOP,FSAI,SRF,FPMF,FOIP,FOP,APMR,MARC,FSAF,IRFS,SRP)
A  $PFR.K=$ECER.K+$EFSR.K                     PRCVD FACIL REQTS
A  $ECER.K=PREP.K*CERR*FSAI                        EST CAP EQUIP REQTS
A  $EFSR.K=APMR.K*FSRR                       EST FLR SPC REQTS
A  $TAFR.K=$PFR.K-FOP.K-AFCE.K-FOIP.K     TRIAL ADDTL FAC REQT
A  $AAFR.K=MAX($TAFR.K,0)                     ALLOC ADDTL FAC REQT
R  $TRFS.KL=$AAFR.K/DFOD                      TR INTD RATE FAC SPNDG
R  $RFCE.KL=DELAY3(IRFS.JK,DPFO)           RATE ORDG FAC
L  $TOIP.K=$TOIP.J+DT*(IRFS.JK-$RFCE.JK)    TR FAC ORD IN PROC
A  FOIP.K=MAX($TOIP.K,0)                             FAC ORD IN PROC
A  $MASF.K=MARC.K*FSAF                   MAX ALLOW SPDG RATE
R  IRFS.JK=MIN($TRFS.JK,$RRFS.K)     INTD RATE FAC SPDG
N  IRFS=.5E6
N  $TOIP=DPFO*$RFA
N  $RFA=.5E6
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FILE: MPDM024  DYNAMO   P1                  MASSACHUSETTS INSTITUTE OF TECHNOLOGY
R  $RFA.KL=DELAY3($RFCE.JK,DFA)                RATE FAC AVAIL                MPD04410
L  $TOP.K=$TOP.J+DT*($RFCE.JK-$RFA.JK)         TR FAC ORDS PLCD              MPD04420
A  FOP.K=MAX($TOP.K,0)                              FAC ORDS PLCD            MPD04430
N  $TOP=DFA*$RFA                                                             MPD04440
L  AFCE.K=AFCE.J+DT*$RFA.JK                  AVAIL FACS                      MPD04450
N  AFCE=15.7E6                                      INIT AVAIL FACS          MPD04460
A  SRF.KL=(FOIP.K+FOP.")/DPFB              SPDG RATE FACS                    MPD04470
A  FPMF.K=TABHL(TFMF,$FAR.K,.2,1.0,.2)         FAC PROD MULT FACTOR          MPD04480
A  $DSRF.K=SRF.K*FSAF                      DES RATE FAC SPDG                 MPD04490
A  $RRFS.K=MIN($DSRF.K,$MASF.K)            REQSTD RATE FAC SPDG              MPD04500
A  $FAR.K=AFCE.K/$PFR.K           FAC AVAIL RATIO                            MPD04510
MEND                                                                         MPD04520
C  FSAF1=0.05                        FRACT SPDG ALLOWD FACIL                 MPD04530
C  DPFB=6                                      DLY PAYING FAC BILLS          MPD04540
C  CERR=110                                 CAP EQUIP REQT RATIO             MPD04550
C  DFOD=12                                 DSRD FAC ORD DLY                  MPD04560
C  DPFO=3                                  DLY PLCG FAC ORDS                 MPD04570
T  TFMF=.6/.75/.9/1.0/1.05                 TAB,FAC PROD MULT FACTOR          MPD04580
C  FSRR=1800                               FLR SPACE REQTS RATIO             MPD04590
C  DFA=10                                  DLY FACIL AVAIL                   MPD04600
NOTE   OVERTIME                                                              MPD04610
MACRO OTUP(URFS,DMIP,TMCP,EMOP,OTPM)                                         MPD04620
A  OTUP.K=MIN($SOTR.K,MAOT)                    OT USED ON PROJ               MPD04630
A  $TOTR.K=URFS.K*((DMIP.K/TMOP.K)+1)      TR INDX OT REQD                   MPD04640
A  $IOTR.K=MAX($TOTR.K,MPOL)               INDX OT REQD                      MPD04650
A  OTPM.K=TABHL(TOPM,OTUP.K,1.05,1.25,.05)  OT PROD MULT                      MPD04660
A  EMOP.K=OTUP.K*TMOP.K                      EQUIV MEN ON PROJ               MPD04670
A  $SOTR.K=SMOOTH($IOTR.K,DUOT)            SMTHD OT REQT                     MPD04680
N  $TOTR=MPOL                                                                MPD04690
MEND                                                                         MPD04700
T  TOPM=1/1/.99/.95/.88                      TABL, OT PROD MULT              MPD04710
C  MAOT=1.25             MAX ALLOW OT                                        MPD04720
C  MPOL=1.05                               MIN PRACTCL OT LVL                MPD04730
C  OTPR=1.5           OT PREM RATIO                                          MPD04740
C  DUOT=1                                  DLY USG OT                        MPD04750
NOTE   SUSCEPTIBILITY TO BUDGET CUTS                                         MPD04760
MACRO CMAR(CECC,WTFP,FRU,ROSA,SBC)                                           MPD04770
A  SBC.K=.333*(1-WTFP.K)+.333*ROSA.JK+.333*$IAAF.K  SUSCPT TO BUDG CUT  MPD04780
A  $FAI.K=(CECC.K/FRU.K)-1                      FUND AVAIL INDEX             MPD04790
A  $IAAF.K=MAX($FAI.K,0)                        INDEX FUND ADQCY             MPD04800
A  $TPBC.K=.5-.5*SIN(6.283*TIME.K/PPP)          TRIAL PRES BUD CUT           MPD04810
A  $TTBC.K=NORMRN(.5,.2)                        ATL TRIAL PRES BUD CUT       MPD04820
A  $PFBC.K=LIMC*SWITCH($TPBC.K,$TTBC.K,SELC)         PRES FOR BUD CUT        MPD04830
A  CMAR.K=TABHL(TCMR,$IBCD.K,0,1,.2)         CUT MAX ALLOW RATE              MPD04840
A  $IBCD.K=$SSBC.K*$PFBC.K                     INDEX BUD CUT DES             MPD04850
A  $SSBC.K=SMOOTH(SBC.K,DRSB)              SMTHD SUSCEPT BUD CUT             MPD04860
N  SBC=0                                                                     MPD04870
MEND                                                                         MPD04880
C  DRSB=3                                  DLY RECGNZG SUSCEPT BUD CUT       MPD04890
C  LIMC=0                                  LIM CONSTANT                      MPD04900
C  SELC=0                                  SEL CONSTANT                      MPD04910
C  PPP=12                                  PER POL PRESS                     MPD04920
T  TCMR=1/1/1/1/.9/.8                      TAB. CUT IN MAX RATE              MPD04930
NOTE   SUBCONTRACTORS                                                        MPD04940
MACRO SEIM(PREP,EFIM,TMOP,IMAS,SFBR,SMAP,SSBP,RASC,STR,ISDP,PJSC,SSCP,MAMPD04950
```

FILE: MPDM024 DYNAMO P1 MASSACHUSETTS INSTITUTE OF TECHNOLOGY

```
X   RC,SRMN,ERP,TEAM,SMI)                                                    MPD04960
A   $SCRP.K=PREP.K*PJSC*SCOH                  SC REQD ON PROJ                MPD04970
L   $SCIP.K=$SCIP.J+DT*($RPSC.JK-$SPSC.JK)    SC IN PROC                     MPD04980
R   RASC.KL=(1/DASC)(($SCRP.K*PMSVB*$RMAS.K)-IMAS.K)   RT ASSGN MEN SC       MPD04990
R   $TRPSC.KL=(1/DSPA)*((IMAS.K/PMSVR)-$SCIP.K-SFBR.K-SSCP.K)                MPD05000
NOTE  TR RATE PLCG SC                                                        MPD05010
A   $RPSC.JK=MAX($TRPSC.KL,0)              RATE PLCG SC                      MPD05020
N   $SCIP=0                                                                  MPD05030
R   $SPSC.KL=DELAY3($RPSC.JK,DSPC)            SC LVG PROC CYC                MPD05040
L   SFBR.K=SFBR.J+DT*($SPSC.JK-SSRP.JK)    SC FUNDS BUDGTD, NOT RELSD        MPD05050
N   SFBR=0                                                                   MPD05060
A   $ATMP.K=SMOOTH(TMOP.K,DSTM)               SM AVG TOT MEN                 MPD05070
A   $TMRCM.K=((TMOP.K-$ATMP.K)*SAHM)/(TMOP.K*DSTM)    TR MAX CHG MEN         MPD05080
A   $MRCMP.K=MAX($TMRCM.K,MSHL)                   MAX RT CHG MEN             MPD05090
A   $MRASM.K=$MRCMP.K*$SCAM.K              MAX RT INCRSG MEN                 MPD05100
A   $SCAM.K=SFBR.K/(SCOH*$BPHS.K)                   SC AUTH MNPWR LVL        MPD05110
A   $TRASM.K=(1/DASM)(SRMN.K-SMAP.K)         TR RT ASSG MEN                  MPD05120
R   $RASM.KL=MIN($TRASM.K,$MRASM.K)            RT ASSG MEN                   MPD05130
L   $TSMAP.K=$TSMAP.J+DT*$RASM.JK                TR SC MEN ASSD PROJ         MPD05140
N   $TSMAP=0                                                                 MPD05150
A   SMAP.K=MAX($TSMAP.K,0)                 SC MEN ASSD PROJ                  MPD05160
A   $MER.K=EFIM.K/TMOP.K                      MNPWR EFF RATIO                MPD05170
A   $SMER.K=SMOOTH($MER.K,STME)                SM MNPWR EFF RATIO            MPD05180
A   SEIM.K=$SMER.K*SMAP.K                     SC EFF INTEG MEN               MPD05190
R   SSRP.KL=SCOH*SMAP.K                       SC SPDG RATE                   MPD05200
L   $TMAS.K=$TMAS.J+DT*RASC.JK       TR INTEG MEN ASSD TO SC                 MPD05210
A   IMAS.K=MAX($TMAS.K,0)                  INTEG MEN ASSD TO SC              MPD05220
A   $SMML.K=(MARC.K*PJSC)/SCOH             SC MAX MNPWR LIMIT                MPD05230
A   $SSML.K=SMOOTH($SMML.K,DSFA)           SMTHD SC MAX MNPWR LIMIT          MPD05240
A   $SDML.K=MIN($SCAM.K,$SSML.K)           SC DSRD MNPWR LVL                 MPD05250
A   $BPHS.K=MIN(STR.K,ISDP)                BUDGET PLNG HORIZ,SC              MPD05260
L   SSCP.K=SSCP.J+DT*SSRP.JK                     SC SPENT COSTS              MPD05270
N   SSCP=0                                                                   MPD05280
A   $PSCC.K=SSCP.K/$SCRP.K                 SC COMPLT                         MPD05290
A   $RMAS.K=TABHL(TRMS,$PSCC.K,0,1,.2)     REM MEN ASSGD SC                  MPD05300
A   $SERP.K=ERP.K*PJSC                     SC REQD EFFORT                    MPD05310
A   $SNMN.K=$SERP.K/(STR.K*TEAM.K)         SC NEEDED MEN                     MPD05320
A   SRMN.K=MIN($SNMN.K,$SDML.K)            SC REQSTD MEN                     MPD05330
N   $TMAS=0                                                                  MPD05340
A   $FSMP.K=SMAP.K/(TMOP.K+SMAP.K)         FRACT SC MANNING                  MPD05350
A   $TSMI.K=$FSMP.K/PJSC                   TP SC MANNG INDEX                 MPD05360
A   SMI.K=MIN($TSMI.K,1)                   SC MANNG INDEX                    MPD05370
MEND                                                                         MPD05380
C   PJSC1=0.5               JOB SC                                           MPD05390
C   DSFA=3                                 DLY SMTHG FUND AUTH               MPD05400
C   ISDP1=84                               INIT SCH DURATION OF PROJ         MPD05410
T   TRMS=1/1/1/1/.8/0                      TAB, REMOV MEN SC                 MPD05420
C   SCOH=2200            SC ENG OH RATE                                      MPD05430
C   PMSVR=.04E-6         MEN/SC VAL RATIO                                    MPD05440
C   DSPC=2               DLY PLCG SC                                         MPD05450
C   DSTM=3               DLY SMTHG TOT MEN                                   MPD05460
C   DASM=1               DLY ASSG SC MEN                                     MPD05470
C   MSHL=100                                 MIN SC HIRING RATE LIMIT        MPD05480
C   SAHM=2                                 SC AGGLOM HIRING MULT             MPD05490
C   STME=6                                 SM TIME MNPWR EFF                 MPD05500
```

