NASA SP-6009

GPO PRICE $ ____________

CFSTI PRICE(S) $ 3.75

Hard copy (HC) ____________

Microfiche (MF) 1.25

ff 653 July 65

FORECASTS AND APPRAISALS FOR MANAGEMENT EVALUATION

Volume 1

FACILITY FORM 602

N66 29966	
(ACCESSION NUMBER)	(THRU)
229	1
(PAGES)	(CODE)
	08
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

Prepared by
APOLLO
PROGRAM OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546

NASA SP-6009

APOLLO PROGRAM

OFFICE OF MANNED SPACE FLIGHT

FORECASTS AND APPRAISALS FOR MANAGEMENT EVALUATION

Volume 1

Prepared by
APOLLO PROGRAM OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $3.75

FOREWORD

This document, though an official release of the Apollo Program Office, is furnished for information purposes only. Its purpose is to create awareness, stimulate interest and further promote understanding in the art and science of making real-life forecasts and their subsequent utilization in the control of space vehicle weight and performance throughout the Apollo Program.

This book is primarily intended for those in the Apollo Program who are responsible for the administration, design, development, manufacture, and test of the Apollo System. New theorems have been developed, as well as application of proven techniques but more importantly, a weight/performance forecasting methodology has been developed and automated. The text emphasizes the utilization of forecasting devices as applied to space vehicle weight and performance since these two parameters are of vital interest to all levels of management as well as technical personnel. Further, weight is tangible and readily measurable and can be readily related to performance.

The text provides, to those who wish to apply the developed methodology, all details necessary to do so and includes the mathematical development, computer program user's manuals and necessary instructions and procedures.

Forecasts and Appraisals for Management Evaluation text is intended to be a constructive aid to the NASA Apollo team in assisting them in the weight and performance area.

Samuel C. Phillips
Major General, USAF
Director, Apollo Program

ACKNOWLEDGEMENTS

It is important to recognize those individuals who have contributed to this work, and to assure others who have aided in no less important way that omission is unintentional.

The Apollo Program Office through Mr. Gilbert L. Roth and Mr. Carl R. Liebermann provided the over-all basic development guidance and technical supervision. The detailed development, computer programming and checkout was provided by the General Electric Company's Apollo Support Department in Daytona Beach, Florida.

Appreciation is expressed to Dr. Emanuel Parzen, Professor of Statistics at Stanford University, Palo Alto, California and Dr. Howard R. Roberts, Research Director at Booz-Allen Applied Research, Inc., in Washington, D.C., for their valuable consultations, constructive criticisms and suggestions for improvement of the basic techniques.

Finally, material and ideas have been extracted from numerous references which are listed at the end of this manual. A bibliography is also appended for additional reading of this subject if desired.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

PREFACE

This book provides an insight into the problems associated with the development of a system for maintaining effective control over large and complex aerospace programs. Chapters 1, 2, and 3 contain general considerations, concepts and the utilization of a general data-handling system with particular application to weight/performance control developed to assist managers and contractors on the Apollo Program. Possible applications to cost and schedule monitoring, reliability, and other fields are briefly discussed.

The specific application to weight and performance control, with attendant exhibits of work sheets, printouts, and reporting forms to management, is contained in Chapter 3. Additional elements of interest to the management evaluation task, along with the mathematical procedures and mechanics of the computational system, are appended for reference purposes in Book II.

The primary objective in compiling this book is to offer, for general consideration and possible utilization, a complete and comprehensive system on Forecasts and Appraisals for Management Evaluation useful in the management of highly complex, increasingly sophisticated, interrelated programs.

CHAPTER 1

AN INTRODUCTION TO FORECASTS AND APPRAISALS FOR MANAGEMENT EVALUATION

1.1 BACKGROUND

Since the end of World War II there has been a growing need for management information systems which can process a mass of technical data from many sources, assess the significance of the distilled information and present clear, concise facts to management. Today we are in a period in which mathematics and decision logic are coupled to provide management with quantitative evaluations of what previously had been purely subjective considerations. The outcome of this union has been the introduction of several new systems for supplying management information. This book describes one of these new systems, called Forecasts and Appraisals for Management Evaluation (Acronym FAME). This system develops forecasts of program status providing management with the increased perception needed to maintain control of large and complex technical programs.

FAME is a process which assesses the facts of yesterday and the actualities of today, and forecasts the probable events of the future. The process provides quantitative values for stated problems, defines their magnitude, and describes the effects of alternative actions or inaction by management. FAME can be applied to data of a historical nature or to information having inherently variable characteristics. The system is dynamic. It is capable of responding to changes in design, shifts of emphasis, and determining the program impact of such changes. It provides the means for giving quantitative values to information which otherwise would be limited to subjective evaluation by management.

The requirement for FAME was spawned by the need for a dynamic management tool which would accurately forecast the weight and performance of Space Vehicles during all phases of program development. The principles of FAME are also applicable to cost, schedule, flight performance, ground facilities utilization and reliability evaluation and trade-offs among them.

1.2 THE LOGIC BEHIND FAME

In a broad sense, FAME may be characterized as being operations research, i.e., research concerned with applying scientific method to the problems facing management.

Yet, as A. Kaufmann points out, operations research is not in itself a science but rather a scientific attitude toward management phenomena. Kaufmann says:

> "There are times when there is little difference of meaning between Econometrics and Operations Research since the borderlines between the economic and physical area of technology and management are not clearly defined." (13)*

Adding to these thoughts, one observes that a revolutionary period of mathematical and decision logic is upon us. This demands that advanced technologies and the science of management be welded together to provide quantitative predictions upon which qualitative management decisions may be based. Therefore, forecasts, as such, are the heart of FAME.

It could be argued that FAME is a hybrid form of statistical analysis. This is not worth debating, for it is through statistical inferences as determined by probability theory that the marriage of mathematics and logic takes place.

Accentuating the word "forecasting" draws attention to an area which concerns us most. Others use "trend" and "projection" in a similar vein. Throughout this book the words "forecast" and "prediction" are used interchangeably. The term "Prediction Analysis" which appears frequently, refers to that one major aspect of the FAME system in which pre-trended data is subjected to mathematical analysis.

1.2.1 REQUIRED ATTRIBUTES OF FAME

Forecasting techniques to be useful must have the attributes of consistency, efficiency, and sufficiency. When applied to space vehicles these attributes must be stringently defined because the total number of observations available are limited and will not increase indefinitely, as normally assumed in the pure statistical sense. Accordingly, the following definitions are provided.

1.2.1.1 Consistency

Consistency is that attribute of FAME which is distinguished by the convergence of the estimated parameter towards a final value each time an additional set of data is added to the initial set of observations. As the parameters converge the probability of predicting a value, other than the one upon which they are converging, diminishes rapidly. This is referred to as "targeting."

---

* Numbers in parentheses refer to references in Section R of this book.

1.2.1.2 Efficiency

Efficiency is that attribute of FAME which is distinguished by the variance of the estimated value toward a finite variance each time an additional set of data is added to the initial set of observations. It is further stipulated that this variance be less than or equal to the allowable variance in the final measured value. This is designated as "accuracy."

1.2.1.3 Sufficiency

Sufficiency is that attribute of FAME which is distinguished by the extraction of all possible information from the observed sets of data.

1.3 THE VALUE OF FORECASTS

All decisions invarably involve predictions. For, if there were not a concern for the future a decision would not be required. Simply stated, a manager must be able to forecast the future, since today's decisions largely influence tomorrow's occurrences. It is the probable impact of these occurrences which dictate today's decisions. It is this concern with key program elements, such as program cost, schedule, and performance that prompts the introduction of new techniques to the field of program control.

In any program subject to management control, budgets are established which designate a sum of appropriated money which can be spent over a specific time for a desired output. This output could, as an example, be a number of production units. With goals and limits established, management usually institutes some type of reporting system in order to measure progress against these goals and limits. In principle, this procedure is a familiar and simple enough means for maintaining control. It amounts to taking a look at existing conditions and determining whether progress is acceptable. If the rate of spending suddenly rises, the expenditure rate may result in costs per production unit exceeding the sale price. If the trend in spending can be sensed at an early date, the problem may be solved by instituting cost reductions or increasing the sale price of the production unit. If the problem is recognized too late in the program, the result could be substantial losses in time, dollars, and performance.

In many respects technical parameters can be viewed along similar lines. Technical budgets (control limits) are established which are compatible with the over-all technical program requirements. These requirements are then further detailed into technical requirements by specifications at each program tier. These specified controls then become the technical budget. These budgets are not irrevocably fixed, that is there may be several other combinations of parameters which will be compatible with over-all program objectives. On a very complex engineering development program such as Apollo, these budgets are established using the latest "state-of-the-art" data and the highest caliber of technical personnel. In general, there are three supporting areas of engineering know-how: proven engineering facts, engineering calculations based on proven theory, and estimations of what can be accomplished based on knowledge obtained from previous programs. Hence, at the beginning of a program there is an uncertainty that the established technical requirements are near optimum or even that they are truly compatible, or that the work can be accomplished within the monetary and schedule constraints.

1.3.1 THE IMPORTANCE OF TIMING

As a program progresses, problems are recognized and requirements are adjusted by conducting trade-off studies. However, it is not enough for management to base requirement changes on current status.

Consider the situation of the program manager who is given the program status charts shown in Figure 1-1. He is generally aware of a rising value of the particular item reported, but relies on assurances from many sources that the program is being brought under control. Consequently, no further action is taken.

Next month, the shock arrives. The growth, illustrated in Figure 1-2, has not abated. The value is now over its control limit and continuing to climb. Corrective actions, which now must be made late in the program will result in inordinately large expenditures of time and money, with concurrent scrapping or reworking of hardware items. Delays are now to be anticipated, since reworked parts, must be requalified with schedule slippage in turn reflected in an ever widening wave throughout the program.

The key ingredient supplied by FAME is the timely recognition of problems and determination of their magnitude such that program disturbances can be minimized.

Figure 1-3 illustrates the impact of timing on the progress of a program which has an established control limit and a target (delivery) date. Line "A" represents current, on-going progress; dotted line "B" indicates a forecasted trend where recognition of problems and resultant management action are not taken until late in the program. Line "B" graphically illustrates the necessity for management to recognize problems

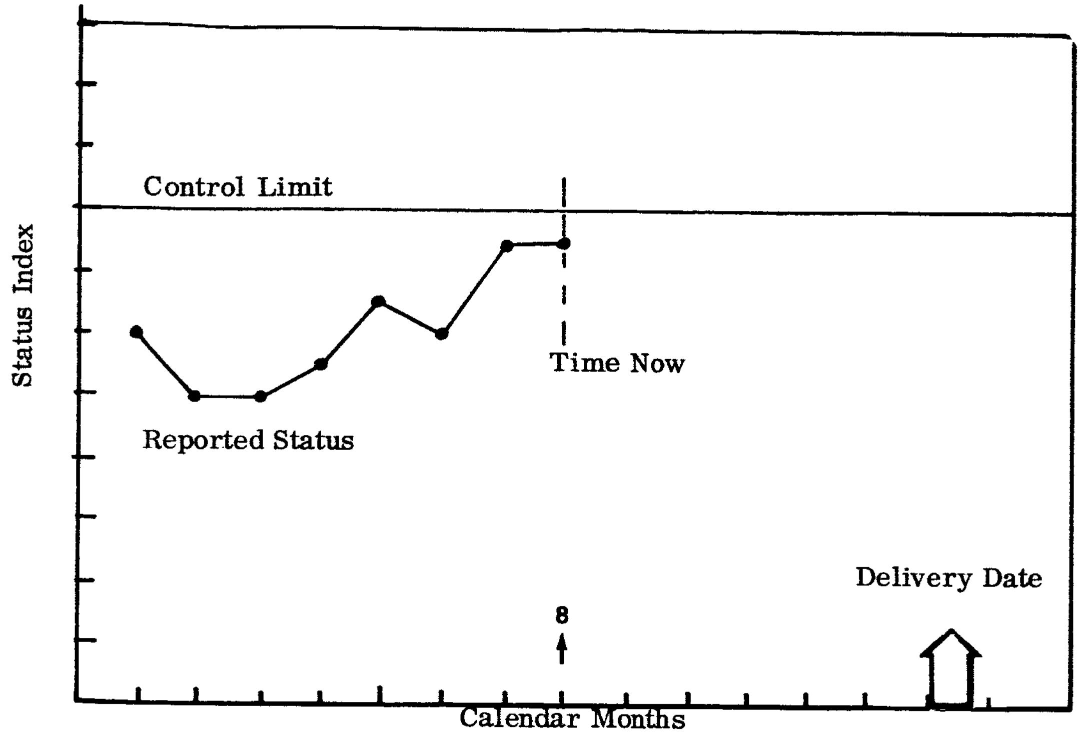


Figure 1-1. Typical Program Status as Seen at Month Eight

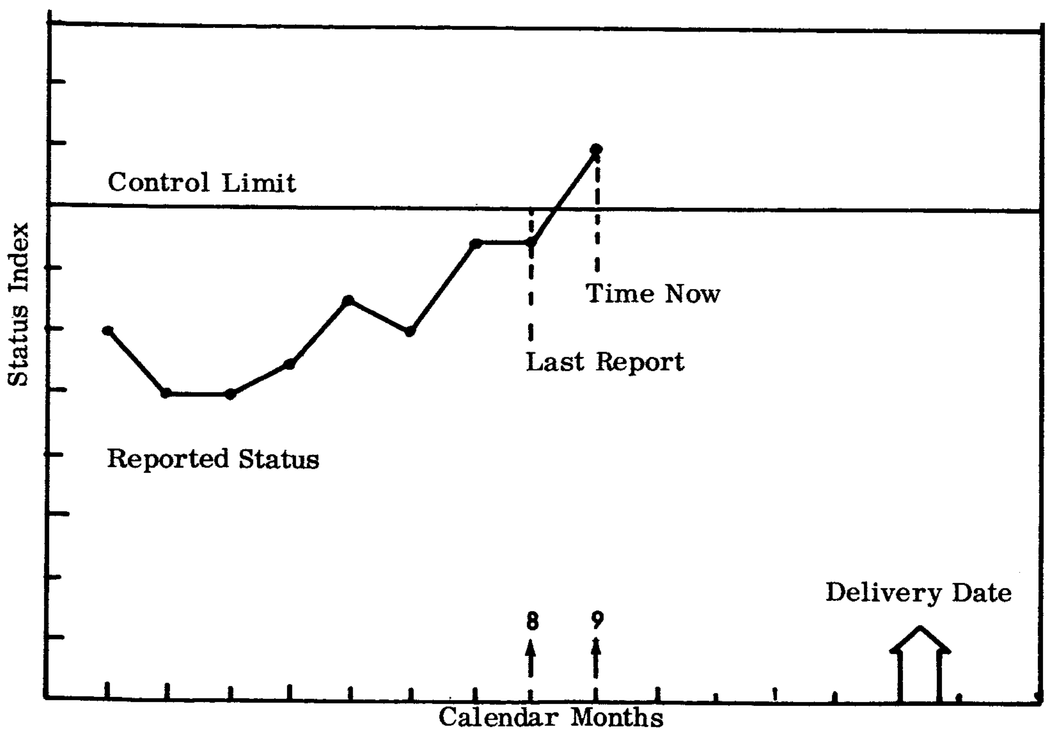


Figure 1-2. Typical Program Status as Seen at Month Nine

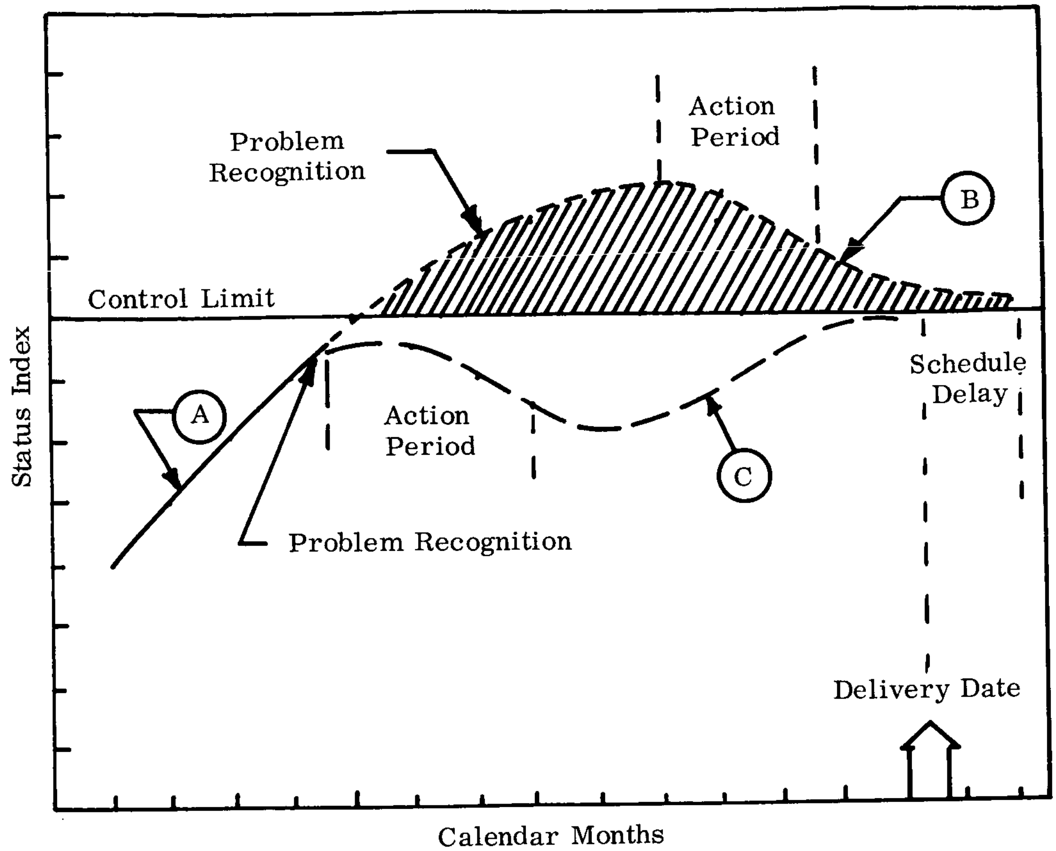


Figure 1-3. Impact of Timing on Program Control

early enough to economically take the necessary corrective actions. Line "C" indicates the results of early corrective action where managers have anticipated problems.

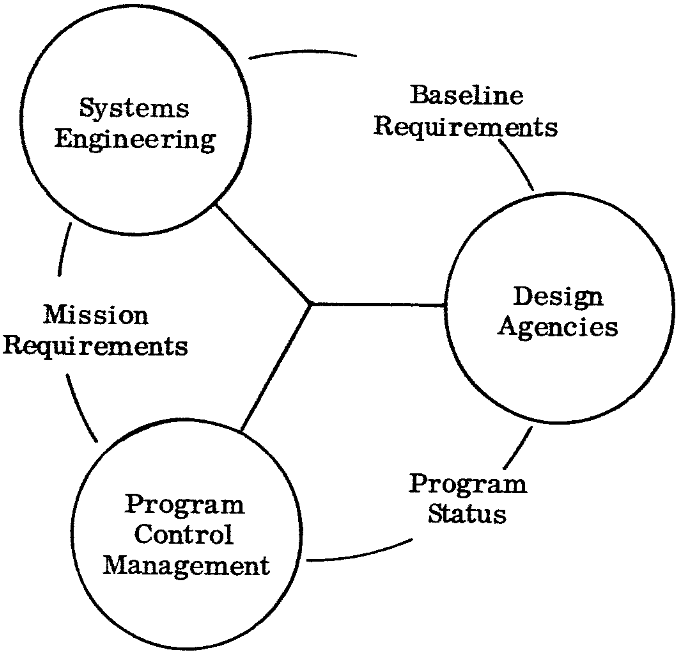
Actually, of course, real-life situations are of considerably greater complexity. Many independent contractors are engaged in design, production, test, and operation of a myriad of interdependent space vehicle components.

1.4 ORGANIZATION AND OPERATION OF FAME

1.4.1 PROGRAM CONTROL ELEMENTS

Three organizational elements are of special interest in Program Control:

a. Program Control Management.
b. Systems Engineering.
c. Design Agencies.



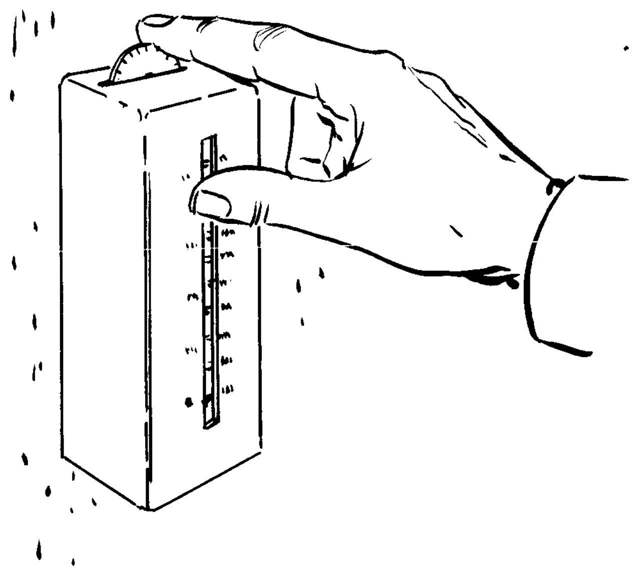
Management responsibilities include keeping a project within control limits; constant surveillance to assure that these limits provide for the best utilization of time and money, and the successful design and development of the end product.

The ingredients necessary for program control include:

a. Mission requirements.
b. Baseline requirements.
c. Program status (data and displays).

Mission requirements establish the over-all objectives of the program which are of highest importance. The baseline requirements are the control limits for the myriad of constituent elements which go into the complex equipment being designed to meet mission requirements. For the Apollo Program, an operational mission requirement is the successful landing of Astronauts on the moon; and their safe return. Baseline requirements or control limits have been established for the individual space vehicle stages and modules, for example, for their weights and performance. Program status information supplies the necessary data on progress to permit program control to function.

In analogy, program control is much like the operation of a room thermostat. The mission requirements are analogous to the desired temperature for comfort. Baseline requirements correspond to the setting of the thermostat, as well as establishing the limits of operation of the heating or cooling equipment. Operation of a heating and cooling system is analogous to the actions taken by the design agencies to produce the required result. Room temperature, like status data, is sensed and corrective actions are produced accordingly by the thermostat. So far, there is nothing radically different from conventional program control techniques.



1.4.2 THE TIME DIMENSION

The analogy of program control to a thermostat changes, however, when a new dimension, time, is added to this control system. On complex programs, such as Apollo, as well as in many similar areas of management concern, there is a recognized need to meet requirements not today but at some point in the future, usually at the time of launch -- "the moment of truth." Because the design, tooling, production, and development cycle involves a period of many years, information is required by management which reflects not only present status, but also anticipated problems. By looking ahead, costly emergency actions and schedule slippages can be avoided.

Incorporation of this dimension of future time in program control can be achieved with FAME. This system was developed to meet the expanding needs of Aerospace Program management. FAME has demonstrated its value for Apollo Program Control and appears to have potential application to numerous other programs. Today, FAME techniques are providing program management with valuable information of proven accuracy.

1.4.3 ORGANIZATION OF FAME

The organization and operation of FAME are simple in concept. Figure 1-4 is a schematic illustration of the total process. The three key organization elements: Design Agencies, Systems Engineering, and Program Control Management are shown at the top and bottom of this chart. The large, central box indicates the relationship and nature of the Forecast and Appraisal System and encompasses the several kinds of operations performed by FAME.

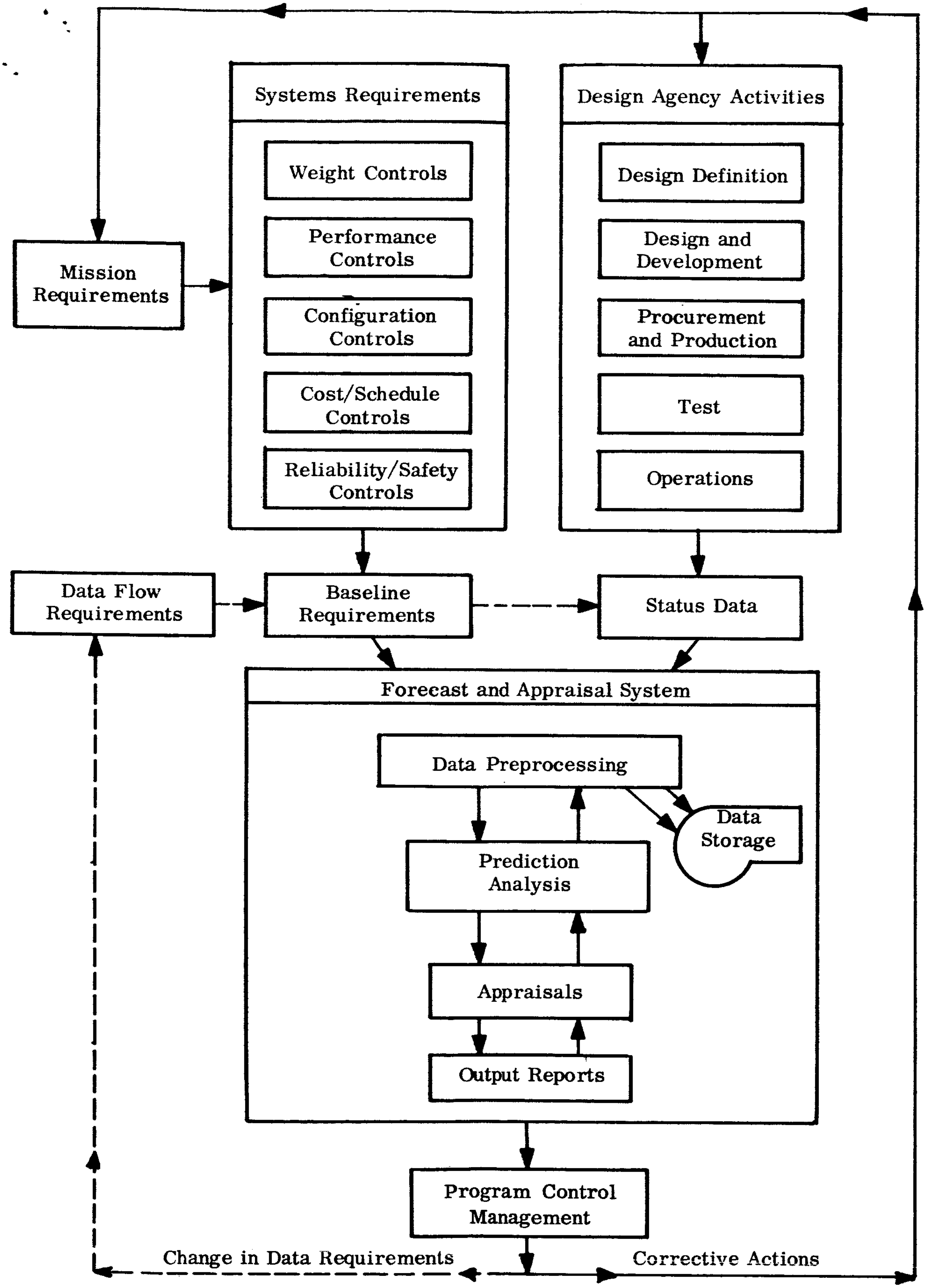


Figure 1-4. Basic Organization and Operation of FAME

The heart of this system is Forecast Analysis (shown in Figure 1-5) which anticipates the expected health of the program, using observed status and control information to produce the forecasts necessary for program appraisal. The appraisal calculations translate these forecasts into meaningful indices which pinpoint key problem areas as well as indicate the significance of problem solutions. Both actual and potential problems are identified. The criticality of suggested corrective action is noted for each

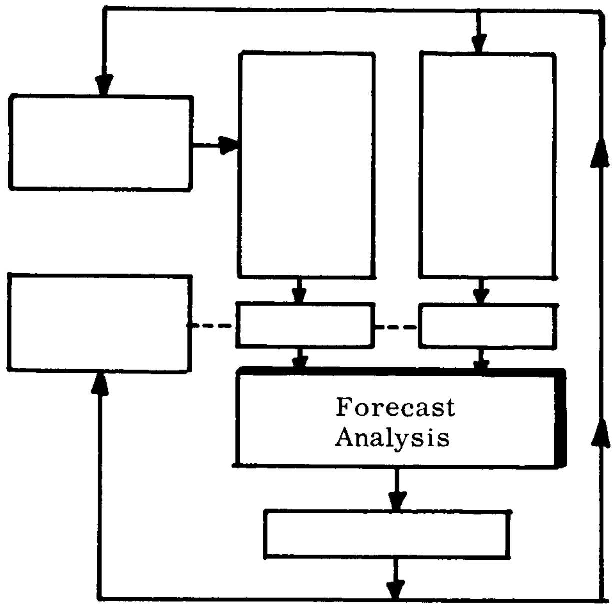


Figure 1-5. Forecast Analyses Shown as the Heart of FAME, Using the Schematic Diagram of Figure 1-4 as a Basic Reference

tier of concern, from the smallest component to the total space vehicle itself. In addition, key, program-wide interrelationships are noted so that inter-program trade-offs can be made by program management when required to correct the problems noted. The FAME system provides total program control through application of statistical Forecasting techniques, with details reported on a regular (monthly) basis to keep management appraised of progress and notified of key potential problems. The essential steps of FAME are described in simplified form in the following sections and in detail in the following chapters.

1.4.4 REQUIREMENTS

Essential to the operation of Forecast Analysis are clearly defined control limits, for without a firm basis for making comparisons or measuring progress, there can be no evaluation of progress. Mission requirements are established at the inception of the program and updated periodically but only after careful evaluation of the consequences of such changes. The mission requirements, reduced to specific baseline requirements, are displayed as the starting point of a history control chart. On Figure 1-6 two kinds of requirements are introduced: the control limit or ceiling for growth and the schedule dates of importance. The control requirements can be depicted in simplest form as two boundaries on the y and x axis respectively.

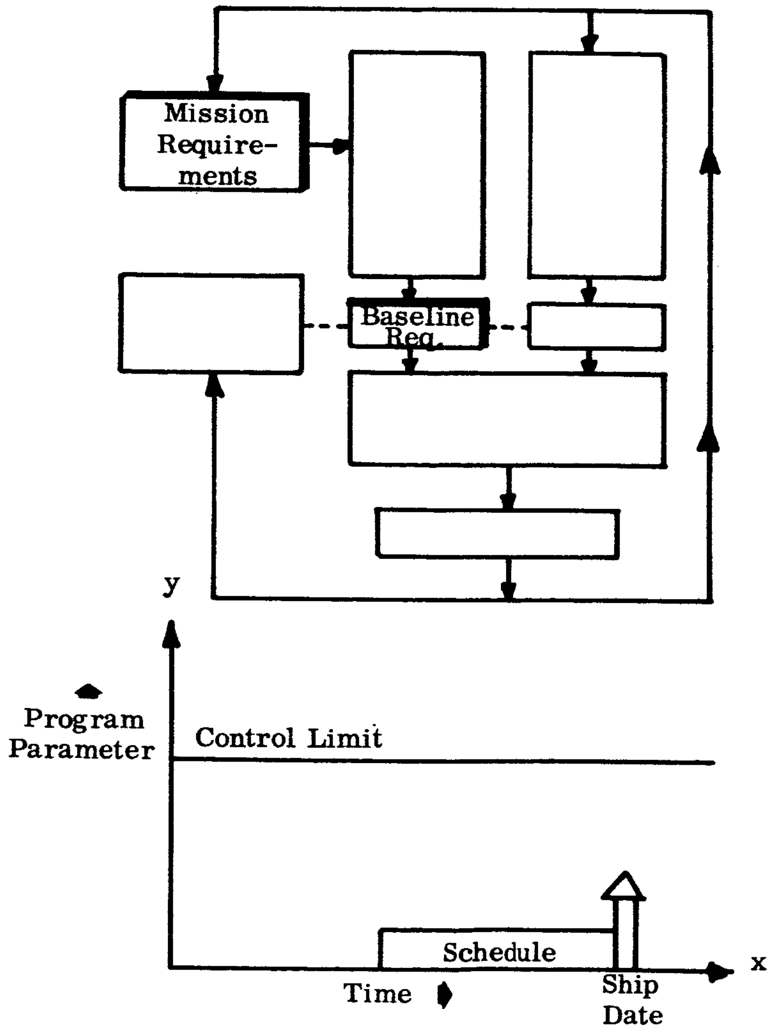


Figure 1-6. Measurable Requirements Reflected in Forecast Analysis Plot

1.4.5 DATA INPUT

Status report information is the next ingredient required. Frequently, data is generated by contractors and passed upward through many levels of management. Since such data are used as measures of contractor performance, each level in the management scale may be apprehensive about data going to higher management and a possible reluctance to supplying data may result. To overcome this reluctance, assurance about the intended use of the data is essential. Confidence can be generated by the fact that the output from the data is open for inspection and investigation by all concerned. The principal motivation for supplying data, however, is the data flow documentation requirements. For the Apollo Program this requirement was established for weight/performance control by the "Weight and Performance Data Submittal Directive." The data supplied monthly shows observed values of weight and related data and would be displayed on a weight-time control chart, such as illustrated in Figure 1-7. For ease of reference, data points in Figure 1-7 are connected by a line, and absolute values are printed alongside the plotted curve versus months.

1.4.6 DATA PRE-PROCESSING AND FORECAST ANALYSIS

Even though data provided by design agencies are accurate and authentic, changes in ground rules frequently occur and result in data presented on an inconsistent basis. To insure that data are being viewed on a consistent basis, the data is treated by a normalization process to remove the influence of non-random changes (delineated in paragraph 4.4). Following this the Forecast Analysis calculations are performed. This involves assessing inherent growth trends of the normalized, unbiased data and then solving mathematically for a forecast line which is extended to the shipping or launch date.

This process is graphically shown on Figure 1-8. In this example, the forecast line exceeds the control limit, upper limit, indicating that management action is necessary.

Predicted excesses or deficiencies to be removed are termed "buyoff" since this reduction is presumably purchased at some cost in dollars, scheduling or reduced technical performance.

1.4.7 APPRAISAL

Calculations are then performed to express this buyoff in terms of over-all program parameter numbers, designated as "deficiency." The seriousness of the excesses over the control limit are assessed and assigned a "criticality" or "decision relevancy" rating which in effect indicates the impact such deficiencies may have on the program.

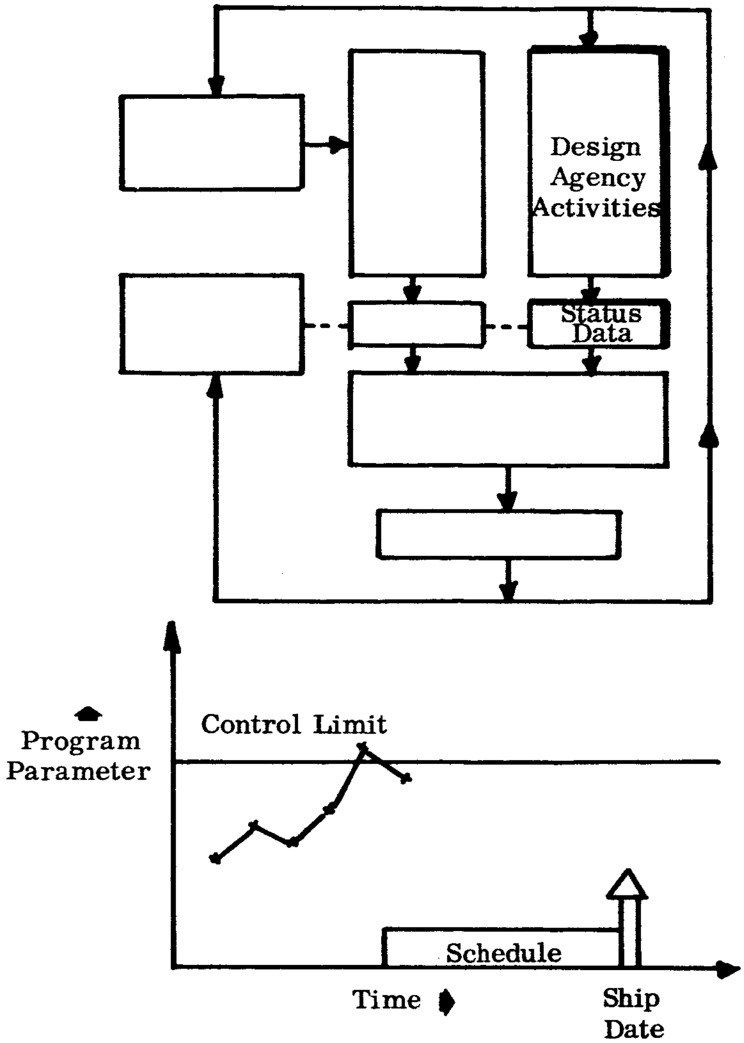


Figure 1-7. Measurable Status Reflected in Forecast Analysis Plot

The extracted information, together with any action recommendation, is transmitted formally to management via FAME reports which are issued regularly. A typical report currently being submitted for Weight/Performance is the Forecast and Appraisal Status Transmittals conveniently named "FAST".

1.4.8 MANAGEMENT DECISIONS

The most apparent management decisions to be made from these FAST (Forecast and Appraisal Status Transmittals) reports and graphically shown on Figure 1-9 are:

a. To make the necessary buyoff at the earliest consistent date, or,

b. To raise the control limit to allow for the anticipated growth utilizing trade-offs in other system parameters.

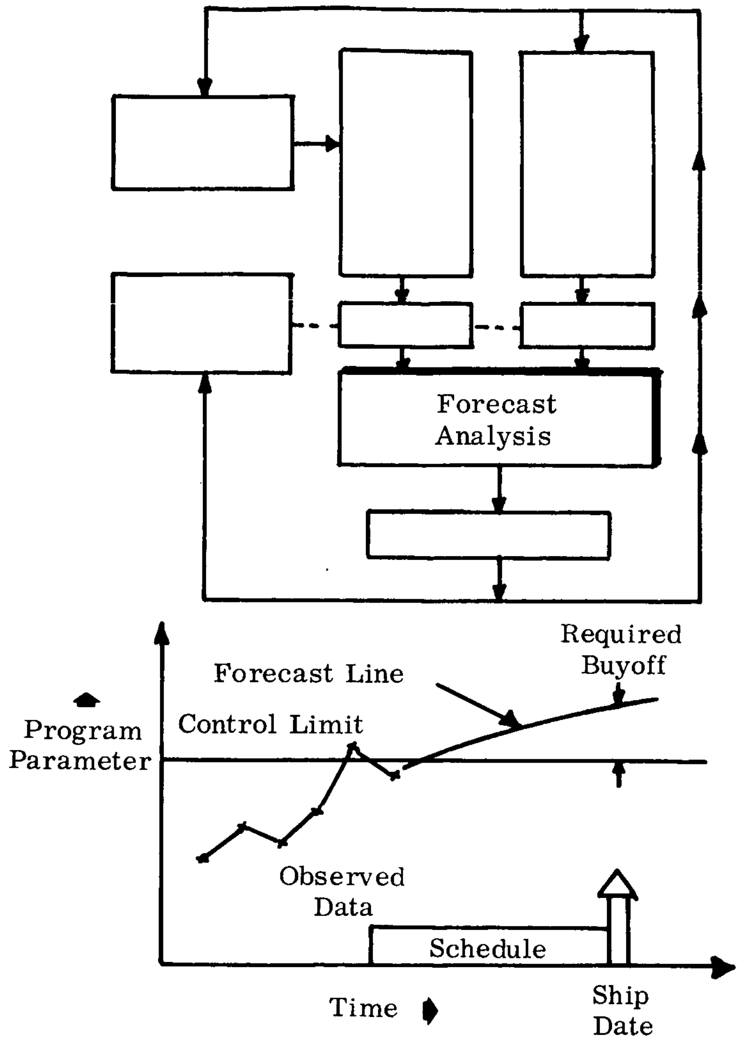


Figure 1-8. Forecast Analysis Plot Showing Forecast Line and Buyoff

While either of these, individually or in combination, is possible, the first management action customarily consists of providing for the conduct of studies to define the best method for achieving the indicated buyoffs. At this point the process reverts to the design agencies who study and with program management implement the proper change as indicated by such studies. The Forecast Analysis operation thereupon returns to its original surveillance status.

Final judgment about the rate of program progress and any actions to be taken are made by management. To expedite the making of decisions, a degree of criticality is estimated for each problem identified by the analysis.

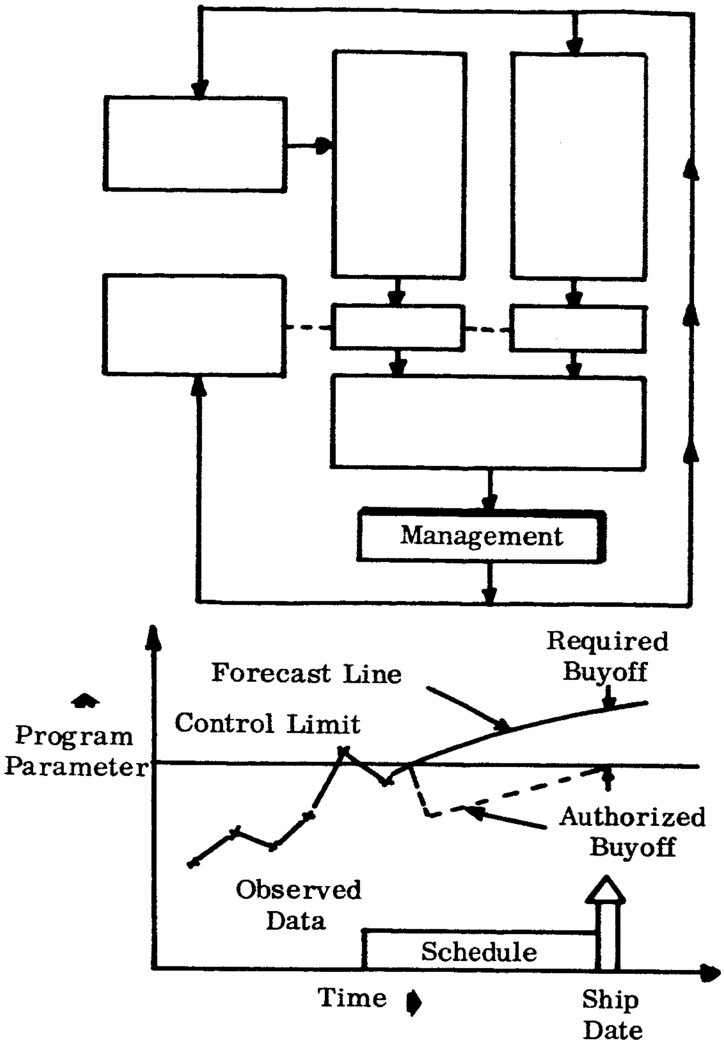


Figure 1-9. Program Management Decision

The criticality notation pinpoints mission weight and performance weaknesses and aids in assessing, on a consistent basis, the magnitude of the problems likely to be encountered in meeting weight and performance design criteria. The four degrees of criticality may be defined as follows:

a. Critical - High probability that forecasted deficiencies will seriously impede successful accomplishment within control limit and requires major program decisions.

b. Major weakness - Substantial probability that forecasted deficiencies will impede successful accomplishment within control limit. This alerts management to a potential problem due to a deficiency being higher than normally acceptable associated with this limitation.

c. Minor weakness - Probability that forecasted deficiencies are acceptable and consistent with similar deficiencies that were successful in the past. No action or decision is required.

d. Good shape - Excellent probability that forecasted values will continue below control limit.