```
C  DASC=1
C  DSPA=3            DLY STG PROC
NOTE        MACRO FUNCTIONAL EQUATIONS
A  DMIPT.K=DMIPT(AMIP1.K,AMIP2,AMIP3,AMIP4,NHP.K,TMOC.K,IMPT.K,PAH.K,
X  PCM1.K,PCM2.K,PCM3.K,PCM4.K,IPBA.K,NHBA.K,NRNH.K,RLNH.K,NRIP.K,
X  RLIP.K)
A  IMPT.K=IMP(DFIM1.K,DFIM2,DFIM3,DFIM4,DITM1.K,DITM2,DITM3,
X  DITM4,PCM1.K,PCM2.K,PCM3.K,PCM4.K,IPBA.K,NRIP.K,RLIP.K,RLCI.JK,RIMP1
X  .JK,RIMP2.JK,RIMP3.JK,RIMP4.JK)
A  TMENT.K=TMEN(NRNH.K,RLNH.K,IMPT.K,PCM1.K,PCM2.K,PCM3.K,PCM4.K,NHBA.K
X  ,FRU1.K,FRU2,FRU3,FRU4,TSCR1.K,TSCR2,TSCR3,TSCR4,TMOP1.K,
X  TMOP2,TMOP3,TMOP4,DEAM1.K,DEAM2,DEAM3,DEAM4,FIM1.K,FIM2
X  ,FIM3,FIM4,NHP.K,PAH.K,MIHD.K,HR.JK,TMOC.K,RLCE.JK,BKLG.K,COP.K,
X  MLO.K,TMAC.K,FIMT.K,REMP1.JK,REMP2.JK,REMP3.JK,REMP4.JK,NRIP.K,FSAI1,
X  SRP1.K,SRP2,SRP3,SRP4,TPSR.K)
A  AMIP1.K=AMIP(EMOP1.K,TMOP1.K,FSAI1,IMPT.K,TMOC.K,SRFM1.K,APMR1.K,DMIP
X  1.K,FMRA1.K,MISA1.K,ERP1.K,PFMP1.K,STR1.K)
A  IFRL.K=IFRL(ROB1.JK,ROB2,ROB3,ROB4,RCF1.JK,IRLA.K,RIFRL.JK)
A  SIMP1.K=SIMP(RCF1.JK,CDI.K,RERP1.K,MARC1.K,IRLA.K,CFRL1.K,DI1.K)
A  ACVP1.K=ACVP(BEMF1.K,STR1.K,IVPT1,PCC1.K,RLVC1.K)
A  CRP1.K=CRP(AFCE1.K,FPMF1.K,EMOP1.K,EFIM1.K,PFIM1.K,PREP1.K,PRP1.K,
X  RERP1.K,TEAM1.K,PCC1.K,PPCC1.K,MMET1.K,RPR1.JK,SEIM1.K,PERP1.JK,SMAP1
X  .K)
A  TMOP1.K=TMOP(REMP1.JK,RWEA1.JK,RIMP1.JK,IDIM1.K,OTUP1.K,PCC1.K,
X  RFSC1.K,OTPM1.K,SIMP1.K,FIM1.K,RWIT1.JK,EAMP1.K,RRIM1.JK,EFIM1.K,
X  PFIM1.K,RASC1.JK,IMAS1.K,DFIM1.K,DITM1.K,DEAM1.K)
A  RFSC1.K=RFSC(EMOP1.K,ERP1.K,TEAM1.K,SCOP1.K,FCD1.K,SMAP1.K,STR1.K,URF
X  S1.K,APMR1.K,TMOP1.K,OTUP1.K)
A  SRP1.K=SRP(RERP1.K,PREP1.K,TEAM1.K,MARC1.K,OTUP1.K,SRF1.K,SSRP1.JK,
X  TMOP1.K,FSCP1.K,ERP1.K,ECCP1.K,RCF1.JK,AMCR1)
A  DMIP1.K=DMIP(MARC1.K,STR1.K,TEAM1.K,ERP1.K,PAH.K,CFRL1.K,XMOP1.K,
X  FMLL1.K,MMLL1.K,RMEN1.K,IDIM1.K,DIMP1.K,NMEN1.K,PFMP1.K,TMOP1.K,SRF1.
X  K,SSRP1.JK,FBNR1.K,PJSC1,FSAF1,FSAI1,AMCR1,SRFM1.K,ANMN1.K,SMI1.K)
A  FBNR1.K=FBNR(ECCP1.K,MRDA1.K,RERP1.K,PREP1.K,ACVP1.K,ROS1.JK,DRCF1.K
X  ,MBPU1.K,CECC1.K,WTFP1.K,RBF1.JK,ACCC1.K,BEMF1.K,TSCR1.K)
A  MARC1.K=MARC(SRP1.K,CMAR1.K,FBNR1.K,DRCF1.K,STR1.K,ROS1.JK,CSCP1.K,
X  MRDA1.K,FRU1.K,ROB1.JK,ACCC1.K)
A  SCOP1.K=SCOP(FCD1.K,MBPU1.K,STR1.K,ROSA1.K)
A  PREP1.K=PREP(PCC1.K,RTCC1,FERC1.K,FRER1,AMCR1)
A  AFCE1.K=AFCE(PREP1.K,TMOP1.K,FSAI1,SRF1.K,FPMF1.K,FOIP1.K,FOP1.K,
X  APMR1.K,MARC1.K,FSAF1,IRFS1.JK,SRP1.K)
A  OTUP1.K=OTUP(URFS1.K,DMIP1.K,TMOP1.K,EMOP1.K,OTPM1.K)
A  CMAR1.K=CMAR(CECC1.K,WTFP1.K,FRU1.K,ROSA1.K,SBC1.K)
A  SEIM1.K=SEIM(PREP1.K,EFIM1.K,TMOP1.K,IMAS1.K,SFBR1.K,SMAP1.K,SSRP1.JK
X  ,RASC1.JK,STR1.K,ISDP1,PJSC1,SSCP1.K,MARC1.K,SRMN1.K,ERP1.K,TEAM1.K,
X  SMI1.K)
NOTE                   CONSTANTS
C      SR=40
C  FRD=0.2
C  DAVC=4                             DLY ACCPTG VALUE
C     TFER*=0/0/0/0/0/C.3/C.5/0.75/0.9/1.0/1.0
C  DRRP=1                             DLY RPTG REAL PROG
C     DRIM=1.0
C  DIIM=2                             DLY INTETG INT MEN
C  DEIM=4                             DLY CONVTG EXT TO INT MEN
```

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FILE: MPDM024  DYNAMO   P1                    MASSACHUSETTS INSTITUTE OF TECHNOLOGY
C      PRTR=0.70/PRIT=0.60/PRFI=1.0/PREA=0.40                             MPD06060
C      PRUM=0.2                                                           MPD06070
C      NMPT=8                               INV TRAIN REQ / NEW MANMPD06080
C      TMDKH*=0.6/0.85/1.2/1.5/1.8/2.0                                    MPD06090
C      TSPM*=0.25/0.27/C.38/0.65/1.C6/1.25/1.06/0.75/0.5                  MPC06100
C      TEPM*=2.0/2.0/2.0/2.0/1.75/1.25/1.1/1.0                            MPD06110
C   MEOH=1550                       MEAN LABOR RATE                       MPD06120
C      DSFMR=1                                                            MPD06130
C      DACC=3                                                             MPD06140
C      TIMC*=3.0/2.0/1.6/1.3/1.25/1.25/1.25/1.25/1.25                     MPD06150
T   TABRB=.3/.6/.85/1.0/1.0/1.0     TAB, RATE BIAS GRWTH                  MPD06160
C      TBEMF*=0/C.12/C.5/0.92/1.00                                        MPD06170
C      TIWTF*=0/0/0/0/0/0/0/.03/.04/.04/.05/.05/.05/.05/.05/.07/.13/.25/.MPD06180
X1     43/.85/1                                                           MPD06190
T   TWFPU=0/0/0/0/0/0/.2/.5/.8/.89/.94/.96/.97/.98/.99/1/1/1/1/1/1        MPD06200
C      ROIC=1.5                                                           MPC06210
C      FDBF=6/VDBF=12                                                     MPD06220
C      DPAP=2                                                             MPD06230
C   DICS=6                          DLY IN CHG SCHD                       MPD06240
C      TDICP*=3/3/6/9/12/15                                               MPD06250
C   PAIP=0.06                       ALLD IN POOL                          MPD06260
T   IVPT1=2.06E9/2.45E9/2.45E9/2.10E9/1.66E9/1.40E9/1.10E9/.80E9/.59E9    MPD06270
T   TDRV=36/24/18/12/9/6            DLY RECOGNZG VALUE                    MPD06280
C   DEPR=2                          DLY IN PERSONL RCSTS                  MPD06290
NOTE                   ADDITTIONAL EQUATIONS                              MPD06300
PRINT  DMIPT,NHP,TMOC,PAH,PCM1,IPBA,NHBA,NRNH,RLNH,NRIP,RLIP,IMPT,DFIM1,MPD06310
X   DITM1,RLCI,RIMP1,TMENT,FRU1,TSCR1,DEAM1,FIM1,MIHD,HR,RLCE,            MPD06320
X   BKLG,COP,MLO,TMAC,FIMT,REMP1,IFRL,ROB1,RCF1,IRLA,RIFRL,SIMP1,CDI,RERPMPD06330
X   1,CFRL1,DI1,ACVP1,BEMF1,STR1,PCC1,RLVC1,CRP1,FPMF1,                   MPD06340
X   EMOP1,EFIM1,PFIM1,PRP1,TEAM1,PPCC1,MMET1,RPR1,PERP1,TMOP1,RWEA1,IDIM1MPD06350
X   ,OTPM1,RWIT1,EAMP1,RRIM1,RASC1,IMAS1,RFSC1,ERP1,ECCP1,DMIP1,          MPD06360
X   XMOP1,FMLL1,MMLL1,RMEN1,DIMP1,NMEN1,PFMP1,SRF1,SSRP1,FBNR1,MRDA1,ROS1MPD06370
X   ,DRCF1,MBPU1,CECC1,WTFP1,RBF1,ACCC1,BEMF1,MARC1,SCOP1,FCD1,SRP1,      MPD06380
X   FSCP1,CSCP1,ROSA1,PREP1,AMCR1,FERC1,AFCE1,FOIP1,FOP1,IRFS1,           MPD06390
X   OTUP1,CMAR1,SBC1,SEIM1,SFBR1,SMAP1,SSCP1,SRMN1,ANMN1,TPSR,URFS1,      MPD06400
X   FMRA1,MISA1,APMR1,AMIP1,SMI1                                          MPD06410
PLOT  PCC1=%/TMOP1=T,SMAP1=S/CSCP1=C,SSCP1=E/FSCP1=F,AFCE1=Q/WTFP1=W/SCOMPD06420
X   P1=D/PREP1=R                                                          MPD06430
PLOT  NMEN1=N,PFMP1=F,APMR1=X,TMOP1=T,RMEN1=R,ANMN1=A,IDIM1=I,            MPD06440
X   /SMAP1=S,SRMN1=Q/AMIP1=Y                                              MPC06450
PLOT  NHP=N,IMPT=P/TMAC=M,MIHD=D/HR=H,RIMP1=I,REMP1=E,RLCE=L,RLCI=F       MPD06460
PLOT  MARC1=M,SRF1=F,SRP1=$,SSRP1=S/FBNR1=B,SFBR1=A/ACVP1=V,ACCC1=C/WTFPMPD06470
X   1=W                                                                   MPD06480
PLOT  SCOP1=D,FCD1=F/STR1=S/PCC1=%,PPCC1=P/RFSC1=R,URFS1=U/OTUP1=O        MPD06490
PLOT  CRP1=C,PRP1=P,REBP1=R/ERP1=E,PREP1=S/TEAM1=T                        MPC06500
SPEC  DT=0.25/LENGTH=120/PRTPER=6/PLTPER=3                                MPD06510
RUN  081 D                                                                MPC06520
```

# APPENDIX D

## DETAILED DESCRIPTION OF TWO-PROJECT MODEL

## I. DESCRIPTION OF TWO PROJECT MODEL

Relatively few changes were required in the single project model description in Appendices B and C in order to expand the model to two project operation. The reader is referred to the equation print-out for the two project model, Appendix E. Reference is made to equations by line number, giving the last four digits of the identifying line number for each equation. Only significant functional differences between the single project model and the two project model will be discussed herein.

### A. REALLOCATION OF FACILITIES

The single project model did not have the capabilities for releasing unneeded facilities at the completion of the project and reassigning time to other projects. This capability is required for the two project model.

When the calculated value of additional facility requirements becomes negative, this means the project has more facilities on hand or on order than it actually needs. A certain percentage of these are general purpose facilities which could be relinquished to other projects, while the remainder are special purpose facilities.

Equations 4320, 4500

TAFR - Trial additional facilities requirements - dollars
TFR - Perceived facility requirements - dollars
FOP - Facilities orders processed - dollars
FOIP - Facility orders in progress - dollars
AFCE - Available facility and capital equipment - dollars
EGF - Excess general facilities - dollars
FGF - Fraction of general facilities - dimensionless

Excess general facilities are released by the project after some delay in determining that they are not needed. Facilities are reassigned to other projects, based upon ratio of the project's total approved manpower increment, divided by the sum of all approved manpower increments for all projects in the corporation. The acquiring projects' perceived rate of facility requirements is taken as the project's initial allocation of additional facility requirements again divided by the delay in reassigning facilities. A feedback equation is included which prevents the firm from assigning new facilities to a project which is simultaneously releasing general facilities. This represents some simplification of the situation which exists in practice, where facilities are not completely general purpose. Finally, the rate at which facilities are reassigned to new projects once released, is taken as the minimum of the firm's allocation, based upon approved manpower increments, or the request furnished by the project itself. The available facilities and capital equipment is then calculated as an integration, depending upon the rate of facility availability from the normal procurement process, plus the rate at which released facilities are reassigned to a project, minus the project's rate of releasing facilities.

Equations 4330, 4510 through 4580

AAFR - Allocated additional facilities requirements - dollars
RRF - Rate of releasing facilities - dollars/months
TFCE - Trial available facilities and capital equipment - dollars
AFCE - Available facilities and capital equipment - dollars

TAFP - Trial rate of assigning facilities to project - dollars/month
AMIP - Approved manpower increment to project - men/month
FARA - Facilities available for reassignment - dollars/month
DRF - Delay in reassigning facilities - months
DMIP - Total manpower increments to project - men
TPFR - Trial project facility requirements - dollars/month
FBRF - Feedback from release of facilities - dimensionless
RAFP - Rate of reassigning facilities to project - dollar/month

A central corporate staff group accounts for the total pool of facilities available to the firm. By integrating the facility releases from projects and reassignments to other projects, they maintain a continuous accounting of the facilities available for reassignment to projects within the firm.

Equations 4760 to 4780

TFRA - Trial facilities available for reassignment to projects - dollars

## B. RESTATEMENT OF INITITAL CONDITIONS

Since most of the initial conditions are different for each project, it becomes necessary to restate the initial conditions in the model to allow for insertion of separate values for each project. This requires entering the initial condition as a constant into the macro functional equation. This technique has been used in several places throughout the model; I will simply give one example, based upon the Facilities macro function which we have been discussing.

The separate project initial conditions can be included either as initial condition equations given outside the macro function, or constants. In either case, the initial condition must appear in the macro function, and also in the corresponding macro functional equation. Consider the following examples from the facilities macro.

The intended rate of facility spending (IRFS) is given initial conditions by means of separate initial condition equations outside the macro.

Equations 4270, 4280, 4390, 4600 and 4610

IRFS 1 - Intended rate of facilities spending for
Project 1 - dollars/month
IRFS 2 - Intended rate of facilities spending for
Project 2 - dollars/month

The amount of facilities and capital equipment which are initially available is specified by the alternate technique, using separate constants.

Equations 4270, 4280, 4520, 4540, 4620 and 4630

IFCE 1 - Initially available facilities and capital equipment for Project 1 - dollars
IFCE 2 - Initially available facilities and capital equipment for Project 2 - dollars

The above examples are typical of the treatment of initial conditions throughout the model. In addition, a change was made in the Perceived Required Effort on Project macro (PREP) in order to reflect more accurately the two step nature of aircraft program contracting, as distinct from spacecraft programs. This was accomplished by inserting separate table functions for TFRC into the PREP macro. The table function for Project 2 represents the abrupt increase in perception of the scope of the job which occurs when the follow-on Lot 2 contract is awarded.

Equations 4080, 4130, 4220 and 4230

TFRC 1 - Table, fraction of error recognized in required effort for Project 1 - dimensionless
TFRC 2 - Table, fraction of error recognized in required effort for Project 2 - dimensionless

## C. EXPANSION OF MACRO FUNCTIONAL EQUATIONS

The other major alteration to the model was simply the expansion of the macro functional equations to include the macro functions as operating variables for Project 2, in addition to Project 1. This section can be seen in the printout from lines 6200 through 6510.

## D. CHANGES REQUIRED FOR SEQUENTIAL PROJECT OPERATION

Certain changes were required to the model to achieve satisfactory sequential project operation. In sequential operations, Project 2 may start several years after the start of Project 1. In such cases, initial conditions cannot be used to trigger the start of Project 2. Project 2 is activated by the function Intrinsic Value of the Project (IVPT 2) and all other functions are activated through normal operations of the model. Specific functional changes required for sequential project operation are described herein.

Because the sequential project model is so similar to the model given in Appendix E, it has not been reproduced herein, but equation changes are shown. The initial condition inputs for the sequential Project 2 differ from the simultaneous Project 2 used previously.

## 1. Scheduling Startup Keyed to Percent Completion

To avoid the difficulties associated with different startup times for each project, the start of scheduling is keyed to percentage completion rather than to elapsed time. The threshold for startup of planning (DSUP) is expressed in percent completion terms rather than as a time interval.

Substitute for Equation 2680 in Appendix E:
A $XTRP.K=CLIP ($TTRP.K, STR.K, PCC.K, DSUP)

Substitute for Equations 2810 and 2820:
C DSUP1=.05
C DSUP2=.05

## 2. Perceived Required Effort Inhibited by Percent Completion

The existing equation for Perceived Required Effort on Project (PREP) allowed a small rate of correction of perceived required effort to take place even in the absence of any work or progress on the project. This results from the form of the Table function fraction of error recognized (TFRC, Equations 4230 and 4240). Since no improvement in perception of the scope of the job occurs unless work is being performed on the project, the PREP function was inhibited as shown in the Equation printout to eliminate the small rate of correction of perceived effort in the absence of significant progress on the project.

Substitute for Equation 4150 in Appendix E:

```
A $REEC.K=$EEC.K*FERC.K*$EFER.K
  Add the following new equation
A $EFER.K=CLIP (1,0, PCC.K, .02)
```

EFER - Early fraction of error recognized - Dimensionless

PCC - Percent completion - Dimensionless

### 3. Changes in Initial Conditions and Table Functions

With sequential operation of Project 2, many of the initial conditions for Project 2 should be zero, since the project is not active at T=0. However, zero values for these initial conditions cannot be used because of difficulties resulting from division by zero. The same problem was noted with the Table function Intrinsic Value of Project (IVTP, Equations 1810 through 1840). This difficulty was eliminated by using one instead of zero for all initial conditions and Table functions having negligible value. In almost all cases the value one is negligible, since subsequent values of the functions are in the millions.