The outputs of Forecast Analysis, in short, can be compared to a health chart which shows current status and forecasts the health of the program at launch time.

1.5 DETAILED DESCRIPTION OF THE FORECAST AND APPRAISAL SYSTEM

Specific elements which are included in the routine exercised by the FAME System are listed in Table 1-1.

Table 1-1

Elements of Forecast and Appraisal System

Data Pre-Processing

a. Assessment of Mission Requirements, Trade-off Factor Extraction
b. Change Analysis (Identification of Non-Random Changes)
c. Normalization (Removal of Non-Random Changes)
d. Time Transformation (when required)

Forecast Analysis

e. Trend Analysis Using Observed Estimated/Calculated/Actual Values and Mathematical Models
f. Trend Model Selection
g. Confidence Limits - Probable Error
h. Forecast Line Bias
i. Forecast of Program Maturity Factors
j. Forecast Line Bending with Program Maturity
k. Forecast Line Adjustment Due to Expected Changes
l. Targeting Analysis

Post-Trend Processing

m. Summing of Trends
n. Performance Calculations
o. Calculated Deficiencies, Buyoffs, Performance Adjustments
p. Decision Relevancy (Criticality)
q. Trade-off Factor Derivation
r. Cost Change Analysis
s. Schedule Slip Analysis
t. Reliability Change Analysis
u. Validation of "Follow-on" Vehicles

A brief explanation is included to give a better understanding of what these elements are.

a. Assessment of Mission Requirements and Trade-Off Factor Extraction - These data define the performance constraints and provide the necessary factors to facilitate relating predicted problem magnitudes to a common base.

b. Change Analysis - The analysis of monthly changes to identify non-random changes which are not mathematically a part of expected growth.

c. Normalization - Process which adjusts data for non-random changes noted in b, as well as for other changes which are mathematically excludable.

d. Time Transformations - Required to adjust progress to match program time rather than real time. Such a transformation eliminates the problems of forecasting when there have been lengthy delays due to program stoppages or other program time disturbances.

e. Trend Analysis - The observed points are assessed and a curve fit made through these data which will be extended to the critical future date. Several mathematical models are available to facilitate such analyses.

f. Trend Model Selection - The selection of the particular model which best fits the inherent growth patterns.

g. Confidence Limits - Determined statistically about the mean trend line for both observed and predicted time periods. Probable Error is an expression used to describe the range of expected errors in the mean predicted weight at the final date and is numerically equal to the difference between the upper confidence limit and the mean.

h. Forecast Line Bias - Having found the trend line, the forecast line is mathematically unbiased so as to extend from the most recent data point into the future time domain.

i. Program Maturity Factors - Forecast factors made from a knowledge of expected progress and comparison of actual maturity with this preselected model.

j. Prediction Line Bending - Program maturity factors are in turn used to improve the forecast line in the future time domain to deflect the forecasts in accordance with known behavior.

k. Adjust for Expected Changes - Analysis of observed monthly changes to permit forecast of rate of incorporation of buyoffs which are also used to correct and shape the forecast line.

l. Targeting Analysis - Final forecast results are observed and trended to indicate prediction accuracy.

m. Summary of Trends - Predictions made for pieces of the total, these are summed to produce predictions for the total part.

n. Performance Calculations - Where required, performance calculations are performed to permit expressions of deficiencies or buyoffs on a common basis for direct comparison.

o. Deficiencies, Buyoffs - The end result of Forecast Analysis is the determination of deficiencies and buyoffs which express the required management action in specific numbers.

p. Criticalities - The impact or risk associated with the noted problems are assigned a criticality rating by a final evaluation process which weighs related program constraints.

q. Trade-Off Factor Derivation - Trade-off factors, derived during the performance calculations are provided for Management use in making adjustments between corrective actions and program constraints.

r. Cost Change Analysis - The costs associated with making the corrective actions, noted as buyoffs or deficiencies, are estimated from program funding rates.

s. Schedule Slippages - Estimated from current and historical relationships between program changes and schedule changes.

t. Reliability Change Analysis - Reliability effects associated with required buyoffs can be calculated from existing Reliability Models.

u. Validation of "Follow-On" Vehicles - The experience on Vehicle Number 1 and the extension of such experience to the vehicles which follow.

Numerous additional elements can be included in Forecasting Analysis for other applications. Accordingly, any system of Forecast Analysis must be constructed with maximum flexibility and the ability to select one or many potential analytical routines. The basic elements, however, are those listed above and are described in greater detail in subsequent chapters.

CHAPTER 2

FORECAST AND APPRAISAL SYSTEM CONCEPTS

2.1 INTRODUCTION

While subjective evaluation almost always enters into the decision making process, today's complex technical programs call for an increasing amount of objective, quantified information upon which to base decisions. The probability theories and sampling procedures developed by mathematicians have proven useful in quantizing decisional problems and are being used increasingly in large-scale industrial and Government programs. Evidence of this is found in the Government-wide utilization of PERT (Program Evaluation and Review Technique) and similar techniques.

In the FAME approach, useful forecasts of probable events are generated by plotting present events and generating trend lines to determine program direction. The underlying pattern and direction of these trends are then translated into quantitative forecasts. This procedure is familiar enough, having wide application in instances where there is a continuous recurrence of similar events which lend themselves to fairly precise measurement. But in large programs where each unit is designed and constructed by a different contractor, the discernment of an underlying trend of development becomes quite complicated. The following discussions illustrate how this is accomplished through the FAME concept. The definition of the Forecast and Appraisal System is followed by a brief discussion of the techniques used to implement it. Detailed description of the techniques are found in Book II.

2.2 THE SYSTEM CONCEPT

A basic tenet of control system theory is that the stability of a process output can be improved by introducing control actions proportional to the rates at which output errors occur. This involves anticipating the future behavior of the process so that corrections can be made before the process goes "out of control." Program management is aided by this feedback of information because forecasts of anticipated program behavior provide a decidedly clear advantage over a management control plan based on reports of current status only. A general block diagram of the Forecast and Appraisal System, in a program management configuration, is presented in Figure 2-1.

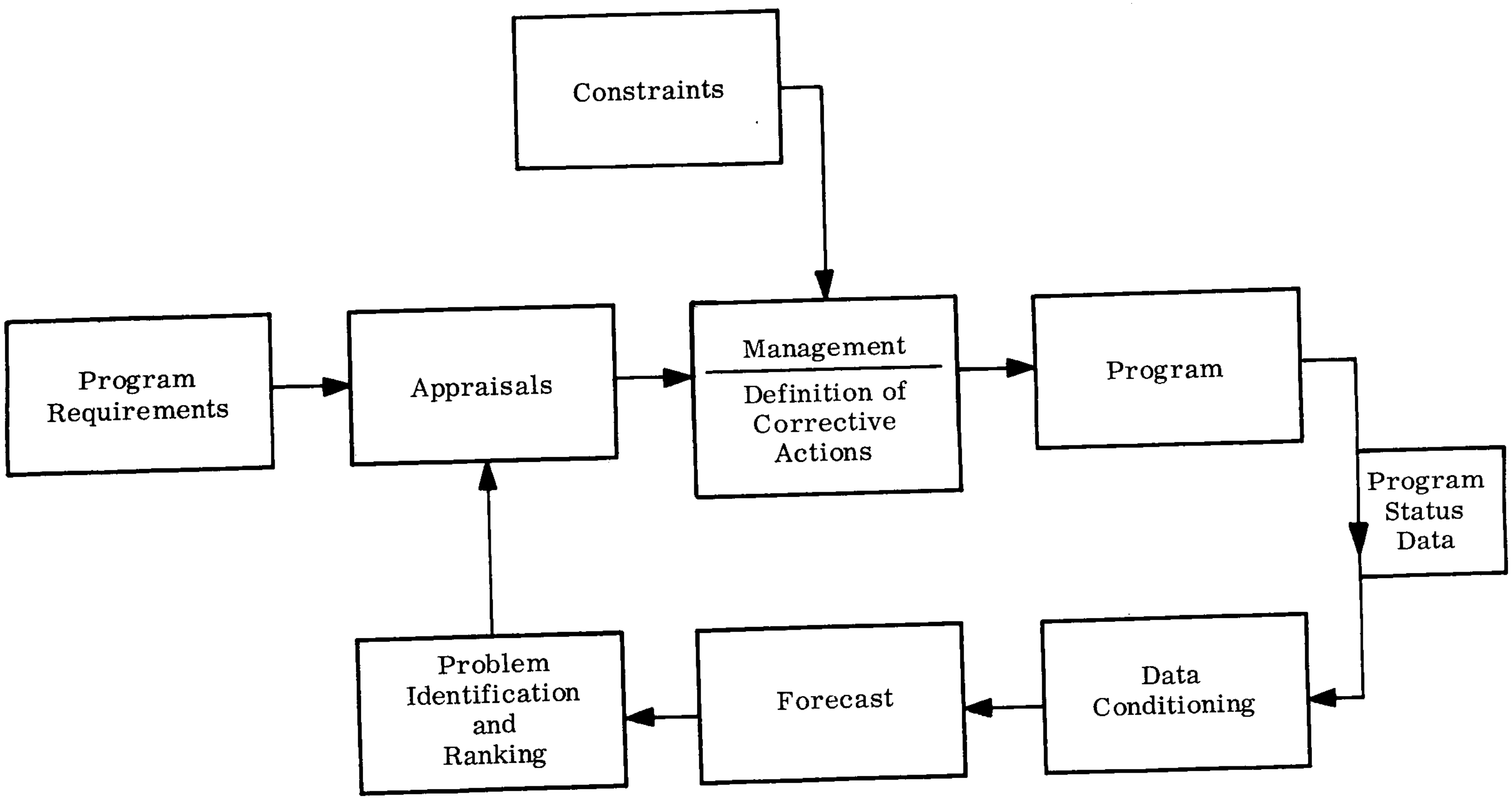


Figure 2-1. Analogous Control Loop for Forecast and Appraisal System

The program or process to be controlled is shown providing status information to the system. This information is generated periodically (say, monthly) and the total of such data received to date is used to predict the program's status at some future time. These forecasts are examined in light of known constraints and interrelationships among the program parameters being tracked, to define and rank problems predicted to occur in the future. The forecasted identity of the problems and their criticality are based on the assumption that remedial action will be taken in the future. Management must then evaluate the problems in view of program requirements, constraints, already planned actions and various trade-off relationships to determine what new or modified corrective actions should be initiated to prevent the forecasted problems from actually occurring. Such actions are then transmitted to management at the program-office level for their implementation. The results will eventually be reflected in the status data, thereby producing revised forecasts from which the program management can determine the effectiveness of their decisions.

This predictive ability is thus seen to provide management with a means to prevent otherwise inevitable problems. The result is a smoother running program experiencing fewer major problems calling for quick response with associated overshoot.

An obvious extension of such a system concept is the optimization of its performance. That is, development of a means for minimizing the deviations of the program status from a pre-established "trajectory" or to minimize the cost of program problems or some other function of performance. One common approach is to construct an appropriate model of the process and exercise it by introducing a variety of inputs and noting its response. That response, optimizing the selected objective function, identifies the appropriate input - management directed corrective action, in this case. This capability is not a part of FAME at this time but would be a valuable addition.

2.2.1 GENERATING AND CONDITIONING STATUS DATA

The feedback information generated by the program must be meaningful in the sense that it represents salient characteristics of the process and contains sufficient information for control purposes. Naturally, the variables pertinent to the prediction process must be defined for each program. In manufacturing and construction processes the technical variables are readily measurable. The critical dimensions of an item, the number of defective items produced, etc., are physical quantities which are subject to actual measuring techniques and can be controlled by the well established methods of statistical control.

There are, however, economic and technical variables which are neither easily measured nor amenable to established traditional control techniques. Such variables are especially common to research and development programs. They are characterized by physically unmeasurable quantities and by relatively low frequency of occurrence. They are subject, therefore, to the usual degree of error attached to estimated measurements. Further, they are not measured often enough to lend themselves to sampling and to statistical analysis. If, in spite of these characteristics, the observed variables represent significant elements in the exercise of program control, some means must be found to include them in the control loop.

The fact that they can indeed be included is expressed in the following theorem which resulted from the application of FAME to just such data as is illustrated later in the book:

> Theorem - Specific measurements of program parameters such as weight, cost, performance, can be treated statistically as though extracted from a large population whose expected value varies with time in a "natural growth" progression.

Requirements are thus established not only for including these "non-physical" parameters in the control loop but also for predicting their future behavior. Before considering methods for obtaining the necessary predictions, the nature of the data or value of the parameters of interest deserves emphasis.

2.2.2 DATA CHARACTERISTICS

As a general rule relevant data will be generated at some fixed frequency. For a variety of reasons this frequency may vary from time to time. Also along the time axis (time is the usual independent variable) it is not unusual for the data to reflect accelerations and decelerations in the process. Thus, even at a fixed frequency, the data implicity include the effects of variations in the time process due to changing priorities, etc. For these reasons the information contained in the independent variable must be examined carefully.

A similar situation holds in the information content of the dependent variable, as it too is subject to spurious variations. This is a result of the values not being actual measurements of some physical characteristic but rather of computations based on estimates. As such, they are subject to common sources of error - incomplete information, arithmetical mistakes, garbled instructions, political pressures, and the like.

Often, these data are also affected by conscious and purposeful actions, such as changes in computation methods, changes in the components of a given computation, and changes in specifications.

It can be accepted, then, that the data to be used as bases for prediction and control are two dimensional and that both dimensions are subject to the effects of both known and unknown (or detected) actions. A beginning strategy is to remove the effects of those data changes which are clearly assignable; that is, remove those changes known to have been caused by purposeful or non-random actions. If done in both dimensions data will be obtained which reflects only random actions and the basic, underlying process which is to be controlled will be highlighted. The data then can be considered as points representing the true state of the process, modified by the effects of unidentifiable or random events.

2.2.3 STATUS FORECASTING

With this knowledge of data characteristics, attention can now turn to the task of forecasting the future behavior of the process on the basis of the patterns assumed by the data. Basically, the forecasting problem is two-fold. Before any forecasting as such can be done the trend of the data generated to date must be discerned. That is, a model must be formulated which will represent the process producing the data. The model must relate the independent and dependent variables in a way that permits determination of the value of the dependent variable when related to a specified value of the independent variable. For example, if time and project cost are the independent and dependent variables respectively, the model would be: cost = f(time). Then, for any value of time, a corresponding cost figure could be computed. The model is formulated in such a way that it represents, in some optimal sense, the data in hand. The model is then said to represent the process. Once the model is established, predictions can be made about the performance of the variables.

The usual technique for establishing a model is to "fit the curve" to the data. This defines the mathematical function which fits the data in some best sense. For example, the data might tend to represent a linear function of the variables, so a straight line would be "fitted," perhaps using the method of Least Squares. Although this "fitting" approach is very useful and easy to implement, it lacks the power to provide one important piece of information -- it cannot give an indication of the credibility of resultant prediction. To obtain such information, one must turn to a statistical treatment of the data. The statistical equivalent of "curve fitting" is Regression Analysis.

This technique, especially through the Maximum Likelihood Estimation technique, provides optimal model representations (i.e., tailors a given model to the data in an optimal manner) plus giving confidence intervals for the prediction.

For the purposes of this discussion, Regression Analysis will be considered to include all techniques used for quantizing models on the basis of given data, including such techniques as Least Squares, even though it is not usually referred to as a regression technique.

The general procedure followed in a regression analysis consists of assuming one or more forms for the model and then fitting the available data to them to quantize the model constants. If more than one form is considered, the quantized models can then be compared on the basis of some "goodness-of-fit" measure and the best one selected as the process model. As new data are received, the model constants may change, and even the "best" model form may change. Continuous review in the form of repeated regression analyses is necessary as long as new data are being reported.

A model, theoretically, can be an analytical expression. In practice, however, computational and other considerations tend to narrow the field to those containing only two or three constants to be evaluated.

Typical examples are the following:

$$y = a + bt$$

$$y = a + bt^{-1}$$

$$y = \frac{1}{a + bt}$$

$$y = ab^{t}$$

in which the constants to be evaluated are a and b. There is one formula, the polynomial, which by taking a sufficient number of terms can be used to fit any set of data. This number may be unwieldy, however, and a simpler form can be used which is easier to handle and yet gives no significant loss in representation.

In some cases inspection of the plotted data can result directly in the selection of the best form. The data may clearly indicate a linear trend, in which case the $y = a + bt$ form would be used. If the data tend to indicate a linear trend when plotted on semilogarithmic paper, the form $y = ae^{bt}$ or $y = ab^t$ would be used. But, in most cases, the choice is not so clear and, as mentioned previously, more than one approach must be tried and tests applied to determine the preferred one.

Another useful regression approach for predictions is known as "stepwise" regression. This technique, rather than assuming a fixed or specific form for the process model, starts by assuming a general n^{th} order polynomial (say, of order six). Working down from the n^{th} order, successive sets of derived coefficients are tested for significance. This might be done by examining the sensitivity of the fit quality to the order of the polynomial. In this way, an optimum order is determined below which the fit deteriorates rapidly and above which fit improvement is slow.

Recursive estimation can also be employed. This technique is generally desirable when the data sets are large and/or there are numerous model constants to be quantized. If the constants (i.e., model parameters) are denoted by θ_i, let $\theta_{i,T}$ denote the parameters evaluated at time T. When observations are made subsequent to time T, say at T + 1, the recursive estimation technique computes $\theta_{i,T+1}$ on the basis of $\theta_{i,T}$. This would appear to save computation time as the $\theta_{i,T+1}$ computations do not start "from scratch" each time but start with the stored values of the previous computation.

Autoregressive techniques also hold promise. These do not start with the assumption of some mean value function for the model but instead utilize identifiable tendencies in the most recent data. That is, the later data are treated as more meaningful and so are used as the bases for prediction. Advances in these techniques are recent and the subject of considerable interest. One such advance is discussed in, "The Role of Spectral Analysis in Time Series Analysis" by Dr. E. Parzen. Quoting from this report*, "Given an observed time series of finite length, or a time series derived from it, one defines various sample spectral functions such as windowed sample spectral density functions and distribution functions. Their properties can be determined for each possible model one desires to consider for the observed time series. Consequently, they can be used to form estimates of the parameters characterizing the model. Further, they can be used to determine an appropriate model by comparing

*Technical Report No. 2, 12 July 1965. Prepared under Contract Nonr-225(80) (NR-042-234) for Office of Naval Research. Dr. E. Parzen - Department of Statistics, Stanford University.

the actual appearance of these spectral functions with their expected appearance under the various models; that model for which the correspondence is closest is considered the most likely.

An obvious question to ask about any computational scheme is, "How well does it perform?" The need to answer this is very great in the case of models designed to represent processes and forecast their behavior. The effectiveness of a mangement or control function using forecasts is determined by the quality of the forecasts. The only sure way of measuring this quality is to test the forecasts against the observed data; that is, when extrapolated beyond the observation range they are not a yardstick for measuring quality - this is best done within the observation range. The point can be visualized more easily by considering the following:

> Suppose the data set consists of 100 points. Using say the first 50 as a basis for forecasting how close is the forecast value of the 100^{th} point to the observed value of the 100^{th} point?

This example is oversimplified, of course. One must design a validation program that tests the particular techniques developed against the objectives.

One might want to assess the sensitivity of the predictions to the size of the data sets, to the values of the model coefficients, to pre-prediction removal of non-random change effects, to the different models used, etc. The general term to describe this activity is Error Analysis, for which there are many techniques available. New ones can be developed to fit specific situations.

It was mentioned earlier that one of the advantages of using maximum likelihood estimation is that it permits establishing forecast intervals. These intervals define a range of values about the predicted value within which the actual value is expected to fall a given percent of the time. The usual case is to define the 95 percent confidence limit. The quality of the forecasts is inversely proportional to the size of the prediction interval for a given confidence coefficient or percent level.

To obtain a prediction interval it is necessary to know the distribution of the errors about the forecast line. The interval is then stated in terms of the prediction value and the number of error distribution standard deviations (σ_e) corresponding to the desired confidence coefficient. For instance, if the errors are normally distributed and a 95 percent confidence interval is wanted, the interval would lie between $\pm 1.96\ \sigma_e$.

The confidence limits are then found by adding and subtracting 1.96 σ_e to and from the predicted value. If σ_e is not a known quantity but rather an estimated one, or if the sample size is small, the Student t distribution would be used. The interval size is then a function of sample size as well, approaching the normal distribution asymptotically as the sample size increases to say 30 or more.

Greater detail on this subject is given in later chapters. It is enough at this point to note that this "confidence limit" measure of forecast quality is very desirable and that it can be obtained when Maximum Likelihood Estimation is used.

2.2.4 PROBLEM IDENTIFICATION, RANKING, AND APPRAISAL

When appropriate operations on the data have been performed and predicted histories for the process variables of interest have been generated a reasonable question to ask is, "How can the results be presented so as to be of most use in the management or control functions?" Specific answers to this question depend upon the particular process in question and the management philosophy employed in its control. An analogous question, "What information should be presented to management?" can be approached by examining the generic management function and the associated decision making process. In the first place, the manager needs to be continuously aware of the general state of the process under his control. Two of the by-products of the control loop discussed here are:

a. It apprises the manager of the current process state.

b. It contributes additionally to process stability by instituting an internal reporting system.

That such a control loop exists is a large plus factor in that it serves to keep management continuously informed.

In addition to current information, predicted values should be presented. Even more important is an appropriate interpretation of the data. Problem areas must be identified when predicted values exceed pre-specified limiting values, and criticality indicated. From this information the type and magnitude of corrective actions required can be determined, as well as how important and urgent it is to implement them.

An important consideration in developing a problem criticality index is the level, within the context of the process analyzed, of the parameters being tracked. If they come from the first tier, (total program cost, for example) problem <u>ranking</u> is simple, as all interrelationships are implicitly included in the parameters. But, because of this, identification of necessary corrective actions is very difficult. On the other hand, if the parameters of interest come from a very low tier, pinpointing problems and corrections is easy but establishing the importance of the problems is difficult in as much as the parametric interrelationships may be nearly all destroyed as a result of the level of the examination. Then there is the amount of computation involved in the prediction activity. It increases as the tier depth increases. Some compromise must be reached in deciding what parameters to track and at what level? Also to be weighed are the relative desirability of problem identification, problem ranking and the amount of computation involved.

Generally, some intermediate level is selected. After the problem areas have been identified, a careful assessment of the parametric interrelationships is necessary before any attempt at problem ranking is made. As an illustration of this principle, consider the following example. Suppose the problem is to track and predict the power requirements for a piece of electronic equipment being designed. As the design progresses the power requirements grow and as a result it is predicted they will exceed pre-specified limits, thus presenting a problem. But at the same time the design is proceeding so that capacity is growing. It is very possible that, although a power requirement problem is currently identified, the capacity of the power supply may well grow at a rate which at design completion will be more than adequate. In this case, a real problem doesn't actually exist because of the interrelationship between power requirements and supply.

2.3 FORECASTING TECHNIQUES

The central role played by the prediction process is evident from the preceding description of the Forecast and Appraisal System. Thus, it is no surprise that the system's effectiveness depends to a large extent upon the availability of valid means of forecasting. This capability is provided by mathematical techniques which formulate models of the process based on the set of status observations to date. These models describe the primary trends of the observation values and are used to generate forecast values by extrapolation.

In the general case, one would expect data to exhibit wide variations in patterns or trend forms. If the system is to have the flexibility to accommodate these various forms in an optimal manner, either a very general modeling technique must be used or a number of specific models must be made available. The concept discussed here is based on the latter approach.

The following paragraphs describe the forecasting techniques employed in the application of FAME to the control of space vehicle design weight. The techniques are not limited to this application however. It also should be noted that they are not all inclusive. Other particular applications, perhaps having significantly different data characteristics, may well use some of the techniques mentioned earlier but not employed in this application.

2.3.1 DATA CONDITIONING

The first step in constructing a math model is to examine the nature of the data to be utilized. The parameter of interest in this case is weight growth over a measured period of time. Along with transmitted weight data are indicators of its relative value determined by that proportion of the reported weights which is Estimated, Calculated, or Actual. As the design program advances, the actual (measured) proportion increases while the estimated and calculated shares drop. Therefore, the data becomes more credible as time passes. Typical variation in the proportions of E/C/A weights are illustrated in Figure 2-2. The utilization and value to be derived from E/C/A data, whether it be in the weight, cost, or other areas, is stated here as a theorem and is discussed more fully in paragraph 2.3.4.

> Theorem - Forecast quality (i.e., accuracy and validity) is improved through incorporation of program maturity factors.

A certain amount of variation in reported weight data can be attributed to random occurrences. If data exceeds an established acceptable level it is most likely due to design changes which are non-random in nature and which therefore must be removed from the data by a process-referred to as "Change Analysis." Ordinarily, it is planned ahead of time to take some defined adjusting action if this acceptable level of activation is exceeded, knowing full well that there is some probability that the decision to adjust may be wrong. The decision strategy should be designed so as to minimize the probability of making a wrong decision in either direction, that is, to adjust or not to adjust the data. Such considerations entail an entire field of study - decision theory - and cannot be elaborated upon here. In any case, caution must be used in deciding what action to take regarding the effects of "non-random" events.

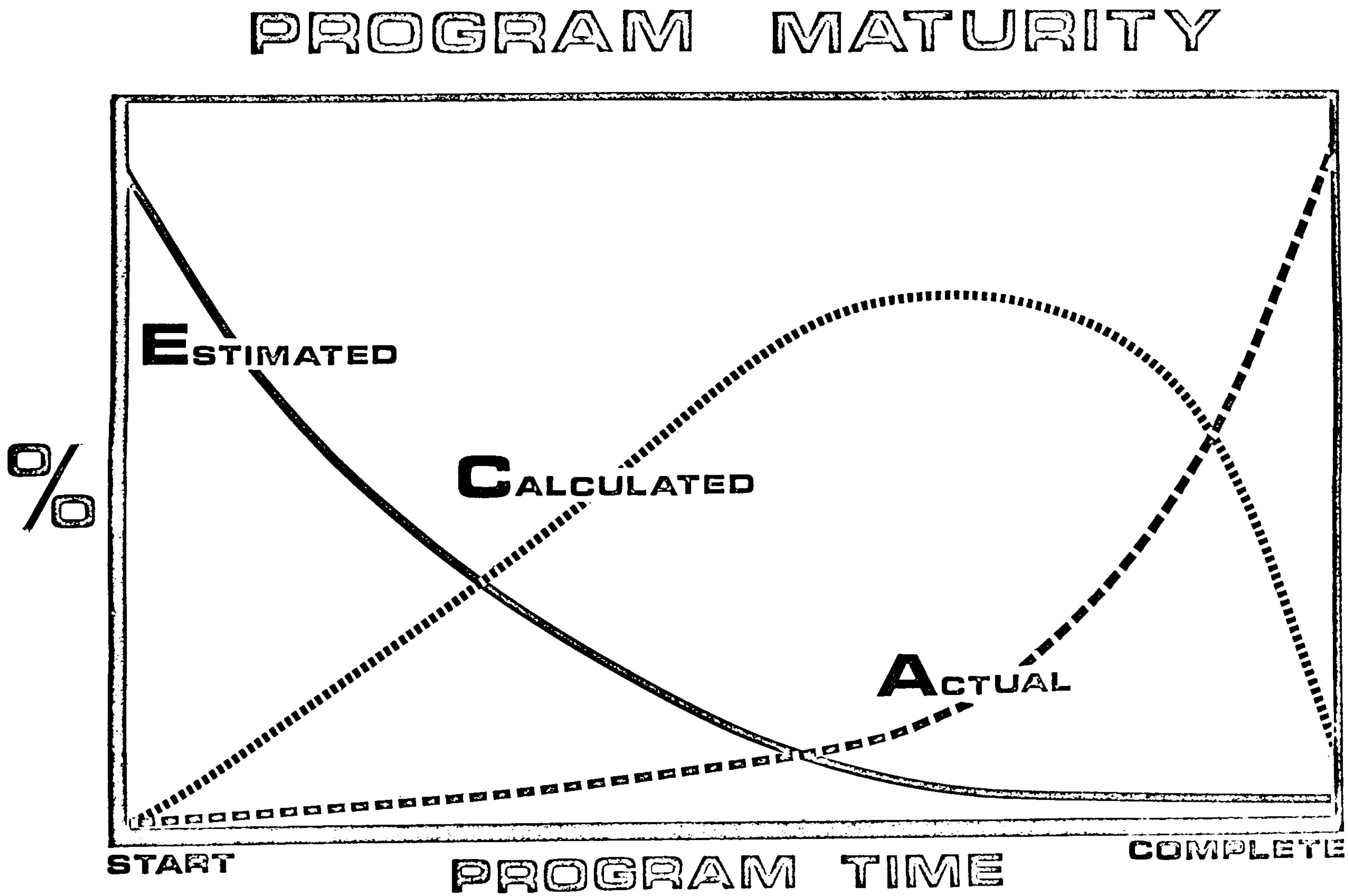


Figure 2-2. Typical E/C/A Profiles

Figure 2-3 illustrates two types of effects which may result from non-random events. One is a wild point which falls outside the historical data envelope and the other represents a step change in the data base. The first type can be handled by comparing the point's value with the historical variance. If it exceeds a specified number of standard deviations (the decision level) its effect will be removed or modified. Of course, if a reason is given for the extra large deviation, that is, its cause is assignable, there is reason enough for altering its influence. This is the case with the second type illustrated by a discontinuity in the trend line. A fruitful area for further effort is the development of a means for identifying such discontinuities where the cause is not known.

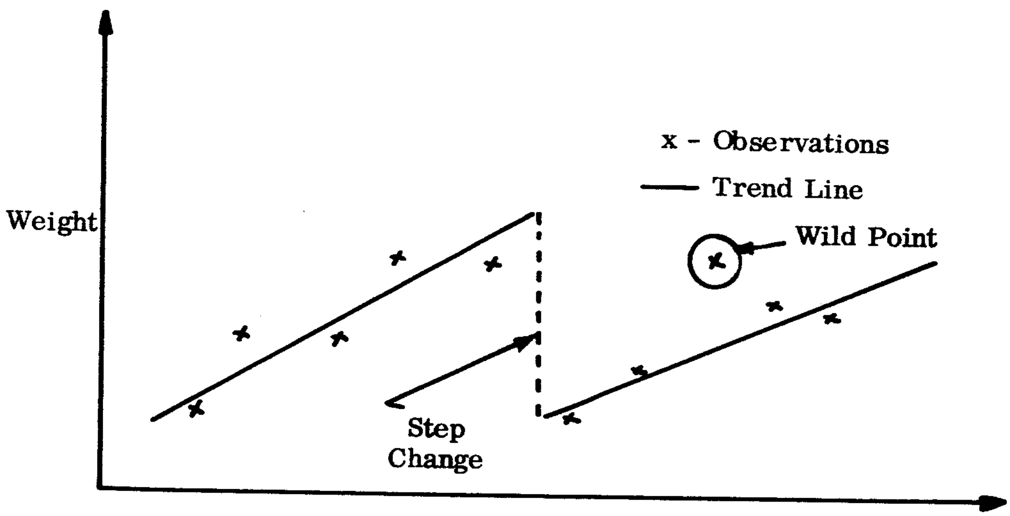


Figure 2-3. Effects of Non-Random Events

Removal of these effects has proven through experience with FAME application to uncover the true trend of the data thus permitting more accurate forecasts. This is reflected in the following theorem:

> Theorem - Forecast validity is enhanced through the removal of non-random effects from the observed data. (Application of this theorem is termed "normalization" in this book.)

Those effects known to result from non-random events can be removed as follows.

Let the observations or data points be denoted by $U_1, U_2, \ldots U_n$. When the magnitude of the undesired effect is determined it becomes identified as a change r_i to be made to the i^{th} observation U_i.

The changes are made by

$$V_k = U_k = \sum_{i=k+1}^{n} r_i, \quad k = 1, 2, \ldots n$$

which has the effect of raising or lowering all points prior to the i^{th} by the sum of this and all subsequent changes. If the i^{th} point happens to be the last observation and r_i is associated with it, all earlier points are raised or lowered by an amount equal to r_i.

Thus it is seen that not only is the true trend maintained but the predicted values will be based on the fact that the last point is the "best" point. Clearly, if the $(i+1)^{st}$ point changes in the opposite direction by the same amount, another change $(r_i + 1)$ is obtained which is equal to $-r_i$. In this case, all points prior to i and i+1 itself remain unchanged but the i^{th} point is brought back into line. It should be noted that a non-random change is defined to be positive if the datum was forced down. Consequently, a positive non-random change result is subtraction of weight while a negative non-random change results in addition of weight.

Now, in the case of points suspected of being non-random, that is they lie outside the general data envelope for no assignable reason, some test is required to establish a decision criterion. One way to do this is to compute the average increment $\overline{U}$.

$$U = \frac{U_n - U_1}{n - 1}$$

and the standard deviation

$$\sigma_U = \frac{\sqrt{\sum_{i=2}^{n} [(U_i - U_{i-1}) - \overline{U}]^2}}{n - 2}$$

Each increment $U_i - U_{i-1}$ is compared with the average $\overline{U}$. If it deviates from the average by more than say $\pm 2\sigma_U$ it is assumed that the particular increment was not completely random. Now, a non-random charge r_i' is postulated as

$$r_i' = \begin{cases} -(U_i - U_{i-1} - \overline{U}) & \text{if } (U_i - U_{i-1} - \overline{U}) \geq 2\sigma_U \\ (U_i - U_{i-1} - \overline{U}) & \text{if } (U_i - U_{i-1} - \overline{U}) \leq 2\sigma_U \\ 0 & \text{otherwise} \end{cases}$$

these changes are incorporated as are the others, by

$$V_k = U_k - \sum_{i=k+1}^{n} r_i', \quad k = 1, 2, \ldots n$$

There are additional means which one might use to detect and incorporate non-random changes. These examples serve to illustrate solution techniques and provide some idea of what can be accomplished.

2.3.2 MODELING METHODS

The two commonly used techniques for adapting specific mathematical functions or models to sets of data are the method of least squares and the maximum likelihood principle. These are discussed briefly here. Detailed treatments are available in numerous references, for example, References 18 and 29.

2.3.2.1 Least Squares

The least squares criterion says that the best representation of a set of data is that which minimize the sum of the squares of the residuals. This assures small values for the residuals as the squared quantities are all positive. In other words, application of this principle yields a function which passes as closely as possible to all data points.

In equation form, this criterion requires the minimization of

$$S = \sum_{i=1}^{n} [w_i - \hat{w}_i]^2$$

where

w_i = observed value of the dependent variable at time t_i

$\hat{w}_i$ = value given by model at time t_i

the general procedure now consists of substituting for w_i the model at which the data are to be fitted, taking the partial derivatives of S with respect to each unknown parameter in the model, equating these derivatives to zero and solving for the parameters.

For example, if the model to be quantized is a linear form, say $w_i = a + bt_i$, this procedure yields the following values for a and b,

$$\begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} = \begin{bmatrix} n & \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i & \sum_{i=1}^{n} t_i^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{n} w_i \\ \sum_{i=1}^{n} w_i t_i \end{bmatrix}$$

This general treatment assumes implicitly that all the observed data are of equal worth, that is, there is no reason to believe any one point more or less than another. There may be cases where one or more of the points are known to be exact values. It is required then that the function or model produce these values and fit the remainder in some best sense. This results in a constrained least squares fit where the model is constrained to reproduce the exact values.

Another form of least squares application is known as the weighted least squares wherein no points are exact but some measure of the relative worth of the data is available. Such weighting information may follow from program maturity. Improved data generating techniques, etc. With such information, the residuals can be weighted appropriately.

Least squares, then, is a straightforward method which can be used to fit empirical data to any desired model. In some cases, however, information about the relative value of data is available in greater depth than is required for weighted least squares and since confidence intervals are also desirable, the maximum likelihood method is used. Maximum likelihood has the same effect as weighted least squares but is statistically optimum and provides a basis for computing confidence intervals.

2.3.2.2 Maximum Likelihood

It is often required to know the values of the parameters in a probability density function whose general form has been assumed to represent a particular population's distribution. Random samples are taken from the population in question and treated in such a way that estimates of the population distribution parameters are obtained. If this estimation process utilizes the maximum likelihood principle it can be said that the resulting specific distribution function has the greatest likelihood of representing the population's distribution. Note, however, that the general form of the function or model is assumed, just as in the least squares treatment. The results are analogous. Given the assumed form of the model, the resulting specific model (specified by the values assigned to the model parameters) is the fit or representation of the data.

To illustrate this, consider the case where the random variable $\underline{w}$ is normally distributed according to the following law

$$f_{\underline{w}}(w_i, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\underline{w}_i - \mu}{\sigma}\right)^2}$$

Application of the maximum likelihood technique yields estimators for the two parameters μ and σ,

$$\underline{\hat{\mu}} = \frac{1}{n}\sum_{i=1}^{n} \underline{w}_i \qquad \underline{\hat{\sigma}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\underline{w}_i - \underline{\hat{\mu}})^2}$$

These estimators are expressible as functions of the model parameters. Solving the simultaneous equations which result from the application provides expression for the model parameters which, when evaluated, provide the optimal representation of the observed data for the model considered.

2.3.3 SPECIFIC MODELS

The following paragraphs discuss four specific process models designed for a space vehicle weight control task. Three of them are based on assumed functional forms while the fourth is a modification of an autoregressive technique. This latter modification was required in this case due to the nature of the reported weight data. Details of these models can be found in Book II, Appendix C.

2.3.3.1 Linear Maximum Likelihood

The method of maximum likelihood is a well established statistical principle. It is used here to estimate the parameters of a hypothetical population whose expected value E $\{\underline{w}_i\}$ is a linear function of time, t_i,

$$E\{\underline{w}_i\} = \underline{w}_i = a + bt_i$$

as illustrated in Figure 2-4 and where a and b are unknown values to be estimated. It is further assumed the observed weights, $\underline{w}_1$, $\underline{w}_2$, ..., $\underline{w}_i$ are random (and independent) variables derived from a normally distributed population.

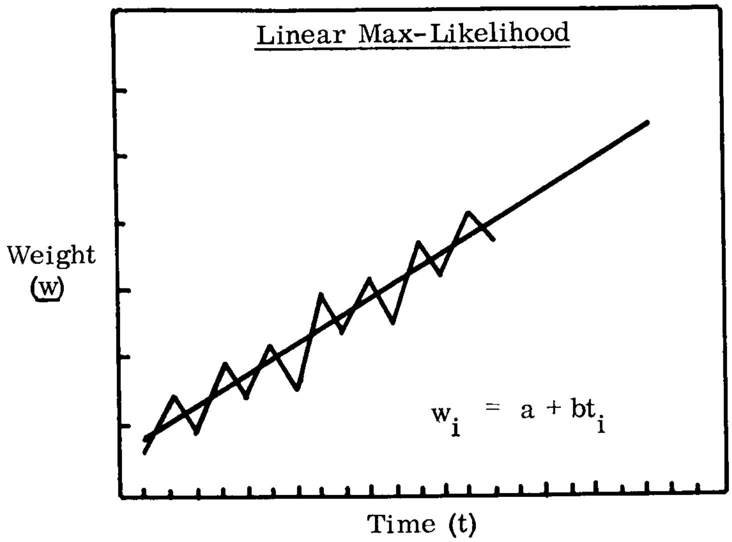


Figure 2-4. Linear Max-Likelihood

The observed weights, $\underline{w}_i$, are assumed to be displaced randomly from the expected value by a displacement, e_i,

$$\underline{w}_i = w_i + \underline{e}_i$$

where $\underline{e}_i$ is normally distributed with zero mean and standard deviation σ_i.

It is important to understand that this model does not presuppose that weight follows exactly along a linear growth line. Even if the "exact" weight could be accurately determined, its value would be displaced from the mean line by a random amount e_i.

The additional knowledge of the proportions of the observed weights, $\underline{w}_i$, which is estimated, calculated, or actually measured is introduced through the assumption that σ_i is reduced as the proportion of $\underline{w}_i$ which is estimated is decreased and the proportion of $\underline{w}_i$ which is calculated or actually measured is increased. That is, the expected excursions of $\underline{e}_i$ reduces as the program matures and the estimation processes give way to better calculation and actual measurements. This is represented mathematically as

$$\sigma_i^2 = s^2 \cdot m_i^2$$

where s is the relative standard deviation of the actual weight and m_i is a weighting factor related to expected changes of σ_i with E/C/A, the Estimated, Calculated, and Actual proportions.

The likelihood function, L, then becomes

$$L = \prod_{i=1}^{n} \left[\frac{1}{s \cdot m_i \sqrt{2\pi}} \; e^{-\frac{1}{2}\left(\frac{\underline{w}_i - a - bt_i}{s \cdot m_i}\right)^2} \right]$$

for which the maximum is found by an iterative computer solution for those values of the parameters a, b, and s which maximize L.

Maximum likelihood estimates are consistent and efficient; further they are sufficient if sufficient statistical measurements exist. However, it is axiomatic to note that the results are only as good as the theory selected for the model. Other principles lead to different models, but in general the maximum likelihood principle represents one of the best general-purpose estimation tools available for Forecast Analysis.

Probably the most limiting assumption, here, as in all four models, is that the random variables, $\underline{w}_i$, are independent. In a number of instances the reported weights are identical month after month. A most likely situation if weights were independently reported each month. They may have been the result of a freeze of design or weight, or simply use of the previous months data rather than re-estimation for the current month. This is not attributable to randomness, but is a result of dependence. Over a long time period, however, the randomness of the process is more evident and eventually dominates the trend pattern.

In recognition of the dependence of weight data in the short time pattern, and that the most likely weight at the latest reported time is the reported weight, the prediction line is extended from the observed weight parallel to the trend line.

Simply stated, the maximum likelihood methods are used to discern the so-called "natural" growth, and that growth line is extended from the latest data point as the prediction line. This process of moving from the trend line to the prediction line is referred to as removing the bias.

A further advantage of maximum likelihood methods, noted earlier, is that a confidence interval can be readily established in the prediction range. This confidence interval provides the bias for determining the probable error associated with the estimated weight.

2.3.3.2 Non-Linear Maximum Likelihood

Review of weight data from aerospace programs indicated that in many cases, the weight growth is non-linear, approaching the final weight as a horizontal asymptote. There are numerous reasons for such a growth pattern, such as the presence of a control limit as a forcing function and the application of weight control pressures as a program matures. To represent this situation, an exponential model was introduced of the form

$$w_i = a - be^{-ct_i}$$

as illustrated in Figure 2-5 and where a, b, and c are parameters to be estimated and c is restricted to positive values.

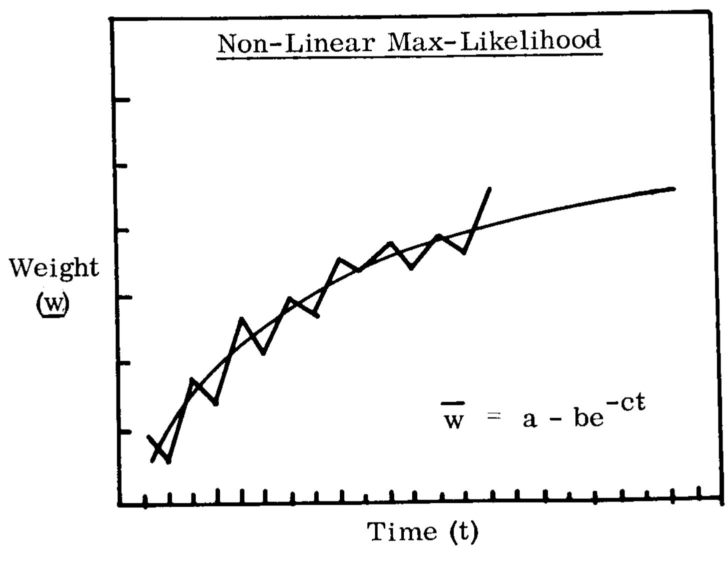


Figure 2-5. Non-Linear Max-Likelihood

As with Linear Maximum Likelihood, a hypothetical population is presumed as the source of the observed data and whose expected value $E\ \underline{w}_i = y_i$ is an exponential function of time, t_i. As before, the observed weights $\underline{w}_1, \underline{w}_2, \ldots, \underline{w}$, are assumed random (and independent) variables, deviating from the trend line by a displacement $\underline{e}_i$

$$w_i = w_i + \underline{e}_i$$

where $\underline{e}_i$ is assumed to be normally distributed with zero mean and standard deviation, σ_i.

The concepts of E/C/A are introduced as in the linear case with a weight factor, m_i, on the relative standard deviation of the actual weights, s, through

$$\sigma_i^2 = s^2 \cdot m_i^2$$

and the likelihood function, L, now becomes

$$L = \prod_{i=1}^{n} \left[\frac{1}{s \cdot m_i \sqrt{2\pi}} \; e^{-\frac{1}{2}\left(\frac{\underline{w}_i - a + be^{-ct_i}}{s \cdot m_i}\right)^2} \right]$$

Solution of the values of a, b, c, and s which maximize L is more difficult than for the linear case, and the iterative computer solutions were found to converge quite slowly for cases of limited exponential character.

Accordingly, a linearized approximation of the basic equation is employed through,

$$w_i = a - b\,\psi_i$$

where

$$\psi_i = e^{-ct_i}$$

and ψ_i is assumed to be the independent variable. The value ψ_i is varied by preselecting values of c, and maximum likelihood solutions found for a and b for each value of c. Values of a, b, and c are then selected as those values which result in the highest value of the likelihood function.

This exponential model, however, quite frequently converges toward an asymptote which is ficticious. This occurs when a set of observed data has been growing at a normal rate and then is followed by a period of very little change or a leveling off.

Analysis of data during a leveling off period often results in a prediction which is far short of the final weight, especially if the leveling off period occurs early in the engineering development phase. Careful analysis of this type of situation is required if pre-mature asymptotes are to be avoided.

The model does not allow for independent examination of the various program phases as related to weight growth. Program phases are similar to the seasonal changes of econometric analyses. Since early phases normally have a higher growth rate than others, a lack of sufficient observations in following phases could result in an asymptote which is considerably overestimated.

2.3.3.3 Asymptotic (Logistic) Exponential

This Asymptotic Exponential model incorporates most of the better features of the linear model and the exponential model. The shaping of the logistic curve available through parametric variation makes this model a valuable tool. The model is represented by:

$$w_i = \frac{a}{1 + be^{-ct}}$$

where "a," "b," and "c" are parameters to be estimated and "c" is restricted to positive values so the curve will approach the value "a" asymptotically.

A pictorial representation of the curve, Figure 2-6 is presented below.

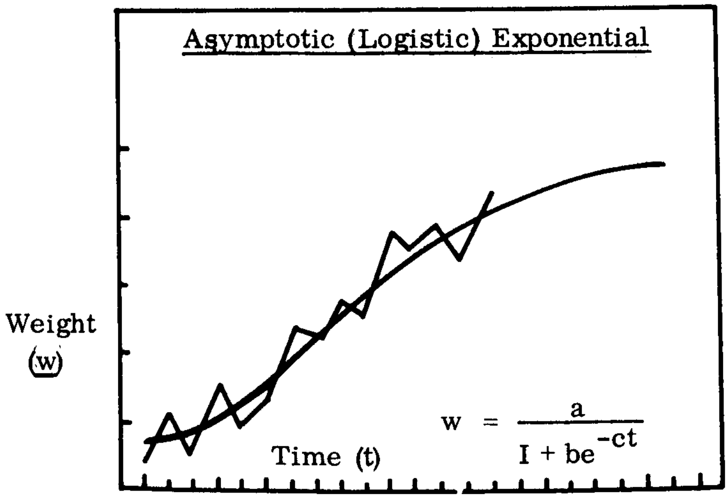


Figure 2-6. Asymptotic (Logistic) Exponential

This type of curve allows for little or no weight increase as a program is started, for an increase (or decrease) as the program moves along in time, and a "leveling off" as the program completion date nears. The shape of a specific curve is influenced greatly by the parameters a, b, and c, which are estimated by a weighted least squares curve fit.

The logistic model is quite adaptive to the data and can assume a variety of forms depending on the values of a, b, and c. If the parameter "c" is small, less than 0.1, the curve behaves similarly to a linear model. Eventually, the prediction curve will bend over to the asymptote "a." On the other hand if "c" is moderately large ($0.2 \leq c \leq 1.0$) and "b" is not large ($b < 30$), then the logistic curve looks very much like an exponential curve.

The initial flat portion is attributed to a reasonably large "b" (> 40) and a "c" that is small enough so that the term "be^{-ct}" is not reduced to zero for small values of "t." If "c" is large, then the logistic model approaches the asymptote "a" very quickly and proceeds horizontally to infinity.

2.3.3.4 Adaptive (Fourier) Exponential Model

The foregoing three models are each based on the assumption that the underlying process can be approximated by an analytical expression of the so-called "natural" growth. While such models are sufficient in many cases, there are some instances where greater adaptibility is desired. The use of an underlying model is too restrictive to permit rapid sensing of the latest weight progression. Further, it is recognized that individual monthly reported weights are sometimes highly dependent and an autoregressive type of model is needed for study of weight growth.

The adaptive (Fourier) exponential, presupposes no underlying process, rather it senses the growth tendencies, with emphasis on the most recent observations and is therefore highly adaptive. The monthly weight increment is assumed to be the random variable, and the forces which cause the weight increments are assumed to be the random variable, and the forces which cause the weight increments are assumed to decay as the program matures, approaching a constant slope. Behavior of the model is illustrated schematically in Figure 2-7.

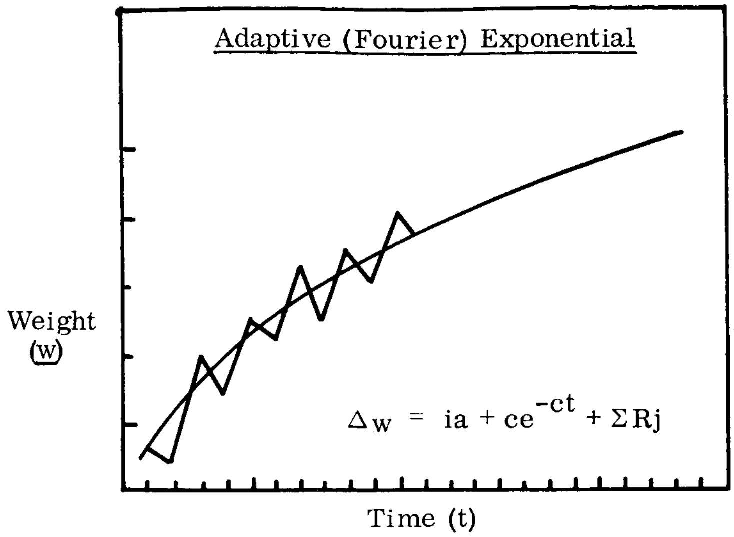


Figure 2-7. Adaptive (Fourier) Exponential

The predicted weight one month beyond time, t_i, is provided by

$$w_{i+1} - w_i = a + be^{-\alpha t_i} + r_i$$

where a, b, and α are the coefficients to be estimated and r_i is a random residual of zero mean. When observations are equally spaced, the above equation is written,

$$w_{i+1} = (w_i - \delta) + ia + ce^{-\alpha t_i} + \sum_j r_j$$

where:

$$c = b(1 - e^{\alpha \Delta t})^{-1}$$

This equation contains a constant term $(w_i - \delta)$, a linear slope term and exponentially decaying term $ce^{-\alpha t}$. The solution is found by first separating the non-linear part by a Fourier analysis, producing a smoothed curve through the observed data, and then considering the remainder of the equation as an increment process. The smoothed exponential curve is allowed to approach a fixed slope in the prediction range.

By nature, the Fourier model predicts from the last point with a prediction line that retains some exponential character for a brief period. The confidence limits, likewise emminate from the last point, since the confidence interval is selected for expected data, and the data point is assumed to be proven with 100 percent confidence.

2.3.4 USE OF E/C/A AS MATURITY FACTORS

The above discussions of prediction models indicate that the program maturity, evidenced by E/C/A values, plays a role in quantizing the model parameters. Although this is explained in greater detail in Appendix C, an important distinction should be noted at this point. This is that only the effects of the reported E/C/A values are included in this manner, i.e., the observation range only. Or, put another way, the prediction now is based only on the observed data and its associated E/C/A content. It makes no provision for the anticipated growth of program maturity.

In the early phases of a program it is clear that the "value" or relative credibility of the reported data is far from its ultimate level. But, if the small amount of such information available is used to quantize the models, it is even more important to include the effects of future program maturity, insofar as it can be determined, in the prediction itself, as it represents a large differential.

The use of E/C/A can be introduced into each math model in the prediction range in several ways, such as changing prediction line slope with different program phases, reducing predicted value as E/C/A progresses, or adjusting expected standard deviation in prediction range. In any case, we are not concerned with first predicting what will happen with E/C/A in the future and then improving the final predicted weight values with corrections from the predicted E/C/A. Methods of predicting E/C/A are discussed in Chapter 9 and are too lengthly to be discussed here except to note that forecasts include a program of applying historical progression rates to adjust predicted values of E/C/A. In some cases, it is sufficient to assume a simple linear interpolation of E to 0 percent, C to 0 percent, and A to 100 percent respectively at shipping date.

In the prediction range, the incorporation of E/C/A percentages is accomplished by adjusting the unadjusted prediction, w_i at time t_i to obtain

$$w_i^A = w_{i-1}^A + \rho_i^P (\underline{w}_i - \underline{w}_{i-1})$$

where the superscript A denotes an adjusted prediction line and is a weighting factor. This model arrives at the adjusted prediction corresponding time t_i by adding the adjusted prediction made for time t_{i-1} to a term consisting of the difference between the unadjusted prediction for t_i and the unadjusted prediction for t_{i-1} multiplied by the weighting factor ρ_i^P such that

$$\rho_i^P = E_i + R_3 C_i + R_4 A_i$$

where E_i, C_i, and A_i, and the percent of E/C/A at time t_i and R_3 and R_4 are predicted coefficients. This model is based on the underlying assumption that if the weight of a particular functional system has a high percentage of Estimated weight, the growth rate will be greater than if the weight is of high Actual percentage. This is a reasonable assumption, as investigation of Actual data verifies. The weight predictions, w_i, made for some future time t_i are normally based on data that contains a higher percentage Estimated weight than will actually be present at time t_i. As time passes the percentage makeup of the functional system weight becomes more Actual and less Estimated. Since the prediction is based on weights having a high Estimated percentage, the predictions made are for a functional system weight having a high Estimated percentage at time t_i. As already observed, this high Estimated percentage will not be present at time t_i and hence the weight growth rate will not be as high as that predicted. The weighting factor ρ_i^P attempts to compensate for this inherent weakness. This is accomplished by selecting 1, R_3, R_4. As the weight becomes more and more Calculated and Actual the weighting factor ρ_i^P decreases. That is, $\rho_i^P < \rho_{i-1}^P$ for $i = n+1, n+2, \ldots, n+p-1, n+p$.

2.4 MODEL SELECTION

As mentioned earlier, the availability of an array of models provides a significant degree of flexibility to the Forecast and Appraisal System. Having such an array, however, presents one with a need to assure that the matching of models and sets of data is optimum. That is, that the best advantage is taken of the available flexibility. Discussed here is an approach to this selection process which is generally applicable. It utilizes two concepts known as Repeating Mode Analysis and Targeting Analysis. Application of these has led to the following theorem, which is the basis of the selection process.

Theorem - Forecasted values made in succeeding time periods tend to converge on a final value. (This is refered to as "targeting" in this book.)

2.4.1 REPEATING MODE ANALYSIS

The repeating mode technique analyzes a sequential set of observations (five to six points beginning with time zero) and makes forecasts for the succeeding months. It then adds the next observed point and makes new forecasts for succeeding months. This process is repeated until all available data is exhausted. A plot is then made of these results as a check on the attribute of consistency, i.e., targeting. Typical results are shown in Figure 2-8.

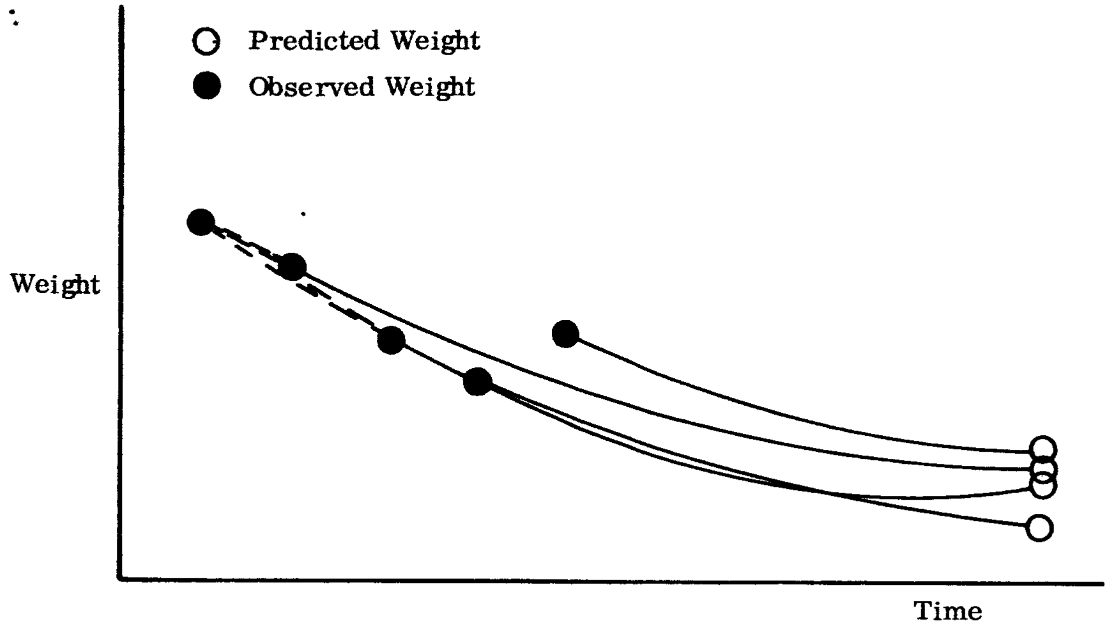


Figure 2-8. Repeating Mode Analysis Results

2.4.2 TARGETING ANALYSIS

Targeting Analysis, briefly stated, consists of a discernment of (a) whether successive predictions are approaching some value asymptotically and (b) if so, what the value is? The data needed to conduct such an analysis are generated by the repeating mode process and appear as illustrated in Figure 2-9.

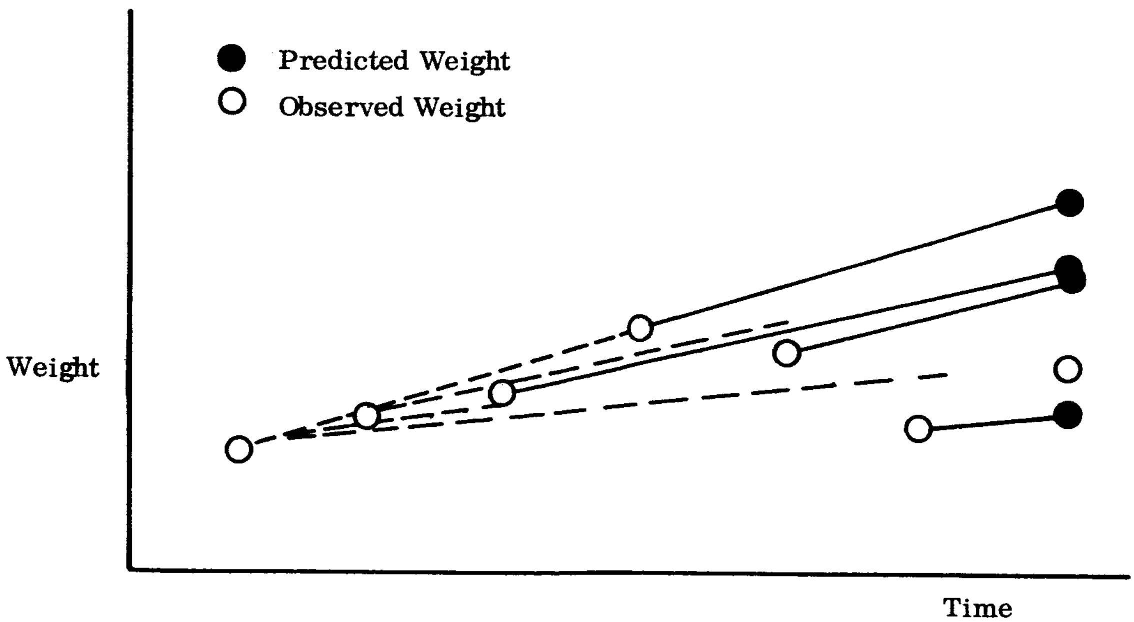


Figure 2-9. Repeating Mode Results in Form for Targeting Analysis

Ideally, the weight as a function of the number of observations should be monotonically increasing or decreasing toward the ultimate weight of the subsystem at the shipping date. However, due to errors in estimation, late design changes, and unreported variations in observation data, the behavior of the curve will not be consistent. In this case, the curve must be fitted to the points in the same manner as the prediction line is fitted to the observed data during the prediction phase. A nonlinear trend model should be used so as to enable the final "leveling off" to be simulated. The fitted curve then represents a "trend of the trends," and provides an indication of the manner in which the trend model responds to changes in the input data. Figure 2-10 shows the data of Figure 2-9 together with the fitted curve. A comparison of the trended curve at the time of the most recent observation with the actual observed data provides a performance criterion that may be used in selecting the best trend mode for use with a given subsystem. If several trend modes produce approximately the same error, the actual choice of the "best" mode may be made on the basis of other considerations such as consistency.

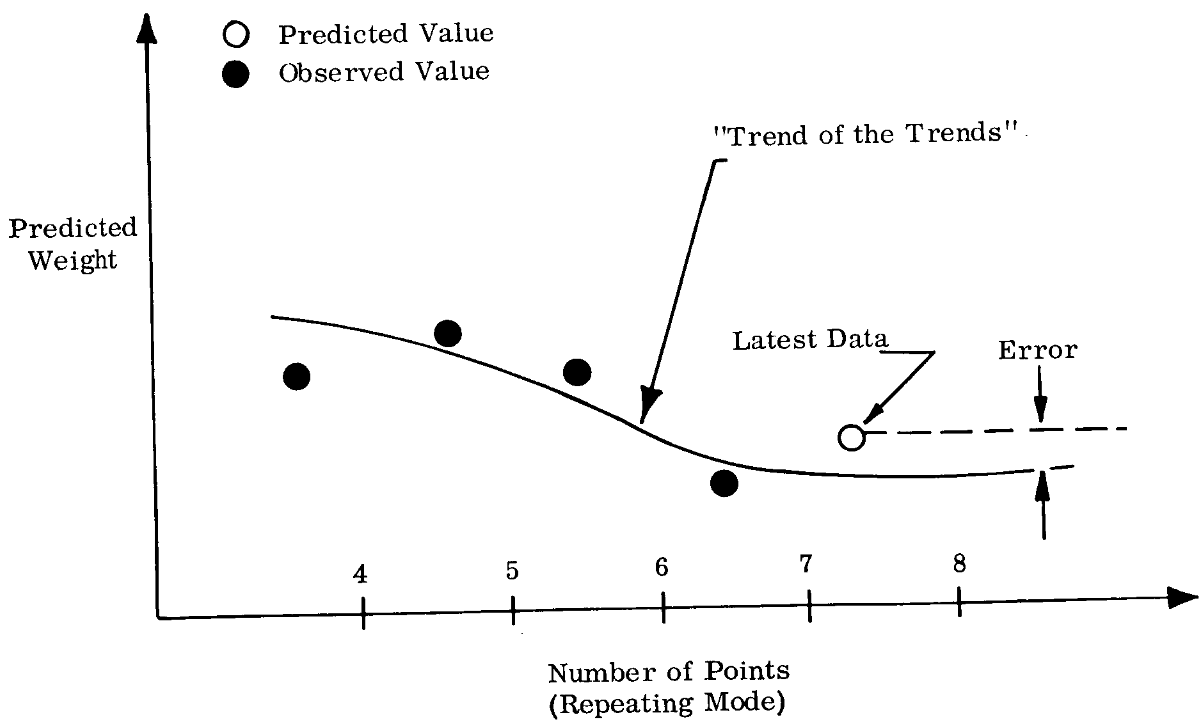


Figure 2-10. Targeting Analysis Results

2.4.3 THE MODE SELECTION PROCESS

Any mode selection scheme consists of three steps - initialization, prediction, and evaluation. The initialization phase delineates the possible trending modes, establishes performance criteria and associated tolerances, and defines the prediction and evaluation procedures which follow. The prediction phase encompasses the actual trending computations together with such intermediate computations as may be required. Finally, in the evaluation phase, the results of the various prediction computations are analyzed within the framework established by the initialization phase.

2.4.3.1 Initialization

The initialization phase, illustrated in Figure 2-11 establishes the order in which the prediction schemes are to be applied. The sequence of operations is as follows.

A priority list is established which contains the names of all trend modes which have been made available for use. (Normally this will amount to four - the linear, non-linear, Fourier, and logistic models.) The relative priority of each mode can be specified by the user if desired. Should two modes prove to be acceptable, the one with the higher priority is always chosen. If only one mode is specified, the mode selection process is bypassed. The last month's mode is always placed at the top of the priority list, provided that mode has been included as an allowable method. If the one month prediction agrees with the observed data for that interval, within some prespecified tolerance, no further computations or predictions are made and last month's mode is retained. If this mode does not produce acceptable results, other modes will be tried in an effort to find an acceptable mode. Control is then passed to a routing routine which executes the proper trending programs.

2.4.3.2 Prediction

The prediction phase is diagramed in Figure 2-12. This phase includes the actual trend prediction process. The first trend established predicts the system weight to ship date. If the particular trend mode selected happens to be last month's mode and the one month extrapolation agrees with the observed value, control is immediately transferred to the decision module.

For all other cases, the next test is to compare the predicted ship weight with a similar computation from last month. If the difference is within tolerance, the prediction is run in the repeating mode form to generate data for later evaluation.

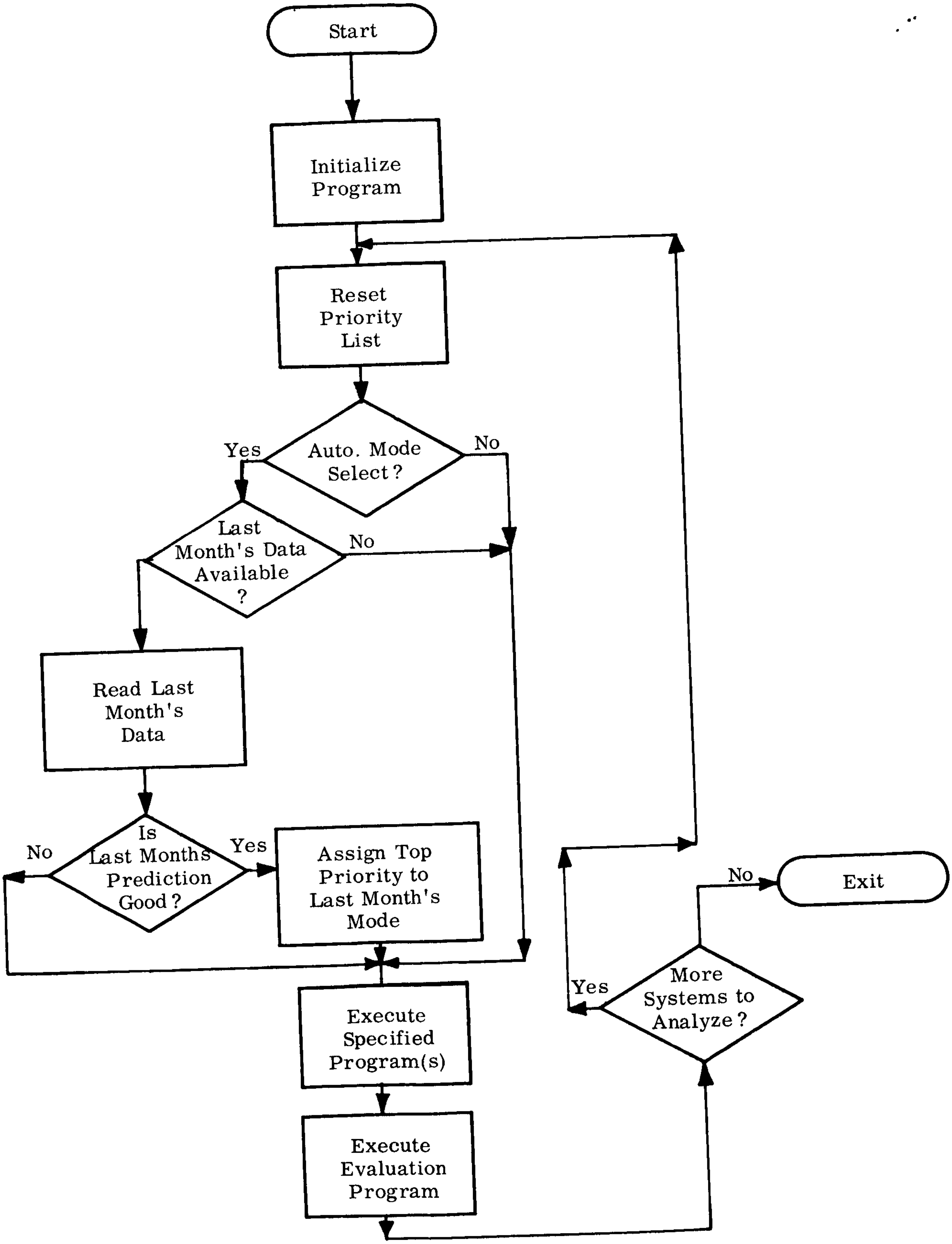


Figure 2-11. Initialization of Trend Mode Selection

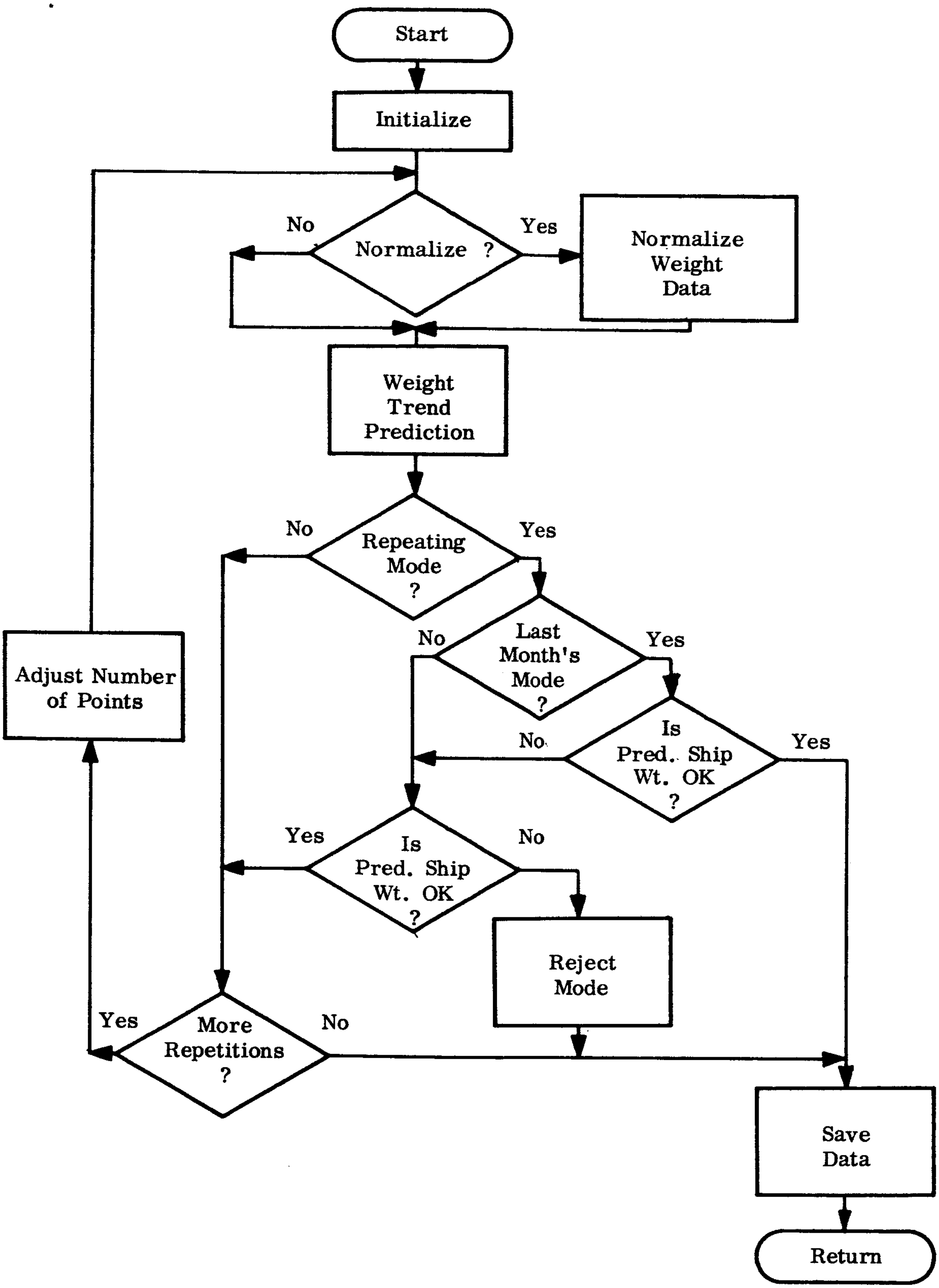


Figure 2-12. Prediction Phase of Trend Mode Selection

The prediction interval for this part of the procedure is one month. If the ship weights do not compare within tolerance, the mode is summarily rejected from further consideration.

2.4.3.3 Evaluation

The evaluation of the prediction data is performed in the decision module shown in Figure 2-13. The decision module makes the final selection of the "best trending mode. If the mode is specified manually, that mode is, by definition, "best." Likewise, if no mode satisfies the tolerance specifications, the decision is also trivial. In this case a straight line is assumed through this month's observed data and last month's predicted ship weight. An appropriate comment identifies this condition to the user.

In the non-trivial case in which several prediction modes need to be compared, the procedure is more complicated. As a result of the repeating mode computations described in the previous selection, several values of predicted weight (as a function of number of observed data points) are available for each trend mode still under consideration. This data, in turn, forms the input to a nonlinear trend program which computes the predicted weight. The predicted value can be regarded as a "trend of the trends." The predicted weight is compared to the Actual (observed) weight, and the first mode on the priority list that produces a result within tolerance is selected as the "best mode. All the intermediate data plus the final results are available for further analysis if desired.

2.5 SUMMARY

The foregoing discussions have described the Forecast and Analysis System and its elements. It was seen that the predictive or forecasting ability is the heart of the system and is that element having the greatest stabilizing effect on program performance. The salient characteristics of the data describing the program status were seen to exert a large influence on the approach taken to implementing the system - in particular, the data conditioning and modeling techniques employed.

These concepts were made more meaningful by illustrating their application to a specific program management problem. The next chapter expands upon this application. Attention is turned to the auxiliary techniques and computations which, together with the forecasting ability, form the whole of the Forecasting and Appraisal System.

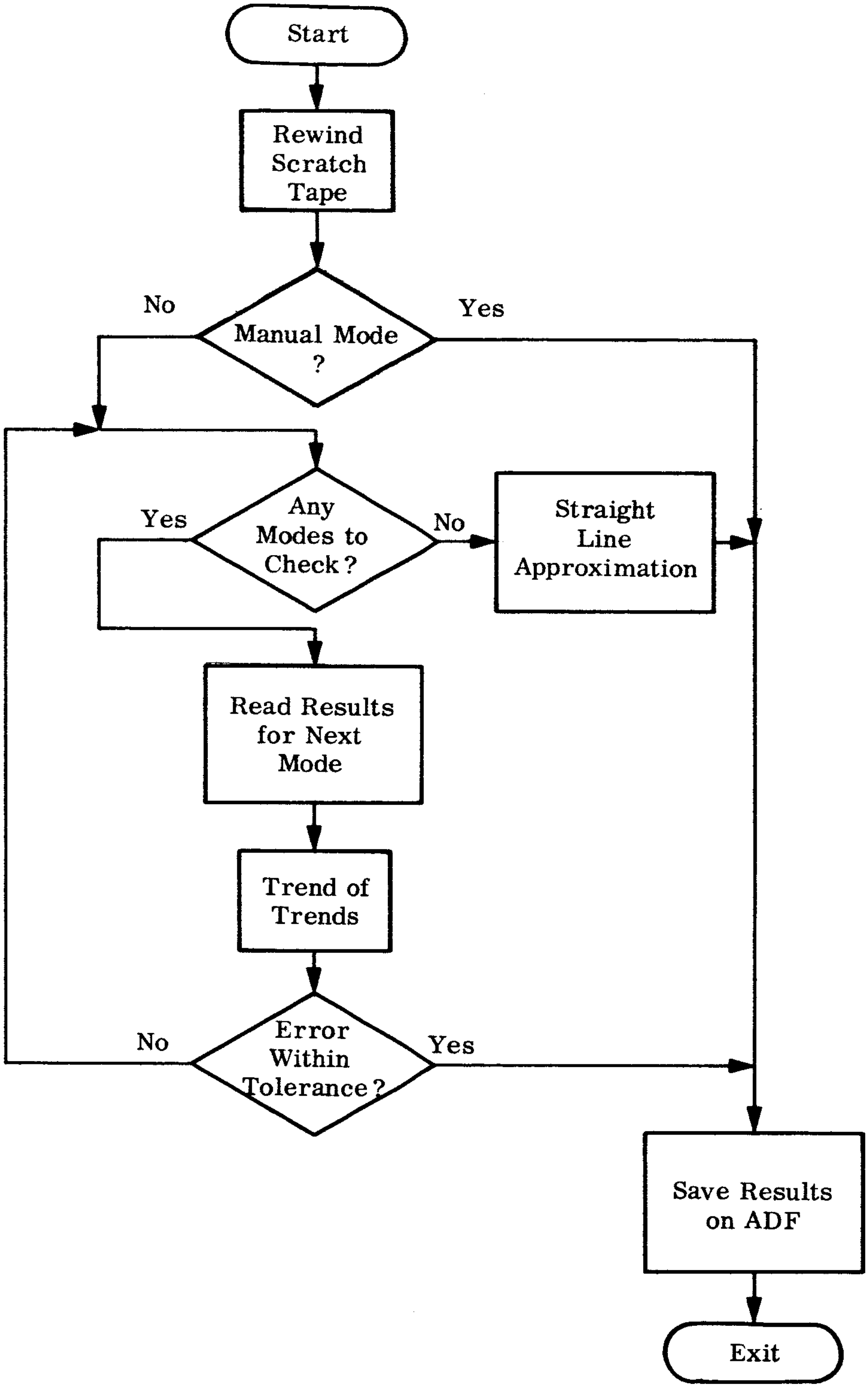


Figure 2-13. Prediction Evaluation

CHAPTER 3

APPLICATION OF FAME FOR WEIGHT/PERFORMANCE CONTROL

3.1 INTRODUCTION

The techniques of FAME are best understood by describing their use in a specific application. The first application of FAME was for weight/performance control on the Apollo Program where a high premium was placed on economy of weight and volume in the design of space vehicles. Therefore each spacecraft, launch vehicle, and their respective functional systems was vigorously evaluated to assure that weight/performance values were within established control limits.

Unplanned weight growth results either in degradation of performance goals or exceeding the capability of the launch vehicle with its attendant delays. Typical was the weight growth problem present throughout the Mercury Program, illustrated in Figure 3-1.

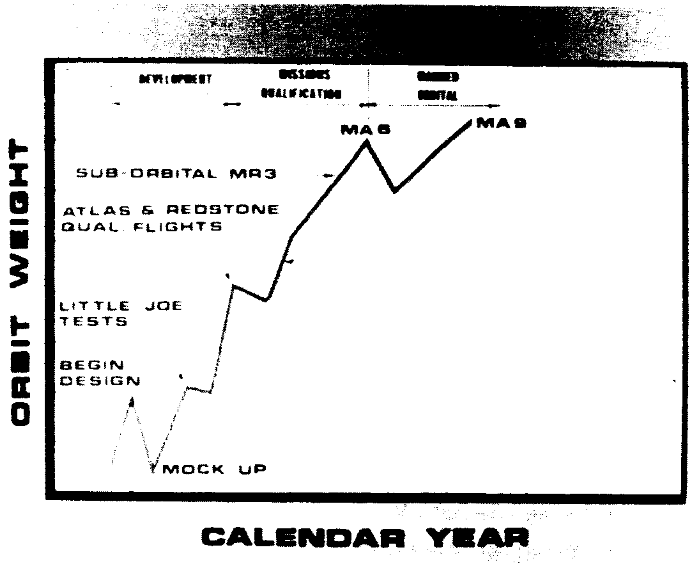


Figure 3-1. Mercury Spacecraft Weight Chronology from Mercury Summary Report

The lesson here is that proper planning must account for the inevitable weight growth in the design of high performance spacecraft, since the consequences of not planning for it are either a degradation of the performance goals or exceeding the capability of the launch vehicle with its attendant delays.

Similar weight growth tendencies were evident in the Apollo Program space vehicles.

The Apollo Program Weight/Performance Management System, by using FAME, provided a systematic procedure which assured the detection of potential weight growth tendencies. Continuous review and assessment of Apollo weight and performance was accomplished through the use of high-speed digital computers illustrated in Figure 3-2.

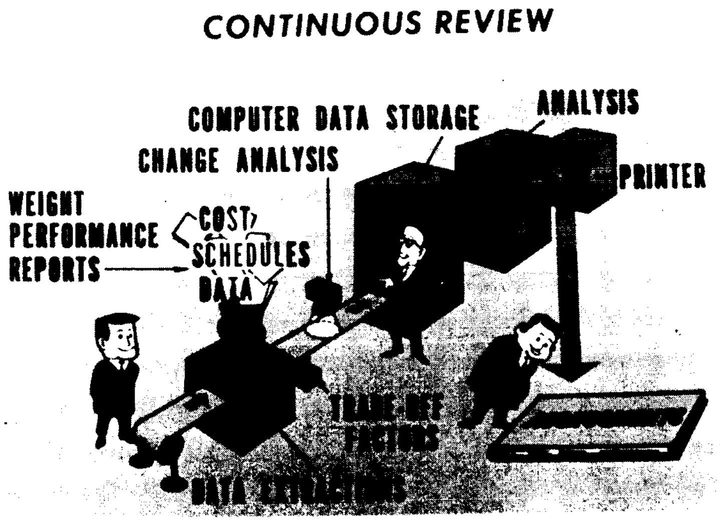


Figure 3-2. Continuous Review and Assessment Through Use of Digital Computers

Weight/Performance management was and is an integral part of the Apollo Program Office (Figure 3-3), and provided a "continuous loop" of data and evaluation flow.

The total Weight/Performance Management System is founded on four basic principles.

- Requirements
- Data Flow
- Assessments
- Management Actions

The establishment of weight control requirements in the Apollo Program Specification and the Flight Mission Assignments document (Level 1) provides a base against which weight/performance progress can be measured.

Level 1 program requirements are further detailed into Level 2 technical requirements by the Centers and are implemented at Level 3 by the Contractors as illustrated in Figure 3-4.

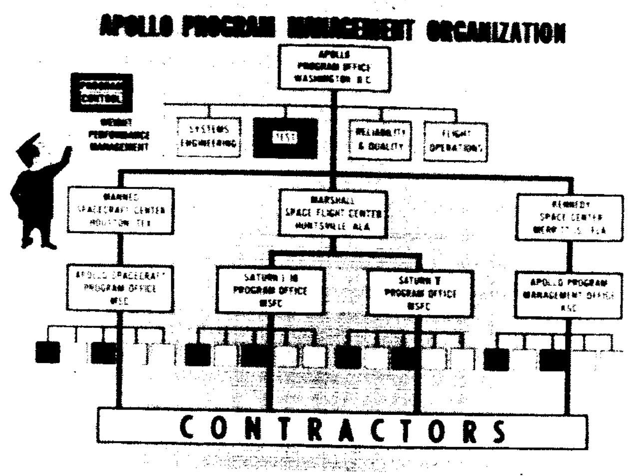


Figure 3-3. Apollo Weight/Performance Management in Relation to Program Organization

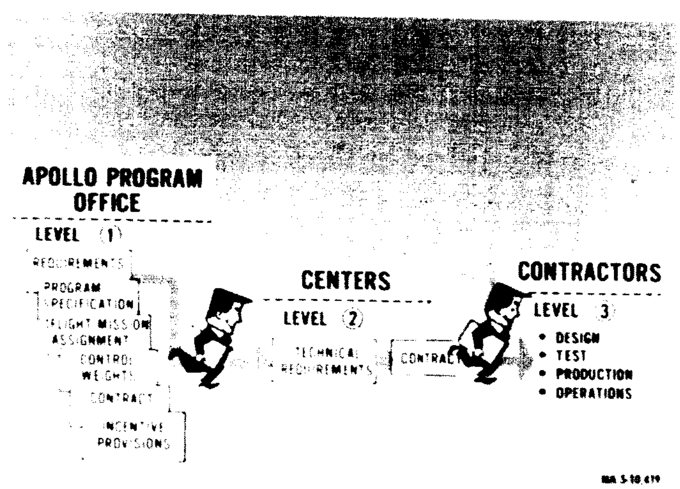


Figure 3-4. Program Requirements Versus Level

The Weight/Performance Management System provides for a data flow system which assures the timely transmittal of pertinent information between Contractors and Centers, Centers and the Apollo Program Office and the Apollo Program Office and other headquarter elements (Figure 3-5). This is accomplished through the utilization of those data flow requirements as detailed in the Apollo Program Mass Properties Standard and the Weight/Performance Data Submittal Requirements document.