# APPENDIX E

## EQUATION PRINTOUT -- TWO-PROJECT MODEL

```
FILE: MPDM204   DYNAMO   P1                           MASSACHUSETTS INSTITUTE OF TECHNOLOGY
*  TWO PROJECT DYNAMO
NOTE                   CENTRAL SECTOR                                                 MPD00010
NOTE                           NORMAL     OPERATING     SECTION                       MPD00020
NOTE     FIRM'S MANPOWER ALLOCATION                                                   MPD00030
MACRO DMIPT(AMIP1,AMIP2,AMIP3,AMIP4,NHP,TMOC,IMP,PAH,PCM1,PCM2,PCM3,PCM4MPD00040
X  ,IPBA,NHBA,NRNH,RLNH,NRIP,RLIP)                                                   MPD00050
A      DMIPT.K=AMIP1.K+AMIP2.K+AMIP3.K+AMIP4.K+0.1+0                                 MPD00060
A      PCM1.K=AMIP1.K/DMIPT.K                                                        MPD00070
A      PCM2.K=AMIP2.K/DMIPT.K                      ( MEN TO 1                        MPD00080
A      PCM3.K=AMIP3.K/DMIPT.K                      ( MEN TO 2                        MPD00090
A      PCM4.K=AMIP4.K/DMIPT.K                      ( MEN TO 3                        MPD00100
N   PCM3=0                                         ( MEN TO 4                        MPD00110
N   PCM4=0                                                                           MPD00120
N   AMIP3=0                                                                          MPD00130
N   AMIP4=0                                                                          MPD00140
A      $TRII.K=DMIPT.K-IMP.K                                                         MPD00150
A      IPBA.K=CLIP(IMP.K,DMIPT.K,$TRII.K,0)         TEST OF REG FOR INT              MPD00160
A      $RIRQ.K=CLIP($TRII.K,0,$TRII.K,0)            INT PER TO BE ALLOC              MPD00170
A      $TRNH.K=$RIRQ.K-NHP.K                          REM INER REQ                   MPD00180
A      NHBA.K=CLIP(NHP.K,$RIRQ.K,$TRNH.K,0)         TEST REQ NEW HIRES               MPD00190
A      $IMER.K=IMP.K-IPBA.K                         NEW HIRES BEING ALLOCMPD00200
A      $NHMR.K=NHP.K-NHBA.K                        INT MEN REM POOL                  MPD00210
A      $TMIP.K=$NHMR.K+$IMER.K                     NEW HIRES REM POOL                MPD00220
A      $NOMP.K=$TMIP.K+(-TMOC.K) (PAIP)              TOT MEN IN POOLS                MPD00230
A      $NBRP.K=CLIP($NOMP.K,0,$NOMP.K,0)            NO OVER MAX, POOL                MPD00240
A      $TFNH.K=$NBRP.K-$NHMR.K                       NO BEING REM FOR POOMPD00250
A      NRNH.K=CLIP($NHMR.K,$NBRP.K,$TFNH.K,0)        TEST FROM NEW HIRES             MPD00260
A      NRIP.K=CLIP($TFNH.K,0,$TFNH.K,0)              NO REM NEW HIRE                 MPD00270
N  NRIP=0                                          NO REM INT POOL                   MPD00280
A      RLIP.K=(1/$DTCP.K) ($IMER.K-NRIP.K)                                           MPD00290
A      RLNH.K=(1/$DICP.K) ($NHMR.K-NRNH.K)         RAT LEAV INT POOL                 MPD00300
A      $DICP.K=TABHL(TDICP,PAH.K,0,1,0.2)          RAT LEAV N H POOL                 MPD00310
MEND                                                                                 MPD00320
NOTE     FIRMS INTERNAL MANPOWER POOL                                                MPD00330
MACRO IMP(DFIM1,DFIM2,DFIM3,DFIM4,DITM1,DITM2,DITM3,DITM4,PCM1,PCM2,PCM3MPD00340
X  ,PCM4,IPBA,NRIP,RLIP,RLCI,RIMP1,RIMP2,RIMP3,RIMP4)                                MPD00350
R      RIMP1.KL=(IPBA.K) (PCM1.K)/DT                                                 MPD00360
R      RIMP2.KL=(IPBA.K) (PCM2.K)/DT               RAT INT MEN                       MPD00370
R      RIMP3.KL=(IPBA.K) (PCM3.K)/DT               RAT INT MEN                       MPD00380
R      RIMP4.KL=(IPBA.K) (PCM4.K)/DT               RAT INT MEN                       MPD00390
R      RLCI.KL=RLIP.K+NRIP.K                       RAT TNT MEN                       MPD00400
R      $RIFP.KL=(1/DT) (DITM1.K+DITM2.K+DITM3.K+DITM4.K+$RFFT.K+$RFST.K)             MPD00410
A      $RFFT.K=(1/DRIM) ((DT) (DFIM1.K)+(DT) (DFIM2.K))  RATE FR FIRST TWO           MPD00420
A      $RFST.K=(1/DRIM) ((DT) (DFIM3.K)+(DT) (DFIM4.K))  RATE FR SEC TWO             MPD00430
L      IMP.K=IMP.J+(DT) ($RIFP.JK-RLCI.JK-RIMP1.JK-RIMP2.JK-RIMP3.JK-RIMP4MPD00440
X  .JK)                                                                             MPD00450
N      IMP=1050                                                                      MPD00460
N  RIMP3=0                                                                           MPD00470
N  RIMP4=0                                                                           MPD00480
MEND                                                                                 MPD00490
NOTE     FIRM'S NEW HIRE POOL                                                        MPD00500
MACRO THEM(NRNH,RLNH,IMP,PCM1,PCM2,PCM3,PCM4,NHBA,FRU1,FRU2,FRU3,FRU4,TSMPD00510
X  CR1,TSCR2,TSCR3,TSCR4,TMOP1,TMOP2,TMOP3,TMOP4,DEAM1,DEAM2,DEAM3,DEAM4MPD00520
X  ,FIM1,FIM2,NRIP,SRP1,SRP2,AFSI,NHP,PAH,MIHD,HR,TMOC,RLCR,BKLG,COP,                MPD00530
X  REMP1,REMP2,REMP3,REMP4,TPSR,MLC,TMAC,FIMT)                                       MPD00540
                                                                                     MPD00550
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FILE: MPDM204   DYNAMO    P1                    MASSACHUSETTS INSTITUTE OF TECHNOLOGY
R      REMP1.KL=(NHBA.K)(PCM1.K)/DT
R      REMP2.KL=(NHBA.K)(PCM2.K)/DT                    RATE EXT MEN          MPD00560
R      REMP3.KL=(NHBA.K)(PCM3.K)/DT                    RATE EXT MEN          MPD00570
R      REMP4.KL=(NHBA.K)(PCM4.K)/DT                    RATE EXT MEN          MPD00580
R      RLCE.KL=NRNH.K+RLNH.K                           RATE EXT MEN          MPD00590
A      $FSI.K=$PSF.K/DSL                               RAT LEAV CO, EXT      MPD00600
A      $TPSF.K=BKLG.K/TPSR.K                           FIRMS SEC IND         MPD00610
A   $PSF.K=SMOOTH($TPSF.K,DSBK)                 TR PRES SEC FUND             MPD00620
A   TPSR.K=SRP1.K+SRP2.K+1.0                  PRESNT SEC FUNDG               MPD00630
A      BKLG.K=TSCR1.K+TSCR2.K+TSCR3.K+TSCR4.K+FRU1.K+FRU2.K+FRU3.K+FRU4.KMPD00640
A      $ZMEN.K=TMOC.K+MIHD.K+NHP.K+IMPT.K  TOT PROJ SPDG                     MPD00650
A      TMEN.K=MAX($ZMEN.K,1)                             TOT MEN             MPD00660
A      TMOC.K=TMOP1.K+TMOP2.K+TMOP3.K+TMOP4.K                                MPD00670
A      $LIM.K=-$ZMEN.K+(FIMT.K)(SR)                             TOT MEN AC   MPD00680
A   FIMT.K=$BR1.K*FIM1.K+$BR2.K*FIM2.K  TOT FULLY INTEG MEN                  MPD00690
A      $TBR1.K=(TSCR1.K+FRU1.K+0)/(BKLG.K+1+0)                               MPD00700
A      $BR1.K=MAX($TBR1.K,0)                                                 MPD00710
A      $TBR2.K=(TSCR2.K+FRU2.K+0)/(BKLG.K+1+0)                               MPD00720
A      $BR2.K=MAX($TBR2.K,0)                                                 MPD00730
R      $THR.KL=$HAA.K/DEPR    TR HIRING RATE                                 MPD00740
R   HR.KL=MIN($THR.KL,MAHR)                HIRING RATE                       MPD00750
N      HR=0                                                                  MPD00760
R      $NHA.KL=DELAY3(HR.JK,DONH)                        HIRING DELAY        MPD00770
L      MIHD.K=MIHD.J+(DT)(HR.JK-$NHA.JK)             MEN IN HIR DEL          MPD00780
N      MIHD=0                                                                MPD00790
R      $REFP.KL=(1/DT)(DEAM1.K+DEAM2.K+DEAM3.K+DEAM4.K+0+0)                  MPD00800
R   $CFR.KL=REMP1.KL+REMP2.KL      CON FORM RATE                             MPD00810
L   $TNHP.K=$TNHP.J+(DT)($REFP.JK+$NHA.JK-RLCE.JK-REMP3.JK-REMP4.JK-$CFR.MPD00830
X   JK)                                    TR NEW HIRE POOL
A   NHP.K=MAX($TNHP.K,0)                   NEW HIRE POOL                     MPD00840
R   $RCOP.KL=(NHP.K+IMPT.K)*MEOH            RATE OF POOL CHG                 MPD00850
L   COP.K=COP.J+DT*$RCOP.JK                CHARGES TO POOL                   MPD00860
L   MLO.K=MLO.J+DT*(RLCE.JK+RLCI.JK)       MEN LVG COMPANY                   MPD00870
N   MIO=0                                                                    MPD00880
N   COP=0                                                                    MPD00890
S   TMAC.K=TMEN.K-MIHD.K                                                     MPD00900
N      $TNHP=0                             TOT MEN AVAIL                     MPD00910
A      PAH.K=CLIP(1,$FSI.K,$FSI.K,1)                                         MPD00920
A   $HINC.K=($FSI.K-1)*TMEN.K*AFSI                 PRESS AGAINST HOARDINMPD00930
A   $THAA.K=MAX($QAAA.K,0)                HIRING INCR DES                    MPD00940
A   $RLOM.K=NRIP.K+NRNH.K                   TR HIRE AT ALL?                  MPD00950
A   $HFB.K=SWITCH(1,0,$RIOM.K)              RATE LAYING OFF MEN              MPD00960
A   $HAA.K=$THAA.K*$HFB.K                   HIRING FEEDBACK                  MPD00970
A   $QAAA.K=MIN($HINC.K,$LIM.K)             HIRE AT ALL?                     MPD00980
N   REMP3=0                                                                  MPD00990
N   REMP4=0                                                                  MPD01000
MEND                                                                         MPD01010
N   AFSI=(FSAI1+FSAI2)/2                                                     MPD01020
C   DSL=18                                 AVG FRACT SPDG AILWD INT          MPD01030
C   MAHR=700                               DES STABILITY LVL                 MPD01040
C   DCNH=6                                 MAX ATTAIN HIRING RATE            MPD01050