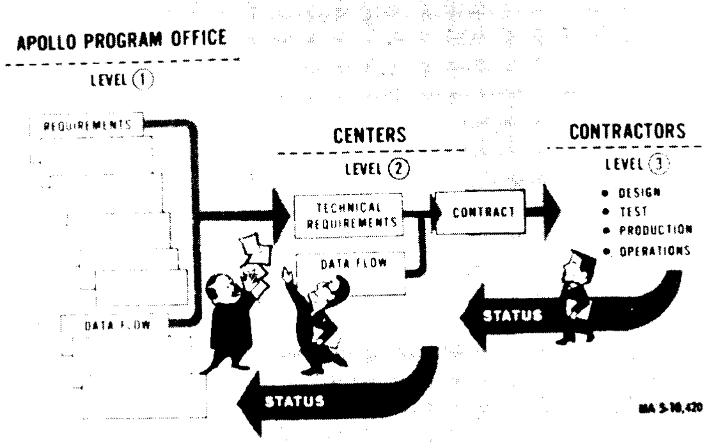


Figure 3-5. Data Flow System

Such acquired data is utilized for weight/performance assessments which define the current and anticipated program status.

The contractor status reports received by the Centers are evaluated against Level 2 requirements. These results are forwarded to the Apollo Program Office for evaluation against Level 1 requirements (Figure 3-6).

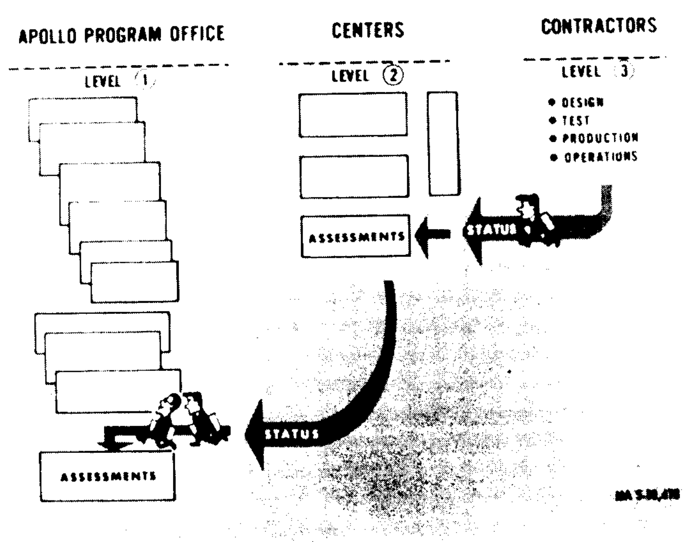


Figure 3-6. Status Reporting and Assessments

The results of these assessments are documented in the Apollo Space Vehicle Forecast Analysis and Management Evaluation Report (Figure 3-7).

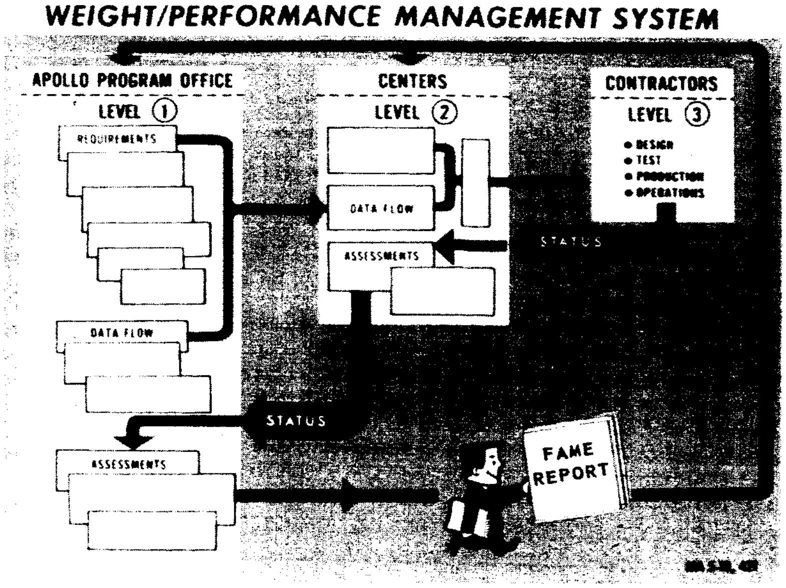


Figure 3-7. FAME Reports Complete the Data Flow System

The Weight/Performance Forecast Analysis and Management Evaluation Report is distributed to key managers in the Apollo Program Office in Washington, D.C., and applicable NASA Centers. The Weight/Performance Management System is in itself an action essential to the achievement of all weight/performance goals.

3.2 REQUIREMENTS

The Apollo Program Specification, a Level 1 document, delineates performance, design, and test requirements for the Apollo Program. The body of the specification applies to the Apollo Program equipment to be provided for operational versions of space vehicles leading to and including the lunar landing missions.

Appendices to the body of the specification delineate the performance, design, and test requirements as they apply to Apollo Program equipment to be used on individual missions as specified in the Flight Mission Assignments document.

The Control Weights Requirements document establishes the control weights for launch vehicles and spacecraft for each space vehicle mission presented in the Flight Mission Assignments document.

The establishment of these control weight requirements and mission requirements provide a base against which weight/performance progress can be measured. The control weight is defined as the minimum acceptable value, when evaluating launch vehicle payload capability, and as the maximum acceptable value when evaluating spacecraft and individual launch vehicle stage weights.

3.3 DATA FLOW AND PROCESSING

An essential aspect of the Forecast and Appraisal System is the flow of data between the various management, contracting, and contractor agencies involved in the Apollo Program. For weight and performance data, information is transmitted down to the level of spacecraft and launch vehicle functional systems. Apollo Program managers must be able to control weight at the functional system level to provide effective control. The status reports available to major program management elements must be timely and consistent.

3.3.1 DATA SUBMITTAL REQUIREMENTS

In the Apollo Program, a Weight/Performance Management System provides for transmittal of information between Contractors and the NASA Centers, between the NASA Centers and the Apollo Program Office, and between the Apollo Program Office and other NASA headquarters elements. This is graphically illustrated in Figure 3-8. Data submittal requirements are documented in the Apollo Program Mass Properties Standard and the Apollo Program Weight/Performance Data Submittal Requirements document. The Mass Properties Standard requires that Contractors report current weight, performance, center of gravity, and mass moment of inertia data to the Centers. The Weight/Performance Data Submittal Requirements document requires that the Centers report to the Apollo Program Office current stage and module weight, propellant loading, and engine performance data, as well as launch vehicle payload capability and total spacecraft weight. A detailed description of these documents is included in the reference section of Book I.

3.3.2 DESCRIPTION OF INPUT DATA

Various kinds of information are included in the data submittals and many of the characteristics of the data are known. Table 3-1 lists the known facts about examined data.

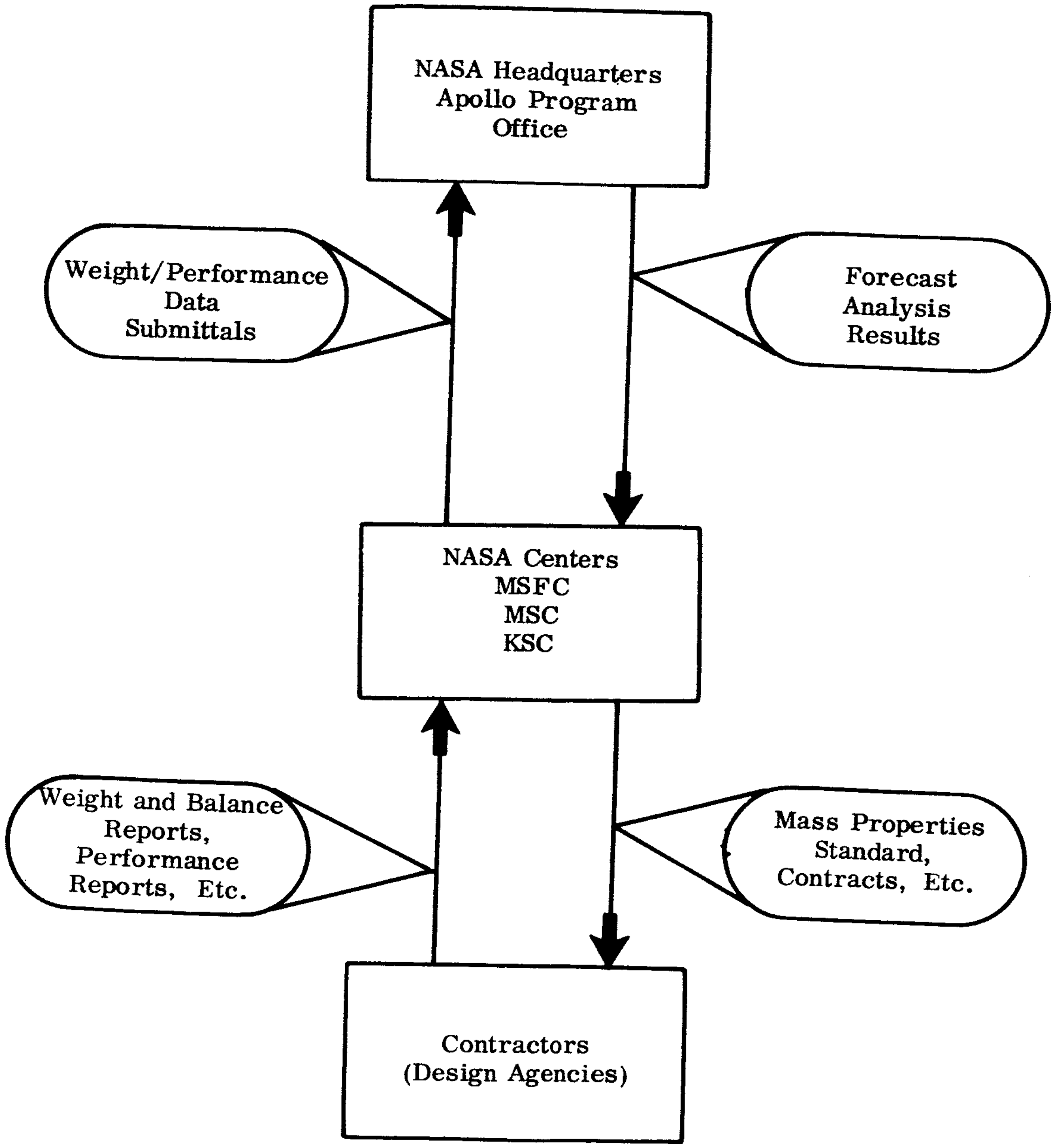


Figure 3-8. Data Submittal Requirements Flow

Table 3-1

Known Facts About Examined Data

1. Data is formally reported once a month.
2. Reported data is a result of
   (a) Actual weight measurement.
   (b) Calculations based on detail.
   (c) Estimations based on design layouts, i.e., also calculated but based on less information than that found on detail drawings.
3. Reported data is accomplished by change analyses.
4. Authorized, Pending, Planned, and Proposed Weight/Performance change information is submitted monthly.
5. Data is reported on a functional system basis.
6. There are schedules for hardware development (design, manufacture, test, checkout, etc.)
7. There is interdependence between functional systems.
8. There is interdependence between stages and modules.
9. Functional system development schedules are different.
10. Functional system design criteria are defined in specifications and contractual documentation.
11. Design reviews are held quarterly (approximate) with resultant design changes reflected in change data.
12. Actual weight data has relatively small error.
    Calculated weight data has modest error.
    Estimated weight data has high error.
13. Data ot early phases subject to high random variation (due to refinements in design criteria which were previously approximated; first and second level optimization; trade-offs between systems, and previously ignored secondary design conditions becoming primary design conditions).
14. Weight accounting is a daily procedure and if a daily procedure audit were to be made and the results plotted, a waveform pattern would be evident as opposed to month saw-tooth trend.
15. The effectivity (i.e., schedule) of authorized, pending, and planned changes can be established, thus providing for knowledge of future happenings.
16. Weight data is dependent on engineering releases. Releases are planned and scheduled. Weight is, therefore, time dependent.
17. Weight data is supplemented by % Actual, % Calculated, and % Estimated information.
18. Government furnished equipment is included in weights and is not normally subjected to strict weight control requirements.
19. Contractors are contractually obligated to specification weights.
20. Design constraints exist (e.g., tank capacities, size restrictions, factors of safety, etc.).
21. Month-to-month reporting frequently reflects step function when plotted (can be attributed to stretchout of schedule, several months of status quo due to major redesign effort, design nearing completion, or changes which are sporadic and far apart).
22. The number and magnitude of weight changes decrease rapidly after the design and manufacturing phases.
23. Major changes can occur as a result of testing effort waveform pattern begins to resemble a harmonic.
24. Reported status of Estimated, Calculated, and Actual data does not necessarily coincide with reported engineering releases.

Some of the features of the data can be summarized as follows:

1. Weights derived from layouts and sketches are referred to as Estimated weights. Weights calculated from officially released detail drawings are referred to as Calculated weights. Weights determined by measurements, with inherent instrument and part tolerance errors of the actual hardware are referred to as Actual weights. The class of weight is reported each month for each functional system. Each class has its own inherent error, but nevertheless gives to the reported weights a built-in statistical weighing factor which reflects program maturity.
2. The behavior of certain functional systems can be traced to system interdependence. For example, electrical power system weight is a direct function of power supply and power demand. Another example is structure, where weight changes or changes in design criteria in other systems are frequently reflected in structural load changes, and hence structural weight changes.
3. The relationship of the reported data to the program schedule phase (i.e., design, engineering, manufacturing, test, refurnishment, checkout, delivery, etc.) provides a measure of program maturity. A correlation can be made between the reported data and the current schedule phase.
4. The change analysis data tells why a weight change has occurred. This data provides the basis for the normalization of previously reported weight data. Normalization here is analagous to the removal of seasonal effects quite frequently found in econometric data. Normalization contributes to the determination of a true rate of weight growth by eliminating effects caused by transfer of weights between functional systems.
5. Authorized changes are those which have completed the engineering approval cycle but have not been officially incorporated via an engineering release. The approximate dates when these changes will become effective can be established (± one month). Pending changes are those which are in the approval cycle. Approximate effective dates can also be established for pending changes (± two months). Planned changes are those which are still being reviewed before going through the approval cycle. Approximations of the effective dates of this type change are more difficult. Proposed changes must be studied to determine feasibility, impact, and actual worth in terms of weight and performance. The chances of survival for proposed changes are small unless they meet predetermined standards. This type of change is usually held in reserve until circumstances warrant its incorporation.

3.3.3 PRE-PROCESSING OF DATA

3.3.3.1 Weight Data

Current weights, Estimated, Calculated, and Actual weight percentages, plus applicable non-random weight changes, are extracted for the launch vehicles and spacecrafts from their respective documents.

a. Extracted launch vehicle weight information specifically includes:
   (1) Payload capabilities, stage and functional system weights for the Saturn IB and Saturn V missions.
   (2) Estimated, Calculated, and Actual weight percentages at the stage and functional system level.
   (3) Non-random weight changes at the functional system level.

b. Extracted spacecraft weight information specifically includes:
   (1) Earth orbit injection weights, translunar injection weights, module, and functional system weights for the Block I and Block II spacecraft.
   (2) Estimated, Calculated, and Actual weight percentages at the spacecraft module and functional system level.
   (3) Non-random weight changes at the functional system level.

3.3.3.2 Schedule Data

Launch vehicle and spacecraft schedule information is extracted on a mission-by-mission basis.

a. Extracted launch vehicle schedule information specifically includes:
   (1) The long lead-time procurement date (date when action must be started to procure long lead-time items in order to assure scheduled mission completion).
   (2) Start of fabrication and assembly.
   (3) Start inplant checkout.
   (4) Start acceptance tests.
   (5) Start of refurnishment and checkout.
   (6) Ship date to KSC.
   (7) Launch data for indicated launch vehicle.

b. Extracted spacecraft schedule information specifically includes:
   (1) Start of subsystems.
   (2) Start of subsystem installation.
   (3) Start of inplant checkout.

(4) Ship date to KSC.

(5) Launch data for indicated spacecraft.

It should be pointed out that a single shipping date is generally acceptable for all functional systems and stages or modules of a given launch vehicle or spacecraft. This date will be the latest shipping date of any of the components of that particular vehicle or spacecraft.

3.3.3.3 Mission Data

Mission data consists of factors that are influenced by the over-all mission requirements (i.e., mission trajectory, mission plan, mission goals, etc.).

a. Control Weights - A control weight is a limit which if exceeded may cause mission failure or serious degradation. Control weights are established by the apportioning of launch vehicle lifting capability and total spacecraft weight. Control weights for launch vehicle payload capabilities, spacecraft injection weights, and stage and module gross weights are currently being used in the Forecast Analysis Program.

b. Trade-off Factors - The trade-off factor is used to express the stage and module growth in terms of payload capability. These factors are determined for each stage and module of a mission by using control weights with compatible mission data.

3.3.3.4 Levels of Comparison

There are several levels of system breakdown for an Apollo space vehicle at which the vehicle can be studied or compared with other vehicles. These breakdown levels include, in ascending order, the functional system level, the stage or module level, the launch vehicle or spacecraft level, and the total space vehicle level. A typical functional system breakdown is shown in Table 3-2. The lowest level at which management must maintain its awareness of status and problems determines the degree of visibility which must be provided by Forecast Analysis.

For the Apollo Program this level is the functional system level. There are several reasons for this. First, the growth rates for similar functional systems differ from one stage or module to another. For example, the service module structure may grow faster (or slower) than the command module structure. In cases where mission requirements (and where sufficient data is available), it has been found that functional

Table 3-2

Typical Functional System Breakdown

System	Components
Structure	Stages, Interstages, Crew Compartments, etc.
Landing and Docking	Landing Gear, Docking Structure, Flotation Systems
Protection Systems	Ablator, Acoustic, Meteorite, Radiation
Personnel Accommodations	Furnishings, Seats, Food, etc.
Propulsion	Engines, Plumbing, Pressurization
Environmental Control	Temperature, Pressure, Fire
Guidance and Navigation	Inertial, Stellar, Planetary
Electrical Power	Fuel Cells, Batteries, Wiring, etc.
Instrumentation	Sensors, Antenna, Transmitters, etc.
Communications	Tranceivers, Antenna, Cameras, etc.
Personnel	Crew, Suits, Life Support Equipment, etc.
Cargo	Scientific Instruments, Experiments
Propellant Reserves	Flight Performance, Launch Window Propellant Utilization, etc.
Residual Propellants	Pressurants, Trapped Propellants, Bias, etc.
Propellants	Thrust Buildup and Decay, and Full Thrust

system growth rates for a given functional system differ between two manufactured models of the same stage or module. In other words, structures in the first service module to be manufactured might have had a higher (or lower) growth rate than structures in the second service module.

Another reason for studying Apollo vehicles at the functional system level is that change analysis data is reported at this level. As already noted, change analysis data is used to normalize previous weight data. Normalization is essential to the Forecast Analysis process because it removes the effect of non-random changes, which then allows the determination of meaningful weight growth rates. Without normalization, the results of Forecast Analysis would be misleading, and without change analysis at the functional system level, there could be no normalization.

A third reason for functional system studies is that problem areas are reported at the functional system level by the Contractors and the Centers. Systems or equipment which have excessive weight growth rates or which are already overweight are usually discussed at the functional system level.

For these several reasons the lowest level at which Forecast Analysis techniques are applied, and for which results are presented to management, is the functional system level.

3.4 NORMALIZATION OF INPUT DATA

To arrive at valid forecast of future occurrences by extrapolation from data, it is necessary to assure that the data is of a consistent nature.

It is not practical, for example, to base a forecast on historical status data which involves a system that has been changed from one with a single functional purpose to one having a multiple functional purpose. The multiple purpose system will, in all probability, have more equipment and support structure, different thermal requirements, testing procedures, etc., all of which affect system weight, cost, schedule, and reliability.

Before the status data on the system can be used as a base for a forecast, an analysis must be made of the changes that have taken place within the system throughout its history. The purpose of the analysis is to normalize the reported information by making adjustments to remove the effect of non-random change. In this way, a forecast of future status will be based upon only random changes resulting from the normal design cycle. The data will then more accurately reflect the actual status of the multiple purpose system mentioned in our example - treating it as though it had always been such a system.

In performing Forecast Analysis of weight/performance growth, many reports and specifications are reviewed. Weight data is extracted and entered in the computer. Concurrently, weight changes since the last status are assessed to isolate those changes considered "non-random" and to eliminate the perturbation effects of those changes. This procedure normalizes weight/performance data.

The normalization process is necessary to determine true weight growth and has a marked influence on prediction line characteristics, as demonstrated in Figure 3-9. Shown are two forecast lines of interest, indicated by B and C. Forecast line B represents the logical extension of a trend line through reported, un-normalized data. The non-random change A has not been eliminated and so forecasts are forced away from the normal growth expectations. Line C represents the forecast line after removal of effects of non-random change A. This is accomplished by adjusting each previously reported data point by an amount equal to the weight increment at A. The adjustment is indicated by the black dots. Line C now represents a normalized trend line based upon consistent historical weight information which affords confidence in the forecast of expected natural weight growth of the system. The wide divergence of forecast lines B and C indicate substantially different weights at shipping date, (indicated by the arrow), and illustrate the importance of data normalization.

To achieve valid forecasts representing expected natural weight growth patterns of the many Apollo functional systems, sound rationale must be consistently employed when performing normalization procedures. The logic and ground rules of normalization steps are illustrated in Figure 3-10.

The type of data extracted is shown to the left of Figure 3-10. As indicated, the normalization process is concerned with stage and module functional system change data. A determination that any change is random excludes the possibility of <u>non</u>-randomness and stops the process for that change, because the effects of random changes only are included in the Forecast Analysis. Changes arising from reallocation of weight between functional systems are readily discerned as non-random and so are eliminated by Ground Rule 1 shown in Figure 3-10. The next four questions in the figure are

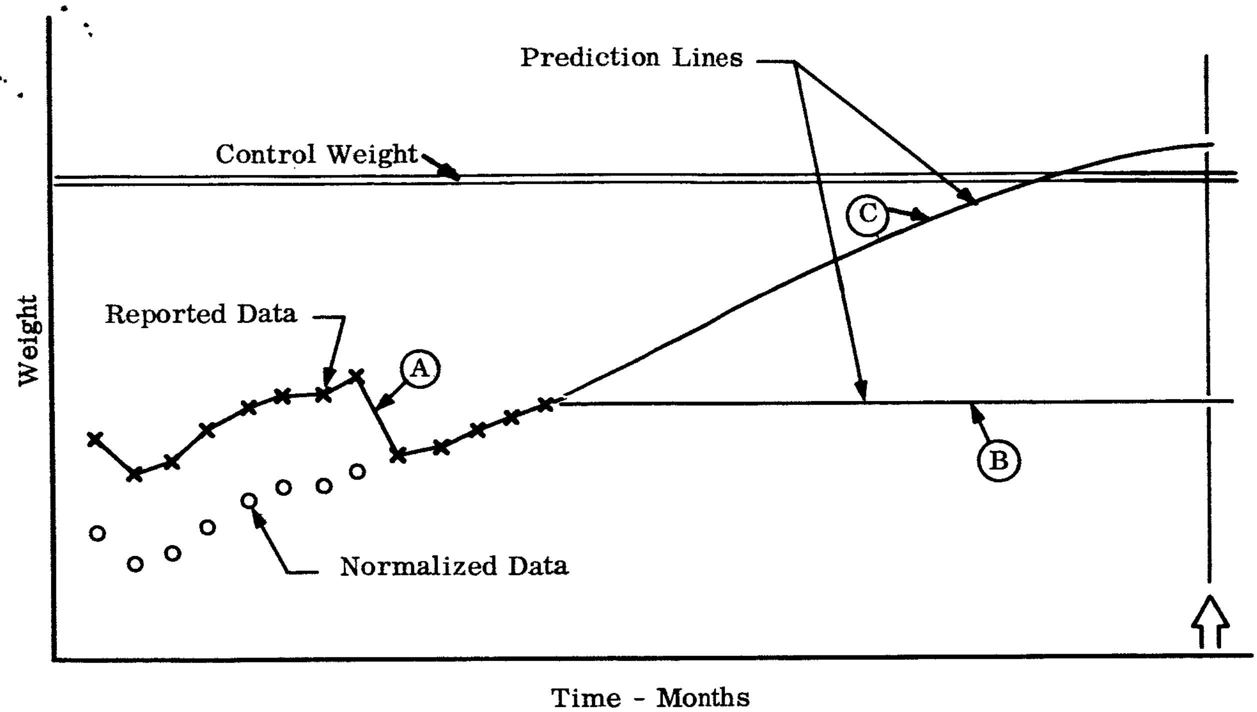


Figure 3-9. Normalization Process

concerned with changes which represent basic inequalities in over-all criteria. Non-valid values of historical weight are discerned through applying these questions and can be removed as non-random in accordance with Ground Rule 2. The sixth and final question leads to removal of those changes which are a result of a major buy-off to meet specification requirements, as established by Ground Rule 3. Identified non-random changes then are stored in the computer weight data file, along with the other weight data and, as forecast runs are called for, adjustments are automatically made for these changes, resulting in - for each functional system - consistent historical data which can now serve as a basis for valid forecasts.

3.5 FORECAST MODEL SELECTION

3.5.1 GENERAL

A critical operation in Forecast Analysis is the selection of the appropriate trend model to match data behavior. The rational for model selection is described in a general sense in Chapter 2 and will be discussed here as applied to weight/performance analysis.

There are four models as illustrated in Figure 3-11, each with different characteristics to match weight growths of different intrinsic nature. In addition, a line of constant slope may be used when indicated by experience with a particular type of component.

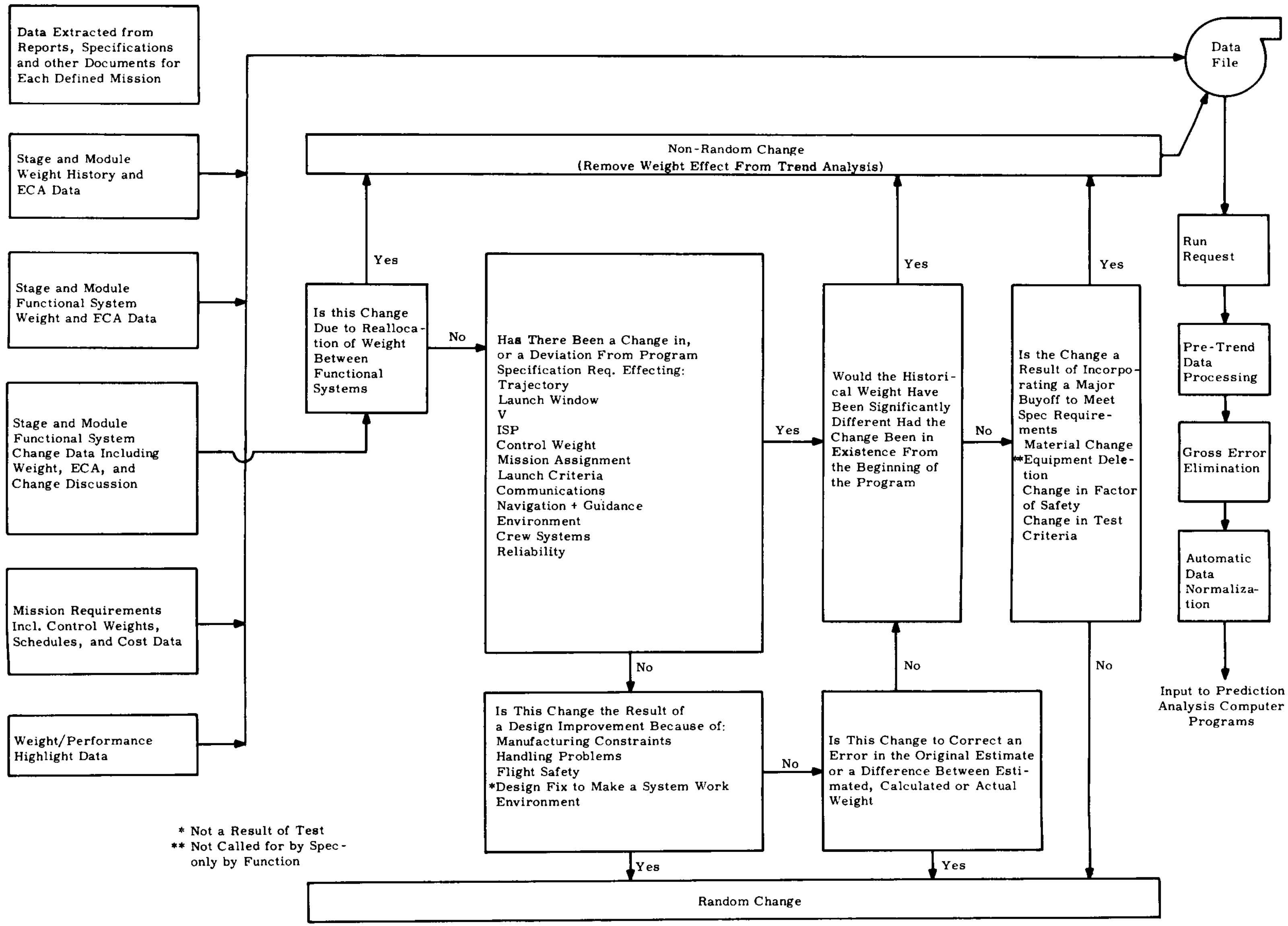


Figure 3-10. Data Normalization Logic, Assessment of Change Data

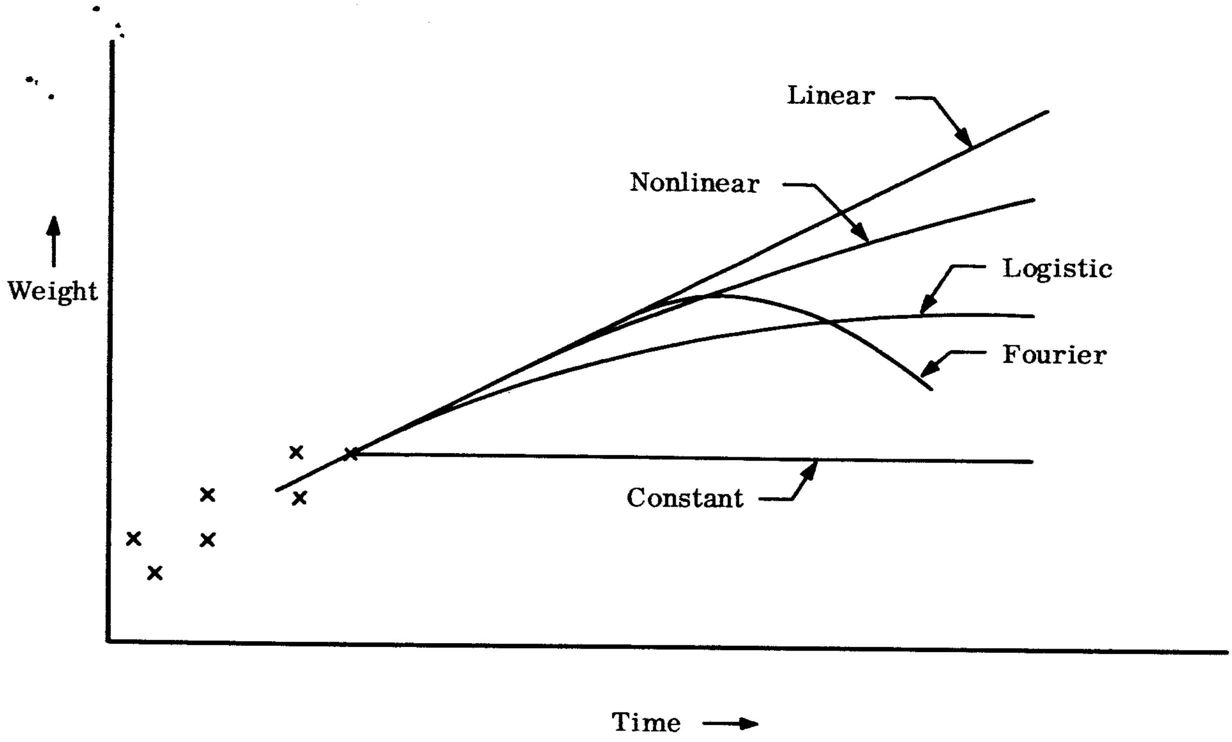


Figure 3-11. Trend Model Characteristics

3.5.2 SELECTION OF TREND MODEL

The selection of a Trend Model can be performed by either manual or automatic means, this choice usually being determined by the amount of data available. In the early stages of weight growth it is very difficult to determine which trend mode the growth will assume. Experience has indicated that at least six weight observations are required before trending can be attempted; and twelve or more observations are required before a trend of the trends is meaningful.

As an example, assume that at a given time, six weight observations have been made to date. On one of these six observations an increase in weight is indicated. What prediction trend model should be selected? Past experience and sound engineering judgment are helpful factors at this point. The linear or non-linear trend models are generally the most logical selection since only six weight observations are available, the final selection depending on engineering judgment and experience. The use of a constant slope model is avoided if possible or replaced as soon as sufficient data becomes available in favor of either the Logistic or Non-linear Model, unless from past experience it has been found that this particular item responds to one of the other trend modes. However, the fact remains that it is difficult to objectively select trend models until approximately twelve observations are available.

Figure 3-12 summarizes in capsule form the logic used for model selection, particularly for the selection where minimal data is available in the early stages of a program.. Blocks 1 and 3 in Figure 3-12 apply where there is sufficient prior knowledge for selection, thereby by-passing the remainder of the selection considerations. Assuming such is not the case, Block 5 is entered and last months trend mode (if any) is selected and checked to assure ship weight is within prescribed bounds. If there is an unexpectedly large change, or if trend mode was not selected the previous month, then Block 6 is entered and analysis is based on a repeating mode analysis for Blocks 9 and 10.

3.5.3 TREND OF THE TRENDS

When the number of weight observations increase to at least twelve, targeting analysis using a trend of the trends can be made to determine which trend mode is the most representative or appropriate. Figure 3-13 illustrates targeting analysis for weight/performance analysis. Assume at time "L," after twelve observations have been made, that the item's weight is known to be 10,000 pounds. A comparison now can be made between the linear and the non-linear trend modes to determine which of the two has made the best prediction as to what the predicted weight of the item will be at time "L." From Figure 3-13 it can be seen what each of the predicted weights were for time "L" when made at times "A," "B," "C," etc., and the final predictions at time "L." Say the non-linear trend of the Linear Trend Model shows a 10,400 pound prediction and the non-linear trend of the Non-linear Trend Model shows a prediction of 9,900 pounds at time "L." From this trend of trends it can be concluded that at this early stage a selection of the Non-linear Trend Model will provide the best results for forecasting the continuing weight growth of the item as it moves toward the shipment date, and therefore the Non-linear Trend Model would be selected in this example.

3.6 FORECAST ANALYSIS

3.6.1 ANALYSIS

Comparative results of the four forecasting models are illustrated for a representative functional system on Figures 3-14 and 3-15. Figure 3-14 illustrates graphically the resulting curves fit through the normalized data. The heavy lines connect the actual reported data points. The distance between the actual points and the trend line shown by a heavy dashed line is due to normalization of the data. The forecast line, shown as a light dashed line, is extended from the last data point to remove the bias from the trend line. The purpose of this unbiasing in this manner is to improve the models with

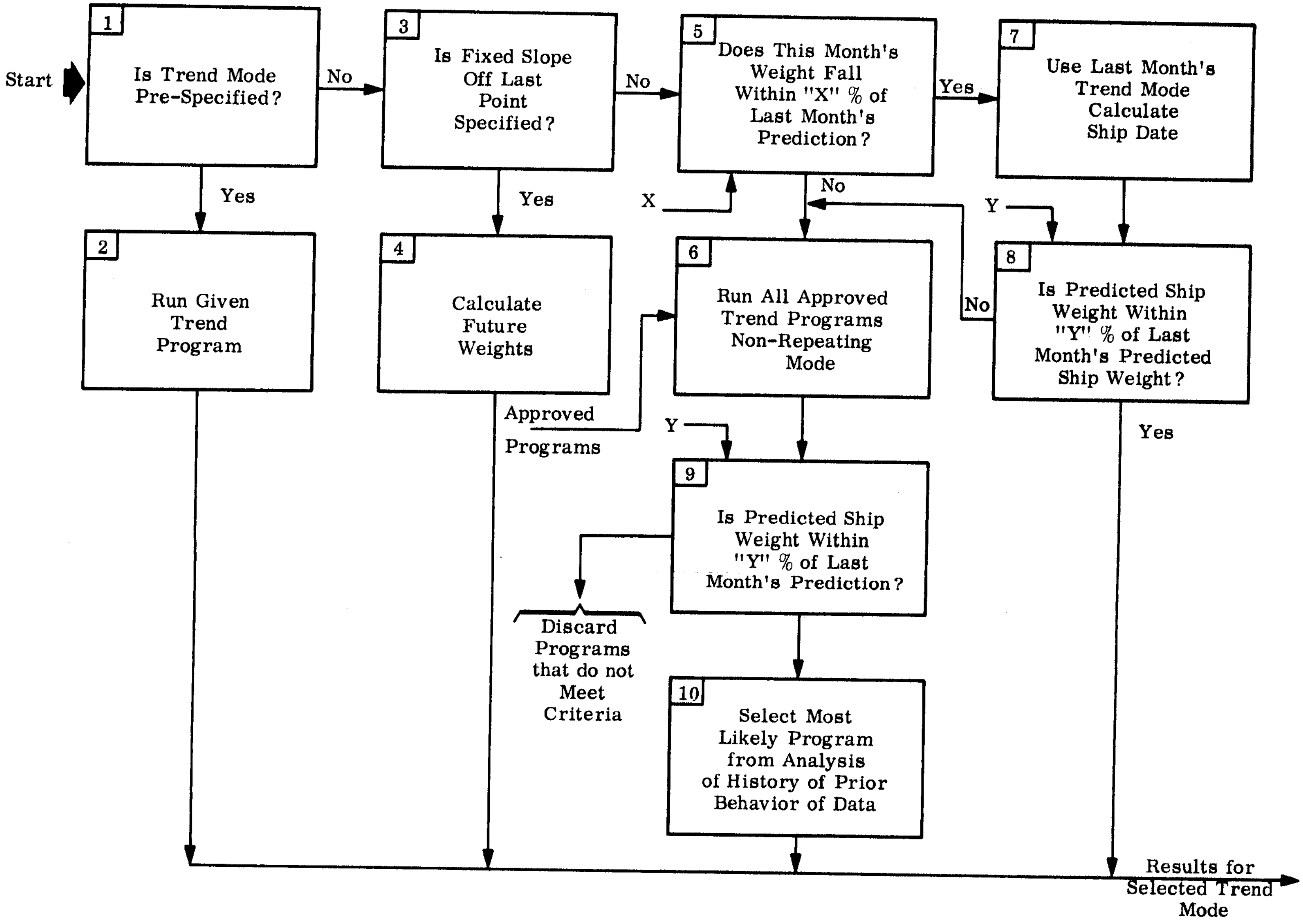


Figure 3-12. Application of Trend Mode Selection Logic for Weight/Performance Analysis