C   DSBK=6                                      DLY OBTNG NEW HIRES          MPD01060
NOTE          FIRMS CORPORATE MANPOWER CONTROL  DLY SMTHG BKLG               MPD01070
MACRO AMIP(EMOP,TMOP,FSAI,IMPT,TMOC,SRPM,APMR,DMIP,FMRA,MISA,ERP,PPMP,STMPD01090
X   R,TFMR)                                                                  MPD01080
                                                                             MPD01100
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A  $PFMN.K=((ERF.K*FSAI)-(EMOP.K*MPH))/STR.K  PROJ PUT MNPWR NDS
A  $NMIP.K=CLIP(DMIP.K,0,$PFMN.K,EMOP.K)     NEGOT MNPWR INCRMNT
A  FMRA.K=TABHL(TFMR,$ILMP.K,0,1.2,.2)  FRACT MNPWR RQST APPRVD
A  $ILMP.K=IMPT.K/(TMCC.K*PAIP)          INDX LVL MNPWR IN POOL
A  $TMSA.K=$NMIP.K*FMRA.K                 TR MNPWR INCR SUBMTD FOR APPRVL
A  MISA.K=SMOOTH($TMSA.K,DCMA)           MNPWR INCR SUBTD FOR APPRVL
R $RAMI.KL=(MISA.K-$DRMU.K)/DCMA         RATE APPRVG MNPWR INCR
A  $PRTM.K=DMIP.K+TMOP.K                 PROJ REQT TOT MEN
A  $DARM.K=APMR.K-$PRTM.K                DIFF APPRVD RWSD MEN
A  $DRMU.K=MAX($DARM.K,0)                DIFF REQ MEN UTILXD
L  $TAPR.K=$TAPR.J+DT*($RAMI.JK+$RRFM.JK)    TR APP MNPWR REQTS
A  APMR.K=MAX($TAPR.K,0)                 APPRVD PROJ MNPWR REQTS
A  $TRFM.K=MIN(SRFM.K,0)                 TR RATE REMVL FUNDD MNPWR
A  $RRFM.K=CLIP(0,$TRFM.K,PFMP.K,APMR.K)     RATE RMVL FUND MNPWR
A  AMIP.K=APMR.K-TMOP.K                  APPRVD MEN INTO PROJ
N  $TAPR=TMOP+IMPT
MEND
C  MPH=6                                 MNPWR PLNNG HORIZ
T  TFMR1=.6/.75/.85/.95/.98/1.0               TABL, FRACT MNPWR INCR APPVD
T  TFMR2=.6/.75/.85/.9/.95/.98/1.
C  DCMA=2                                DLY CORP MNPWR APPRVL
NOTE         R&D ALLOCATION
MACRO IFRL(ROB1,ROB2,ROB3,ROB4,IRLA,RIFRL)
A       $ROBT.K=ROB1.JK+ROB2.JK+ROB3.JK+ROB4.JK
L       $SROB.K=$SROB.J+(DT)(1/DSRB)($ROBT.J-$SROB.J)
N       $SROB=0
A       $NIFRL.K=(PCAO)($SROB.K)/MECH                  NEG INT FUND RGS LEV
R       RIFRL.KL=(1/DAIF)($NIFRL.K-IFRL.K)           RAT INT FUND R + S
L       IFRL.K=IFRL.J+(DT)(RIFRL.JK+0)
N  ROB3=0
N  ROB4=0
N       IFRL=0
A  IRLA.K=MAX(IFRL.K,0)                  INT MEN TO BE ALLOC
MEND
C  DSRB=3                                DLY SMTHG RATE OF BILLING
C  PCAO=.04                              R&D ALLOWABLE
N  DAIF=DT
NOTE    DIVISION OF R&D
MACRO SIMP(RCF,CDI,RERP,MARC,IRLA,CFRL,DI)
A     $AIFL.K=(IRLA.K)($PRD.K)
A     $DCFR.K=(1/DT)($AIFL.K-CFRL.K)
R       SIMP.KL=MAX(-$CFM.K,$DCFR.K)
N  SIMP=0
A     $CFM.K=RCF.K/((MEOH)(DT))
L      CFRL.K=CFRL.J+(DT)(SIMP.JK+0)
N      CFRL=0
A     $PRD.K=DI.K/CDI.K
A      DI.K=(FRD)($DUI.K)($FDU.K)
A     $IUI.K=(-MARC.K/.25E6)+1
A      $DUI.K=MAX(0,$IUI.K)
A     $FDU.K=CLIP(0,1,RERP.K,2000)
MEND
NOTE   SUMMATION OF R&D
A  CDI.K=DI1.K+DI2.K+DI3+DI4+0.1      CUM DIVIS INDEX
N  DI3=0
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N  DI4=0
NOTE                        VALUE
MACRO ACVP(BEMF,STR,IVPT,PCC,ICVP,IRLV,RLVC)
A       $IVP.K=TABHL(IVPT,TIME.K,0,192,12)            INTP VAL PROJ
A       $DRV.K=TABHL(TDRV,PCC.K,0,0.05,0.01)
R    $RVRC.KL=($IVP.K-RLVC.K)/$DRV.K    RATE VAL REL, CUST
L      RLVC.K=RLVC.J+(DT)($RVRC.JK+0)            REC LEV VAL CUST
N    RLVC=IRLV
L    ACVP.K=ACVP.J+(DT/DAVC)*(RLVC.J-ACVP.J)   ACC CUST VAL, PROJ
N    ACVP=ICVP
MEND
C    IRLV1=776E6
C    ICVP1=776E6
C    IRLV2=185E6
C    ICVP2=185E6
T    IVPT1=2.06E9/2.45E9/2.45E9/2.10E9/1.66E9/1.40E9/1.10E9/.8E9/.59E9/.4E
X    9/.3E9/.25E9/.2E9/.02E9/0/0/0
T    IVPT2=756E6/900E6/900E6/771E6/610E6/515E6/404E6/294E6/217E6/147E6/110
X    E6/92E6/73E6/7E6/0/0/0
NOTE                        PROGRESS
MACRO CRP(APCE,FPMF,EMOP,EFIM,PFIM,PPEP,PRP,RERP,TEAM,PCC,PPCC,MMET,RPP,
X    SEIM,PERP,SMAP)
L      CRP.K=CRP.J+(DT)(RPR.JK+0)               CUM REAL PROG
N       CRP=0
R    RPR.KL=FPMF.K*PFIM.K*(EFIM.K+SEIM.K)    RATE REAL PROG
A       PCC.K=CRP.K/PREP.K
L      PRP.K=PRP.J+(DT)(PERP.JK+$PECR.JK)        PER  PROG
N       PRP=0
R       $PECR.KL=$ERRP.K/DT                        PER ERR CORR RATE,PP
A      $ERRP.K=($EPP.K)($FER.K)                   ERR REC PROJ  PER PROG
A       $EPP.K=CRP.K-PRP.K                        ERR PERC P-OG
A       PPCC.K=PRP.K/PREP.K                        PERCENT COMPLETE
A       $DPCC.K=MAX(PPCC.K,PCC.K)
A       $FER.K=TABHL(TFER,$DPCC.K,0,1,0.1)         FRAC ERR PER PROG REC
L    RERP.K=RERP.J+(DT/DRRP)*(PRP.J-RERP.J)    REP REAL PROG
N       RERP=0
R       $RCT.KL=$ERRP.K/((MMET.K)(DT))            RATE CORR TEAM
L      $TREAM.K=$TREAM.J+(DT)($RCT.JK+0)            TR TECH EFF AVG MAN
N       $TREAM=1.0
A    TEAM.K=MAX($TREAM.K,0.1)                   TECH EFF AVG MAN
L    MMET.K=MMET.J+DT*(EMOP.J+SMAP.K)      MAN MOS EXPD
N       MMET=0.1
R    PERP.KL=TEAM.K*(EMOP.K+SMAP.K)      PRCVD RATE PROGRESS
MEND
NOTE            PROJECT MANPOWER
MACRO TMOP(PEMP,RASC,RIMP,IDIM,OTUP,PCC,IFIM,RPSC,OTPM,SIMP,FIM,RWIT,EAM
X    P,RRIM,EFIM,PFIM,PWEA,IMAS,DFIM,DITM,DEAM)
A       TMOP.K=EAMP.K+$ITMP.K+FIM.K+IMAS.K             TOTAL MEN PROJ
L       $TFIM.K=$TFIM.J+(DT)($RIIM.JK-RRIM.JK+SIMP.JK-RASC.JK)
N    $TFIM=IFIM
A       DFIM.K=MAX($TDIM.K,0)                      DECR FULLY INT MEN
R       RRIM.KL=DFIM.K/DRIM                       RATE RED INTEG MEN
A    FIM.K=MAX($TFIM.K,0)                        FULLY INTEG MEN ON PROJ
R       $RIIM.KL=$EITM.K/((DIIM)(PRIT))             RATE INT. INTERNAL MEN
L       $ITMP.K=$ITMP.J+(DT)(RIMP.JK+$REIM.JK-$RIIM.JK-RWIT.JK)
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FILE: MPDM204   DYNAMO    P1                          MASSACHUSETTS INSTITUTE OF TECHNOLOGY
A      $RRCM.K=MAX($TDEA.K,0)                          REM REQ CHANGE MEN       MPD02210
A      $TDIM.K=$RRCM.K-$ITMP.K                         TEST INCR INT MEN        MPD02220
A     DITM.K=CLIP($ITMP.K,$RRCM.K,$TDIM.K,0)         DECR INT TRANS MR         MPD02230
R      RWIT.KL=DITM.K/DT                              RATE WITH T INT TR MEN    MPD02240
N      $ITMP=0                                                                  MPD02250
R      $REIM.KL=$EEAM.K/((DEIM)(PREA))                 RATE CONV EXT INT MEN    MPD02260
L      EAMP.K=EAMP.J+(DT)(REMP.JK-$REIM.JK-RWEA.JK+0)                           MPD02270
N      EAMP=0                                                                   MPD02280
A      $TDEA.K=-IDIM.K-EAMP.K                        TEST DECR EXT AC MEN       MPD02290
A     DEAM.K=CLIP(EAMP.K,-IDIM.K,$TDEA.K,0)        DECR EXT AC MEN              MPD02300
R      RWEA.KL=DEAM.K/DT                             RATE WOTH EXT ACQ MEN      MPD02310
A   EFIM.K=OTUP.K*($QFIM.K+$EEAM.K+$EITM.K)       EFF INTEG MEN                 MPD02320
A     $EEAM.K=(PRUM)($EMLP.K)+(-$PCSU.K)(PRUM)($EMLP.K)+($PCSU.K)(PREA)*        MPD02330
X      ($EMLP.K)                                    EFF EXT ACQ MEN             MPD02340
A     $EITM.K=(PRUM)($IMLP.K)+(-$PCSU.K)(PRUM)($IMLP.K)+($PCSU.K)(PRIT)*        MPD02350
X      ($IMLP.K)                                    EFF INT TRANSF MEN          MPD02360
A     $IPCT.K=CLIP($TIS.K,1,$TIS.K,1)                 INVERT PER CENT TR        MPD02370
A      $PCT.K=1/$IPCT.K                                PER CENT TRAINERS        MPD02380
A     $QFIM.K=(PRFI)(FIM.K)+(-$PCT.K)(PRFI)(FIM.K)+($PCT.K)(PRTR)(FIM.K)        MPD02390
NOTE                                                 EQV FULL INTEG MEN         MPD02400
A      $TIS.K=$TPT.K/($EMLP.K+$IMLP.K+1)   TEST INDEX, SUPER                    MPD02410
A      $IMLP.K=$ITMP.K-DITM.K                         INT MEN LEFT ON PROJ      MPD02420
A      $EMLP.K=EAMP.K-DEAM.K                         EXT MEN LEFT ON PROJ       MPD02430
A     $PCSU.K=CLIP(1,$TIS.K,$TIS.K,1)                 PER CENT SUPERVISED       MPD02440
A   $TPT.K=NMPT*(FIM.K+IMAS.K)         TOT POT TRNEES                           MPD02450
A   PFIM.K=$KHAP.K*$SPRM.K*$EPM.K*OTPM.K    PROD INTEG MEN                      MPD02460
A      $KHAP.K=TABHL(TMDKH,PCC.K,0,1.0,0.2)           KNOW-HOW PROJ             MPD02470
A      $SPRM.K=TABHL(TSPM,RFSC.K,0,2,0.25)            SCH RAT PROD MULT         MPD02480
A      $EPM.K=TABHL(TEPM,TMOP.K,0,350,50)              EAR PROD MULT            MPD02490
MEND                                                                            MPD02500
N   DFIM3=0                                                                     MPD02510
N   DITM3=0                                                                     MPD02520
N   DEAM3=0                                                                     MPD02530
N   DITM4=0                                                                     MPD02540
N   DFIM4=0                                                                     MPD02550
N   DEAM4=0                                                                     MPD02560
N   TMOP3=0                                                                     MPD02570
N   TMOP4=0                                                                     MPD02580
C   IFIM2=39                                                                    MPD02590
C   IFIM1=160                                                                   MPD02600
NOTE        SCHEDULE                                                            MPD02610
MACRO RFSC(EMOP,ERP,TEAM,SCOP,SMAP,STR,APMR,TMOP,OTUP,DSUP,FCD,URFS)            MPD02620
A   $TTRP.K=$PTPM.K+$TRPM.K               TR TIME RMNG ON PROJ                  MPD02630
A   $PTPM.K=MAX($TPPM.K,0)                PROJTD TIME TO PEAK MNNG              MPD02640
A   $TPPM.K=(APMR.K-TMOP.K)/MAHR          TR PROJTD TIME TO PEAK MNNG           MPD02650
A   $TRPM.K=((ERP.K-.5*$PTPM.K*(APMR.K-TMOP.K)-TMOP.K*$PTPM.K)                  MPD02660
X   /(TEAM.K*(OTUP.K*APMR.K+SMAP.K)))            TIME RMNG AT PEAK MNNG         MPD02670
A   $XTRP.K=CLIP($TTRP.K,STR.K,TIME.K,DSUP)      XPTD TIM REM PROJ              MPD02680
A   FCD.K=CLIP($SXCD.K,SCOP.K,$SDI.K,TFCS)  FOR COMPL DATE                      MPD02690
A   $SDI.K=$XSDP.K/STR.K                  SCH DISCRP INDEX                      MPD02700
A   URFS.K=$SXCD.K/SCOP.K                      UNOFFL RATIO FORE SCH COMP       MPD02710
A   $XCD.K=$XTRP.K+TIME.K           EXPTD COMPL DATE                            MPD02720
A   $TSDP.K=$SXCD.K-SCOP.K             TRIAL SCHD DISCRP                        MPD02730
A   $XSDP.K=MAX($TSDP.K,0)          EXPTD SCHD DISCRP                           MPD02740
A      RFSC.K=FCD.K/SCOP.K                           RATIO FORE SCH COMP        MPD02750
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A  $SXCD.K=SMOOTH($XCD.K,DCSD)              SMTHD EXPTD COMPLTN DATE
N  $XCD=SCOP
MEND
C  DCSD=2                                   DLY CHGG SCH DATES
C  TFCS=.25                                  TRSHOLD FOR CHGG SCHED
C  DSUP1=12                                 DLY START UP OF PLNNG
C  DSUP2=12
NOTE      FIRM'S COST
MACRO SRP(RERP,PREP,TEAM,MARC,OTUP,SRF,SSRP,TMOP,AMCR,IECP,IFSC,FSCP,ERP
X  ,ECCP,RCF)
A  SRP.K=MEOH*TMOP.K+(OTUP.K-1)*TMOP.K*MEOH*OTPR+SRF.JK+SSRP.JK
NOTE   SPDG RATE AT PROJ
A      ERP.K=MAX($XRP.K,0)
A      ECCP.K=(ERP.K)(AMCR)/TEAM.K
N  ECCP=IECP
A  $XRP.K=PREP.K-RERP.K        TRL EFFORT RMNG
L     FSCP.K=FSCP.J+(DT)(RCF.JK)
N  FSCP=IFSC                                FIRM SUNK COST, PROJ
R     RCF.KL=MAX($TRCF.K,0)
A     $TRCF.K=SRP.K-MARC.K                       RATE COM FUND
MEND                                            TRIAL RATE COST FUND
C  IECP1=384E6
C  IFSC1=4.5E6
C  IFSC2=2E6
C  IECP2=124E6
NOTE          DESIRED MANPOWER
MACRO DMIP(MARC,STR,TEAM,ERP,PAH,CFRL,XMOP,TMOP,SRF,SSRP,FBNR,PJSC,
X  FSAF,SMI,FMLL,MMLL,RMEN,IDIM,DIMP,NMEN,PFMP,FSAI,AMCR,SRFM,ANMN)
L     FMLL.K=FMLL.J+(DT)($RPML.JK+0)
N      FMLL=0                               FUND MEN LEV LIM
R  $RPML.KL=(MMLL.K-FMLL.K)/DT     RAT CHG FUN MAN LEVEL
L  SRFM.K=SRFM.J+(DT/DSFMR)*($RPML.JK-SRFM.J)   SM RATE FUND MEN
A  $TMMLL.K=(MARC.K*FSAI)/MEOH           TR MAX MNPWR LDG LVL
N  FSAI=1-PJSC-FSAF                      FRACT SPDG ALLOWD INTERNLY
A  MMLL.K=SMOOTH($TMMLL.K,DSIM)         MAX MNPWR LDG LVI
N      SRFM=0
A      $TNMN.K=ERP.K/((STR.K)(TEAM.K))       TR NEEDED MEN
A      $SMEN.K=MIN(MMLL.K,PFMP.K)                SUPP MEN
A  NMEN.K=($TNMN.K*(1-SMI.K))+($TNMN.K*SMI.K*FSAI)   NEEDED MEN
A  $DNMN.K=MIN(NMEN.K,ANMN.K)           DOMINANT NEEDED MEN
A    PFMP.K=FMLL.K+(SRFM.K)(DRIM)              PROJ FUNDED MAN LEV
A     $DMEN.K=MIN($DNMN.K,$SMEN.K)                DES MEN
A  $TNMI.K=$TNMN.K-(ERP.K/STR.K)         TR NEEDED MN DUE TO INEFFCY
A  $NMNI.K=MAX($TNMI.K,0)               NEEDED MN DUE TO INNEFFCY
A  $ANMI.K=SMOOTH($NMNI.K,DRCI)         ALLOW NEEDED MN DUE TO INEFFCY
A  $TANM.K=$ANMI.K+(ERP.K/STR.K)        TR ALLOW NEEDED MEN
A    RMEN.K=(PAH.K)($DMEN.K)+($SMEN.K)+(-PAH.K)($SMEN.K)
N  RMEN=5*TMOP
A  ANMN.K=($TANM.K*(1-SMI.K))+($TANM.K*SMI.K*FSAI)    ALLOW NEEDED MEN
N  AMCR=((FSAI*MEOH)+(PJSC*SCOH))/(FSAI+PJSC)     AVG MNPWR CONV RATE
A     DIMP.K=RMEN.K-TMOP.K+CFRL.K              DES INER IN MEN
A     $TIDE.K=MAX(-XMOP.K,$SDIM.K)               TRIAL INCR DES
A     XMOP.K=TMOP.K-CFRL.K
A  IDIM.K=MIN($TIDE.K,0)                INCR DES IN MEN
A  DMIP.K=MAX($SDIM.K,0)                DES MEN INCR
```

```
A   $SDIM.K=SMOOTH(DIMP.K,DPMR)
MEND                                              SMTHD DES INCR IN MEN
C   DPMR=1
C   DSIM=6                                     DLY PROCESS MNPWR RQSTS
C   DRCI=12                                         DLY SMTHG INT MEN
NOTE                                           DLY RSTNCE TO COMP FR INEFCY
MACRO FBNR(ECCP,MRDA,RERP,PREP,ACVP,ROS,IBNR,MBPU,CECC,WTFP,RBF,ACCC,     CUSTOMER FUNDING
X   BEMF,TSCR,DRCF)
A      $FDC.K=(ECCP.K)(WTFP.K)
L    ACCC.K=ACCC.J+(DT/DACC)*(CECC.J-ACCC.J)          FUT FUND DES CUST PROJ
N    ACCC=PREP.K*MEOH*3.0                             ACC COST CUST
A       CECC.K=(ECCP.K)($IMC.K)
A         $TMC.K=TABHL(TIMC,$RPC.K,0,0.08,0.01)       CUST EST COST COMP
A         $RPC.K=RERP.K/PREP.K                            INEXP MULT CUST
A       WTFP.K=(1.0)($IWTF.K)+(-BEMF.K)($IWTF.K)+(BEMF.K)($WFPU.K)   REP PERC COMP
L       MBPU.K=MBPU.J+(DT)($RBG.JK+0)
N         MBPU=0                                      MEAS BIAS PROJ UNDERWAY
R    $RBG.KL=TABHL(TABRB,$RPC.K,0,1,.2)     RATE BIAS GRWTH
A         BEMF.K=TABHL(TBEMF,MBPU.K,0,8,2)
A         $IWTF.K=TABLE(TIWTF,$SPIC.K,0,1,0.05)        BIAS EFF MUTL FULL FUND
A         $WFPU.K=TABLE(TWFPU,$SPIC.K,0,1,0.05)          INT WILL FUND
A         $SPIC.K=MIN($TSPI.K,1.0)                       WILL FUND PROJ UNDERWA
A         $TSPI.K=$VCR.K/ROIC                            SUIT PROJ INV, CUST
A         $VCR.K=ACVP.K/$CCC.K                           TRIAL $SPIC
A         $CCC.K=MAX(ACCC.K,1)                         VAL COST RATIO
A       DRCF.K=(1/$DIBF.K)($FDC.K-FBNR.K)
A    $DIBF.K=FDBF+VDBF*$ESOD.K-$SPIC.K*VDBF*$ESOD.K   DES RATE CHG FUND
A       $ESOD.K=CLIP(1.0,-0.3,TSCR.K,0)                DEL BUDG FUNDS
A         TSCR.K=$FDC.K-FBNR.K                         EFF SUIT DEL
R         RBF.KL=MAX(DRCF.K,-MRDA.K)                   TEST SIGN CHANGE RATIO
N    RBF=0                                             RATE BUDG FUNDS
L       FBNR.K=FBNR.J+(DT)(RBF.JK-ROS.JK)
N    FBNR=IBNR                                      FUND BUDG NOT REL
MEND
N    TSCR3=0
N    TSCR4=0
C    IBNR1=27E6
C    IBNR2=10E6
NOTE     CUSTOMER SPENDING AND ALLOCATION
MACRO MARC(SRP,CMAR,FBNR,DRCF,STR,ROS,CSCP,MRDA,FRU,ROB,ACCC)
A         $TROS.K=$APC.K/DPAP
R         ROS.KL=MIN($RARP.K,$TROS.K)                    TRIAL RATE SPEND
A         $RARP.K=FBNR.K/DT                            RATE SPEND
L       CSCP.K=CSCP.J+(DT)(ROS.JK+0)
N         CSCP=0                                    CUST SUNK COSTS
L       $APC.K=$APC.J+(DT)(ROB.JK-ROS.JK)
N         $APC=0                                     ACC PAY, CUST
R         ROB.KL=MIN(MARC.K,SPP.K)
N         ROB=0                                      RATE BILL
A       $TARC.K=($SMAR.K)($CNO.K)
A    MARC.K=MAX($TARC.K,0)                   TR MAX ALLOW RATE, CUST
A       $CNO.K=CLIP(1,0,$SSCN.K,0)          MAX ALLOW SPDG RATE
A         MRDA.K=FRU.K/DT                     CANC NOT
A         FRU.K=FBNR.K-$APC.K                           MAX RATE DECR ALLOC
A    $TMAR.K=(FRU.K/BPHC)*CMAR.K      TRIAL,MAX ALLOW RATE    FUNDS REM UNSPENT
```

```
 A  $SMAR.K=SMOOTH($TMAR.K,DAFL)          SMTHD MAX ALLOC RATE
 N  $TMAR=PBNR
 A  $SCN.K=DRCF.K+MRDA.K                  SUSCEPT TO CANCEL
 A  $SSCN.K=SMOOTH($SCN.K,DICN)            SMTHD SUSCEPT TO CANCEL
 N  $SCN=ACCC
MEND
 N  FRU3=0
 N  FRU4=0
 C  DAFL=3                                DLY ASSG FUNDG LIMITS
 C  DICN=6                                DLY ISSUNG CANCEL NOTICE
 C  BPHC=12                               BUDGET PLNNG HORIZ, CUST
NOTE        CUSTOMER SCHEDULE
MACRC SCOP(FCD,ICOP,STR,ROSA)
 A      $TTR.K=SCOP.K-TIME.K
 A      STR.K=MAX($TTR.K,DT)                          SCH TIME REM
 A    ROSA.JK=(1/DICS)(FCD.K-SCOP.K)      RATE SCHED ADJUST
 L    SCOP.K=SCOP.J+(DT)(ROSA.JK)             SCH COMP PROJ
 N  SCOP=ICOP
MEND
 C  ICOP1=60
 C  ICOP2=80
NOTE     PERCEIVED REQD EFFORT ON PROJ
MACRO PREP(PCC,RTCC,FRER,AMCR,TFRC,DCPE,FERC)
 L  PREP.K=PREP.J+DT*$RCEC.JK                PRCVD EFFORT RMNG
 N  PREP=$IEC
 N  $IEC=$RREP*FRER                             INIT EST OF EFFORT REQD
 N  $RREP=RTCC/AMCR        REAL REQD EFFORT
 A  FERC.K=TABHL(TFRC,PCC.K,0,1,.1)    FRACT ERROR RECOGZD
 A  $EEC.K=$RREP-PREP.K                   ERROR IN EST TO COMP
 A  $REEC.K=$EEC.K*FERC.K                RECOGND ERROR EST COMPL
 R  $RCEC.KL=$REEC.K/DCPE                RATE CORR EST TO COMP
MEND
 C  RTCC1=2400E6      REAL TOT COST TO COMPL
 C  FRER1=.16                                   FRACT REAL EFF RECOGNZD
 C  FRER2=.2
 C  RTCC2=.6E9
 T  TFRC1=0/.42/.52/.53/.54/.58/.67/.83/.92/.97/1.0
 T  TFRC2=0/.42/.52/.75/.76/.80/.83/.88/.92/.97/1.0
 C  DCPE1=12                                    DLY CHGG PRCVD EFFORT REQD
 C  DCPE2=6
NOTE      FACILITIES
MACRO AFCE(PREP,TMOP,FSAI,APMR,MARC,FSAF,SRP,FARA,AMTP,DMIPT,IFCE,SRF,FP
X   MF,FOIP,FCP,IRFS,RRF,RAFP)
 A  $PFR.K=$ECER.K+$EFSR.K                 PRCVD FACIL REQTS
 A  $ECER.K=PREP.K*CERR*FSAI                   EST CAP EQUIP REQTS
 A  $EFSR.K=APMR.K*FSRR                    EST FLR SPC REQTS
 A  $TAFR.K=$PFR.K-POP.K-AFCE.K-FOIP.K   TRIAL ADDTL FAC REQT
 A  $AAFR.K=MAX($TAFR.K,0)                 ALLOC ADDTL FAC REQT
 R  $TRFS.KL=$AAFR.K/DFOD                  TR INTD RATE FAC SPNDG
 R  $RFCE.KL=DELAY3(IRFS.JK,DPFO)        RATE ORDG FAC
 L  $TOIP.K=$TOIP.J+DT*(IRFS.JK-$RFCE.JK)  TR FAC ORD IN PROC
 A  FOIP.K=MAX($TOIP.K,0)                      FAC ORD IN PROC
 A  $MASF.K=MARC.K*FSAF                MAX ALLOW SPDG RATE
 R  IRFS.JK=MIN($TRFS.JK,$RRFS.K)    INTD RATE FAC SPDG
 N  $TOIP=DPFO*$RFA
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FILE: MPDM204  DYNAMO   P1                    MASSACHUSETTS INSTITUTE OF TECHNOLOGY
R   $RFA.KL=DELAY3($RFCE.JK,DFA)                  RATE FAC AVAIL                MPD04410
L   $TOP.K=$TOP.J+DT*($RFCE.JK-$RFA.JK)           TR FAC ORDS PLCD              MPD04420
A   FOP.K=MAX($TOP.K,0)                                FAC ORDS PLCD            MPD04430
N   $TOP=DFA*$RFA                                                               MPD04440
A   SRF.KL=(FOIP.K+FOP.K)/DPFB              SPDG RATE FACS                      MPD04450
A   FPMF.K=TABHL(TFMF,$FAR.K,.2,1.0,.2)         FAC PROD MULT FACTOR            MPD04460