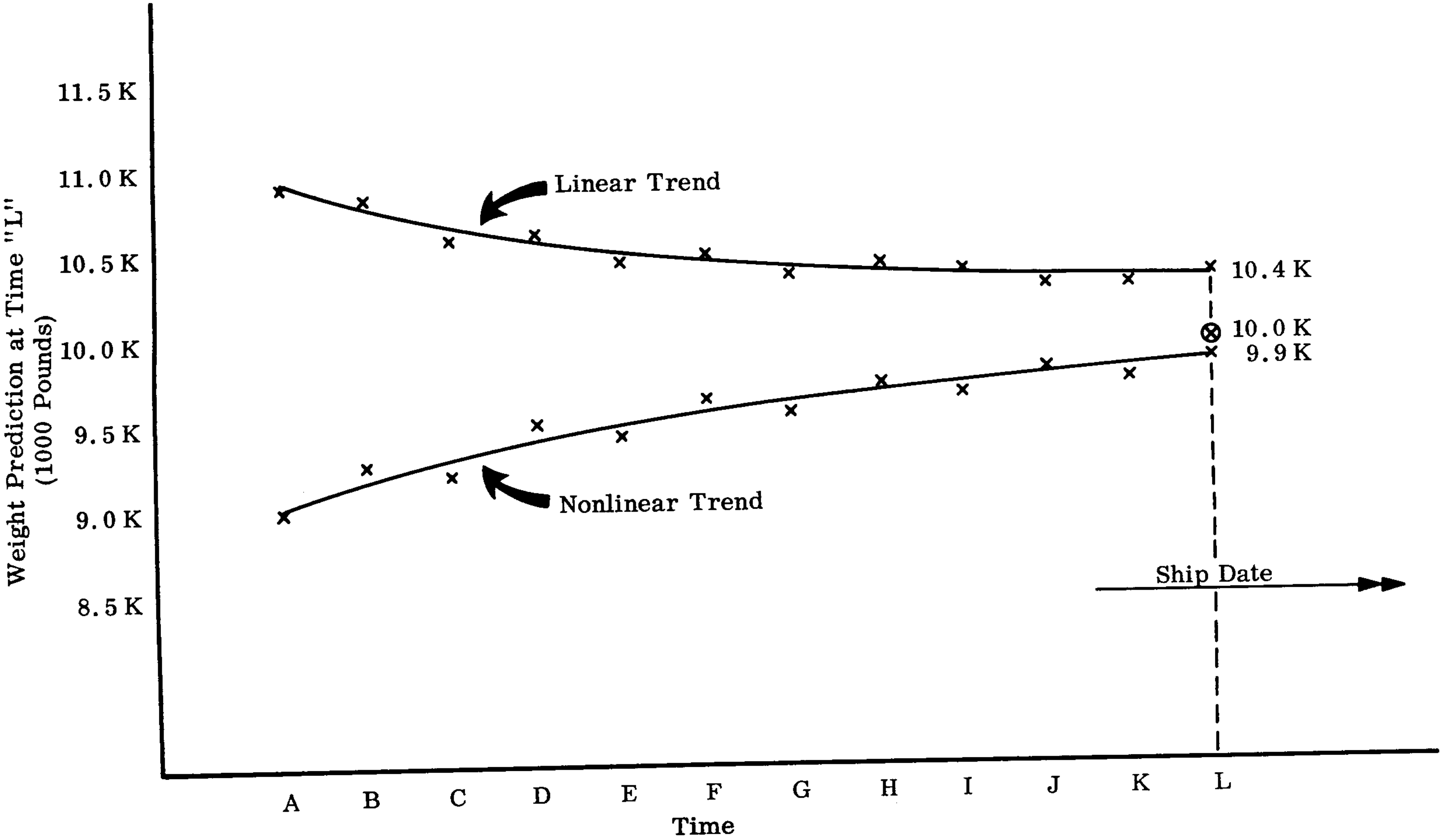


Figure 3-13. Illustration of Targeting Analysis for Weight/Performance Analysis

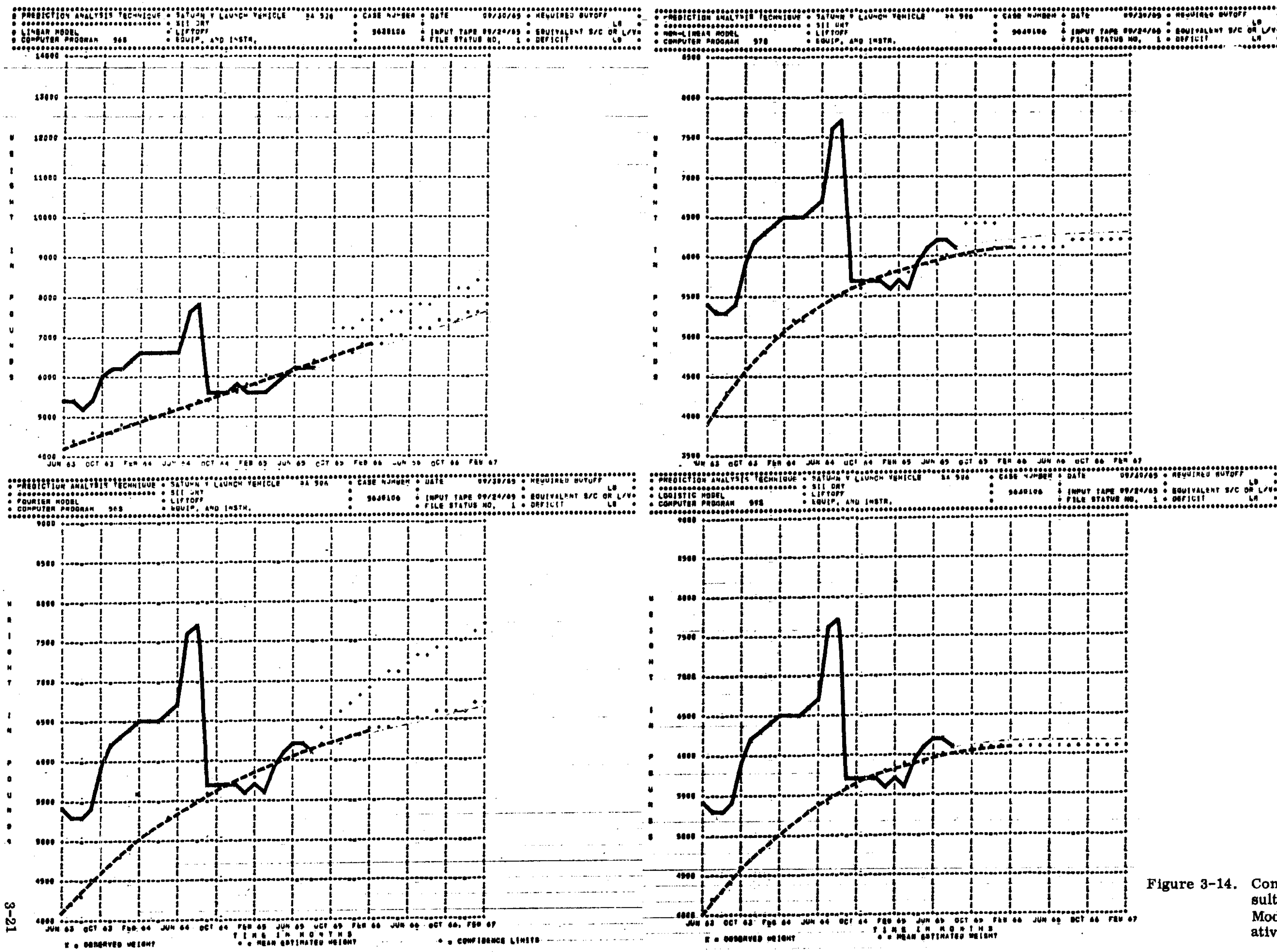


Figure 3-14. Comparative Graphic Results of Four Forecasting Models for a Representative Case

PREDICTION ANALYSIS TECHNIQUE · LINEAR MODEL · COMPUTER PROGRAM 56S
SATURN V LAUNCH VEHICLE SA 506 · SII DRY · LIFTOFF · EQUIP. AND INSTR.
CASE NUMBER 5630106 · DATE 09/30/65 · INPUT TAPE 09/24/65 · FILE STATUS NO. 1
REQUIRED BUYOFF LB · EQUIVALENT S/C OR L/V DEFICIT LB

MONTH	OBSERVED WEIGHT (LB)	OBSERVED PERCENT EST	CAL	ACT	OBSERVED NONRANDOM CHANGES (LB)	OTHER NONRANDOM CHANGES (LB)	NORMALIZED WEIGHT (LB)	NORMALIZED PERCENT EST	CAL	ACT	MEAN TREND VALUE (LB)	UPPER 95 PCT. CONF.LIM. (LB)	AVERAGE WEIGHT GROWTH (LB/MO)
JUN 63	5358	100	0	0	0	0	4087				4272		57
JUL 63	5344	100	0	0	0	0	4073				4351		58
AUG 63	5293	99	1	0	0	0	4022				4430		60
SEP 63	5400	99	1	0	0	0	4129				4508		59
OCT 63	5945	99	1	0	0	0	4674				4587		50
NOV 63	6235	99	1	0	0	0	4964				4666		46
DEC 63	6255	100	0	0	0	0	4984				4745		46
JAN 64	6412	100	0	0	-40	0	5101				4823		44
FEB 64	6503	100	0	0	0	0	5192				4902		43
MAR 64	6503	100	0	0	0	0	5192				4981		44
APR 64	6518	100	0	0	0	0	5207				5059		44
MAY 64	6550	100	0	0	0	0	5239				5138		45
JUN 64	6661	85	15	0	0	0	5350				5217		43
JUL 64	7630	85	15	0	-800	0	5519				5296		23
AUG 64	7724	85	15	0	0	0	5613				5374		21
SEP 64	5666	100	0	0	-825	2852	5592				5453		69
OCT 64	5679	100	0	0	0	0	5595				5532		71
NOV 64	5679	100	0	0	0	0	5595				5610		72
DEC 64	5725	100	0	0	0	0	5641				5689		73
JAN 65	5642	100	0	0	0	0	5558				5768		77
FEB 65	5680	100	0	0	0	0	5596				5847		76
MAR 65	5602	100	0	0	0	0	5518				5925		82
APR 65	5875	100	0	0	0	0	5791				6004		77
MAY 65	6055	100	0	0	0	0	5971				6083		74
JUN 65	6179	100	0	0	84	0	6179				6161		73
JUL 65	6229	100	0	0	0	0	6229				6240		73
AUG 65	6129	100	0	0	0	0	6129				6319		79
.... PREDICTED VALUES													
SEP 65	6208	97	0	3			6208				6398	7040	79
OCT 65	6286	94	0	6			6286				6476	7112	79
NOV 65	6365	91	0	9			6365				6555	7185	79
DEC 65	6444	88	0	13			6444				6634	7259	79
JAN 66	6523	84	0	16			6523				6712	7333	79
FEB 66	6601	81	0	19			6601				6791	7409	79
FINAL PREDICTED VALUES													
APR 68	9648	0	0	100			8646				8838	9884	0

PREDICTION ANALYSIS TECHNIQUE · NON-LINEAR MODEL · COMPUTER PROGRAM 57S
SATURN V LAUNCH VEHICLE SA 506 · SII DRY · LIFTOFF · EQUIP. AND INSTR.
CASE NUMBER 5630106 · DATE 09/30/65 · INPUT TAPE 09/24/65 · FILE STATUS NO. 1
REQUIRED BUYOFF LB · EQUIVALENT S/C OR L/V DEFICIT LB

MONTH	OBSERVED WEIGHT (LB)	OBSERVED PERCENT EST	CAL	ACT	OBSERVED NONRANDOM CHANGES (LB)	OTHER NONRANDOM CHANGES (LB)	NORMALIZED WEIGHT (LB)	NORMALIZED PERCENT EST	CAL	ACT	MEAN TREND VALUE (LB)	UPPER 95 PCT. CONF.LIM. (LB)	AVERAGE WEIGHT GROWTH (LB/MO)
JUN 63	5358	100	0	0	0	0	4087				3929		18
JUL 63	5344	100	0	0	0	0	4073				4114		16
AUG 63	5293	99	1	0	0	0	4022				4289		19
SEP 63	5400	99	1	0	0	0	4129				4441		18
OCT 63	5945	99	1	0	0	0	4674				4586		8
NOV 63	6235	99	1	0	0	0	4964				4719		3
DEC 63	6255	100	0	0	0	0	4984				4841		2
JAN 64	6412	100	0	0	-40	0	5101				4953		-1
FEB 64	6503	100	0	0	0	0	5192				5057		-2
MAR 64	6503	100	0	0	0	0	5192				5152		-3
APR 64	6518	100	0	0	0	0	5207				5240		-3
MAY 64	6550	100	0	0	0	0	5239				5321		-4
JUN 64	6661	85	15	0	0	0	5350				5395		-6
JUL 64	7630	85	15	0	-800	0	5519				5463		-26
AUG 64	7724	85	15	0	0	0	5613				5526		-31
SEP 64	5666	100	0	0	-825	2852	5592				5584		17
OCT 64	5679	100	0	0	0	0	5595				5637		17
NOV 64	5679	100	0	0	0	0	5595				5686		17
DEC 64	5725	100	0	0	0	0	5641				5732		16
JAN 65	5642	100	0	0	0	0	5558				5773		19
FEB 65	5680	100	0	0	0	0	5596				5811		18
MAR 65	5602	100	0	0	0	0	5518				5847		21
APR 65	5875	100	0	0	0	0	5791				5879		14
MAY 65	6055	100	0	0	0	0	5971				5909		9
JUN 65	6179	100	0	0	84	0	6179				5936		6
JUL 65	6229	100	0	0	0	0	6229				5962		5
AUG 65	6129	100	0	0	0	0	6129				5985		4
.... PREDICTED VALUES													
SEP 65	6150	97	0	3			6150				6006	6429	7
OCT 65	6170	94	0	6			6170				6026	6434	7
NOV 65	6188	91	0	9			6188				6044	6443	7
DEC 65	6205	88	0	13			6205				6061	6450	6
JAN 66	6220	84	0	16			6220				6076	6456	6
FEB 66	6234	81	0	19			6234				6090	6462	6
FINAL PREDICTED VALUES													
APR 68	6379	0	0	100			6379				6234	6686	0

PREDICTION ANALYSIS TECHNIQUE · FOURIER MODEL · COMPUTER PROGRAM 58S
SATURN V LAUNCH VEHICLE SA 506 · SII DRY · LIFTOFF · EQUIP. AND INSTR.
CASE NUMBER 5630106 · DATE 09/30/65 · INPUT TAPE 09/24/65 · FILE STATUS NO. 1
REQUIRED BUYOFF LB · EQUIVALENT S/C OR L/V DEFICIT LB

MONTH	OBSERVED WEIGHT (LB)	OBSERVED PERCENT EST	CAL	ACT	OBSERVED NONRANDOM CHANGES (LB)	OTHER NONRANDOM CHANGES (LB)	NORMALIZED WEIGHT (LB)	NORMALIZED PERCENT EST	CAL	ACT	MEAN TREND VALUE (LB)	UPPER 95 PCT. CONF.LIM. (LB)	AVERAGE WEIGHT GROWTH (LB/MO)
JUN 63	5358	100	0	0	0	0	4087				4087		28
JUL 63	5344	100	0	0	0	0	4073				4214		29
AUG 63	5293	99	1	0	0	0	4022				4340		31
SEP 63	5400	99	1	0	0	0	4129				4464		29
OCT 63	5945	99	1	0	0	0	4674				4584		28
NOV 63	6235	99	1	0	0	0	4964				4700		15
DEC 63	6255	100	0	0	0	0	4984				4811		14
JAN 64	6412	100	0	0	-40	0	5101				4917		12
FEB 64	6503	100	0	0	0	0	5192				5016		10
MAR 64	6503	100	0	0	0	0	5192				5110		10
APR 64	6518	100	0	0	0	0	5207				5197		10
MAY 64	6550	100	0	0	0	0	5239				5278		10
JUN 64	6661	85	15	0	0	0	5350				5354		7
JUL 64	7630	85	15	0	-800	0	5519				5424		-14
AUG 64	7724	85	15	0	0	0	5613				5490		-16
SEP 64	5666	100	0	0	-825	2852	5592				5552		31
OCT 64	5679	100	0	0	0	0	5595				5610		32
NOV 64	5679	100	0	0	0	0	5595				5666		32
DEC 64	5725	100	0	0	0	0	5641				5720		32
JAN 65	5642	100	0	0	0	0	5558				5772		35
FEB 65	5680	100	0	0	0	0	5596				5824		35
MAR 65	5602	100	0	0	0	0	5518				5875		38
APR 65	5875	100	0	0	0	0	5791				5926		31
MAY 65	6055	100	0	0	0	0	5971				5976		27
JUN 65	6179	100	0	0	84	0	6179				6027		24
JUL 65	6229	100	0	0	0	0	6229				6078		24
AUG 65	6129	100	0	0	0	0	6129				6129		27
.... PREDICTED VALUES													
SEP 65	6170	97	0	3			6170				6170	6395	27
OCT 65	6209	94	0	6			6209				6209	6528	27
NOV 65	6248	91	0	9			6248				6248	6638	26
DEC 65	6284	88	0	13			6284				6284	6735	26
JAN 66	6320	84	0	16			6320				6320	6824	25
FEB 66	6354	81	0	19			6354				6354	6906	25
FINAL PREDICTED VALUES													
APR 68	7005	0	0	100			7005				7005	8200	0

PREDICTION ANALYSIS TECHNIQUE · LOGISTIC MODEL · COMPUTER PROGRAM 59S
SATURN V LAUNCH VEHICLE SA 506 · SII DRY · LIFTOFF · EQUIP. AND INSTR.
CASE NUMBER 5630106 · DATE 09/30/65 · INPUT TAPE 09/24/65 · FILE STATUS NO. 1
REQUIRED BUYOFF LB · EQUIVALENT S/C OR L/V DEFICIT LB

MONTH	OBSERVED WEIGHT (LB)	OBSERVED PERCENT EST	CAL	ACT	OBSERVED NONRANDOM CHANGES (LB)	OTHER NONRANDOM CHANGES (LB)	NORMALIZED WEIGHT (LB)	NORMALIZED PERCENT EST	CAL	ACT	MEAN TREND VALUE (LB)	UPPER 95 PCT. CONF.LIM. (LB)	AVERAGE WEIGHT GROWTH (LB/MO)
JUN 63	5358	100	0	0	0	0	4087				4039		16
JUL 63	5344	100	0	0	0	0	4073				4180		16
AUG 63	5293	99	1	0	0	0	4022				4316		17
SEP 63	5400	99	1	0	0	0	4129				4447		16
OCT 63	5945	99	1	0	0	0	4674				4572		6
NOV 63	6235	99	1	0	0	0	4964				4692		1
DEC 63	6255	100	0	0	0	0	4984				4806		0
JAN 64	6412	100	0	0	-40	0	5101				4914		-3
FEB 64	6503	100	0	0	0	0	5192				5017		-5
MAR 64	6503	100	0	0	0	0	5192				5113		-5
APR 64	6518	100	0	0	0	0	5207				5203		-7
MAY 64	6550	100	0	0	0	0	5239				5287		-6
JUN 64	6661	85	15	0	0	0	5350				5366		-8
JUL 64	7630	85	15	0	-800	0	5519				5439		-30
AUG 64	7724	85	15	0	0	0	5613				5507		-33
SEP 64	5666	100	0	0	-825	2852	5592				5570		14
OCT 64	5679	100	0	0	0	0	5595				5629		14
NOV 64	5679	100	0	0	0	0	5595				5683		14
DEC 64	5725	100	0	0	0	0	5641				5732		14
JAN 65	5642	100	0	0	0	0	5558				5778		16
FEB 65	5680	100	0	0	0	0	5596				5820		16
MAR 65	5602	100	0	0	0	0	5518				5858		16
APR 65	5875	100	0	0	0	0	5791				5893		11
MAY 65	6055	100	0	0	0	0	5971				5926		6
JUN 65	6179	100	0	0	84	0	6179				5955		3
JUL 65	6229	100	0	0	0	0	6229				5982		1
AUG 65	6179	100	0	0	0	0	6129				6007		4
.... PREDICTED VALUES													
SEP 65	6150	97	0	3			6150				6028		4
OCT 65	6168	94	0	6			6168				6046		3
NOV 65	6184	91	0	9			6184				6062		3
DEC 65	6197	88	0	13			6197				6075		3
JAN 66	6209	84	0	16			6209				6086		2
FEB 66	6218	81	0	19			6218				6090		2
FINAL PREDICTED VALUES													
APR 68	6273	0	0	100			6273				6151		0

Figure 3-15. Comparative Tabular Results of Four Forecasting Models for a Representative Case

respect to time dependency and the recognition of the fact that the most recent data point is the most valuable information at any time.

The comparative data resulting from calculation of each of the prediction models is tabulated in Figure 3-15.

Interpretation of these charts is assisted by a discussion of content of each column. Referring to Figure 3-16, these columns are numbered from one to ten, representing the flow of calculations from initial weight data to forecast results as follows:

- Column 1. Calculations start with the data as a chronological tabulation of all weights and E/C/A weight percentages in the observed range.
- Column 2. The observed non-random changes, as deduced from the reported data, are listed at the month of introduction.
- Column 3. Other non-random changes, if any, are data points found to exceed a reasonable predetermined limit.
- Column 4. The normalized weights, Column 4, are then the resultant of Columns 1 to 3.
- Column 5a. The mean trend line is a tabulation of results produced by trending of normalized data by a particular computer model.
- Column 5b. The mean trend line is extrapolated to the ship date of the particular system being trended.
- Column 6. The upper 95 percent confidence limit is calculated about the mean trend line, using the parameters of the particular computer model.
- Column 7. Normalized weight values in the forecast range are values having the same slope as the mean trend line in that range. However, they are taken from the last observed weight. (See Figure 3-15.)
- Column 8. Other non-random changes in the forecast range are generated for the forecast range, using predetermined criteria.
- Column 9. The forecast values are the values of the normalized line in the forecast range, and non-random changes in the forecast range are incorporated into them. The Estimated, Calculated, and Actual weight percentages in the forecast range are projected interpolation from current values to values at the ship date.
- Column 10. The average weight growth is the difference between the final forecast weight value and the current weight value with this difference divided by the time span in months.

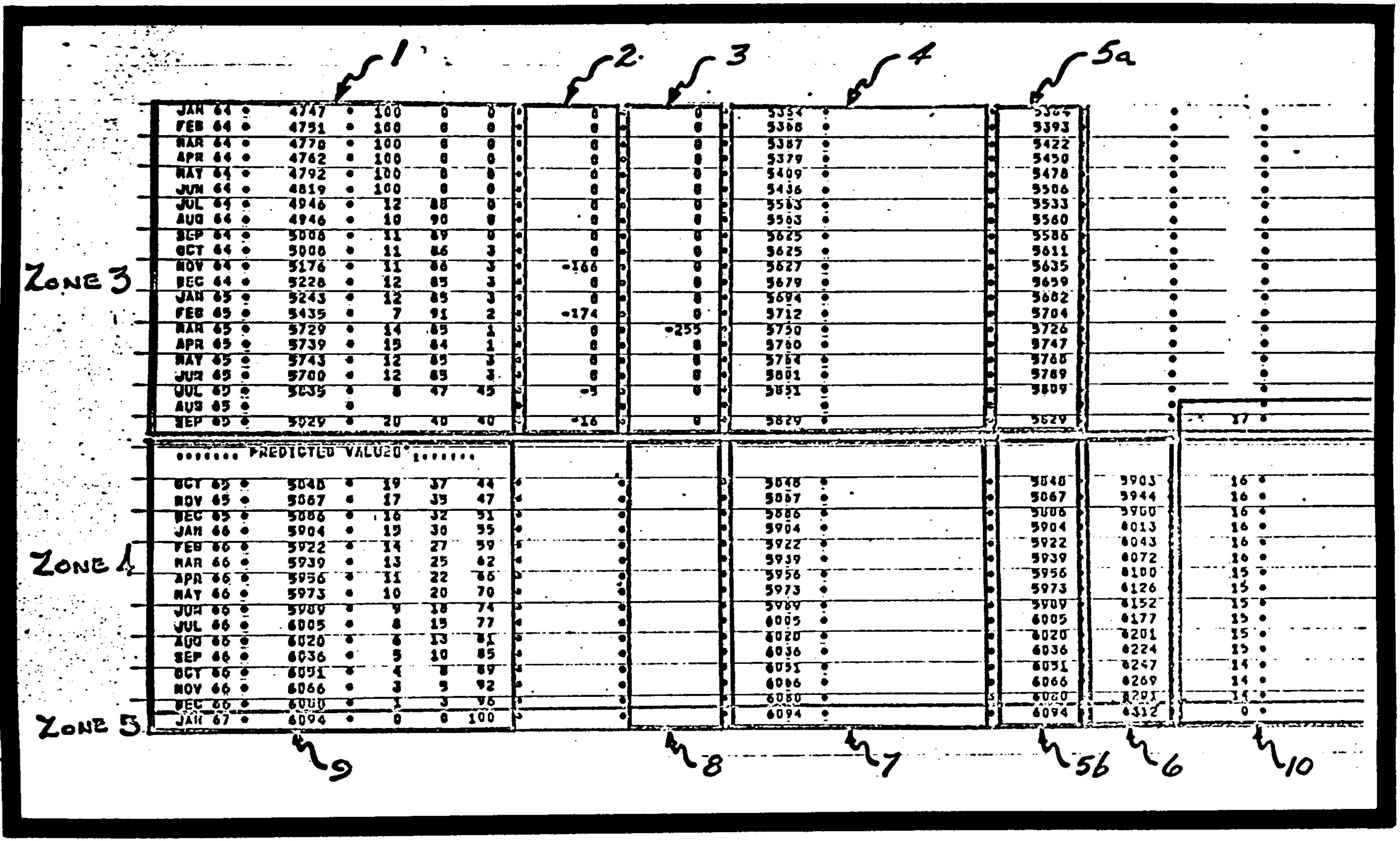


Figure 3-16. Key to Interpretation of Tabular Prediction Analysis Results

3.6.2 FORECAST MODEL COMPARISON

Comparison between the various charts and graphs of Figures 3-14 and 3-15 can now be made to illustrate differences between the four models. The linear results, which are normally similar to a linear least squares tend to produce excessive weights at ship date. For this particular set of data, the other models produced results which ranged in descending order from the 7005 pounds of the Fourier to the 6379 pounds forecast by the non-linear to the 6273 pounds forecast by the logistic model. The characteristics of these models can be observed here from the nature of the trend data and forecast lines. The model which best represents the expected growth at this time was identified after study and evaluation, as described in paragraph 3.5, was the Fourier Model. Non-stationarity of weight growth behavior, however, necessitates constant surveillance and at some future date one of the other models might be preferred due to changing behavior patterns.

3.6.3 FORECAST LINE ADJUSTMENT DUE TO EXPECTED FUTURE CHANGES

Through the normal design, manufacture, and test cycle weight changes occur. The nature of these changes may be the result of improved design, material substitutions, removal or addition of parts, and many others. There are always proposed and pending changes to be evaluated for authorization, and possible incorporation into the item.

Use of the history of weight changes aids in the forecast of future weight growth and required buy-offs, based on proposed changes, by the development of correction factors. These correction factors are applied to the proposed weight changes on the item and provide management with a higher confidence level when analyzing and forecasting future weight growth.

For example, assume that weight changes amounting to a decrease of one thousand pounds has been proposed on an item in the process of being manufactured. It is important for management to know the probability of these changes being made, if made, the amount of weight changes when incorporated, and how long it takes to process and incorporate the changes. From an analysis of the history of weight changes these correction factors are obtained for appraisal in the following manner. Assume that on a particular item, the records show that seventy-five proposed changes have been made and sixty have been authorized and incorporated in the item. Of the sixty incorporated changes, it has been found that the average time from proposed to incorporated change has been two months. Further study also indicates that the average percentage of the original value of the proposed weight change when incorporated has been eighty-five percent of the original estimate.

From this information, it can now be concluded that:

a. There is an 80 percent probability that the proposed changes will be incorporated.

b. The proposed changes that are authorized will take two months to be incorporated.

c. Instead of the 1000 pounds that was proposed, the forecasted weight when incorporated, two months hence, will be 1000 x .80 x .85 = 680 pounds.

This example is illustrated in Figure 3-17 shown below.

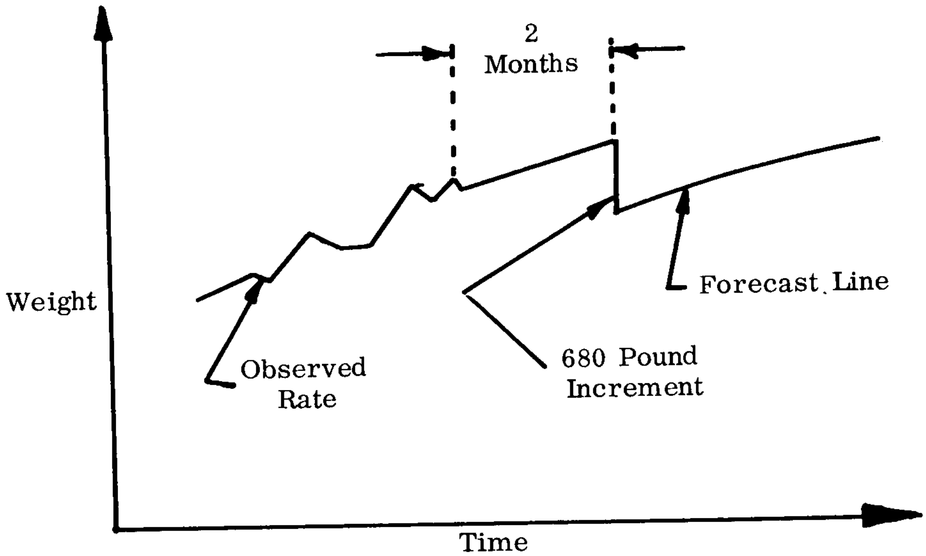


Figure 3-17. Forecast Line Adjustment Using Correction Factors

Although, the example offered here is for an item with a decremental decrease in weight, similar correction factors could be applied as the rate of expected changes. In this case the slope of the forecast curve would be adjusted to include incorporation of forecasted buy-offs based on appraisal of prior rate of buy-off. While specific forecast rates of buy-off will depend on the specific program being considered, there are several observations of general interest. At first thought it would seem that an ideal program would be one that would run from design concept to shipment without changes. However, changes will and do occur for various reasons related generally to the achievement of an efficient design with minimum cost. While equipment is in the process of being designed, changes are relatively easy to make and can be made at minimum cost. As the equipment progresses into the fabrication and test stages, changes become progressively more difficult and expensive. Also, extensive changes late in a program may lead to schedule slippage and possible delay in mission.

Figure 3-18 shows change curves for two items "A" and "B," as they progress through design, fabrication and test to shipment. Curve "A" is a more desirous change pattern for a program to follow than that in curve "B." Curve "A" shows that the majority of changes are made on the item while still in the design and early fabrication stages and then a gradual decrease in changes, or possible buy-offs, through fabrication and test. As shipment date approaches, curve "A" would indicate that only minor changes, as a result of test, are required. Such a curve would indicate close scrutiny on the part of management to assure program success, with changes and buy-offs being made at minimum cost and without endangering the scheduled shipment of the items.

Curve "B," on the other hand, indicates a poorly managed, or possibly a "crash" type program. Fewer changes are made during the design stage, with the majority of changes occurring during fabrication and test. A program such as this, indicates a "wait and see" type approach. The close scrutiny that was observed in the program

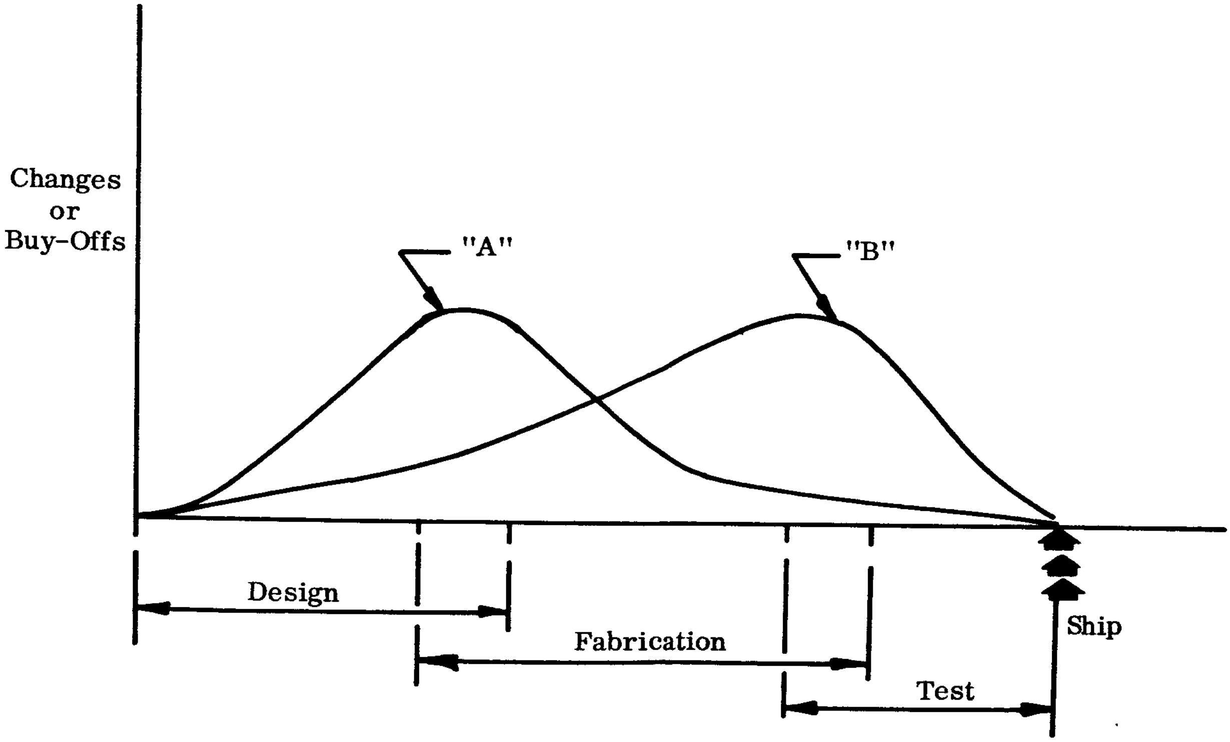


Figure 3-18. Comparison of Changes

represented by curve "A" does not exist here. Potential changes and buy-offs are allowed to build up through the fabrication stages and into test. When changes must be made, and shipment is close at hand, it is possible that changes will have to be made without proper planning and evaluation, at excessive cost, and with the possibility that schedule slippage will result.

3.7 BUILDUP AND PERFORMANCE CALCULATIONS

3.7.1 BUILDUP OF FORECAST ANALYSIS

3.7.1.1 Identification of Application

The Apollo missions will be performed with a launch vehicle comprised of from four to six major stages and a spacecraft with from four to six modules. Each stage or module will have from three to sixteen functional systems. These systems, in turn, will have different performance requirements, different intrinsic weight growths and performance degradations. A breakdown of the units in each flight is shown in Tables 3-3, 3-4, and 3-5. For reasons explained in this chapter, the functional systems are trended rather than the payload weight and launch vehicle capability. Because of this, the predicted launch capability and spacecraft weight must be "built up" from the predicted weight of the functional systems. This procedure requires detailed knowledge of the particular missions and their vehicles so that appropriate mathematical models may be constructed.

An example of how mission details influence the effect of functional-system weight changes on total spacecraft weight, on one mission, is one where the objectives were to verify the performance of the service propulsion subsystem. Several service propulsion subsystem burns of fixed time duration were planned for this purpose. Since obtaining specific velocity change is not a primary objective for these maneuvers, it is obvious that an increase in weight in one of the subsystems does not require additional propellant. Thus, the dry weight increase in a subsystem is the total weight increase of the spacecraft; that is, the trade-off factor for this maneuver is One. Another mission objective required that the Service Propulsion System provide a de-orbit impulse. This requires a fixed velocity increment. An increase in weight of one of the subsystems will result in lower accelerations, which in turn would result in a lower velocity if the burn time and thus the propellant were not increased. So, to maintain the mission objective, propellant must be added, hence the trade-off factor is greater than One for this maneuver. The mathematical model selected for this last maneuver is

Table 3-3

Apollo Launch Vehicle and Spacecraft Stages and Modules

Launch Vehicle No.	201	202	203	204	205	206	207	501	502	503	504 and 504S
Launch Vehicle Stages	Saturn IB Missions							Saturn V Missions			
S-IB	x	x	x	x	x	x	x				
S-IB/S-IVB Interstage	x	x	x	x	x	x	x				
S-IC								x	x	x	x
S-IC/S-II Interstage								x	x	x	x
S-II								x	x	x	x
S-II/S-IVB Interstage								x	x	x	x
S-IVB	x	x	x	x	x	x	x	x	x	x	x
IU (Instrument Unit)	x	x	x	x	x	x	x	x	x	x	x
Spacecraft Modules	Block I Spacecraft							Block II Spacecraft			
LES	x	x		x	x		x	x	x	x	x
Adapter	x	x	L Hi Experiment	x	x	Under Study	x	x	x	x	x
SM	x	x		x	x		x	x	x	x	x
CM	x	x		x	x		x	x	x	x	x
LEM A							x	Inert		x	x
LEM D							x			x	x

Table 3-4

Apollo Launch Vehicle Stage Functional Systems (206) and (504)

Functional System \ Stage	S-IB	S-IB/SNB Interstage	S-IC	S-IC/S-II First Interstage	S-IC/S-II Second Interstage	S-II	S-V/S-IVB Interstage	S-IVB	S-IV
Structure Stage	x	x	x	x	x	x	x	x	x
Propulsion System	x		x		x	x		x	
Equipment and Instrumentation	x	x	x	x	x	x	x	x	x
Residual and Pressure Propellant	x	x	x			x	x	x	x
Ullage Rocket Propellant					x				
Auxiliary Propellant - Power Rell.								x	

Table 3-5

Apollo Spacecraft Module Functional System (504)

Functional System \ Module	LEM Ascent	LEM Descent	Spacecraft Adapter	SM	CM	LES
Structure	x	x	x	x	x	x
Stabilization and Control	x	x			x	
Navigation and Guidance	x	x			x	
Crew Provisions or Systems	x				x	
Environmental Control System	x	x		x	x	
Instrumentation	x	x		x	x	
Electrical Power System	x	x	x	x	x	x
Propulsion System	x	x		x		x
Reaction Control System	x			x	x	
Communications	x	x		x	x	
Control and Displays	x				x	
Landing Gear		x				
Earth Loading System					x	
Ballast						x
Propellant - Useable						x
Reaction Control (Useful Load)				x	x	
Electrical Power (Useful Load)				x		
Environmental Control (Useful Load)				x	x	
Main Propulsion (Useful Load)				x		
Scientific Equipment (Useful Load)					x	
Crew Systems (Useful Load)					x	

the ideal velocity equation. The trade-off factor, obtained by differentiating this equation, is the ratio of the initial weight to final weight.

In addition to the mission description, a description of the vehicle is required for the construction of math models to calculate predicted launch vehicle capability and spacecraft weight. This description must include the breakdown to stages and modules and be related to the mission events.

As development of the Apollo Program progresses, the mission details, the missions themselves, and the vehicle hardware are continually being modified or changed. This necessarily requires that the calculation procedure used to build up forecasted gross weights and launch vehicle capabilities be changed accordingly if the forecasts are to be accurate. An over-all surveillance of all available Apollo documentation, particularly revisions of those documents from which the mission and vehicle descriptions have been obtained, is continually being made so that the math models may be updated to include the latest data.

3.7.1.2 Buildup from Forecast Elements

The major functional system data rather than stage weight, module weight, total payload, or launch vehicle capability was selected to be observed and trended with the trend forecast program. This level of system breakdown was selected because, first, different trend models are permitted for each functional system and the most appropriate may be selected (a subjective decision made by managers experienced in the history of weight growth). Secondly, during the pre-trending analysis it is easier to assess changes in the data as random or non-random. Thirdly, it is easier to pinpoint causes of weight problems when the analysis indicates a problem exists. Finally, experiences of Senior Weights Engineers associated with the development of these Weight/Performance Forecast Analysis techniques indicate that it is essential to observe weight growth at no higher level than these major functional systems. Although it is desirable to trend functional systems from the viewpoint of the Forecast Program, it is not easy to evaluate the mission status from the forecasted weight of these many functional systems. Simple comparison of functional system weight forecasts to a control value or limit would not indicate the existence or non-existence of mission capability unless all or most of the forecasts were within their limits, an unlikely occurrence.

To obtain the over-all mission picture from the forecasted weight of the major functional systems, a buildup of forecasted spacecraft weight and launch vehicle capability is necessary.

Also to be considered is the number of systems to be analyzed. There is an average of ten functional systems for about ten stages and modules, and for perhaps ten missions, this gives a total of a thousand systems. Because functional system data is not always available for all missions and to reduce the amount of data to be trended, functional system growth forecasts are made only for selected, representative vehicles. For example, the Block II spacecraft functional systems are trended only for one mission. The forecasted module inert weights for the spacecraft are obtained by summing the weight forecasts, at the time of shipment, of the functional systems. The forecasted module inert weights for other Block II spacecraft modules are obtained by assuming their growth is the same over the period of time that they are being constructed. A sample calculation is shown in Figure 3-19 for the forecast analysis of the Block II command module.

The control weights, established by program management from reference performance and trajectory requirements, represent the maximum weights for each individual stage or module. Should any stage forecasted weight exceed this control limit, the need is indicated for a required buy-off or reduction in weight, with some expenditure in money and time. Following the calculation of inert weights from the forecasted functional system weights, the total forecasted spacecraft module weights are calculated by appropriate use of trade-off factors. These calculations may be simple and straightforward or, they may become somewhat involved, as in cases where the trade-off factors are not applied directly to the built-up inert weight, because of considering jettisoned and expendable items. The forecasted launch vehicle payload capability is calculated as shown in the sample calculation of Figure 3-20. The forecasted stage inert or burnout weight is compared to the reported current weight, and the difference multiplied by the stage trade-off factor to yield the payload capability change resulting from weight change of that stage. These stage payload capability changes are summed for all of the stages of a launch vehicle and added to the current reported launch vehicle capability to give the total forecasted launch vehicle capability.

The buildup of the total spacecraft weight and launch vehicle capability described above is depicted in Figure 3-21. The first column illustrates the forecasted representative functional system weight, essentially obtained by summing the functional systems data, as described above. Finally, the last column shows the total launch vehicle capability or spacecraft weight which was built up from an appropriate combination of summing items from the previous column and multiplication with trade-off factors as described in preceding paragraphs.

Apollo Spacecraft Block II Mission 506
C/M Gross
S/C Injection

The following arbitrary cases and their associated weights have been used to replace those on record.

Case Numbers in this Listing	Mode for this Case	Date	Prediction Line	Maximum Likelihood Line	Percentage Est	Percentage Cal	Percentage Act	Case 661502	Case 661503	Case 661521	Case 661537
661501	LIN	Apr 65	10370	10168	56	43	2	139	5410	295	101
661502	ARB	May 65	10386	10390	54	42	3	139	5410	297	101
661503	ARB	Jun 65	10402	10414	53	41	6	139	5410	299	101
661506	NLN	Jul 65	10417	10429	51	40	9	139	5410	301	101
661511	NLN	Aug 65	10431	10443	50	38	12	139	5410	303	101
661516	NLN	Sep 65	10446	10458	48	37	14	139	5410	305	101
661517	LIN	Oct 65	10461	10473	47	36	17	139	5410	307	101
661521	ARB	Nov 65	10473	10485	45	35	20	139	5410	309	101
661526	LIN	Dec 65	10487	10499	44	34	23	139	5410	311	101
661531	NLN	Jan 66	10502	10514	42	32	25	139	5410	313	101
661536	NLN	Feb 66	10513	10525	41	31	28	139	5410	315	101
661537	ARB	Mar 66	10526	10538	39	30	31	139	5410	317	101
661546	LIN	Apr 66	10540	10552	37	29	34	139	5410	319	101
661556	NLN	May 66	10553	10565	36	28	37	139	5410	321	101
661557	NLN	Jun 66	10565	10577	34	26	39	139	5410	323	101
		Jul 66	10578	10590	33	25	42	139	5410	325	101
		Aug 66	10590	10602	31	24	43	139	5410	327	101
		Sep 66	10602	10614	30	23	40	139	5410	329	101
		Oct 66	10614	10626	28	21	50	139	5410	331	101
		Nov 66	10626	10638	27	20	53	139	5410	333	101
		Dec 66	10638	10650	25	19	56	139	5410	335	101
		Jan 67	10650	10662	24	18	59	139	5410	337	101
		Feb 67	10661	10673	22	17	61	139	5410	339	101
		Mar 67	10673	10685	20	15	64	139	5410	341	101
		Apr 67	10684	10696	19	14	67	139	5410	343	101
		May 67	10696	10708	17	13	70	139	5410	345	101
		Jun 67	10707	10719	16	12	72	139	5410	347	101
		Jul 67	10718	10739	14	11	75	139	5410	349	101
		Aug 67	10730	10742	13	10	70	139	5410	351	101
		Sep 67	10740	10752	11	8	81	139	5410	353	101
		Oct 67	10751	10763	9	7	83	139	5410	355	101
		Nov 67	10763	10775	8	6	86	139	5410	357	101
		Dec 67	10774	10786	6	5	89	139	5410	359	101
		Jan 68	10784	10796	5	4	92	139	5410	361	101
		Feb 68	10795	10007	3	2	94	139	5410	363	101
		Mar 68	10806	10010	2	1	97	139	5410	365	101
		Apr 68	10817	10829	0	0	100	139	5410	367	101

Figure 3-19. Sample Trend Summing Program Output

a.	Command Module (CM) Predicted Inert Weight (from functional system predicted sums)		10422
b.	Service Module (SM) Predicted Inert Weight (from functional system predicted sums)		+9425
c.	Command/Service Module (CSM) Predicted Inert Weight (a + b)		19847
d.	Lunar and Earth Orbit Expendables Weight (from current reported data)		-485
e.	CSM Buyoff Weight at Transearth Injection (c - d)		19362
f.	SM Injection Propellant Weight (Tradeoff Factors x buyoff weight) (0.5130 x e)		+9933
g.	CSM Gross Weight at Transearth Injection (e + f)		22925
h.	Lunar Excursion Module (LEM) Ascent Dry Weight at Buyoff (from functional system predicted sums)	4334	
i.	LEM Ascent Propellant Weight (trade-off factor x buyoff weight) (0.4326 x h)	+1875	
j.	LEM Gross Weight at Liftoff (h + i)	6209	
k.	Weight of Items Jettisoned on Lunar Terrain (from current reported data)	376	
l.	LEM Dry Weight at Touchdown (from functional system predicted sums)	+3472	
m.	LEM Lunar Landing Weight (u + k + l)	10057	
n.	LEM Descent Propellant Weight (trade-off factor x buyoff) weight) (0.5540 x m)	5572	
o.	LEM Total Weight at Separation (m + n)	15629	
p.	Crew and Equipment Weight (from current reported data)	-436	
q.	LEM Total Weight at Injection (o - p)	15193	15193
r.	LEM Lunar Orbit Expendables Weight (from current reported data)		+337
s.	Weight at Lunar Orbit Injection (g + q + r)		44825
t.	Injection Propellant Weight (trade-off factor x buyoff weight) (0.3962 x s)		+17760
u.	Gross Weight in Earth Orbit (s + t)		62585
v.	Miscellaneous Weight Left in Earth Orbit (d - r)		148
w.	Spacecraft Adapter Weight (from functional system predicted sums)		+3142
x.	Injected Weight Less Reserves (u + v + w)		65875
y.	NASA Design Reserves Propellant Weight (from current reported data)		+1000
z.	Total Spacecraft Injected Weight (x + y)		66875
aa.	Launch Escape System (LES) Weight (from functional system predicted sums)		+6521
ab.	Total Spacecraft Liftoff Weight (z + aa)		73396

Figure 3-20. Sample Calculation of Spacecraft Weight Buildup

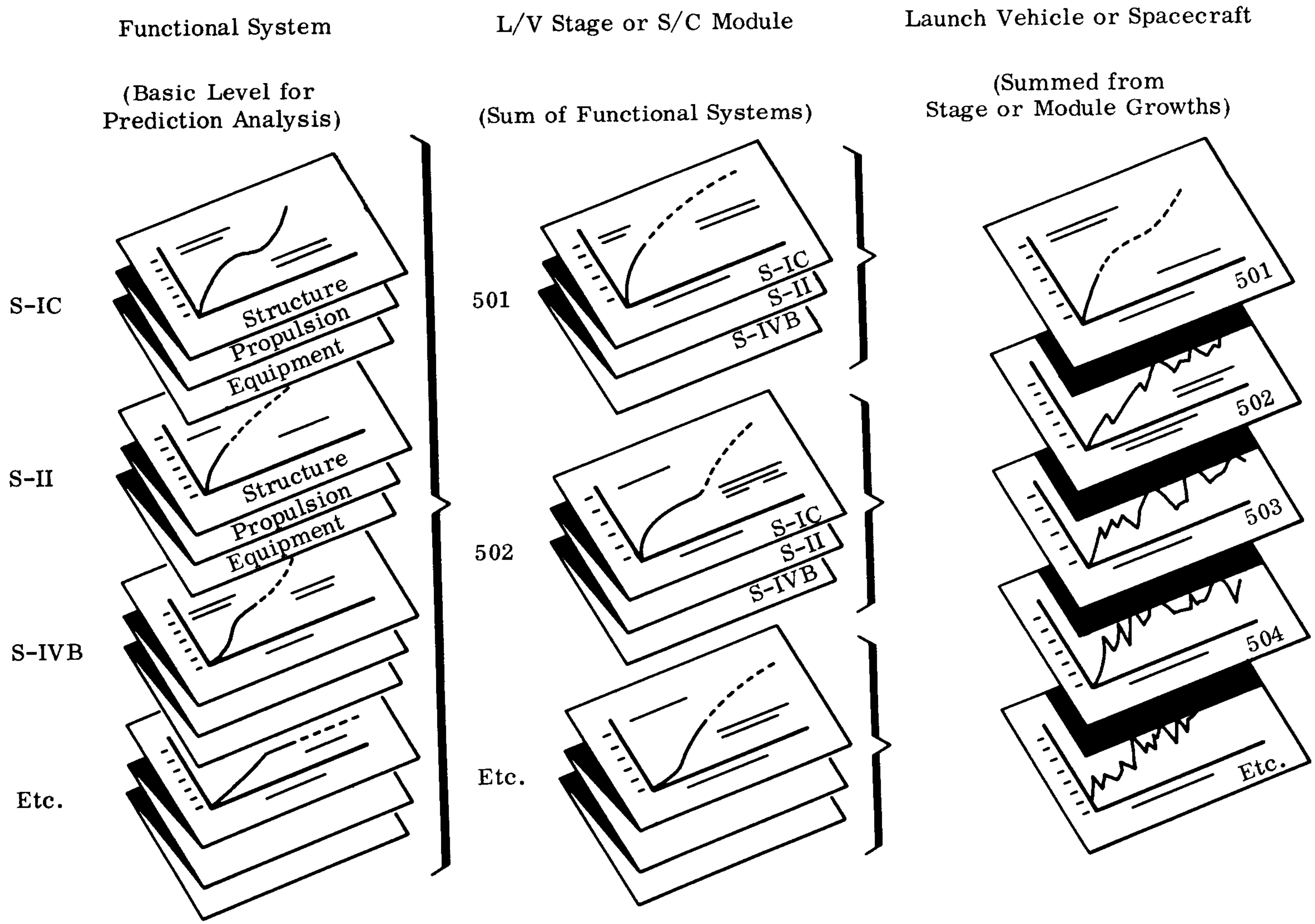


Figure 3-21. Buildup of L/V-S/C Weight Data

The comparison of reported and predicted launch vehicle capability to spacecraft weight is shown clearly on curves of the form of Figure 3-22. The implications of these curves, particularly when the predicted launch vehicle capability drops below the spacecraft weight, is discussed in detail in the next section.

3.7.2 INTERFACE COMPARISONS

Spacecraft and launch vehicle forecasts, which are compared to control limits for the purpose of identifying potential problems and obtaining quantitative data for management decisions, can also be compared at the major interfaces for each vehicle. These comparisons are made in order to obtain an over-all perspective of the weight-to-performance status of the vehicle.

In order to understand the logic behind interface comparisons it is valuable to first consider control limits. Control limits comprise weight and performance budgets which are integral and compatible with the mission requirements. Changes in the control limits require compensating changes in related vehicle and mission specifications. Individual stage and module control limits are inextricably interrelated through performance criteria.

Control limits are established down to the stage and module level, the lowest level to which weight, propulsion capability, and mission requirements can be conveniently related. Control limits are also mission oriented; they are established at each mission event at which a stage or module with propulsion capability is critical to mission success. Some stages or modules have more than one control limit due to weight changes during the mission resulting from the transfer or ejection of material and to differing propulsion system relationships.

The buildup of data for the interface charts is similarly mission oriented. For example, the data prepared for the launch vehicle payload capability and spacecraft weight comparisons is oriented to the earth orbit or translunar injection event. The launch vehicle payload capability is adjusted for the effect of lifting the launch escape system which is ejected before earth orbit injection and therefore is not included in the spacecraft weight.

It should be noted that in the buildup of data for the launch vehicle payload capability and spacecraft weight comparisons, compensating changes in the stage or module control limits and related vehicle or mission specifications have been assumed. These

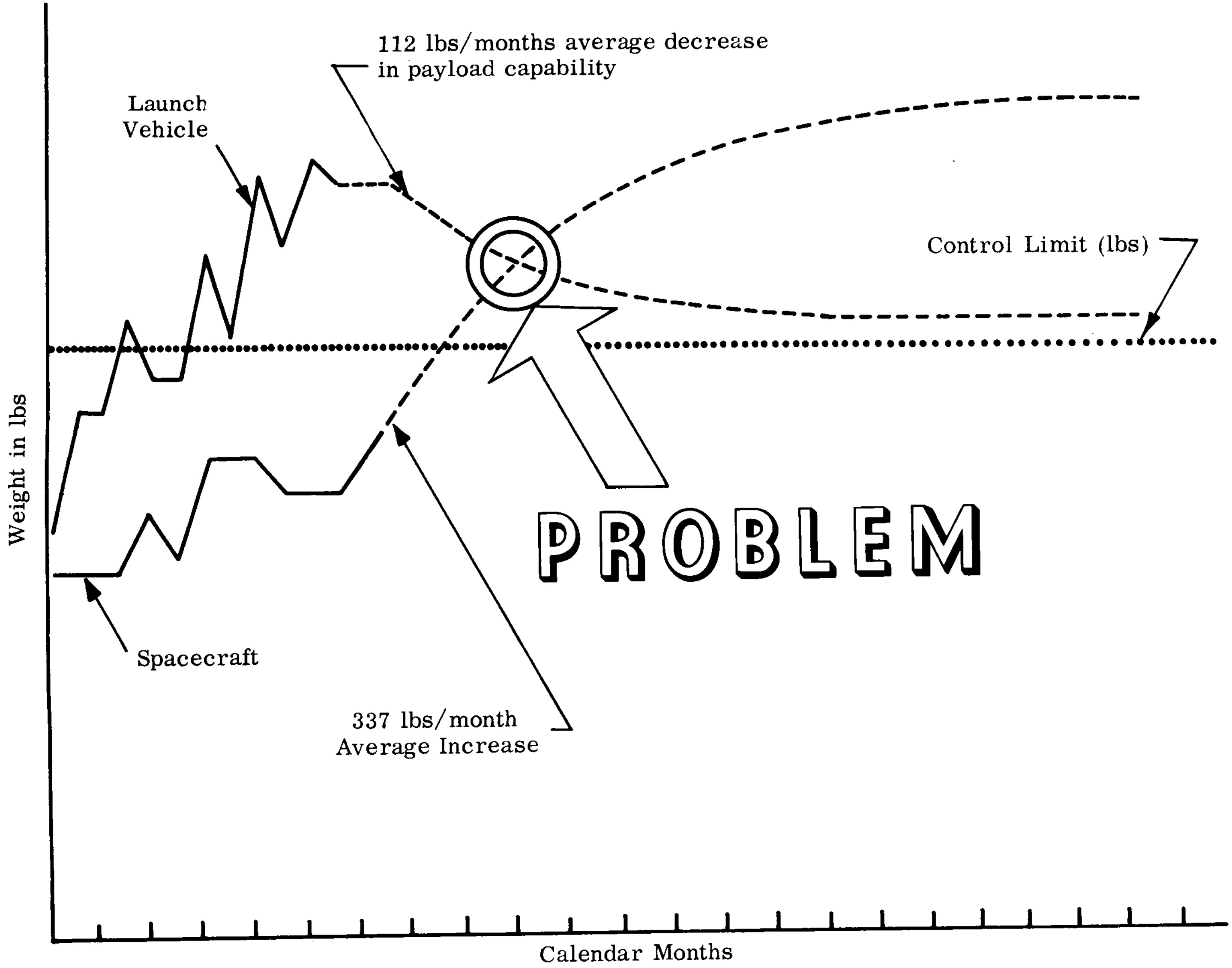


Figure 3-22. Comparison of Reported and Predicted L/V-S/C Capability versus Weight

assumptions are inherent in the procedures of summing the stage and module data, irrespective of control limits. The interface comparisons assume that the control limit can be increased for a stage or module having excessive growth providing a compensating decrease is made in the control limit of a stage or module for which the reported or forecasted weight is under its control limit. Concurrent changes in vehicle or mission specifications, such as propellant loading or velocity schedule, are thereby presupposed. These assumed "trade-offs" are included in the launch vehicle payload capability and spacecraft weight comparisons in order to present the over-all picture, as illustrated in Figure 3-22.

These types of trade-offs within the spacecraft or launch vehicle are resolved through use of trade-offs factors to reapportion the launch vehicle capability and spacecraft weight control limits. They are considered at the stage and module interface level. Examples of interface charts that depict the stage and module comparisons are shown in Figures 3-23 and 3-24. A problem is indicated when the reported or forecasted weight for a stage or module exceeds the control limit. This occurs in the charts when the reported or forecasted weight line ascends through the control limit line.

In the launch vehicle to spacecraft interface charts the reported and forecasted payload capability of the launch vehicle and the reported and forecasted gross weight of the spacecraft are compared with their respective control limits and with each other. Comparison to each other identifies problems of injecting the spacecraft into earth or translunar orbit. Problems are indicated when the spacecraft reported or forecasted weight exceeds the launch vehicle forecasted capability curve, as shown in Figure 3-22. Beyond the intersection of the curve the spacecraft weight exceeds the launch vehicle's capability to carry it. However, this problem is preceded by the indication of internal problems within the spacecraft or launch vehicle evidenced by the respective curves exceeding their control limits. The spacecraft exceeds its control limit when it ascends through its control line on the chart; and the launch vehicle capability exceeds its control limit when it descends through the control limit line on the chart. The interface charts presented in the Forecast Analysis Status Transmittal Report do not depict the problem of the spacecraft weight exceeding the launch vehicle capability but indicate the existence of the internal problems within the spacecraft or launch vehicle by a buy-off notation on the chart.

Problems identified in the individual spacecraft module comparisons are difficult to assess relative to their status with other modules which are related by common propulsion system requirements. This is particularly true of the Lunar Orbit Rendezvous (LOR) mission vehicle because of the complex interrelations required to conduct this mission. Apportionment and the subsequent specification of weight and propulsion requirements are necessary in order to meet the spacecraft's mission requirements and yet not exceed the launch vehicle's capabilities.

As another example, tank capacities are sized close to their specified requirements to minimize weight. These in turn impose physical restraints on weight growths and "trade-offs." Therefore, charts which present the interface relationships of modules with common propulsion system requirements are prepared for the LOR mission spacecraft at the translunar orbit mission event. The comparisons are referenced at the translunar orbit mission event although it would be more logical to orient the interface chart for the LEM modules to the lunar descent event. The comparisons were referenced at the translunar orbit mission event in order to maintain correlation of values with the spacecraft weight to launch vehicle capability interface comparison. These charts are shown in Figures 3-23 and 3-24. The figures present the following comparisons:

a. Figure 3-23 shows the combined reported and forecasted weight with fuel for the command module, service module, and adapter, and the total reported and forecasted weight with fuel for the lunar excursion module as compared to each other and to their appropriate control limits. Also, included on the same chart, the fuel required for service module propulsion is compared to the service module tank capacity.
b. Figure 3-24 shows a comparison, like the preceding one, of the weight of the lunar excursion module ascent stage and lunar excursion module descent stage with fuel; and the fuel requirements for LEM descent stage propulsion and LEM ascent stage propulsion to their respective tank capacities.

3.7.3 WEIGHT/PERFORMANCE TRADE-OFFS

3.7.3.1 Introduction

Weight/performance trade-off factors are the means by which space vehicle stages and modules can be compared on a common, consistent, and meaningful basis. These factors relate the change in weight of a given stage or module at any point in the mission to the change in weight of any other stage or module at any point in the mission. Using these trade-off factors, all weight deviations from control values are compared in terms of a single measure.

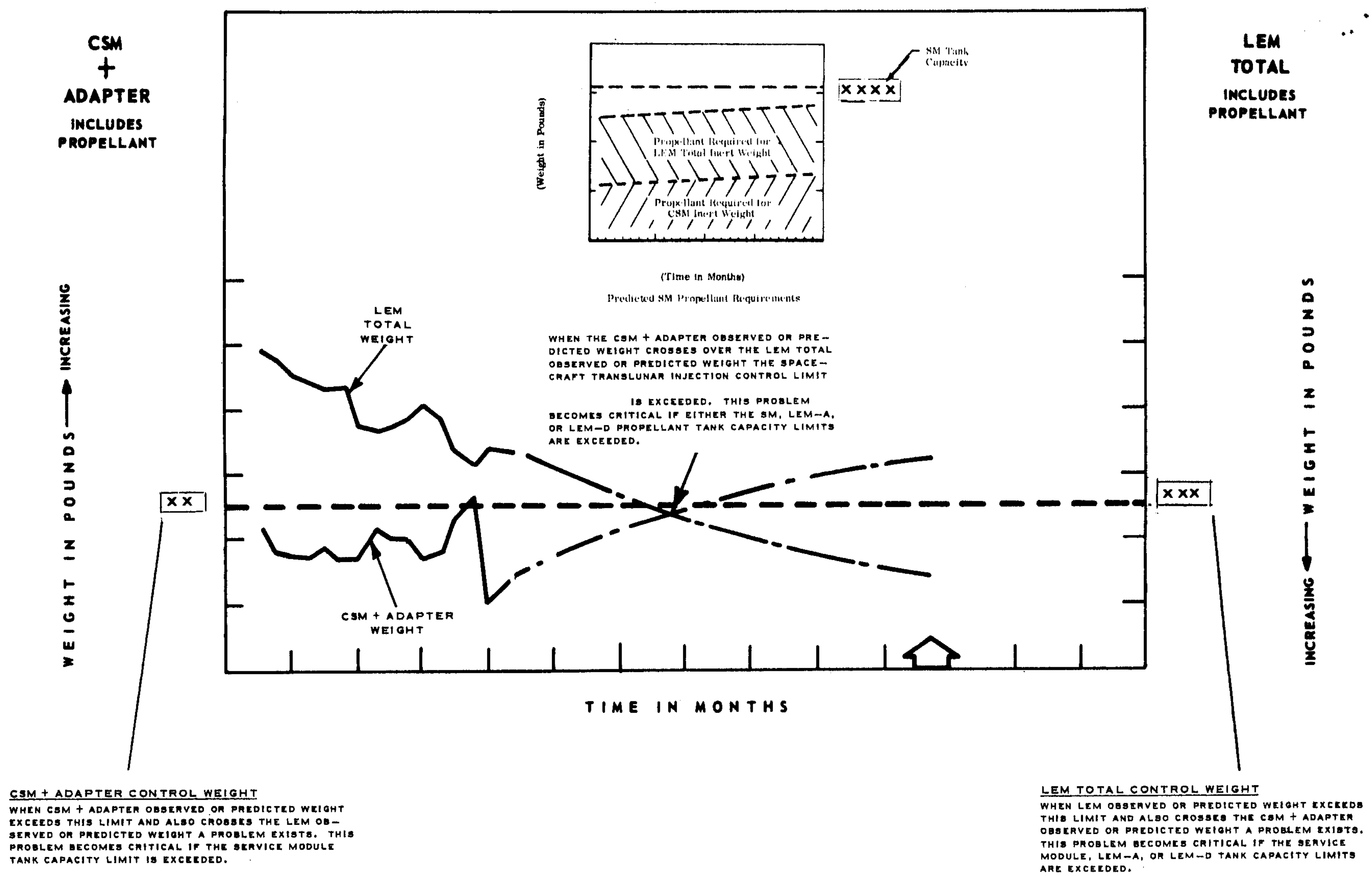


Figure 3-23. CSM/LEM Weight/Performance Constraint Interface

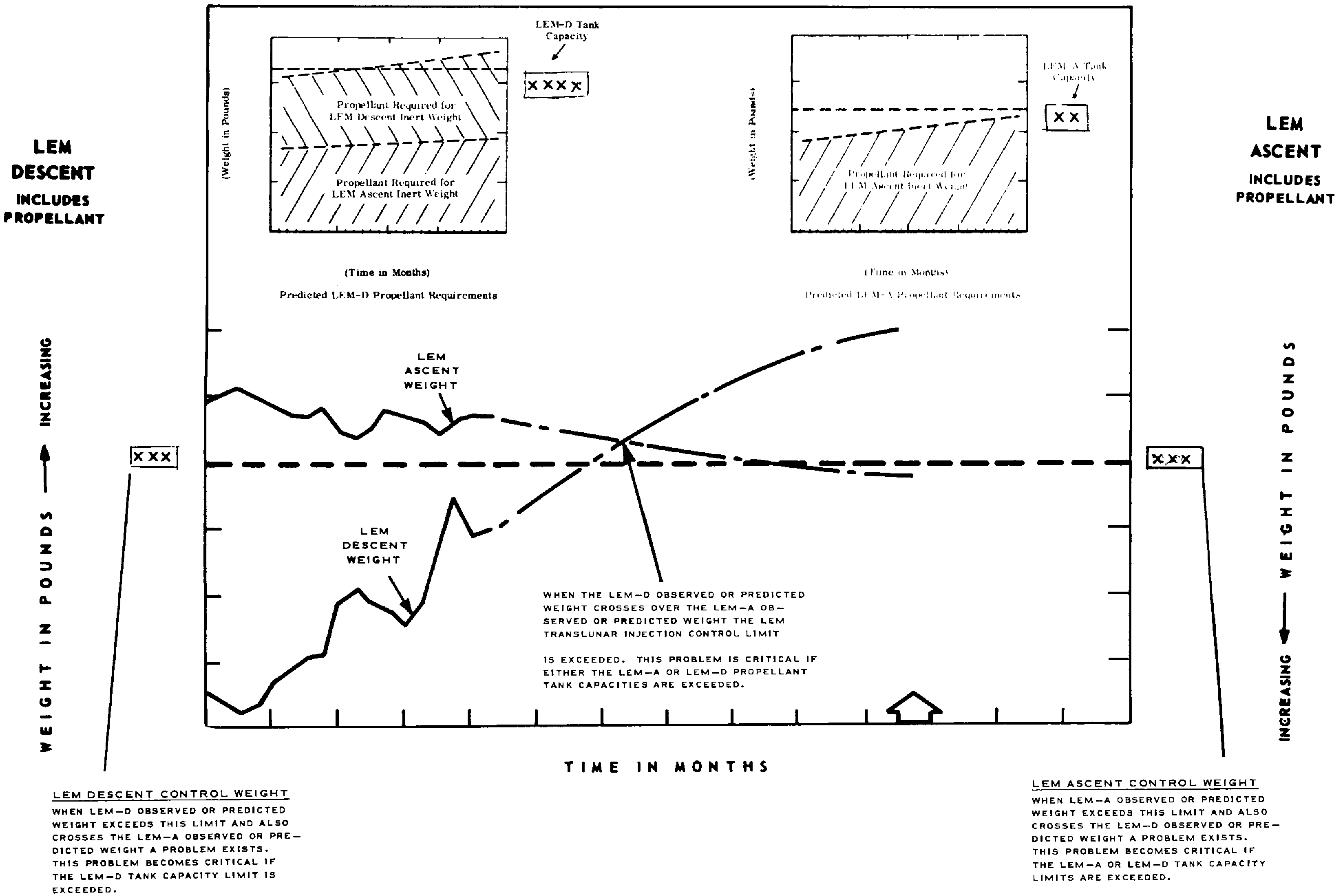


Figure 3-24. LEM Ascent/Descent Weight/Performance Constraint Interface

3.7.3.2 Determination of Trade-off Factors

Trade-off factors are determined by varying one weight or performance parameter and observing its effect on other parameters of interest. The trade-off factor is then the ratio of the observed change to the imposed change.

This measure in the LOR mission launch vehicle is equivalent to pounds of payload at (just after) translunar injection. For example, if a launch vehicle stage has a dry weight/payload, capability trade-off factor of 10.0, it means that a weight change of 10 pounds in that launch vehicle stage will result in a 1.0-pound change in payload just after injection, based on a postulated mission run with control weights.

Therefore, a forecasted weight at launch showing 500 pounds overage in that launch vehicle stage represents a 50-pound decrease in payload capability. Assuming another stage of the same launch vehicle has a trade-off factor of 3.0 and a forecasted weight margin (negative overage) of 210 pounds it can contribute a payload capability margin of 70 pounds. The net effect of the off-control value forecasted launch weights of these two launch vehicle stages is then a 20-pound margin (over control value) in payload capability.

The forecasted spacecraft (payload) weight at launch must be less than or equal to the forecasted payload capability at launch. A spacecraft module trade-off factor of 5.0 on a given spacecraft module for example, indicates that each one-pound change in the dry weight of this module results in a 5-pound change in the spacecraft weight required at translunar injection to accomplish the mission (including control performance and reserves).

3.7.4 PROBABLE ERROR

Probable error, as used in Forecast Analysis, is the numerical difference between the upper confidence limit and the forecasted weight at the shipping time. Probable errors are used as a simple indication of the degree of accuracy of the forecasted values, rather than confidence limits which are more difficult to portray in tabulated result form.

The confidence limits, used in calculating the probable errors, are determined by the computer programs for calculating the forecast trend of the functional system data. In these computer programs the expected observations are assumed to be normally distributed about the prediction line, with a standard deviation σ_t. For cases where there is a large sample, say $n > 10$, it is a reasonable approximation to let probable error, $\overline{PE}$, be:

$$\overline{PE} = c\,\sigma_t$$

where c is assumed to be a constant, equal to 1.645 for an infinitely large sample.

The probable errors of the stages and modules and over-all spacecraft and launch vehicle are "built up" from the functional systems in a manner similar to the "buildup" of the forecasted weights as discussed in paragraph 3.7. The functional system forecasted weights are added numerically to produce stage or module weights as follows:

$$W_{\substack{\text{stage or}\\ \text{module inert}}} = \overline{FS}_1 + \overline{FS}_2 + \overline{FS}_3 + \ldots$$

where W is the composite weight and FS designates functional system weight. Assuming that the functional systems are uncorrelated;* the weight standard deviation σ_W is:

$$\sigma_{W_{\substack{\text{stage or}\\ \text{module inert}}}} = \sqrt{\sigma^2_{FS_1} + \sigma^2_{FS_2} + \sigma^2_{FS_3} + \ldots}$$

where σ_W is the composite standard deviation and σ_{FS} the individual functional system standard deviations. Substituting and cancelling the constant c, the composite probable error of the stage or module is the square root of the sum of the squares of the probable errors of the functional systems as follows:

$$\overline{PE}_{\substack{\text{stage or}\\ \text{module inert}}} = \sqrt{\overline{PE}^2_{FS_1} + \overline{PE}^2_{FS_2} + \overline{PE}^2_{FS_3} + \ldots}$$

As discussed in paragraph 3.7.2, there are many functional systems to be monitored in the Apollo Program for the many mission vehicles with a single set of functional system data frequently used to forecast several like vehicle stages or modules. The ship date for the specific vehicle under consideration is used in the extrapolation of the functional system data.

*Uncorrelatedness, as stated in Reference 26 is satisfied when the covariance is zero, or the expected value of the product of any two functional systems is equal to the expected value of the first times the expected value of the second.

Typical results of the computer analysis of the probable error for a series of similar modules is shown in Figure 3-25. Functional systems of the modules were identified by code numbers shown to the left, a typical mission with ship date shown at the top and the probable errors and probable error squared in the two columns. The number at the bottom, i.e., 33.57 is the square root of the sum of the squares and is the probable error for the total module.

The "buildup" of stage and module, and over-all spacecraft and launch vehicle forecast data is mission oriented as discussed in paragraph 3.7. Probable error for the over-all forecasts are also mission oriented and "built up" in a similar fashion. Trade-off factors are applied in the calculation of the probable error of the spacecraft or launch vehicle weights with each of the modules or stage inert weight probable error values multiplied by an appropriate trade-off factor to account for the mission propellants and other performance requirements.

The total weight is the sum of the products of the stage or module weights W_1, W_2, etc., and their appropriate trade-off factors F_1, F_2, etc., as follows:

$$W_{total} = F_1 W_{1\ \substack{\text{module}\\ \text{or stage}}} + F_2 W_{2\ \substack{\text{module}\\ \text{or stage}}} = + F_3 W_{3\ \substack{\text{module}\\ \text{or stage}}} + \cdots$$

Assuming uncorrelatedness between stage or module growths and assuming the trade-off factors F_1, F_2, etc., are constant, the over-all probable errors as well as probable errors associated with gross stage are calculated as follows:

$$\overline{PE}_{\substack{\text{spacecraft or}\\ \text{launch vehicle}}} = \sqrt{(F_1\overline{PE}_1)^2 + (F_2\overline{PE}_2)^2 + (F_3\overline{PE}_3)^2 + \cdots}$$

where $\overline{PE}_1$, $\overline{PE}_2$, etc., are the individual module or stage probable errors.

The assumption that the factors (F) above are constant is equivalent to the assumption that the spacecraft or launch vehicle probable errors are due totally to changes in the module or stage inert weights and that there are no tolerances on the trade-off factors. The factors are used for calculating weights of propellants; therefore, errors in forecasting propellant loading or utilization are not included in this analysis at this time. The influence of this assumption should be checked in more detail to evaluate the significance on the over-all results.

Mission:	201		202		204	
Ship Date:	October 1965		January 1966		May 1966	
7451403	11.60	134.48	23.19	537.93	32.80	1075.85
7451404	16.56	274.14	33.11	1096.55	46.83	2193.10
7451416	3.28	10.74	6.35	42.95	9.27	85.89
7451417	0.00	0.00	0.00	0.00	0.00	0.00
7451426	5.79	33.52	11.58	134.07	16.37	268.13
7451427	0.00	0.00	0.00	0.00	0.00	0.00
7451436	24.21	586.01	48.42	2344.05	68.47	4688.10
7451437	0.94	0.87	1.87	3.50	2.64	7.00
7451446	6.34	40.25	12.69	161.02	17.95	322.03
7451447	5.85	34.26	11.71	137.03	16.55	274.06
7451456	3.56	12.70	7.13	50.80	10.08	101.60
			R.M.S. Values			
		33.57		67.14		94.95

Figure 3-25. Module Probable Error Analysis

Typical results of the computer analysis of a spacecraft are shown in Figure 3-26. The column of functional code numbers represents those major modules assembled to form the spacecraft. The next two columns illustrate typical trade-off factors and probable errors calculated for the modules. The spacecraft functional system number of 33.57 in Figure 3-25 now appears on the second row of the final calculation times 1.66 or 55.67. The total spacecraft probable error is then calculated at 166.84.

The relationship and use of probable error are further described in Appendix B of Book II. The details of the computer program to process the probable error calculations is contained in the User's Guide in Appendix E of Book II.

3.8 FORECASTS

3.8.1 DEFICIENCIES AND BUY-OFFS

In terms of over-all mission, the launch capability of the launch vehicle determines the control weight limit of the spacecraft to be launched. When the forecasted or actual weight of the spacecraft exceeds the weight control limit, then a deficiency exists. Deficiencies are necessary buy-offs expressed in terms of total spacecraft weight or launch vehicle capability. They may vary from extremely difficult to relatively easy to correct.

Figure 3-27 shows an example of spacecraft weight plotted against time to shipment. It can be seen that the observed rate of growth is fast approaching the control weight limit.

The trend forecast line indicates that the control limit weight will be exceeded and that by the shipment date deficiencies will exist which will require a ΔW buy-off in spacecraft weight or an increase in launch vehicle capability to offset the increased spacecraft weight.

As an example of calculation of buyoffs and deficiencies, let us suppose that the spacecraft's lunar excursion module has an inert weight of 5100 pounds, and the control limit for the inert weight is 5000 pounds, giving a required inert weight buy-off of 100 pounds. However, the 100 pounds excess inert weight may require an additional 100 pounds of propellant to lift the module from the moon's surface back into lunar orbit. Furthermore, the additional 200 pounds of ascent module gross weight (100 lbs. inert + 100 lbs. propellant) may require an additional 200 pounds of propellant to

Mission:	201		202		204	
Ship Date:	October 1965		January 1966		May 1966	
7440400	1.00	17.76	1.00	35.52	1.00	50.24
7451400	1.66	55.67	2.06	138.40	1.48	140.62
7461400	1.66	154.86	2.06	384.96	1.48	391.15
7471100	0.14	20.94	0.14	41.89	0.14	59.24
			R.M.S. Values			
		166.84		412.75		422.86

Figure 3-26. Spacecraft Probable Error Analysis

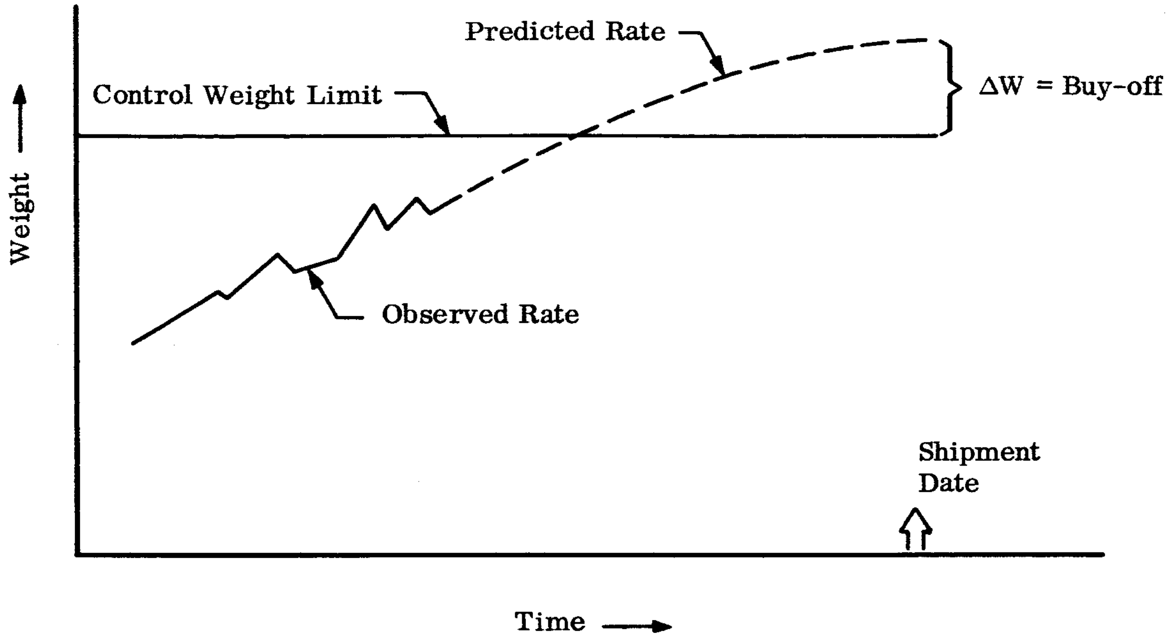


Figure 3-27. Forecast Buy-off at Shipment Date

control the descent to the lunar surface. The penalty for 100 pounds of inert weight on the lunar excursion module is therefore a penalty of 400 pounds on the total LEM. This 400 pounds is called the deficiency of the LEM.

To re-numerate in tabular form:

5100 - 5000 lb	=	+100 lb	LEM - Ascent Inert Buy-off
		+100 lb	Propellant
	=	+200 lb	LEM - Ascent Gross Buy-off
		+200 lb	LEM - Descent Gross Buy-off (Propellant)
	=	+400 lb	LEM - Ascent Deficiency

The deficiency, then, includes the inert weight buy-off plus needed additional propellant, wherever located. In the example given, the total 400 pounds ascent deficiency is comprised of 200 pounds of gross weight buy-off in the ascent module plus 200 pounds of gross weight buy-off in the descent module.

In a similar manner, a 100-pound inert weight buy-off in a launch vehicle stage will require additional propellant to accomplish the mission. In the case of the launch vehicle, additional weight reduces the capability of the vehicle to carry the required payload. The deficiency for any stage is given in terms of reduced payload capability.

Experience shows that determination of buy-offs and deficiencies is an effective method of indicating and forecasting problems.

However, merely to indicate that a stage or module is currently 100 pounds over its control limit and that therefore a problem exists or that there is a current required buy-off, still leaves a lot of questions unanswered. For instance, how difficult is the problem to correct? What is the growth rate? If the system is currently over its control limit and the weight history shows a downward trend it may present less of a problem than a system currently under its control weight but growing at an excessive rate. Where is the best place to look for a possible solution? Will there be a schedule slip involved? These questions and many others must be answered before an intelligent decision can be made. The next step of management decision process is the establishment of the criticality of making a decision.

3.8.2 CRITICALITIES

Apollo mission weight and performance weaknesses are referred to as the "Decision Relevancy Program." The end results of this program are referred to as "criticalities." One may speak of the "criticality" rating of an entire mission or any component of that mission, such as an individual stage or module.

3.8.2.1 General Considerations

After obtaining current status and forecasting vehicle weight and performance data, it is necessary to determine sources of potential problem areas and to obtain a "feel" for the criticality of foreseeable program weaknesses. Current and forecasted values for each launch vehicle, spacecraft, and their corresponding stages and modules can be compared with control values, and forecasted deficiencies can be obtained. To correct forecasted deficiencies, however, may be extremely difficult or relatively easy. The deficiencies may involve major program decisions or simple corrective action that can be handled in the normal design cycle. It has been necessary, therefore, to develop an index of criticality which will emphasize the relative degree of seriousness of the problem.

3.8.2.2 Ground Rules

In developing such an index, the index model will, at best, be a guide based on arbitrary ranges set by experience and engineering judgment. Although the gradation of criticality is established arbitrarily, the procedure should yield results on a consistent basis each time the model is used.

The model must consider current values as well as forecasts, since current values define the base from which actions must be taken. If the current base is below the assigned control value, the action may be one of "holding the line," i.e., tighter management control. If the base is already above the control, a more serious problem exists in taking corrective actions, even with the same forecasted deficiencies.

In weighing the influence of current and forecasted values, it is necessary to consider the effect of program time. Early in a program, current values are largely estimated and so may contain many errors. In this early phase, changes from month to month are extremely important because they indicate the direction that is being taken. Late in the program, current values have become more accurate and the dominating influence. The model, in addition, must consider that for the over-all mission the magnitude of a problem may be measured by the performance margin between launch vehicle payload capability and spacecraft weight, that is, one performance parameter exceeding its control may be compensated by the other parameter being below its control.

In summary, the model developed considers:

a. Launch vehicle capability versus control value.
b. Payload weight versus control value.
c. Launch vehicle capability versus payload weight.
d. Stage or module weight versus control value.
e. Relative importance of current reported values versus forecasts as a function of program phase time.

3.8.2.3 <u>Method</u>

In order that consistency of results can be obtained, a mathematical model was developed and programmed for computer application. This model then determines criticality for:

a. Over-all mission.
b. Spacecraft.
c. Launch vehicle.
d. Spacecraft modules.
e. Launch vehicle stages.

The gradations used are:

a. Critical.
b. Major weakness.

c. Minor weakness.

d. Good shape.

Table 3-6 presents the digital codes arbitrarily assigned to measure the criticality for launch vehicle capability, spacecraft weight, module or stage weight. These codes were selected by past experience and engineering judgment. In general, the digital codes represent a range of variation from control values.

Figure 3-28 represents the influence of program time on the value placed on current reported values and forecasts.

Figure 3-29 is used to quantize the over-all criticality.

The basic steps for determining over-all mission criticality are as follows:

a. Determine the following ratios:

(1) $\frac{\text{L/V Capability (current)}}{\text{Control Value}}$

(2) $\frac{\text{L/V Capability (forecasted)}}{\text{Control Value}}$

(3) $\frac{\text{Control Value (current)}}{\text{Spacecraft Weight}}$

(4) $\frac{\text{Control Value (forecasted)}}{\text{Spacecraft Weight}}$

(5) $\frac{\text{L/V Capability (current)}}{\text{Spacecraft Weight}}$

(6) $\frac{\text{L/V Capability (forecasted)}}{\text{Spacecraft Weight}}$

b. Assign digital codes from Table 3-6 for each of the above ratios.

c. Select time weighting factors from Figure 3-28.

d. Determine over-all mission criticality index (CI).

$$CI = \frac{\text{Digital Codes} \times \text{Corresponding Weighting Factors}}{12}$$

e. Select over-all criticality from Figure 3-29.

Indices are determined in a similar manner for each launch vehicle and its stages and each spacecraft and its modules.