A   $DSRF.K=SRP.K*FSAF                      DES RATE FAC SPDG                   MPD04470
A   $RRFS.K=MIN($DSRF.K,$MASF.K)            REQSTD RATE FAC SPDG                MPD04480
A   $FAR.K=AFCE.K/$PFR.K           FAC AVAIL RATIO                              MPD04490
A   $EGF.K=-FGF*MIN($TAFR.K,0)               EXCESS GENL FACS                   MPD04500
R   RRF.KL=$EGF.K/DRF                       RATE RLSG FACS                      MPD04510
L   $TFCE.K=$TFCE.J+DT*($RFA.JK+RAFP.JK-RRF.JK)                                 MPD04520
N   $TFCE=IFCE                                                                  MPD04530
A   AFCE.K=MAX($TFCE.K,0)                    AVAIL FACIL & CAP EQUIP            MPD04540
A   $TAFP.K=(AMIP.K*FARA.K)/(DRF*DMIPT.K)       TR RATE OF ASSGNG FACS          MPD04550
A   $TPFR.K=$AAFR.K/DRF                     TR PROJ FAC REQTS                   MPD04560
A   $FBRF.K=SWITCH(1,0,RRF.KL)              RDBK FRM RLS OF FACS                MPD04570
R   RAFP.KL=$FBRF.K*MIN($TAFP.K,$TPFR.K)        RATE REASSGNG FACS              MPD04580
MEND                                                                            MPD04590
N   IRFS1=.5E6                                                                  MPD04600
N   IRFS2=.3E6                                                                  MPD04610
C   IFCE1=15.7E6                                                                MPD04620
C   IFCE2=13.8E6                                                                MPD04630
C   FSAF2=.03                                                                   MPD04640
C   FGF=.5                                  FRACT OF GENL FACS                  MPD04650
C   DRF=3                                         DLY REASSG FACS               MPD04660
C   FSAF1=0.05                       FRACT SPDG ALLOWD FACIL                    MPD04670
C   DPFB=6                                        DLY PAYING FAC BILLS          MPD04680
C   CERR=110                                 CAP EQUIP REQT RATIO               MPD04690
C   DFOD=12                                 DSRD FAC ORD DLY                    MPD04700
C   DPFO=3                                  DLY PLCG FAC ORDS                   MPD04710
T   TFMF=.6/.75/.9/1.0/1.05                 TAB,FAC PROD MULT FACTOR            MPD04720
C   FSRR=1800                               FLR SPACE REQTS RATIO               MPD04730
C   DFA=10                                  DLY FACIL AVAIL                     MPD04740
NOTE        REALLOCATION OF FACILITIES                                          MPD04750
L   TFRA.K=TFRA.J+DT*(RRF1.JK+RRF2.JK-RAFP1.JK-RAFP2.JK)     TR FACIL AVAILMPD04760
N   TFRA=0                                                                      MPD04770
A   FARA.K=MAX(TFRA.K,0)                    FACIL AVAIL FOR REASSGNMT           MPD04780
NOTE   OVERTIME                                                                 MPD04790
MACRO OTUP(URFS,DMIP,TMOP,MAOT,EMOP,OTPM)                                       MPD04800
A   OTUP.K=MIN($SOTR.K,MAOT)                    OT USED ON PROJ                 MPD04810
A   $TOTR.K=URFS.K*((DMIP.K/TMOP.K)+1)     TR INDX OT REQD                      MPD04820
A   $IOTR.K=MAX($TOTR.K,MPOL)              INDX OT REQD                         MPD04830
A   OTPM.K=TABHL(TOPM,OTUP.K,1.05,1.25,.05)  OT PROD MULT                       MPD04840
A   EMOP.K=OTUP.K*TMOP.K                      EQUIV MEN ON PROJ                 MPD04850
A   $SOTR.K=SMOOTH($IOTR.K,DUOT)           SMTHD OT REQT                        MPD04860
N   $TOTR=MPOL                                                                  MPD04870
MEND                                                                            MPD04880
T   TOPM=1/1/.99/.95/.88                     TABL, OT PROD MULT                 MPD04890
C   MAOT1=1.25              MAX ALLOW OT                                        MPD04900
C   MAOT2=1.20                                                                  MPD04910
C   MPOL=1.05                              MIN PRACTCL OT LVL                   MPD04920
C   OTPR=1.5            OT PREM RATIO                                           MPD04930
C   DUOT=1                                 DLY USG OT                           MPD04940
NOTE     SUSCEPTIBILITY TO BUDGET CUTS                                          MPD04950
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FILE: MPDM204 DYNAMO P1 MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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MACRO CMAR(CECC,WTFP,FRU,ROSA,SBC)
A  SBC.K=.333*(1-WTFP.K)+.333*ROSA.JK+.333*$IAAF.K   SUSCPT TO BUDG CUT
A  $FAI.K=(CECC.K/FRU.K)-1                    FUND AVAIL INDEX
A  $IAAF.K=MAX($FAI.K,0)                      INDEX FUND ADQCY
A  $TPBC.K=.5-.5*SIN(6.283*TIME.K/PPP)        TRIAL PRES BUD CUT
A  $TTBC.K=NORMRN(.5,.2)                      ATL TRIAL PRES BUD CUT
A  $PFBC.K=LIMC*SWITCH($TPBC.K,$TTBC.K,SELC)       PRES FOR BUD CUT
A  CMAR.K=TABHL(TCMR,$IBCD.K,0,1,.2)        CUT MAX ALLOW RATE
A  $IBCD.K=$SSBC.K*$PFBC.K                    INDEX BUD CUT DES
A  $SSBC.K=SMOOTH(SBC.K,DRSB)               SMTHD SUSCEPT BUD CUT
N  SBC=0
MEND
C  DRSB=3                                   DLY RECGNZG SUSCEPT BUD CUT
C  LIMC=0                                   LIM CONSTANT
C  SELC=0                                   SEL CONSTANT
C  PPP=12                                   PER POL PRESS
T  TCMR=1/1/1/1/.9/.8                       TAB. CUT IN MAX RATE
NOTE       SUBCONTRACTORS
MACRO SEIM(PREP,EFIM,TMOP,STR,ISDP,PJSC,MARC,ERP,TEAM,IMAS,SFBR,SMAP,SSR
X  P,RASC,SSCP,SRMN,SMI)
A  $SCRP.K=PREP.K*PJSC*SCOH                 SC REQD ON PROJ
L  $SCIP.K=$SCIP.J+DT*($RPSC.JK-$SPSC.JK)   SC IN PROC
R  RASC.KL=(1/DASC)(($SCRP.K*PMSVR*$RMAS.K)-IMAS.K)   RT ASSGN MEN SC
R  $TRPSC.KL=(1/DSPA)*((IMAS.K/PMSVR)-$SCIP.K-SFBR.K-SSCP.K)
NOTE  TR RATE PLCG SC
A  $RPSC.JK=MAX($TRPSC.KL,0)                RATE PLCG SC
N  $SCIP=0
R  $SPSC.KL=DELAY3($RPSC.JK,DSPC)           SC LVG PROC CYC
L  SFBR.K=SFBR.J+DT*($SPSC.JK-SSRP.JK)      SC FUNDS BUDGTD, NOT RELSD
N  SFBR=0
A  $ATMP.K=SMOOTH(TMOP.K,DSTM)              SM AVG TOT MEN
A  $TMRCM.K=((TMOP.K-$ATMP.K)*SAHM)/(TMOP.K*DSTM)   TR MAX CHG MEN
A  $MRCMP.K=MAX($TMRCM.K,MSHL)              MAX RT CHG MEN
A  $MRASM.K=$MRCMP.K*$SCAM.K                MAX RT INCRSG MEN
A  $SCAM.K=SFBR.K/(SCOH*$BPHS.K)            SC AUTH MNPWR LVL
A  $TRASM.K=(1/DASM)(SRMN.K-SMAP.K)         TR RT ASSG MEN
R  $RASM.KL=MIN($TRASM.K,$MRASM.K)          RT ASSG MEN
L  $TSMAP.K=$TSMAP.J+DT*$RASM.JK            TR SC MEN ASSD PROJ
N  $TSMAP=0
A  SMAP.K=MAX($TSMAP.K,0)                   SC MEN ASSD PROJ
A  $MER.K=EFIM.K/TMOP.K                     MNPWR EFF RATIO
A  $SMER.K=SMOOTH($MER.K,STME)              SM MNPWR EFF RATIO
A  SEIM.K=$SMER.K*SMAP.K                    SC EFF INTEG MEN
R  SSRP.KL=SCOH*SMAP.K                      SC SPDG RATE
L  $TMAS.K=$TMAS.J+DT*RASC.JK               TR INTEG MEN ASSD TO SC
A  IMAS.K=MAX($TMAS.K,0)                    INTEG MEN ASSD TO SC
A  $SMML.K=(MARC.K*PJSC)/SCOH               SC MAX MNPWR LIMIT
A  $SSML.K=SMOOTH($SMML.K,DSFA)             SMTHD SC MAX MNPWR LIMIT
A  $SDML.K=MIN($SCAM.K,$SSML.K)             SC DSRD MNPWR LVL
A  $BPHS.K=MIN(STR.K,ISDP)                  BUDGET PLNG HORIZ,SC
L  SSCP.K=SSCP.J+DT*SSRP.JK                 SC SPENT COSTS
N  SSCP=0
A  $PSCC.K=SSCP.K/$SCRP.K                   SC COMPLT
A  $RMAS.K=TABHL(TRMS,$PSCC.K,0,1,.2)       REM MEN ASSGD SC
A  $SERP.K=ERP.K*PJSC                       SC REQD EFFORT
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FILE: MPDM204  DYNAMO    P1
                                              MASSACHUSETTS INSTITUTE OF TECHNOLOGY
A   $SNMN.K=$SERP.K/(STR.K*TEAM.K)                 SC NEEDED MEN
A   SRMN.K=MIN($SNMN.K,$SDML.K)                    SC REQSTD MEN
N   $TMAS=0
A   $FSMP.K=SMAP.K/(TMOP.K+SMAP.K)                 FRACT SC MANNING
A   $TSMI.K=$FSMP.K/PJSC                           TR SC MANNG INDEX
A   SMI.K=MIN($TSMI.K,1)                           SC MANNG INDEX
MEND
C   PJSC1=0.50                JOB SC
C   PJSC2=.44
C   DSFA=3
C   ISDP1=60                                       DLY SMTHG FUND AUTH
C   ISDP2=84                                       INIT SCH DURATION OF PROJ
T   TRMS=1/1/1/1/.8/0
C   SCOH=2200                                      TAB, REMOV MEN SC
C   PMSVR=.04E-6            SC ENG OH RATE
C   DSPC=2                  MEN/SC VAL RATIO
C   DSTM=3                  DLY PLCG SC
C   DASM=1                  DLY SMTHG TOT MEN
C   MSHL=100                DIY ASSG SC MEN
C   SAHM=2                                          MIN SC HIRING RATE LIMIT
C   STME=6                                         SC AGGLOM HIRING MULT
C   DASC=1                                         SM TIME MNPWR EFF
C   DSPA=3                  DLY STG PROC
NOTE          MACRO FUNCTIONAL EQUATIONS FOR CENTRAL SECTOR
A   DMIPT.K=DMIPT(AMIP1.K,AMIP2.K,AMIP3,AMIP4,NHP.K,TMOC.K,TMPT.K,PAH.K,
X   PCM1.K,PCM2.K,PCM3.K,PCM4.K,IPBA.K,NHBA.K,NRNH.K,RLNH.K,NRIP.K,
X   RLIP.K)
A   IMPT.K=IMP(DFIM1.K,DFIM2.K,DFIM3,DFIM4,DITM1.K,DITM2.K,DITM3,
X   DITM4,PCM1.K,PCM2.K,PCM3.K,PCM4.K,IPBA.K,NRIP.K,RLIP.K,RICI.JK,RIMP1.
X   JK,RIMP2.JK,RIMP3.JK,RIMP4.JK)
A   TMENT.K=TMEN(NRNH.K,RLNH.K,IMPT.K,PCM1.K,PCM2.K,PCM3.K,PCM4.K,NHBA.K
X   ,FRU1.K,FRU2.K,FRU3,FRU4,TSCR1.K,TSCR2.K,TSCR3,TSCR4,TMOP1.K,
X   TMOP2.K,TMOP3,TMOP4,DEAM1.K,DEAM2.K,DEAM3,DEAM4,FIM1.K,FIM2.K
X   ,NRIP.K,SRP1.K,SRP2.K,APSI,NHP.K,PAH.K,MIHD.K,HR.JK,TMOC.K,RLCE.JK
X   ,FKLG.K,COP.K,REMP1.JK,REMP2.JK,REMP3.JK,REMP4.JK,TPSR.K,MLC.K,TMAC.K
X   ,FIMT.K)
A   IFRL.K=IFRL(ROB1.JK,ROB2.JK,ROB3,ROB4,IRLA.K,RIFRL.JK)
NOTE      MACRO FUNCTIONAL EQUATIONS FOR PROJECT 1