Table 3-6

Digital Code Criticality Assignments

Stage or Module Weight versus Control		
Ratio	Digital Code	Gradation
From 0.00 to 0.92	1	Critical
From 0.92 to 0.96	2	Major Weakness
From 0.96 to 0.98	3	Minor Weakness
From 0.98 to above	4	Good Shape
Launch Vehicle Capability versus Control or Control versus Spacecraft Weight		
Ratio	Digital Code	Gradation
From 0.00 to 0.95	1	Critical
From 0.95 to 0.98	2	Major Weakness
From 0.98 to 0.99	3	Minor Weakness
From 0.99 to above	4	Good Shape
Launch Vehicle Capability versus Spacecraft Weight		
Ratio	Digital Code	Gradation
From 0.00 to 0.95	1	Critical
From 0.95 to 0.98	2	Major Weakness
From 0.98 to 1.00	3	Minor Weakness
From 1.00 to above	4	Good Shape

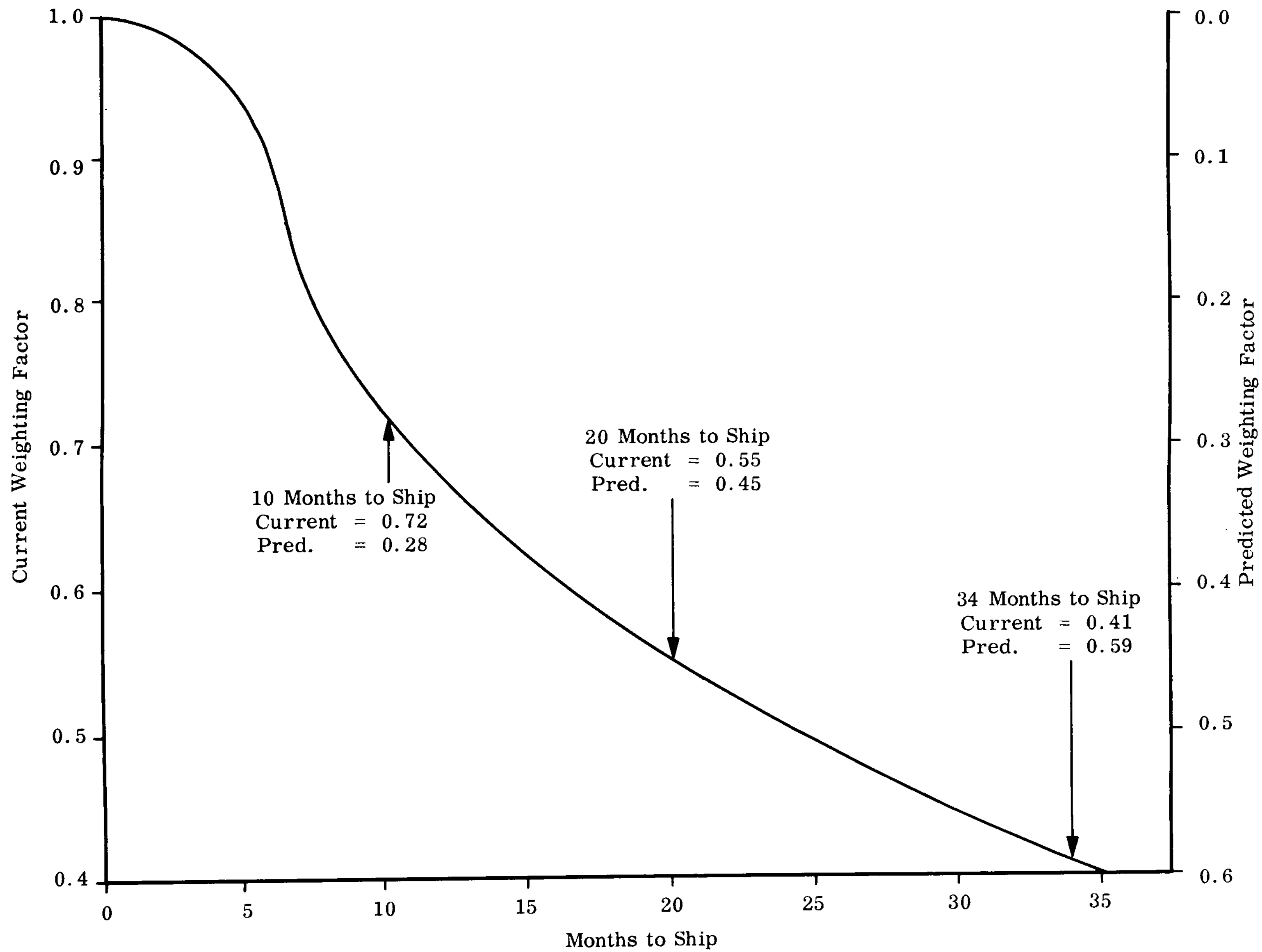


Figure 3-28. Program Phase/Time Weighting Factors

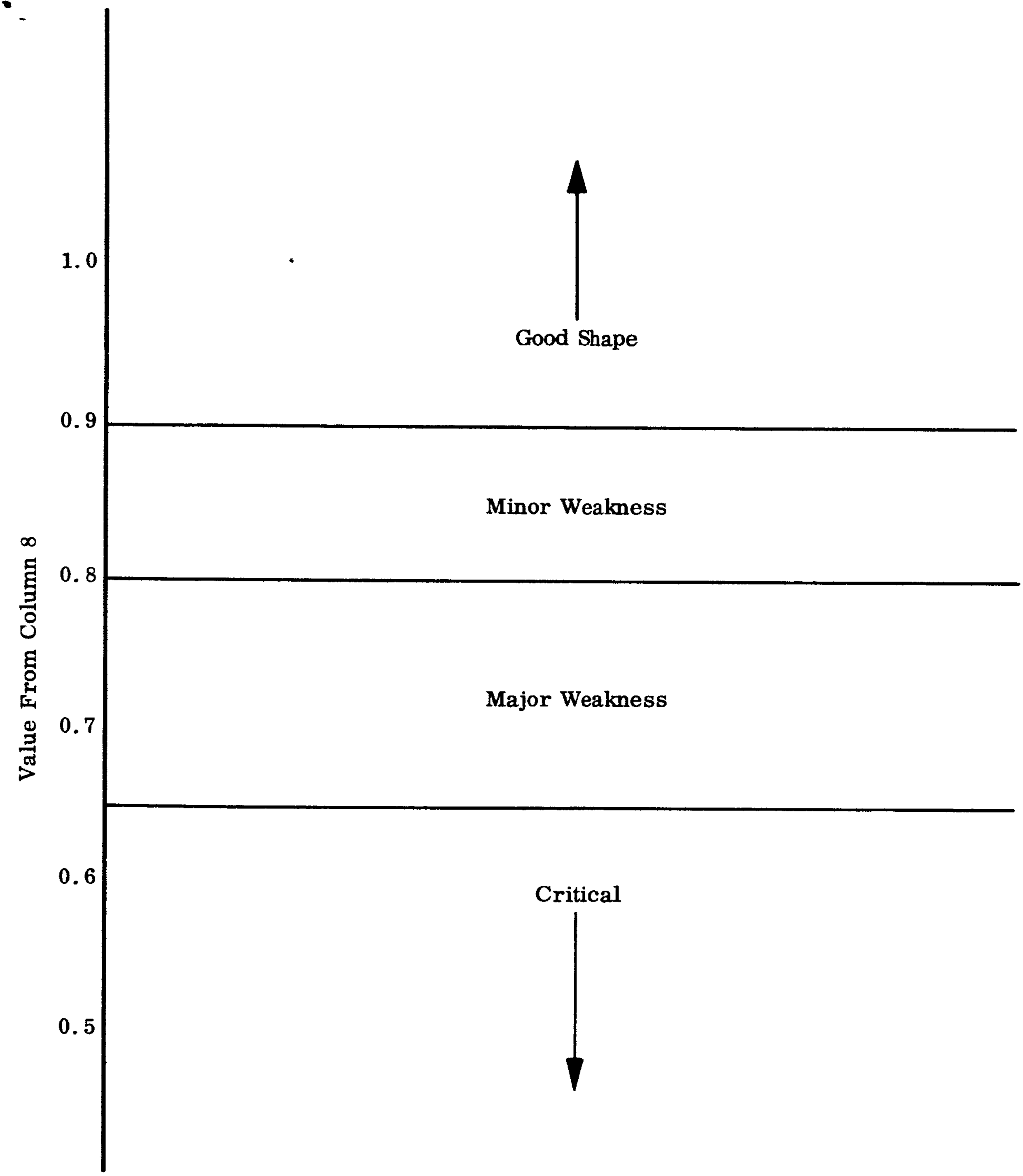


Figure 3-29. Over-all Criticality Determination

3.9 APPRAISALS

3.9.1 COST/WEIGHT RELATIONSHIPS

3.9.1.1 General

Cost is a governing parameter determining the amount of technical development and production work that can be done on a particular space program. Since costs have a direct bearing on what can be done, they must be considered in all trade-offs made during the engineering development effort. An effective and meaningful relationship between cost and program control is essential for program managerial trade-offs.

To arrive at cost estimates some arbitrary assumptions have to be made and available data extrapolated. Cost information is usually available from previous similar programs, the best starting point for cost analysis. Obviously, this extrapolation of old data must be coupled with engineering judgment and analysis in new cost estimations.

The usual procedure is to estimate costs for required buy-offs through a cost/weight relationship on a per pound basis. Admittedly, the procedure yields only a rough estimate, but if used with caution and the full awareness of the assumptions involved, the estimation can serve as a useful forecast of trade-off values.

Costs are affected by many parameters, some more significantly than others. An averaging technique can be used to smooth out the peaks and valleys which tend to give erratic answers. Obviously, it is possible to miss a significant peak in the cost curve, but engineering judgment and specific data on a particular application lend validity to the cost estimating technique. Once cost problem areas have been identified, the detailed analysis which follows becomes the prime consideration in the problem solution.

Weight is a useful relating index of cost. Correlations between weight and cost are well established from known types of equipment, such as aircraft, launch vehicles, machine tools, etc. In other areas, such as electronic equipment, weight bears little relationship to cost because of today's emphasis on miniaturization which in fact creates an inverse cost ratio to weight.

3.9.1.2 Over-all Cost

Fortunately, for reasonable results, cost/weight trade-offs need be considered only at the major stage or module level where detail inequalities tend to be masked by an over-all averaging effect. In addition, cost/weight relationships can be updated from actual cost figures for the specific program of interest.

In general, cost factors can be grouped into five kinds of elements, development costs, production costs, test costs, facility costs, and operational costs. For purposes of developing cost trade-off factors, development and test costs are lumped into R&D costs, as shown in Table 3-7. Non-direct portions of facility cost, operation cost, and other non-direct costs are not computed since these costs are assumed unrelated to the trade-off factors sought for cost/weight.

Monthly production costs can be determined from the cost and schedule data for the latter part of the program, during which time the research and development costs are assumed to be negligible compared to the production costs.

From the data available for the first part of the program, the research and development costs are separated from the production costs by subtracting the production costs from the funding allocated for any given fiscal period.

Research, development, and production costs are summed to obtain the total costs of the indicated weight reductions.

In calculating the additional cost due to a required buy-off, research and development costs are allocated on a per-pound basis, using an exponential distribution. This distribution is obtained by assuming that the re-expenditure of the total research and development cost yields a 10-percent weight reduction; that is, in order to obtain a 100-pound buy-off, 1000 pounds of a stage/module must be redesigned.

Production costs depend on the phase of production which a particular stage/module is in at the time of interest. A 10-percent yield is assumed again as a reasonable return from improved production methods for reduced weight.

The research and development costs of removing a deficiency is assigned to the first vehicle in which it occurs even though the results of the research and development effort may be realized on subsequent stages or modules. The production costs differ for specific stages (or modules) since not all stages are in the same production phase.

To obtain the schedule change due to a required buy-off, the total cost of a specific buy-off is divided by the current monthly spending rate for the applicable stage or

Table 3-7

Sample Costs and Cost Trade-off Factors

	Inert Weight (lbs)	Equivalent Payload (lbs)	Cost (Millions of Dollars)			Total Cost Trade-off Factors ($/lb)
			R&D	Prod.	Total	
CM						
SM						
LEM-A						
LEM-D						
IU						
S-IVB						
S-II						
S-IC						

module. This assumes that the current level of effort on a specific stage or module will be maintained during the implementation of required buy-offs.

A sample calculation of this over-all cost estimating technique is illustrated in Figure 3-30. For this example, a 500-pound weight reduction is assumed to be required in each of two vehicles, A and B. Vehicle A is 20 months along in production, vehicle B is 10 months into production. The necessary R&D costs are computed as indicated in the upper left of Figure 3-30 as 4800 cost units regardless of whether one or two vehicles are involved. The production costs are computed in relation to the phase, or months progress in the production cycle. In the illustration, the costs of reducing weight are indicated as 30,000 and 15,000 for vehicles A or B. For weight reductions in both vehicles, costs are accumulative, or 45,000 cost units. The schedule slippage associated with these weight reductions are computed using the average rate of program expenditures as an adjustment factor. As indicated in Figure 3-30, the expected schedule slip is computed by dividing the total cost of weight reduction of average spending rate.

Typical trade-off factors, shown as hypothetical values, are summarized in Table 3-7 for representative stages and modules. Since performance relationships are known between the various stages and modules, for ease of comparison weight can be expressed in terms of equivalent spacecraft or launch vehicle weight. The numbers in Table 3-7 are directly comparable, showing the hypothetical relationship between cost and weight saving on various stages. The data provides a useful tool for management trade-offs between stages or modules for optimization analysis.

For convenience, the trade-off factors can be shown in slide rule form, such as shown in Figure 3-31. Handy reference and rapid use of cost/weight factors can then be achieved by the various management groups concerned with program control.

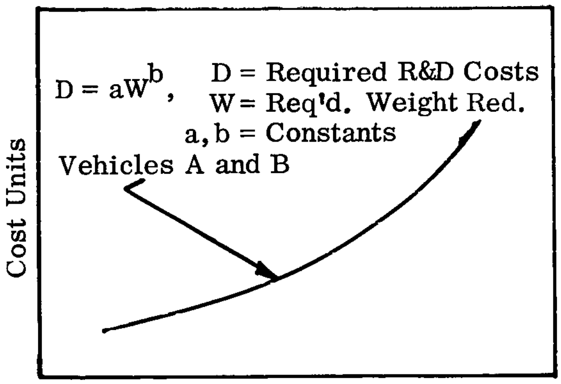
3.9.1.3 System Costs

It is recognized that an accurate cost analysis must be performed on a system basis. To accomplish this refinement, a system cost model is used.

This model allows, for example, structural system costs to be differentiated from navigation and guidance system costs. When considered on a per pound basis, the costs of these two systems are significantly different and must be considered separately. Vehicle costs are defined to the extent that the breakdown allows required buy-offs to

Estimate cost of a 500-pound weight reduction on sample vehicles A and B, which have similar components but fly on different missions.

Production Costs

R&D Costs	Vehicle A and B Production Cost Units/Pounds-Month = 0.3 Production Weight Requiring Redesign (Assume 10% Yield) = 10 x 500 = 5000 pounds
	Vehicle A is 20 Months Into Production Vehicle A Production Cost = 20 x 0.30 x 5000 = 30,000 Cost Units
Required Weight Reduction For Vehicles A and B $D = \gamma W^{1.4} = 8\ (500)^{1.4} = 48,000$ Cost Units	Vehicle B is 10 Months Into Production Vehicle B Production Cost = 10 x 0.50 x 5000 = 16,000 Cost Units

	Cost of Weight Reduction			Schedule*
	R&D (Cost Units)	Production (Cost Units)	Total (Cost Units)	Change (Month)
Vehicle A Only	48,000	30,000	78,000	3
Vehicle B Only	48,000	15,000	63,000	2
Vehicles A and B	48,000	45,000	93,000	3

*Schedule Change

Current Vehicles A and B spending rate = 33,000 cost units/month.

$$\text{Schedule Change due to Weight Reduction} = \frac{\text{Total Cost of Weight Reduction}}{\text{33,000 Cost Units/Month}}$$

Figure 3-30. Estimated Over-all Costs - Sample Vehicles A and B

Figure 3-31. Apollo Program Launch Vehicle/Spacecraft Trade-off Selector

be traded off with the lesser expensive systems and indicates dollar usage efficiency when a given required buy-off is being analyzed.

The model illustrates particular system sensitivity to cost and is primarily intended for analyzing required buy-off costs in detail when specific problem areas occur or are forecasted. The model utilizes past program data to develop cost curves for each system. An example of a system cost calculation is illustrated in Figure 3-32.

3.9.2 SCHEDULE/EVENT RELATIONSHIPS

3.9.2.1 Program Status

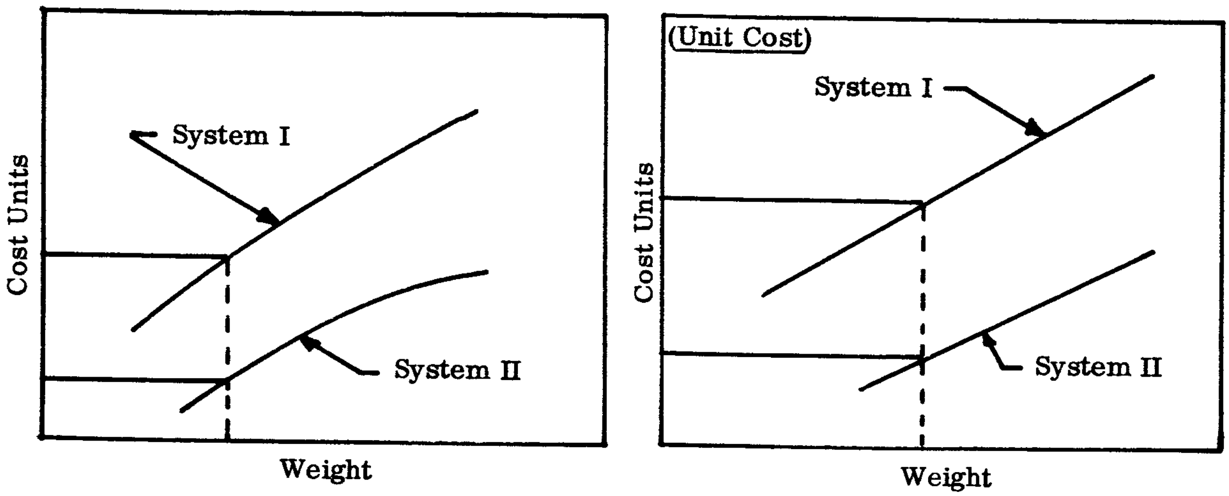
In order to determine whether a program is ahead of schedule, or behind schedule and how far, time-varying program parameters must be utilized. To augment cumulative cost and schedule data for purposes of evaluating program status, Estimated, Calculated, and Actual weight percentages (E/C/A) are considered a related time-varying parameter useful as a program status barometer. On this basis an effective schedule forecast, i.e., an indication of program status is made.

An E/C/A schedule model is developed from available schedule data for each stage and module. This is done by making reasonable assumptions as to what the E/C/A data should be during various phases of development, production, and testing of each stage and module. This model then represents the forecast of the E/C/A data.

Observed E/C/A data is reported monthly, by the appropriate contractors, on each functional system. The reporting of these data, along with the corresponding weight data, is a contractual requirement. The reported functional system E/C/A data are combined proportionately to obtain the reported E/C/A data for each stage and module.

Each month reported E/C/A data for each stage and module is compared with the E/C/A schedule model and the forecasted schedule differences calculated to determine how far the program is ahead or behind of schedule.

As an example, Figure 3-33 illustrates the monthly reported E/C/A data for sample vehicle A, plotted against the model for this particular vehicle. From this plot it can be seen that the model indicates vehicle A to be one month behind schedule (average status).



	System Costs		
	R&D (Cost Units)	Production (Cost Units)	Total (Cost Units)
100 Pounds of System I	300	180	480
100 Pounds of System II	100	75	175

Figure 3-32. Estimated System Costs Sample Systems I and II

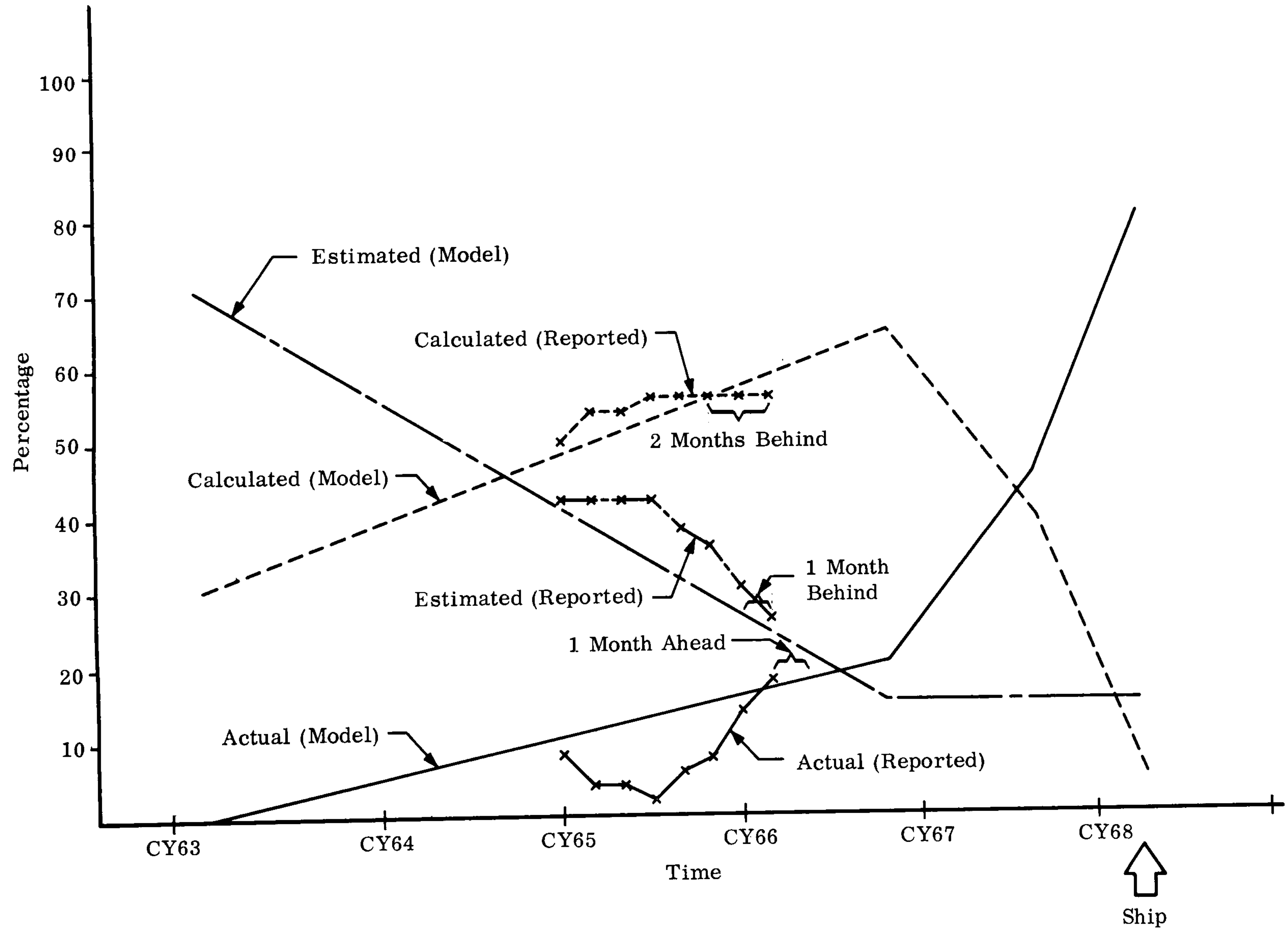


Figure 3-33. Monthly Reported E/C/A Data for Sample Vehicle A

3.9.2.2 Use of E/C/A Values as Program Maturity Indices

Once the model of E/C/A is established for each stage, module or functional system, the predicted portion of this model can be updated as additional monthly observations are made. These corrections can take two forms, first the adjustment of the schedule as noted above and secondly the reshaping of the forecast curves of E/C/A to better conform to trend patterns.

These updated E/C/A curves in the forecast time domain can then be used to improve the slope of the weight prediction line. Here E/C/A values reflect program maturity and can be used as additional factors in shaping forecast line slope. For example, slope is assumed to reduce by a factor related to the completion of the component fabrication and test, as evidenced by decreasing E and C and increasing A. The feedback of actual E/C/A values into this model provides a measure of self-correcting action since the shape of the E/C/A curves become more apparent as additional observations are made.

3.9.3 RELIABILITY/WEIGHT RELATIONSHIPS

3.9.3.1 Object and Scope

Techniques are required for accurately determining the effect of weight changes upon mission reliability. The weight changes considered will be limited to weight reductions of an already designed space vehicle and provide only a cursory examination of the subject. The techniques discussed here are not allocation optimizing methods, which are far more complicated.

3.9.3.2 Definitions

The term mission reliability is commonly used to denote the probability of mission success. However, mission reliability also includes the probability of crew safety. Calculation of the probability of crew safety causes many of the difficulties of computation because of the many different mission aborts which must be considered.

Weight changes, especially removal of redundant equipment, will affect probabilities in different ways. Therefore, both sets of interactions must be considered and computed.

3.9.3.3 Weight Reduction Methods

Weight reduction in a space vehicle can come about only by two methods:

a. The removal of matter from the space vehicle.

b. The substitution of lighter material for heavier material.

The first of these (removal) can come about as a result of a number of operational decisions. The second (substitution) can occur among various elements of the vehicle.

3.9.3.4 The Effects of Weight Reduction on Reliability

There are a number of interactions between weight (reductions) and the probability of mission success. Consider the immediate first order effects:

a. The removal of redundant equipment will decrease the probability of mission success.

b. The removal of a functional requirement and its associated equipment will increase the mission success probability.

c. The use of existing equipment for other functions, or the substitution of a lighter system for a heavier one, may increase or decrease the mission success probability. Each case must be analyzed separately.

d. The elimination of non-essential equipment, waste product dumping, or removal of structural material, has no direct effect on mission success (assuming the structural reliability is not reduced).

In order to analyze the effects of weight reduction on vehicle reliability, a function relating these parameters is required. The function most suited to this is the ratio of reliability decrement per pound of weight removed. This ratio can be calculated for the whole vehicle, or for a stage, module, or system as desired. Generally, a curve of this function will have a constantly increasing slope as shown in Figure 3-34.

An equation for this curve may be established after a number of analyses have been made which will permit its construction from vehicle design data or, the curve can be constructed by individual computations of the function on a system-by-system basis.

3.9.3.5 Reliability Prediction Techniques

3.9.3.5.1 Approximation Method

The approximation technique is a fast, economical tool for obtaining an average ratio for the reliability decrement/pound obtainable from redundancy removals.

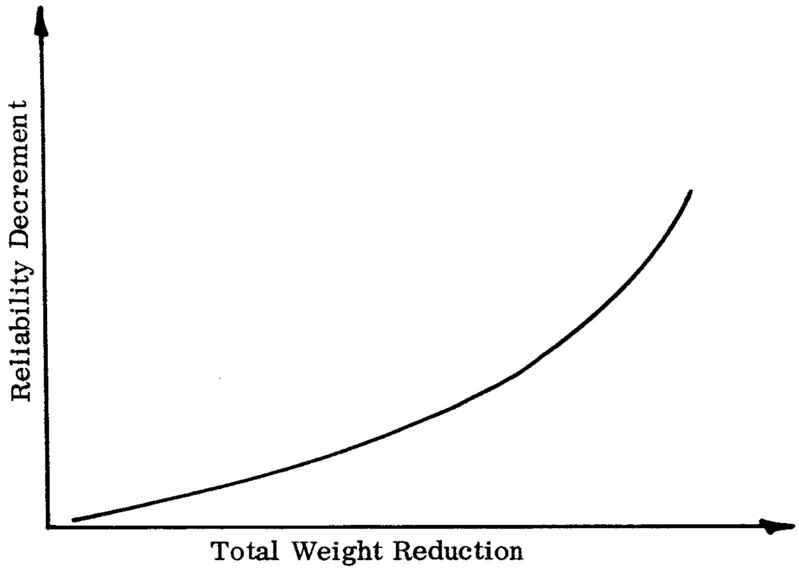


Figure 3-34. Plot of Effects of Weight Reduction on Reliability

While this ratio will not necessarily apply to any single system, the ratio and the total values obtained for weight reduction and reliability decrease can be used as a decision making tool for testing the feasibility of redundancy removal for a particular vehicle, stage, or system. Also comparisons between vehicles, stages, or systems can be made on this basis.

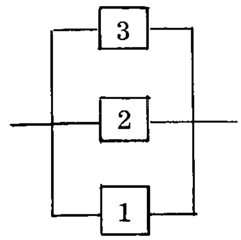
The method is as follows:

a. Given a reliability model, which has been solved for the mission success and crew safety probabilities, remove all redundant elements from the model.
b. The remaining series model can be solved fairly quickly on a desk calculator and a new estimate of mission success obtained.
c. The weight of the parts eliminated can be found and then an average ratio of reliability decrease/pound can be calculated. This calculation can be performed for the whole vehicle, as well as by stage and module. This solution gives the limit of weight reduction by removal of redundant parts, and the change in mission success probability.
d. The change in crew safety probability must be determined by means of a failure effects analysis of the reduced system.

3.9.3.5.2 Selective Redundancy Removal

A simple technique for finding the change in reliability resulting from the removal of some redundancy in a given system is available from the results of the Simulation of Apollo Reliability (SOAR) computer runs.

For example, assume that in a system that consists of three elements in parallel, it is desired to find the effect of eliminating element 3 on the mission reliability. Element 3 will be used only if elements 1 and 2 have failed. Examining the SOAR computer printouts, all Monte Carlo trials where elements 1 and 2 have failed, but where the mission succeeded because of element 3, are reclassified from mission success to mission failure. The new probabilities are then readily found by dividing the revised mission success count by the number of trials.



As an example, consider a spacecraft electrical power system for which a computer run of 10,000 Monte Carlo trials had been made. The components selected for removal were one inverter, one re-entry battery and one fuel cell. The system contained three each of these components which were in various mission phases required to operate in one of three, two of three, or three of three configurations.

In each case, upon removal of the third component, the reliability logic diagram was adjusted to indicate the required use of the remaining two components in either series (two of two) or parallel (one of two) configurations.

The computer results were then examined to determine the changes in probability of mission success.

The results are shown in Table 3-8.

Table 3-8

Sample Selective Redundancy Removal Calculation Results

Component	Approximate Component Wt. (lbs)	Increase in Number of MS Failures	Reduction in Mission Success Probability	Reduction of Reliability Per Pound
Fuel Cell	100	187	0.0187	0.000187
Battery	50	16	0.0016	0.00032
Inverter	50	210	0.0210	0.000420

Examination of these results reveals the following:

a. For weight reduction up to 50 pounds - remove the battery.

b. For weight reduction from 50 to 100 pounds - remove the fuel cell.

c. For weight reduction from 100 to 150 pounds - remove the battery and fuel cell.

d. For weight reduction over 150 pounds - remove all 3 components.

The reliability reductions for multiple removal are:

		ΔR/lb
Battery and inverter	0.0223	0.000223
Battery and fuel cell	0.0200	0.000133
Inverter and fuel cell	0.0397	0.000265
All components	0.0403	0.000202

3.9.3.5.4 Other Techniques

There are many other techniques available for obtaining reliability estimates. Some methods which may be useful are:

a. The minimum cut method.

This method uses Boolean algebra to evaluate the reliability of complex networks, which are subject to configuration changes.

b. The partial derivative method.

This method assesses the effect of changes in component reliability on systems reliability.

c. Correlation techniques.

After a number of analyses have been made and a data bank of reliability/weight relationships has been built up, standard statistical regression and correlation techniques can be used to attempt to establish a direct relationship between these factors.

3.9.3.6 Multiple Factor Relationships

3.9.3.6.1 Introduction

Vehicle weight and reliability are also indirectly related through the factor of performance.

Schematically this can be shown as:

Δ weight $\rightarrow$ $\boxed{\text{transfer function}}$ $\xrightarrow{\Delta \text{ performance}}$ $\boxed{\text{transfer function}}$ $\xrightarrow{\Delta \text{ reliability}}$

In a complex system the "transfer functions" may not be directly expressible as equations, but they can represent the analyses necessary to relate the parameters. In the case of a manned vehicle the "Δ performance" parameter can refer to hardware and/or crew performance.

3.9.3.6.2 Weight - Crew Performance - Reliability

As stated in paragraph 3.5.4, removal of equipment not mission essential has no direct influence on reliability. Removal of such equipment may, however, affect reliability by affecting crew performance. The problem with changes of this type is that they are extremely difficult to quantize. Usually only a qualitative statement about their effect on reliability can be made.

3.9.3.6.3 Weight - Vehicle Performance - Reliability

If weight reduction causes a change in the weight/thrust ratio, the effect of performance changes on reliability will be due to the changes in the length of the mission phases. For example, a heavier vehicle will require longer engine burn times to reach an injection point. This will result in a reduction in engine reliability and will also reduce the reliability of all other systems, due to their increased exposure to the high-stress environment existing during thrust.

This change in performance must in turn be translated into a change in reliability. The analysis is extensive and expensive and should be made only when significant weight and performance changes have occurred. After a number of weight/performance reliability studies have been made, statistical techniques of multiple regression and covariance analysis can be used to discover relationships between the parameters useful in trend forecasts.

The techniques of system optimization under one or more constraints are well described in the references listed in the bibliography.

3.10 ILLUSTRATIVE RESULTS USING HISTORICAL WEIGHT DATA

3.10.1 VALIDATION BACKGROUND

The validation of current weight performance prediction methods is important for three reasons. Perhaps the most important is the determination of their credibility under a variety of circumstances. This information leads directly to the second benefit - an indication of which combinations of available techniques when applied to sets of data exhibiting certain identifiable characteristics will provide the most accurate forecasts of future performance. Thirdly, the validation process provides significant guidance for the development of advanced prediction methods and automatic data handling techniques.

The validation program described here was designed to provide this information in a comprehensive and objective manner. The approach taken consisted of: (a) defining specific objectives, (b) defining specific quantities to be measured and ways of measuring them and (c) developing a matrix of computer runs which when subjected to (b) will satisfy (a). A special effort has been made to include only those analyses directly affecting the stated objectives. The analyses were further restricted by limiting their scope to include necessary and sufficient operations only since the number of potential variables of interest is large.

The following goals of the validation effort are not independent but identify the three distinct types of information required:

a. Determine the extent to which present prediction programs and methods provide accurate forecasts of future weight performance.
b. Determine the sensitivity of the prediction techniques to variations in their manner of application, data characteristics, values of internal program constants, etc.
c. Develop additional insight into and provide guidance for contemplated developments in advanced normalization techniques, trend mode selection and prediction methods.

Accomplishments of the stated goals require the orderly evaluation of the following items:

a. Regression curve goodness-of-fit in the observation range.
b. Forecast Accuracy (measured at end of observation range).

c. Effect of normalization

   (1) removal versus non-removal of non-random changes.

   (2) changes in definitions of non-random changes.

   (3) outlier removal versus no outlier removal.

   (4) changes in outlier limit boundaries.

   (5) multiple application of outlier removal option.

d. Effect of variation in internal constants (R's, α, γ, etc.).

e. Effect of time conversion (real and project time).

f. General applicability of trend-of-the-trends.

g. Correlation between trend-of-the-trends results and (a).

h. Convergence of repeating mode analysis (RMA) results:

   (1) at last observation point.

   (2) at shipping point.

   (3) correlation between (1) and (2).

i. Effect of the number of RMA passes per data set.

j. Effect of normalization on RMA results.

k. Effect of trend mode on RMA results.

l. Consistency between suboptimization and optimization (do optimum functional subsystem results necessarily sum to optimum stage results?).

m. Value of probable error prediction.

n. Validity of confidence intervals.

o. Benefit of running RMA in reverse.

Careful inspection of this list will indicate that there are numerous compound overlaps - that is groups of two or more of the items can be accounted for in individual analyses. Recognition of this fact is the basis for streamlining an otherwise gigantic and unwieldy program.

Performance measurement is a critical element in any evaluation procedure. Measurement means and standards must be clearly defined and adhered to so that objective and consistent evaluations will be obtained.

In the present case, the majority of useful information will be derived from comparative analyses or relative performance. This introduces a subjective element which must be controlled to whatever degree possible by the use of analytic measures. The concept, then, is to make maximum use of such mathematical tests and measures as are available to provide data for the comparative analyses. Those which have been defined to date are:

a. Mean square error - a simple and direct analytical means for measuring the degree to which regression curves represent the subject data.
b. Ratio of mean square successive difference and estimate of variance - an analytical comparison of two quantities each of those expected values is the distribution variance; another means of measuring regression curve fit.
c. Differential between the last observed data point and its predicted values - a measure of prediction accuracy (not applicable to the Fourier Analysis model).
d. Convergence/divergence of RMA results - decay rate in convergent cases will serve as an indicator of relative value.
e. Variantions in trend line slopes.

The actual validation program recognizes the inherent relationships among the items to be evaluated. It assures that the maximum information will be obtained from a given set of computer results and analyses. The net effect is the definition of an efficient program plan containing a minimum of unnecessary effort.

It should be realized, however, that even with a well defined plan it is difficult to foresee exactly how the program's progress will unfold. New relationships will be discovered, some steps will be found unnecessary, additional analysis will be called for in some area, etc. Therefore, even though the program of computer runs developed is felt to be an efficient and sufficient one, it was implemented with the understanding that further reductions or additions may be identified as the program progresses.

An examination of the list on pages 3.71 and 3.72 shows that one way of grouping the items is as follows:

Group I: Those items involving pre-trending operations on the data - consisting of a, b, c, e, l, m.

Group II: Those items involving Repeating Mode Analyses and Trend-of-the-trends - consisting of a, b, f, g, h, i, j, k, o.

Group III: Those items involving variations within the trending programs themselves consisting of a, b, d.

It will be noted that items a and b are common to all three groups. These two items enjoy a double role - being both measures and things to be evaluated. Their role as measures causes the triple inclusion here.

The techniques for Forecast Analysis have been tested against historical weight data from aerospace programs and prior weight data on the Apollo Program to see how well they would have worked if used on those actual programs.

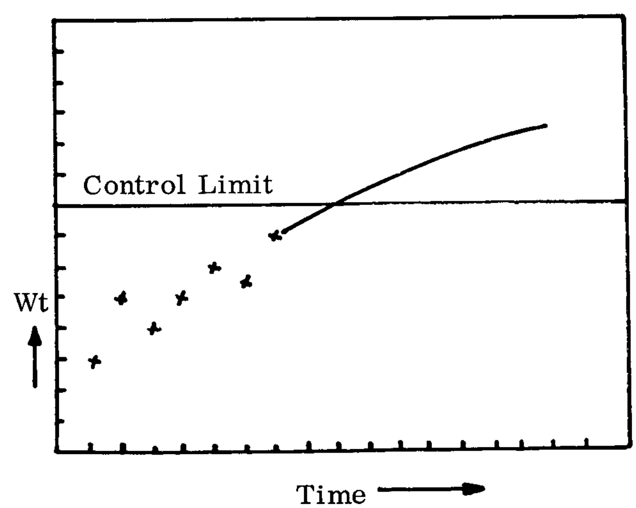
Representative programs used for validation were:

a. Saturn I Launch Vehicle
b. Nimbus Spacecraft
c. Mercury Spacecraft
d. Saturn V Launch Vehicle
e. Saturn IB Launch Vehicle
f. Apollo Spacecraft

In the first three programs listed above, weight data is available, although somewhat inconsistent. On the latter three programs, good weight data is available, but the end results are unknown at the date of writing.

3.10.3 HOW ACCURATE SHOULD A PREDICTION BE?

An interesting question which is raised after some study of validation is, "How accurate should the forecasts be?" Or more specifically, "Should the actual observed launch weight be forecast one to two years in advance?" The answer to this question is dependent on the expected "elbow room" allowed between current weight and upper control weight values. If the forecast growth carries the expected weight past the control limit, it is natural to assume that certain corrective action will be taken. In fact, this action identified as "required buy-offs" are the essential identifications of Forecast Analysis and it is presupposed that necessary managerial action will be taken and the final launch weight will be brought below the control limit.



The benefits from Forecast Analysis come from early recognition of problems so that corrective action may be made in timely, economic fashion.

On the other hand, if there is sufficient "elbow room" between forecasted weight and control weight values, the natural growth would be expected to continue.

Thus, the word "error" is introduced in a mathematical sense only, with recognition that the final weight will be frequently different than the forecasted weight because of incorporation of buy-offs. This leads to the interesting conclusion that it may be self-defeating to attempt to improve forecast accuracy since in some cases it is not reasonable to expect final weight to be equal to the forecasted weight.

It is sometimes argued that forecasts should recognize expected incorporation of future buy-offs and be adjusted accordingly. Such an argument neglects the need for clear presentation to management of the required magnitude of corrective action, and therefore Forecast Analysis validation efforts are caught in a dilemma. "Should management corrective action be presupposed and thus run the risk of failing to emphasize the urgency of such action?"

The alternative which is selected here is to present the "natural" growth expectations, with the forecasted buy-offs incorporated only when actually authorized or actually made. Studies for validation should consider methods by which data can be "prenormalized" so as to permit study on a more consistent basis. Prenormalization is used to describe the preremoval of all buy-offs and is possible by using existing repeating-mode programs which permit a more consistent comparison of all data on the same basis. With prenormalization, forecasts should be close to actual measured values, but this can be done only after the final weight is observed.

3.10.4 A MORE DETAILED STUDY OF S-IV STAGE OF SA-5 VEHICLE

Application of prenormalization and other techniques was studied in a more detailed analysis of the Saturn I, SA-5 vehicle, S-IV stage. Figures 3-36 through 3-42 show the results of analysis with data assessed as it would be during the program, as well as for prenormalized data.

The curves are the percent differences of the forecasted and actual data at the forecast time. Positive values are percentages by which the forecasted values have exceeded the actual value. The data of the "normalized" curve was processed in a form that would occur during a program. The "prenormalized" data was corrected for all non-random changes prior to extrapolation.