A   AMIP1.K=AMIP(EMOP1.K,TMOP1.K,PSAI1,TMPT.K,TMOC.K,SRFM1.K,APMR1.K,DMIP
X   1.K,FMRA1.K,MISA1.K,FRP1.K,PPMP1.K,STR1.K,TFMR1)
A   SIMP1.K=SIMP(RCF1.JK,CDI.K,RERP1.K,MARC1.K,IRLA.K,CFRL1.K,DI1.K)
A   ACVP1.K=ACVP(REMP1.K,STR1.K,IVPT1,PCC1.K,ICVP1,IRLV1,RLVC1.K)
A   CRP1.K=CRP(AFCE1.K,FPMF1.K,EMOP1.K,EFIM1.K,PFIM1.K,PREP1.K,PRP1.K,
X   RFRP1.K,TEAM1.K,PCC1.K,PPCC1.K,MMET1.K,RPR1.JK,SEIM1.K,PERP1.JK,SMAP1
X   .K)
A   TMOP1.K=TMOP(REMP1.JK,RASC1.JK,RIMP1.JK,IDIM1.K,OTUP1.K,PCC1.K,IFIM1,
X   RFSC1.K,OTPM1.K,STMP1.K,FIM1.K,RWIT1.JK,EAMP1.K,RRIM1.JK,EFIM1.K,
X   PFIM1.K,RWEA1.JK,IMAS1.K,DFIM1.K,DITM1.K,DEAM1.K)
A   RFSC1.K=RFSC(EMOP1.K,ERP1.K,TEAM1.K,SCOP1.K,SMAP1.K,STR1.K,
X   APMR1.K,TMOP1.K,OTUP1.K,DSUP1,FCD1.K,URFS1.K)
A   SRP1.K=SRP(RERP1.K,PREP1.K,TEAM1.K,MARC1.K,OTUP1.K,SRP1.K,SSRP1.JK,
X   TMOP1.K,AMCR1,IECP1,IFSC1,FSCP1.K,ERP1.K,ECCP1.K,RCF1.JK)
A   DMIP1.K=DMIP(MARC1.K,STR1.K,TEAM1.K,FRP1.K,PAH.K,CFRL1.K,XMOP1.K,
X   TMOP1.K,SRP1.K,SSRP1.JK,FBNR1.K,PJSC1,FSAF1,SMI1.K,PMLL1.K,MMLL1.K,RM
X   EN1.K,IDIM1.K,DIMP1.K,NMEN1.K,PPMP1.K,PSAI1,AMCR1,SRFM1.K,ANMN1.K)
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A   FBNR1.K=FBNR(ECCP1.K,MRDA1.K,RERP1.K,PREP1.K,ACVP1.K,ROS1.JK,IBNR1
X   ,MBPU1.K,CECC1.K,WTFP1.K,RBF1.JK,ACCC1.K,BEMF1.K,TSCR1.K,DRCF1.K)   MPD06060
A   MARC1.K=MARC(SRP1.K,CMAR1.K,FBNR1.K,DRCF1.K,STR1.K,ROS1.JK,CSCP1.K,  MPD06070
X   MRDA1.K,FRU1.K,ROB1.JK,ACCC1.K)                                      MPD06080
A   SCOP1.K=SCOP(FCD1.K,ICOP1,STR1.K,ROSA1.K)                            MPD06090
A   PREP1.K=PREP(PCC1.K,RTCC1,FRER1,AMCR1,TFRC1,DCPF1,FERC1.K)           MPD06100
A   AFCE1.K=AFCE(PREP1.K,TMOP1.K,FSAI1,APMR1.K,MARC1.K,FSAF1,SRP1.K,PARA.MPD06110
X   K,AMIP1.K,DMIPT.K,IFCE1,SRF1.K,FPMF1.K,FOIP1.K,FOP1.K,IRFS1.JK,RRF1.JMPD06120
X   K,RAFP1.JK)                                                          MPD06130
A   OTUP1.K=OTUP(URFS1.K,DMIP1.K,TMOP1.K,MAOT1,EMOP1.K,OTPM1.K)          MPD06140
A   CMAR1.K=CMAR(CECC1.K,WTFP1.K,FRU1.K,ROSA1.K,SBC1.K)                  MPD06150
A   SEIM1.K=SEIM(PREP1.K,EFIM1.K,TMOP1.K,STR1.K,ISDP1,PJSC1,MARC1.K,ERP1.MPD06160
X   K,TEAM1.K,IMAS1.K,SFBR1.K,SMAP1.K,SSRP1.JK,RASC1.JK,SSCP1.K,SRMN1.K,SMPD06170
X   MI1.K)                                                               MPD06180
NOTE     MACRO FUNCTIONAL EQUATIONS FOR PROJECT 2                        MPD06190
A   AMIP2.K=AMIP(EMOP2.K,TMOP2.K,FSAI2,IMPT.K,TMOC.K,SRFM2.K,APMR2.K,DMIPMPD06200
X   2.K,FMRA2.K,MISA2.K,ERP2.K,PFMP2.K,STR2.K,TPMR2)                     MPD06210
A   SIMP2.K=SIMP(RCF2.JK,CDI.K,RERP2.K,MARC2.K,IRLA.K,CFRL2.K,DI2.K)     MPD06220
A   ACVP2.K=ACVP(BEMF2.K,STR2.K,IVPT2,PCC2.K,ICVP2,IRLV2,RLVC2.K)        MPD06230
A   CRP2.K=CRP(AFCE2.K,FPMF2.K,EMOP2.K,EFIM2.K,PFIM2.K,PREP2.K,PRP2.K,   MPD06240
X   RERP2.K,TEAM2.K,PCC2.K,PPCC2.K,MMET2.K,RPR2.JK,SEIM2.K,PERP2.JK,SMAP2MPD06250
X   .K)                                                                  MPD06260
A   TMOP2.K=TMOP(REMP2.JK,RASC2.JK,RIMP2.JK,IDIM2.K,OTUP2.K,PCC2.K,IFIM2,MPD06270
X   RFSC2.K,OTPM2.K,SIMP2.K,FIM2.K,RWIT2.JK,EAMP2.K,RRIM2.JK,EFIM2.K,    MPD06280
X   PFIM2.K,RWEA2.JK,IMAS2.K,DFIM2.K,DITM2.K,DEAM2.K)                    MPD06290
A   RFSC2.K=RFSC(EMOP2.K,ERP2.K,TEAM2.K,SCOP2.K,SMAP2.K,STR2.K,          MPD06300
X   APMR2.K,TMOP2.K,OTUP2.K,DSUP2,FCD2.K,URFS2.K)                        MPD06310
A   SRP2.K=SRP(RERP2.K,PREP2.K,TEAM2.K,MARC2.K,OTUP2.K,SRF2.K,SSRP2.JK,  MPD06320
X   TMOP2.K,AMCR2,IECP2,IFSC2,FSCP2.K,ERP2.K,ECCP2.K,RCF2.JK)            MPD06330
A   DMIP2.K=DMIP(MARC2.K,STR2.K,TEAM2.K,ERP2.K,PAH.K,CFRL2.K,XMOP2.K,    MPD06340
X   TMOP2.K,SPF2.K,SSRP2.JK,FBNR2.K,PJSC2,FSAF2,SMI2.K,FMLI2.K,MMLL2.K,RMMPD06350
X   EN2.K,IDIM2.K,DIMP2.K,NMEN2.K,PFMP2.K,FSAI2,AMCR2,SRFM2.K,ANMN2.K)   MPD06360
A   FBNR2.K=FBNR(ECCP2.K,MRDA2.K,RERP2.K,PREP2.K,ACVP2.K,ROS2.JK,IBNR2   MPD06370
X   ,MBPU2.K,CECC2.K,WTFP2.K,RBF2.JK,ACCC2.K,BEMF2.K,TSCR2.K,DRCF2.K)   MPD06380
A   MARC2.K=MARC(SRP2.K,CMAR2.K,FBNR2.K,DRCF2.K,STR2.K,ROS2.JK,CSCP2.K,  MPD06390
X   MRDA2.K,FRU2.K,ROB2.JK,ACCC2.K)                                      MPD06400
A   SCOP2.K=SCOP(FCD2.K,ICOP2,STR2.K,ROSA2.K)                            MPD06410
A   PREP2.K=PREP(PCC2.K,RTCC2,FRER2,AMCR2,TFRC2,DCPE2,FERC2.K)           MPD06420
A   AFCE2.K=AFCE(PREP2.K,TMOP2.K,FSAI2,APMR2.K,MARC2.K,FSAF2,SRP2.K,FARA.MPD06430
X   K,AMIP2.K,DMIPT.K,IFCE2,SRF2.K,FPMF2.K,FOIP2.K,FOP2.K,IRFS2.JK,RRF2.JMPD06440
X   K,RAFP2.JK)                                                          MPD06450
A   OTUP2.K=OTUP(URFS2.K,DMIP2.K,TMOP2.K,MAOT2,EMOP2.K,OTPM2.K)          MPD06460
A   CMAR2.K=CMAR(CECC2.K,WTFP2.K,FRU2.K,ROSA2.K,SBC2.K)                  MPD06470
A   SEIM2.K=SEIM(PREP2.K,EFIM2.K,TMOP2.K,STR2.K,ISDP2,PJSC2,MARC2.K,ERP2.MPD06480
X   K,TEAM2.K,IMAS2.K,SFBR2.K,SMAP2.K,SSRP2.JK,RASC2.JK,SSCP2.K,SRMN2.K,SMPD06490
X   MI2.K)                                                               MPD06500
NOTE                       CONSTANTS                                     MPD06510
C      SR=40                                                             MPD06520
C   PRD=0.2                                                              MPD06530
C   DAVC=4                                DLY ACCPTG VALUE               MPD06540
C      TFER*=0/0/0/0/0/0.3/0.5/0.75/0.9/1.0/1.0                          MPD06550
C   DRRP=1                                                               MPD06560
C      DRIM=1.0                           DLY RPTG REAL PROG             MPD06570
C   DIIM=2                                                               MPD06580
C   DEIM=4                                DLY INTETG INT MEN             MPD06590
                                          DLY CONVTG EXT TO INT MEN      MPD06600
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C       PRTR=0.70/PRIT=0.60/PRPI=1.0/PREA=0.40
C       PRUM=0.2
C       NMPT=8
C       TMDKH*=0.6/0.85/1.2/1.5/1.8/2.0                 INV TRAIN REQ / NEW MAN
C       TSPM*=0.25/0.27/0.38/0.65/1.06/1.25/1.06/0.75/0.5
C       TEPM*=2.0/2.0/2.0/2.0/1.75/1.25/1.1/1.0
C   MEOH=1550
C       DSFMR=1                           MEAN LABOR RATE
C       DACC=3
C       TIMC*=3.0/2.0/1.6/1.3/1.25/1.25/1.25/1.25/1.25
T   TABRB=.3/.6/.85/1.0/1.0/1.0
C       TBEMF*=0/0.12/0.5/0.92/1.00        TAB, RATE BIAS GRWTH
C       TIWTF*=0/0/0/0/0/0/0/.03/.04/.04/.05/.05/.05/.05/.05/.07/.13/.25/.
X1      43/.85/1
T   TWFPU=0/0/0/0/0/0/.2/.5/.8/.89/.94/.96/.97/.98/.99/1/1/1/1/1/1
C       ROIC=1.5
C       FDBF=6/VDBF=12
C       DPAP=2
C   DICS=6
C       TDICP*=3/3/6/9/12/15               DLY IN CHG SCHD
C   PAIP=0.06
T   TDRV=36/24/18/12/9/6                   ALLD IN POOL
C   DEPR=2                                 DLY RECOGNZG VALUE
NOTE     OUTPUT FOR CENTRAL SECTOR AND PROJECT 1    DLY IN PERSONL ROSTS
PRINT   DMIPT,NHP,TMOC,PAH,IPBA,NHBA,NRNH,RLNH,NRIP,RLIP,IMPT,
X   RLCT,TMENT,MIHD,HR,RLCE,TPSR,AFSI,FARA,
X   BKLG,COP,MLO,TMAC,FIMT,IFRL,ROB1,IRLA,RIFRL,CDI,
X   DFIM1,PCM1,DITM1,RIMP1,FRU1,TSCR1,DEAM1,FIM1,REMP1,ROB1,RCF1,SIMP1,
X   CFRL1,DI1,ACVP1,BEMF1,STR1,PCC1,RLVC1,CRP1,FPMF1,RERP1,
X   EMOP1,EFIM1,PFIM1,PRP1,TEAM1,PPCC1,MMET1,RPR1,PERP1,TMOP1,RWEA1,IDIM1
X   ,OTPM1,RWIT1,EAMP1,RRIM1,RASC1,IMAS1,RFSC1,ERP1,ECCP1,DMIP1,
X   XMOP1,FMLL1,MMLL1,RMEN1,DIMP1,NMEN1,PFMP1,SRF1,SSRP1,FBNF1,MPDA1,ROS1
X   ,DRCF1,MBPU1,CECC1,WTFP1,RBF1,ACCC1,BEMF1,MARC1,SCOP1,FCD1,SRP1,
X   FSCP1,CSCP1,ROSA1,PREP1,AMCR1,FBRC1,AFCE1,POIP1,FOP1,TRFS1,PAFP1,PRF1
X   ,OTUP1,CMAR1,SBC1,SEIM1,SFBR1,SMAP1,SSCP1,SRMN1,ANMN1,PSAI1,URFS1,
X   PMRA1,MISA1,APMR1,AMIP1,SMI1
PLOT   PCC1=1,PCC2=2/TMOP1=A,TMOP2=B/CSCP1=X,CSCP2=Y/SCOP1=U,SCOP2=V/PREP
X   1=P,PREP2=Q
PLOT   NMEN1=N,PFMP1=F,APMR1=X,TMOP1=T,RMEN1=R,ANMN1=A,IDIM1=I,
X   /SMAP1=S,SRMN1=Q/AMIP1=Y
PLOT   SCOP1=D,PCD1=P/STR1=S/PCC1=%,PPCC1=P/RFSC1=R,URFS1=U/OTUP1=O
PLOT   PCC1=%/TMOP1=T,SMAP1=S/CSCP1=C,SSCP1=E/FSCP1=F,AFCE1=O/WTFP1=W/SCO
X   P1=D/PREP1=R
PLOT   MARC1=M,SRF1=F,SRP1=$,SSRP1=S/FBNF1=B,SFBR1=A/ACVP1=V,ACCC1=C/WTFP
X   1=W
PLOT   CRP1=C,PRP1=P,PERP1=R/ERP1=E,PREP1=S/TEAM1=T
PLOT   NHP=N,IMPT=P/TMAC=M,MIHD=D/HR=H,RLCE=L,RLCE=F
NOTE     OUTPUT FOR PROJECT 2
PRINT   DFIM2,PCM2,DITM2,RIMP2,FRU2,TSCR2,DEAM2,FIM2,REMP2,ROB2,RCF2,
X   SIMP2,RERP2,
X   CFRL2,DI2,ACVP2,BEMF2,STR2,PCC2,RLVC2,CRP2,FPMF2,
X   EMOP2,EFIM2,PFIM2,PRP2,TEAM2,PPCC2,MMET2,RPR2,PERP2,TMOP2,RWEA2,IDIM2
X   ,OTPM2,RWIT2,EAMP2,FRIM2,RASC2,IMAS2,RFSC2,ERP2,ECCP2,DMIP2,
X   XMOP2,FMLL2,MMLL2,RMEN2,DIMP2,NMEN2,PFMP2,SRF2,SSRP2,FBNF2,MRDA2,ROS2
X   ,DRCF2,MBPU2,CECC2,WTFP2,RBF2,ACCC2,BEMF2,MARC2,SCOP2,FCD2,SRP2,
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X    FSCP2,CSCP2,ROSA2,PREP2,AMCR2,FPRC2,AFCE2,FOIP2,FOP2,IRFS2,RAFP2,RRF2MPD07160
X    ,OTUP2,CMAR2,SBC2,SEIM2,SFBR2,SMAP2,SSCP2,SRMN2,ANMN2,FSAI2,URFS2,   MPD07170
X    FMRA2,MISA2,APMR2,AMIP2,SMI2                                         MPD07180
PLOT NMEN2=N,PFMP2=F,APMR2=X,TMOP2=T,RMEN2=R,ANMN2=A,IDIM2=I,             MPD07190
X    /SMAP2=S,SRMN2=Q/AMIP2=Y                                             MPD07200
PLOT SCOP2=D,FCD2=F/STR2=S/PCC2=%,PPCC2=P/RFSC2=R,URFS2=U/OTUP2=O         MPD07210
PLOT PCC2=%/TMOP2=T,SMAP2=S/CSCP2=C,SSCP2=E/FSCP2=F,AFCE2=Q/WTFP2=W/SCOMPD07220
X    P2=D/PREP2=R                                                         MPD07230
PLOT MARC2=M,SRF2=F,SBP2=$,SSRP2=S/FBNR2=B,SFBR2=A/ACVP2=V,ACCC2=C/WTFPMPD07240
X    2=W                                                                  MPD07250
PLOT CRP2=C,PRP2=P,REFP2=R/ERP2=E,PREP2=S/TEAM2=T                         MPD07260
SPEC DT=0.25/LENGTH=120/PRTPER=12/PLTPER=3                                MPD07270
RUN  099 V                                                                MPD07280
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