An illustration of benefits of prenormalization can be seen in Figure 3-36 where a large increase in weight occurred in the Equipment and Instrumentation System between January 1963 and June 1963. The large difference between the normalized and prenormal-

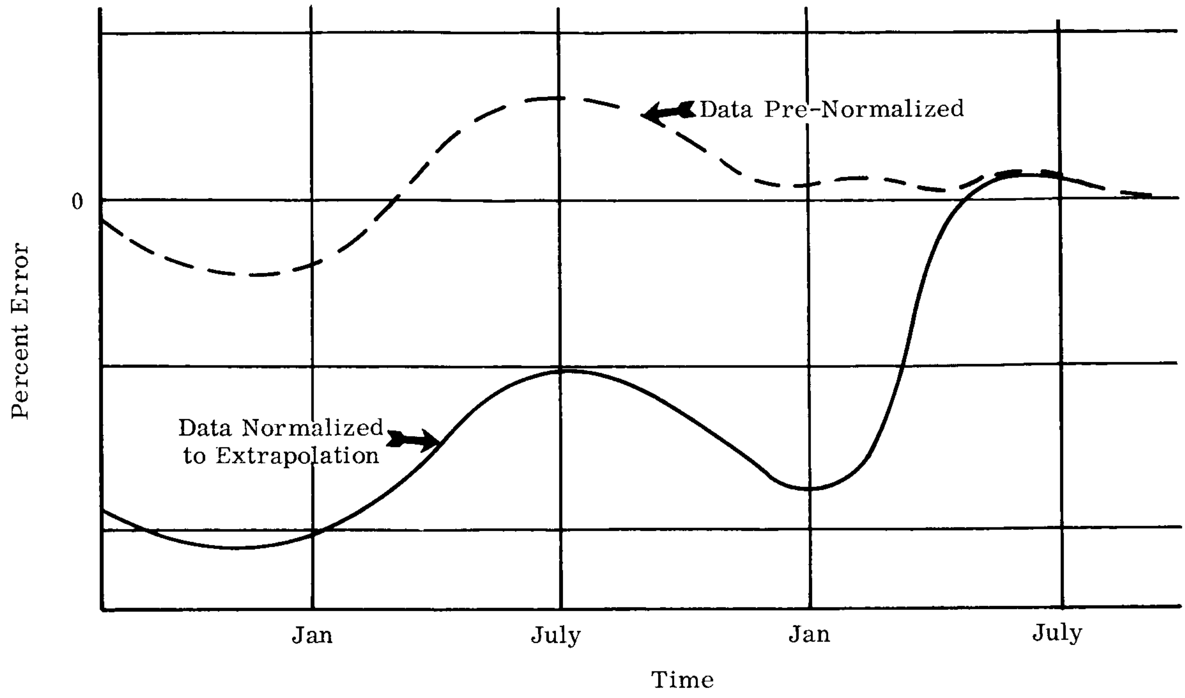


Figure 3-36. Equipment and Instrumentation System

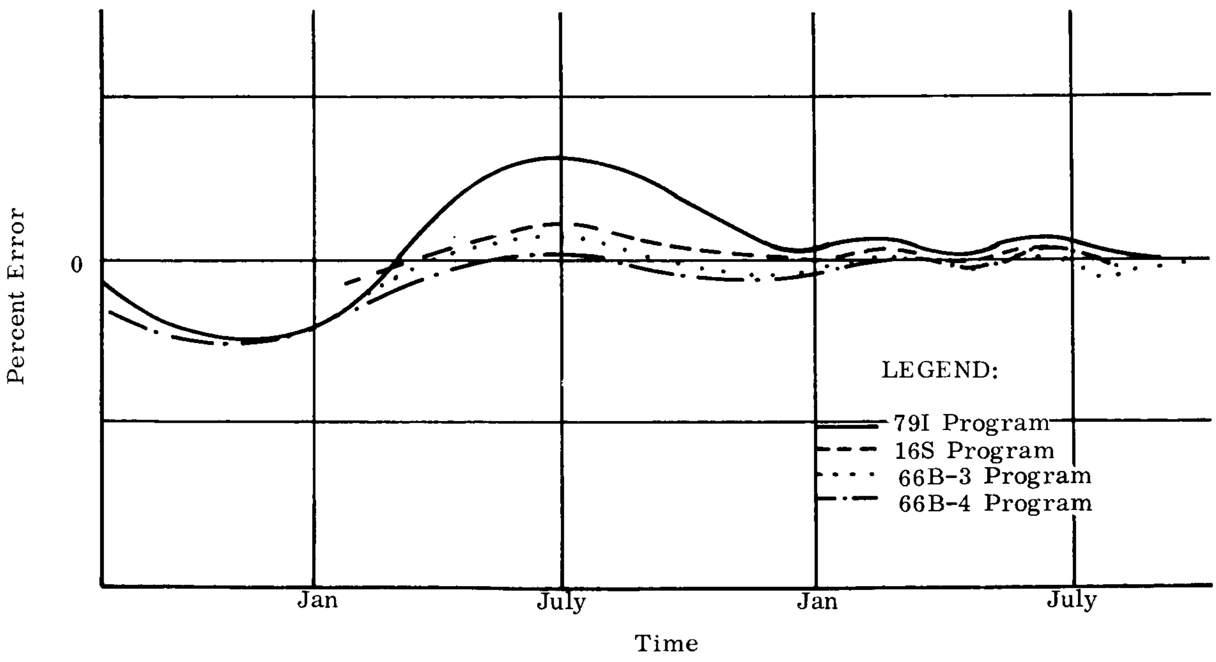


Figure 3-37. Equipment and Instrumentation System Comparison of Computer Programs Prenormalized Data

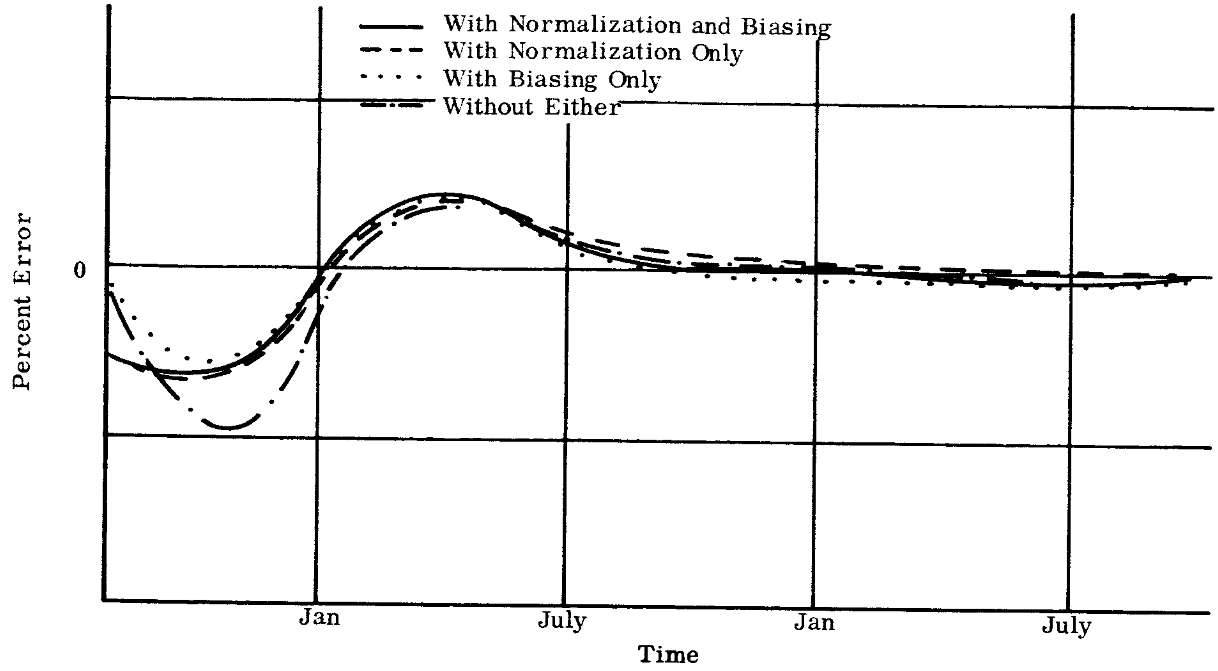


Figure 3-38. Structure System 79I Program Normalization and Biasing Comparisons

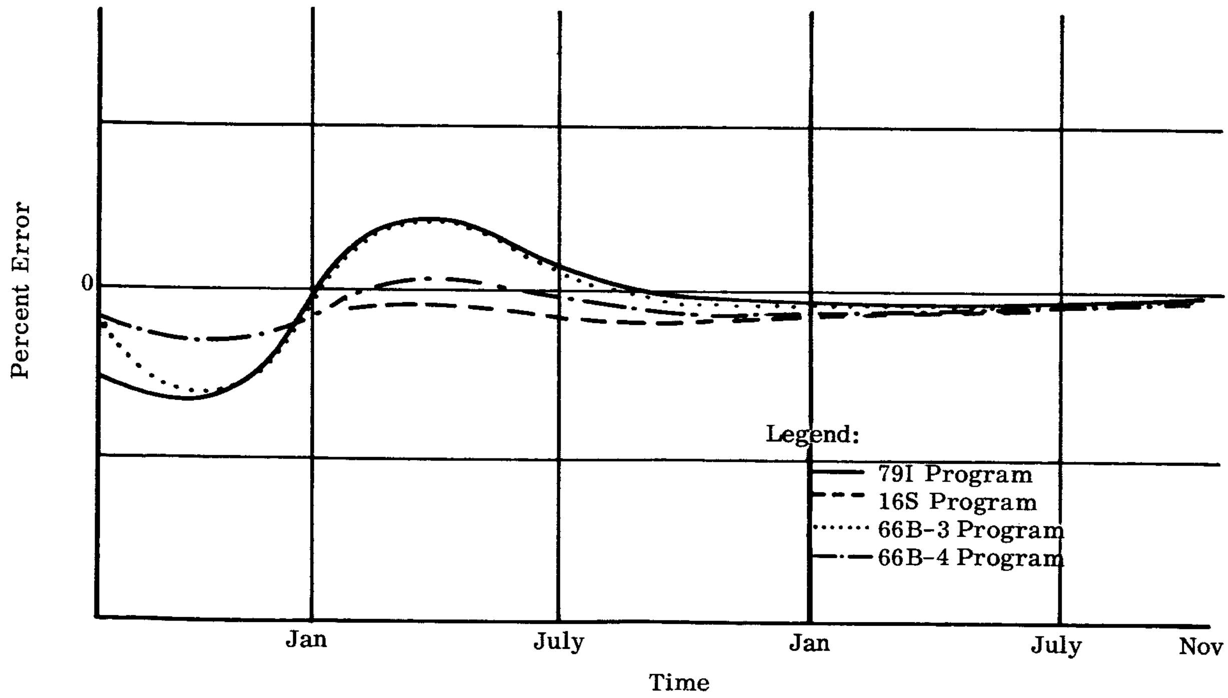


Figure 3-39. Structure System Comparison of Computer Programs

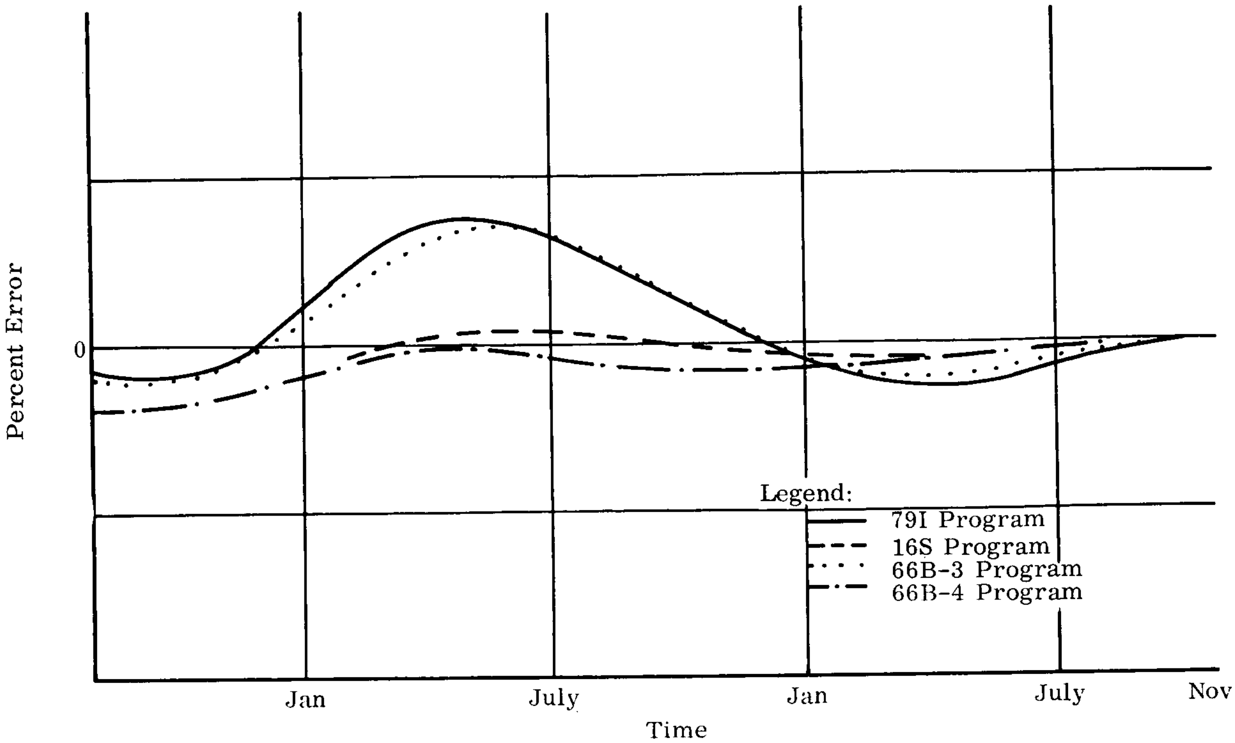


Figure 3-40. Propulsion System Comparison of Computer Programs

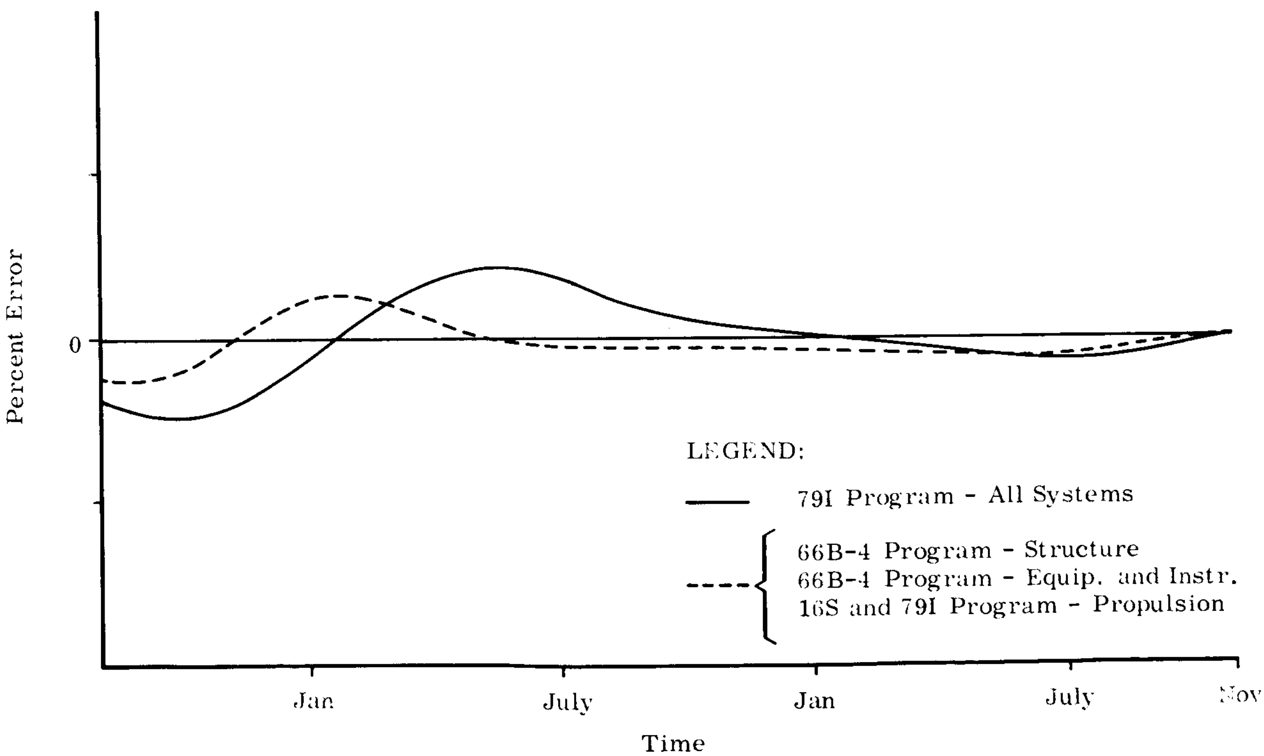


Figure 3-41. S-IV Stage Separation Weight (Sum of Systems) Trend Selection Comparison Prenormalized Data

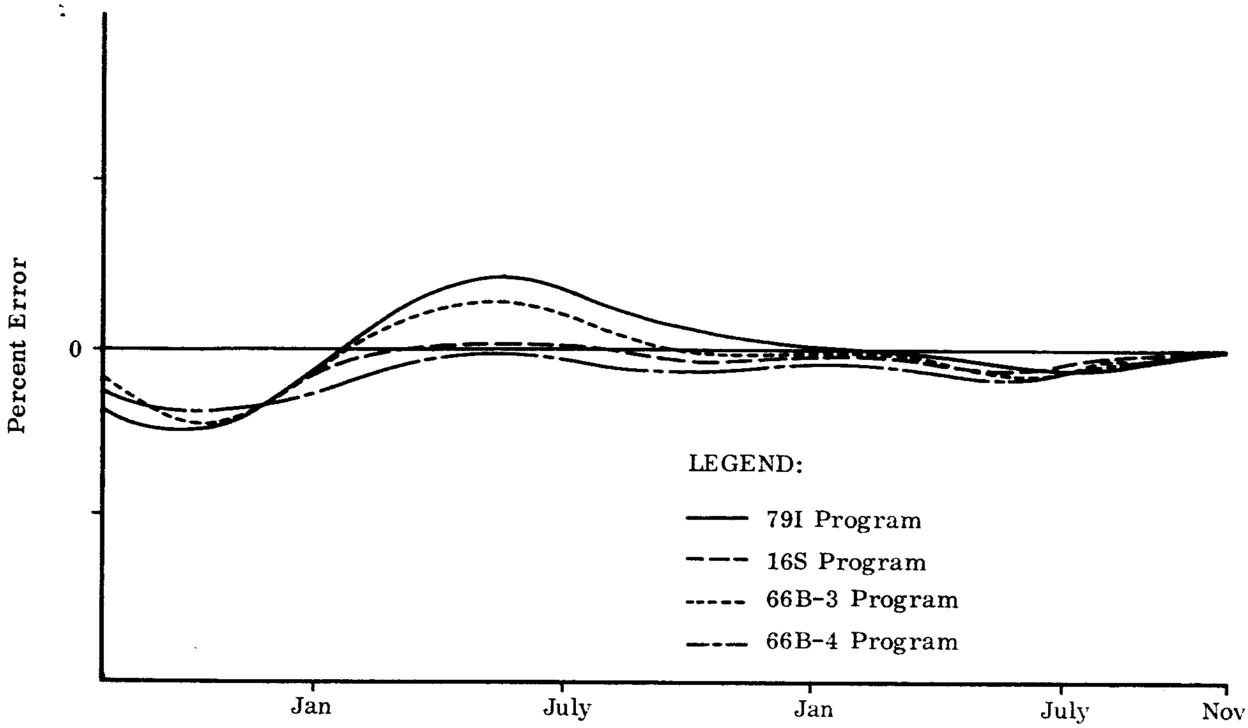


Figure 3-42. S-IV Stage Separation Weight (Sum of Systems) Comparison of Computer Programs Prenormalized Data

ized curves for the system are as expected and point up the need for careful, continued study of normalization and forecast adjustment for management actions.

The influence of biasing is shown in Figure 3-37. Forecast data is biased in order to give a positive response to changes and improve forecasts in the near future. Normalization also has the effect of accelerating the influence of changes on forecasts. Normalization is primarily incorporated to maintain a correlation between the system and and the mathematical model as shown in the preceding paragraph. In the beginning of the program, normalization has a greater effect on the forecasts than does biasing. Biasing becomes effective during the program and more so toward the end of the program. This is to be expected because normalization of a change has a salutory effect on the slope of the trend line early in the program as small unnormalized changes would have an appreciable adverse effect due to the small sample size. In Figure 3-37 the dotted line represents data that has been biased only, the dashed line is data that has been normalized only and solid line is data that has been both normalized and biased. The alternate dash and dotted line is data that has been neither biased nor normalized. It will be noted that the dashed line (normalized data) is nearly coincident with the solid line (biased and normalized data) at the beginning, and that the dotted line (biased data) is nearer the solid line toward the end.

Comparison of the computer program forecasts are shown for the Saturn I, SA-5, S-IV stage and systems in Figures 3-38 through 3-42. The comparative accuracy of each program is evident.

Since Forecast Analysis is an evaluating process, it is essential that validation studies be conducted parallel with its development and application. The results can be significant in establishing the credibility of the techniques developed and in generating guidelines for future development.

3.10.5 ANALYSIS OF REPRESENTATIVE APOLLO SYSTEMS

Six cases were selected from the weight program. The only requirements were that they have on the order of 20 points and that they be "typical" - that is, that the data variations are no smoother than one would ordinarily expect.

Each case was treated by each of the four prediction models and the Repeating Mode Analysis (RMA) routine. Thus, 24 case/model combinations were processed by RMA. The first prediction, in every instance, was made using the first 8 points in the set. One additional point, in chronological order, was added during each pass through RMA until the last prediction was made using the complete data set less the last point. All 6 cases used the outlier removal option while 2 of them were also run without it, for the sake of comparison.

The predictions themselves extended only to the last observation point. Thus, all predictions and analyses are based on an artificial prediction range, wholly contained within the actual observation range. The change removals were made only as they occurred, that is, the data were not "prenormalized."

Three types of error were formed and recorded. The Type I error is the sum of the squares of the differences between the trend line and the normalized data points used to generate it. The Type II error is the Type I error plus the sum of the squares of the differences between the prediction values and the corresponding un-normalized observation values. The Type III error, computed once for each RMA sequence, is the sum of the squares of the differences between the predicted and observed values of the last observed point. The Type I error indicates the goodness-of-fit and the Type III error is a measure of the average ability to predict the last observed value. (In practice, these two measures never coincided.) Upper confidence limits were also printed out in the hopes that some useful correlation might be uncovered. As it turned out, all observations were either outside the limits or well inside, suggesting that a further evaluation of the confidence limits themselves is required.

In developing the results listed in Chapter 2, the RMA outputs were examined in the following ways:

a. The prediction error at the last observation point, for each model, was plotted versus the number of points used in the prediction.
b. The observed values, both pre- and post-normalization, were plotted versus the observation time.
c. The prediction error at the observation point immediately following the last point used for the prediction, both pre- and post-normalization, was plotted versus the number of points used in the prediction.
d. Tabular comparisons of the 3 error types.
e. Tabular listing of the prediction errors at each observation point versus the number of points used in the prediction.
f. Tabular comparisons of the prediction errors at the last observation point expressed as percentages.

A typical result is presented in Figure 3-43.

It should be stressed that the following discussions are based on the analysis of a small sample. Therefore, conclusions about the predictions themselves are considered as tentative only. The reader's interest should be concentrated upon the measuring techniques and the nature of the information they provide.

Figure 3-44 presents the results of applying the repeating mode routine to one set of data set, consisting of 30 points. The first pass predicted the value of the 30th point based on the first 8 points. The second predicted the value of the 30th point using the first 9 points, and so on. These predicted values, using all four prediction models, are shown here plotted versus the number of points used and are compared with the actual or observed value of the 30th point. The important thing to note is the convergence on the observed value as time passes.

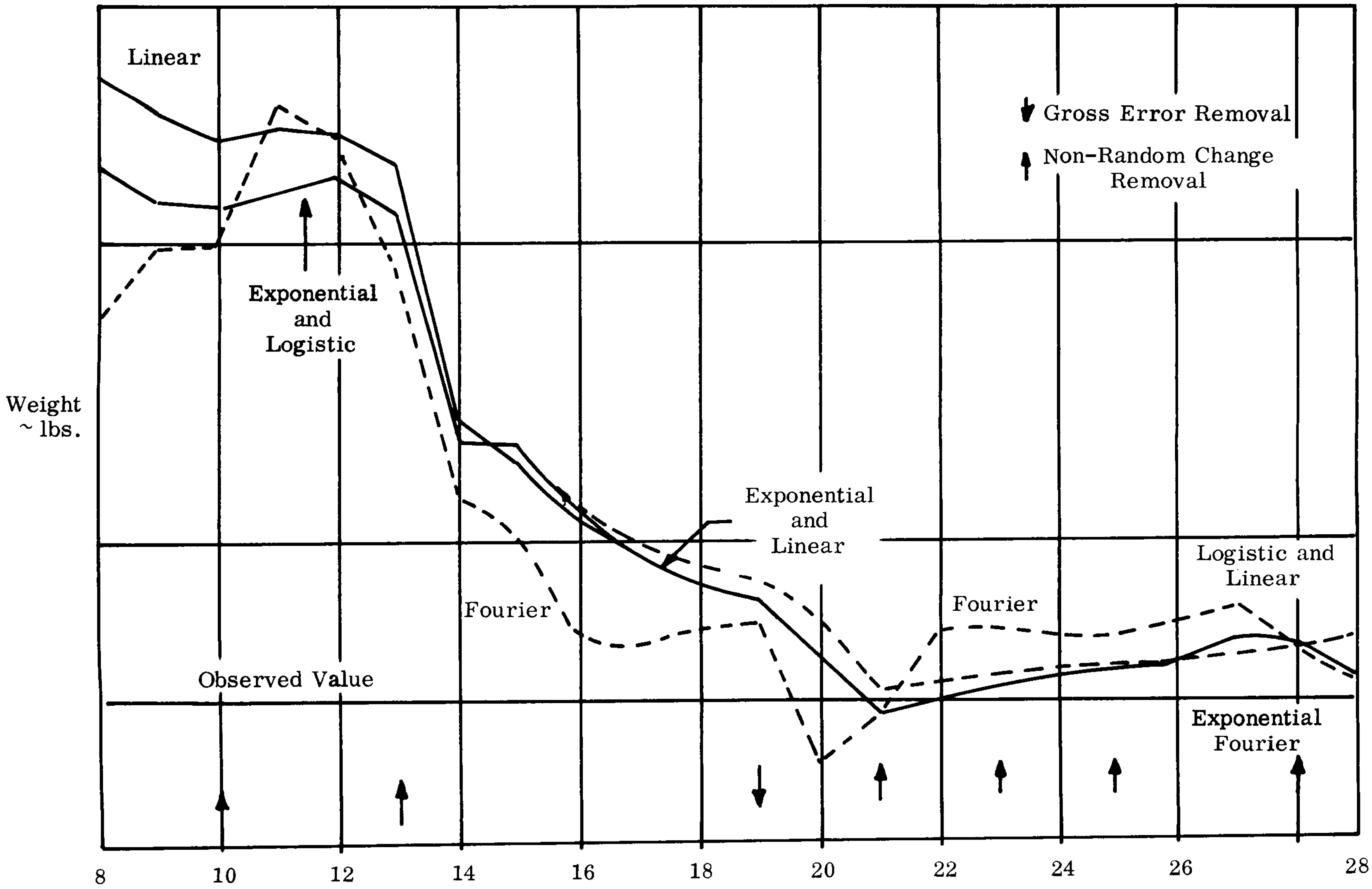


Figure 3-43. Prediction Error at Last Observation Point of a Representative Case

Also indicated in Figure 3-43 are the times at which gross errors and non-random changes were removed from the original data. Further insight is provided by Table 3-9 which tabulates the prediction accuracy and the magnitude of the non-random changes applied. Note the 11-percent improvement in accuracy when the 14-percent change is made and the relatively minor improvements when the smaller changes are made (a positive change is effectively towards the observed value). The significance of this lies in the possibility of quantizing the correlation between prediction accuracy and the number and/or magnitude of the non-random changes removed.

3.11 SUMMARY OF RESULTS

The following items were fully expected:

a. Removal of non-random changes from the raw data has a very significant effect on predictions.

b. Prediction quality is inversely proportional to the length of the prediction range.

c. Prediction quality is inversely proportional to the number of non-random change removals.

The following represent some surprises:

a. The model providing the best fit to a given set of data very rarely yields the best predictions.

b. All four models, in many cases, yield long range predictions varying from one another by only a few percent. The envelope containing the predictions contracts as the prediction range decreases.

c. The removal of gross errors or outliers seems to improve the prediction quality.

d. For a prediction range of 12-13 months, a value can be predicted within a few percent if,

   (1) No significant (>3%) data normalizations are made within that 12-13 months, or

   (2) The total of normalization changes is relatively small in number (≤ 4) and in magnitude.

Table 3-9

Long Range Prediction Accuracy ~ Observed Value/Predicted Value

Number of Points	Linear	Exponential	Logistic	Fourier	Non-Random Changes (Percent)
8	68.0	71.6	71.9	78.3	
9	69.6	73.0	73.0	75.0	
10	70.6	73.2	73.3	74.8	
11	70.1	72.6	72.7	69.3	0.602
12	70.4	72.0	72.0	70.5	
13	71.5	73.5	73.4	76.2	
14	83.0	84.0	84.0	87.0	14.0
15	85.0	84.1	84.3	89.1	
16	88.4	88.2	87.9	95.9	
17	90.8	90.8	90.0	96.1	
18	92.3	92.3	91.3	95.1	
19	93.3	93.1	92.0	94.6	
20	97.0	97.0	94.5	105.0	
21	101.5	101.5	100.0		
22	100.0	100.0	99.3	95.3	0.146
23	99.5	99.3	98.8	95.3	
24	99.0	98.8	98.1	95.8	-0.105
25	98.0	98.0	98.0	95.7	
26	97.8	97.0	97.8	94.8	0.063
27	96.9	96.3	96.9	93.8	
28	96.9	96.2	96.9	96.5	
29	96.0	96.0	95.8	99.3	-2.03

CHAPTER 4

COMPUTATIONAL SYSTEM DESCRIPTION

4.1 INTRODUCTION

The mathematical analyses of FAME can involve many numerical calculations and frequently process large masses of data. Accuracy and speed considerations dictate the use of a digital computer to perform these analyses. Since there are many interdependent calculations to be performed it has proven expedient to develop them as separate programs and then use an executive routine or controller to tie them together into a computing "system." The use of a system reduces the need to input data into each program separately and also reduces the attendant chances for numerical and keypunch errors. It also reduces the over-all elapsed job time since the calculations for several programs can be done at one "pass" on the computer or in desired combinations, at the discretion of the analyst.

4.2 COMPUTATIONAL SYSTEM

4.2.1 BASIC REQUIREMENTS

Two basic competing requirements are recognized in designing the computational system:

a. Since large amounts of data have to be processed the system must be efficient to keep computer time at a practical level.

b. The system must be as flexible as possible; FAME calculations embrace a wide range of operations with new techniques continually being developed and new outputs required. In addition, the system profits from the capability to serve in many fields, as yet uninvestigated, to improve and refine program control in these areas. This system, as applicable to weight/performance control is shown in Figure 4-1. It can be thought of as an executive routine controlling the following individual programs:

(1) Weight data file update program

(2) Trend programs, including:

(a) Maximum likelihood linear.

(b) Maximum likelihood non-linear.

(c) Adaptive (Fourier) exponential.

(d) Asymptotic (logistic) exponential.

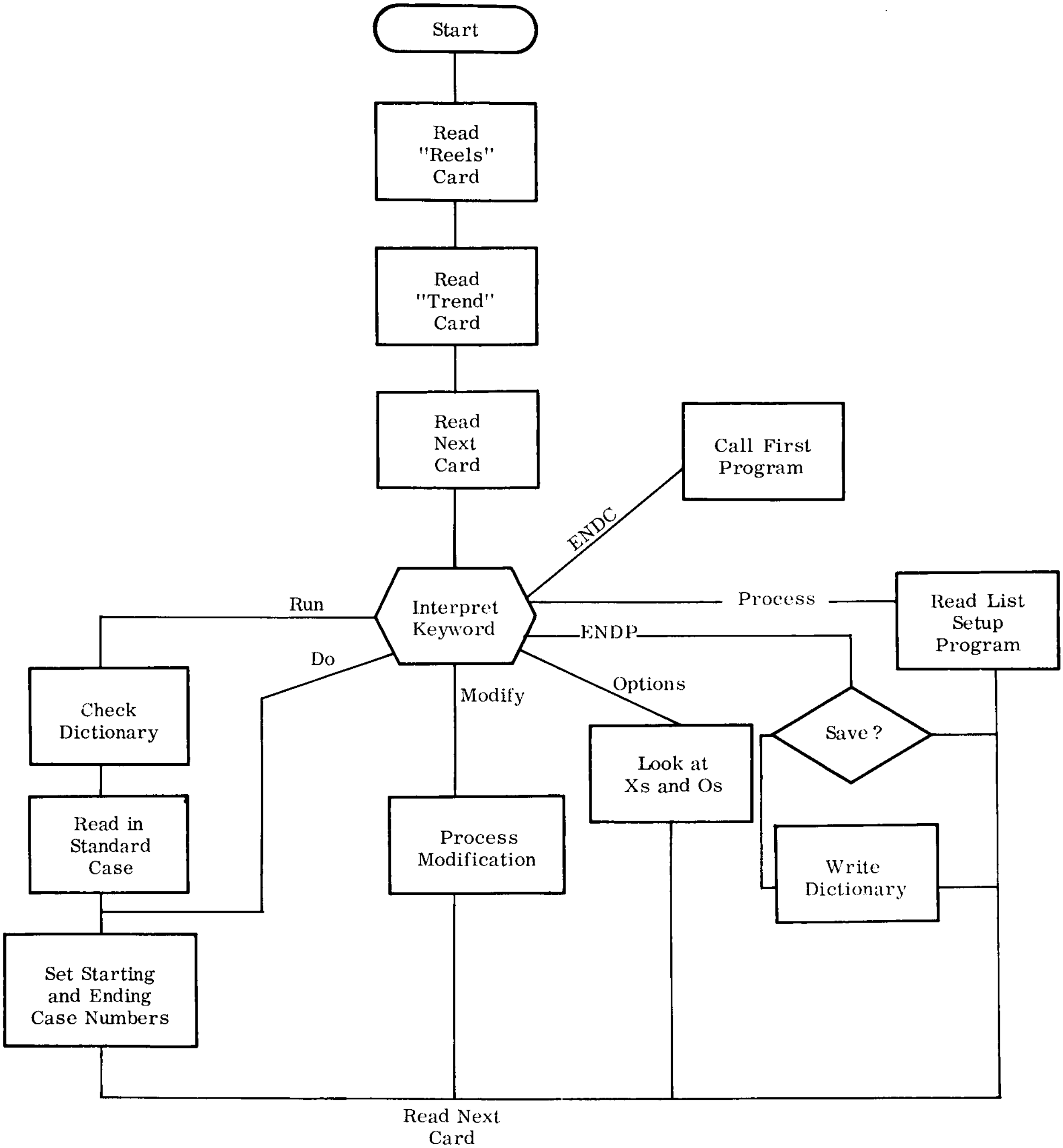


Figure 4-1. Control Card Input Processor Flow Chart

(3) Automatic mode selector including repeating mode analysis.

(4) Summing program including calculation of probable error.

(5) Spacecraft performance calculations.

  (a) Block I spacecraft.

  (b) Block II spacecraft.

(6) Launch vehicle performance calculations for:

  (a) Saturn IB launch vehicle.

  (b) Saturn V launch vehicle.

(7) Criticality program.

(8) Cost program.

(9) Output program including history plots.

The system is not limited to the above programs. Since the design of the system is modular in concept, programs can be substituted or added without affecting any other section. In addition, any number of programmers can work on the various modules or programs at one time since the basic interface logic between modules is not a part of the individual calculation programs, but is controlled by the executive routine. This modular construction greatly adds to system flexibility.

4.2.2 EXECUTIVE ROUTINE

The executive routine can be considered in two sections. The first section controls an administrative program designated as "Subsystem Processor for the Apollo Computing Effort" (SPACE) (Appendix E - Book II of this manual). This administrative program is centered around a collection of seven versatile input/output subroutines. It takes care of file positioning, loading individual programs into core and other "bookkeeping" chores required for the successful operation of the system. The large amount of data processed and required to be available for other programs makes this a sizeable task. In addition the number and size of the individual calculation programs preclude their being loaded into core all at once. Instead these programs are stored on peripheral memory (tape on drum for example) in groups or "links." These links are loaded into core by SPACE, as required. In most cases a link is composed of more than one calculation program. The judicious selection of programs for each link, to eliminate the unnecessary loading of programs into core, is one of the methods by which the requirement of computational efficiency is met.

4.2.2.1 Input Information

There are two sets of information which must be supplied to the system. First of all, the type of job must be specified. The number and type of allowable prediction techniques must be specified, and the sequence and extent of processing must also be indicated. This data allows the system to set up the required sequence of operations for proper execution. The second set of information is the numerical data itself. (The problems of processing numerical data are considered in the Appendix E - Book II of this manual.)

The second part of the executive routine is the control program. The purpose of the control data processing operations is to provide the monitor with sufficient data to enable it to properly execute a job.

To do this it must be able to interpret the control data cards which specify job type, extent, techniques to be used, and so forth. Certain parameters must be available before any computations can be made, whereas other data may not be utilized until much later in the job. Specifically, the control data answers the following basic questions.

a. What operations are to be performed and in what sequence?
b. What techniques are available and what is the relative priority?
c. Which systems are to be analyzed?
d. Where is the reference data located?
e. Are any special values required?
f. What action should be taken in the event of an error during the job?
g. What type of output is required?

4.2.3 OPERATION

4.2.3.1 Operation Sequence

One of the significant features of the system is its ability to handle in sequence many diverse operations. Every operation, from updating the weight data file where functional system weight history data is stored to plotting final graphs, could be a part of a single operating system. Complete automation of any technique requires thorough understanding of all the factors influencing weight trends and associated phenomena. Additional elements can be added after exploration in greater depth to improve the capability of the system for making the "engineering judgments" required for application of Forecast Analysis to a specific task.

In using the system, a list of the jobs to be accomplished is required. Such a list might consist of the following:

a. Update the weight data file and list it.
b. Trend the subsystem data of a given launch vehicle or spacecraft.
c. Accumulate the total weight.
d. Print out the results and plot the history curves, trend lines and confidence limits.
e. Calculate deficiencies and required buyoffs for the spacecraft or launch vehicle.
f. Determine criticalities associated with the spacecraft or launch vehicle.
g. Compute costs required to accomplish the given buyoffs.
h. Summarize and format the above data for print/out.

The above list summarizes the important steps in Forecast Analysis for Apollo weight performance control. In order to convey this information to the system, a list of keywords is employed. The actual data card might look as follows:

PROCESS FAME UPDATE TREND SUM OUTPT1 COMPUTE CRITICALITY COST REPORT*

The first word (PROCSS) above indicates that a process or procedure is defined. The second word is the name associated with the procedure - in this case, FAME. The words are interpreted by the monitor and input processor in the same manner as the list presented first would be interpreted by an experienced engineer.

An important capability of the monitor is its ability to remember a procedure. Once primed with the above data, the system will execute the FAME procedure by merely specifying

RUN FAME *

Modifications to a standard procedure can also be accommodated without completely redefining the procedure.

4.2.3.1 Specification of Techniques

It may be advisable for reasons of efficiency or economy to limit the number of techniques available to the system. For example, it might be deemed advisable to omit for a given run the Fourier model from the repertoire of the automatic mode selector.

In another case, it may be advantageous to specify priorities for a set of otherwise equal techniques. In either case, the information is used by the monitor to determine the programs and subroutines to be used for the run. A diagram of the over-all control logic used by the input processor is shown in Figure 4-1.

4.2.3.2 Determination of System to be Analyzed

The structure to be analyzed can be specified in a variety of ways. The most obvious method is to indicate starting and ending case numbers. Another method would be to merely specify the spacecraft or launch vehicle and let the program decide what functional subsystems are included. This sophistication however, does not appear to offer any significant advantages.

Functional systems are identified by a seven-digit code number. The significance of each digit or group of digits is shown in Figure 4-2.

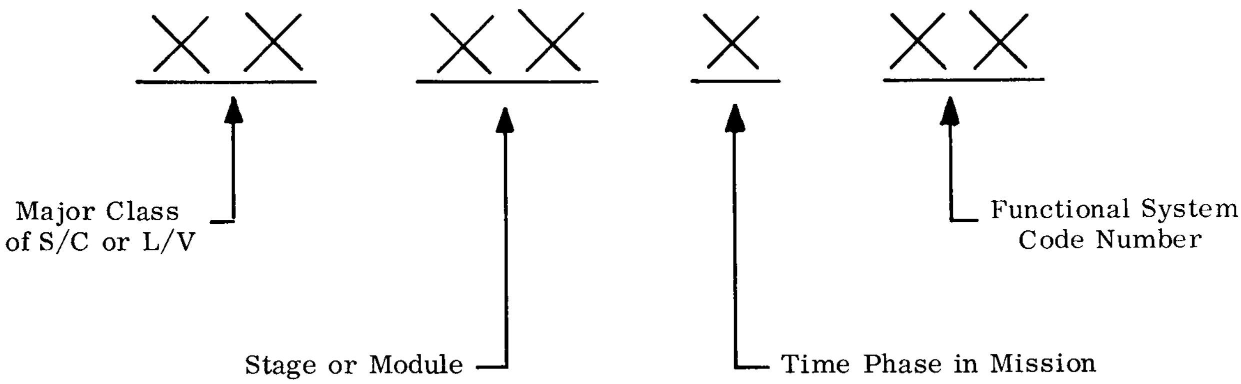


Figure 4-2. Functional System Code Numbering

4.2.3.3 Location of Reference Data

One of the drawbacks in any large data processing program is the tremendous amount of data that must be made available to the system. At this point in the system design, the following separate tapes are required.

a. Weight data file.
b. Analytical data file (contains the results of the current job).
c. Old analytical data file (referred to by automatic mode selector).
d. Dictionary (contains standard processes and file references).
e. Library (contains all the programs of the system).

This part of the data problem is very well defined. Two header cards containing tape data will be required for every run. The first card is needed to establish the relation between physical reels and the tape drives. The second card is needed to provide the relation between the physical reels and the program parameters. These two cards are the first two in every job deck. Presently weight and performance data are extracted from monthly reports and entered on the weight data file via input cards. Provisions can also be included for updating the weight data file directly from other computer tapes, should these tapes become available.

4.2.3.4 Data Modification

An irritating feature of most programs is the difficulty of modifying some of the parameter values without revising the programs. This problem will be at least alleviated, if not eliminated, in the FAME system. Any variable in core can be modified using header cards.

4.2.3.5 Error Control

In a program of the size and complexity of this system, it is important to detect errors as soon as possible. Errors can be several types. Some can be anticipated by the programmer and some cannot. It is important that an effort be initiated immediately to analyze possible error sources so they can be monitored.

The modular nature of the program should make it easy to handle error conditions. Until error analysis procedures have been established, the job will be terminated as soon as an error is detected. Since all data of consequence is saved on the analytical data file, restarting the program at the last good data should be a straightforward procedure.

4.2.3.6 Output Specification

Traditionally, the rule of thumb regarding output frequency and quantity has been "When in doubt Print it Out."

This is acceptable for a small program with no permanent tape storage capability but neither of these two characteristics apply to this system. The quantity of output that can be generated by this system is overwhelming. It seems inadvisable to spew out such quantities of output until quality has been analyzed. The following procedure utilizing three output modes is recommended:

a. In the absence of specific instructions to the contrary, output will consist solely of FAME data.

b. A second mode will consist of FAME data, specified checking data and execution comments. This mode will be specified automatically by the monitor if an error occurs.

c. The last mode is the DUMP mode. Extreme care should be exercised in specifying this mode since the entire contents of the analytical data file is printed out.

4.3 AUTOMATED RESULTS PRESENTATION

The Forecasting data resulting from the analysis by the computer models of weight and performance information is received in the form of tabulation and a supplementary digital computer plot. Options are also available for Calcomp plots of the data. The three types of output available are shown in Figure 4-3. All trend programs utilize the same output formats.

4.3.1 TABULATION OF DATA

The tabulated data resulting from a typical computer run in the Forecast Analysis system is shown in Figure 4-4. It should be noted that only data at the functional system level is utilized by the computer models in Forecast Analysis. Zone 1 lists information applicable to the particular plot in question, e.g., the type of trend run, the case title, and the case number. Also listed in Zone 1 is the data the case was run, and the date and number of the data file used to supply the weight and performance information for the run. Zone 2 lists the titles of the data columns tabulated on the form. Zone 3 is the tabulation of weight and performance data in the observed range. Zone 4 is the tabulation of weight and performance data in the Forecast range. Zone 5 is the final forecast values for the particular case shown.

4.3.2 DIGITAL COMPUTER PLOTS

Plots are printed out in two forms. The first of these forms (Figure 4-3) illustrates the functional system plot corresponding to the tabulation of data discussed in the preceding paragraphs. The second form (Figure 4-5) illustrates the history plot used for stage and module data plotting and for plotting of launch vehicle and spacecraft total weight.

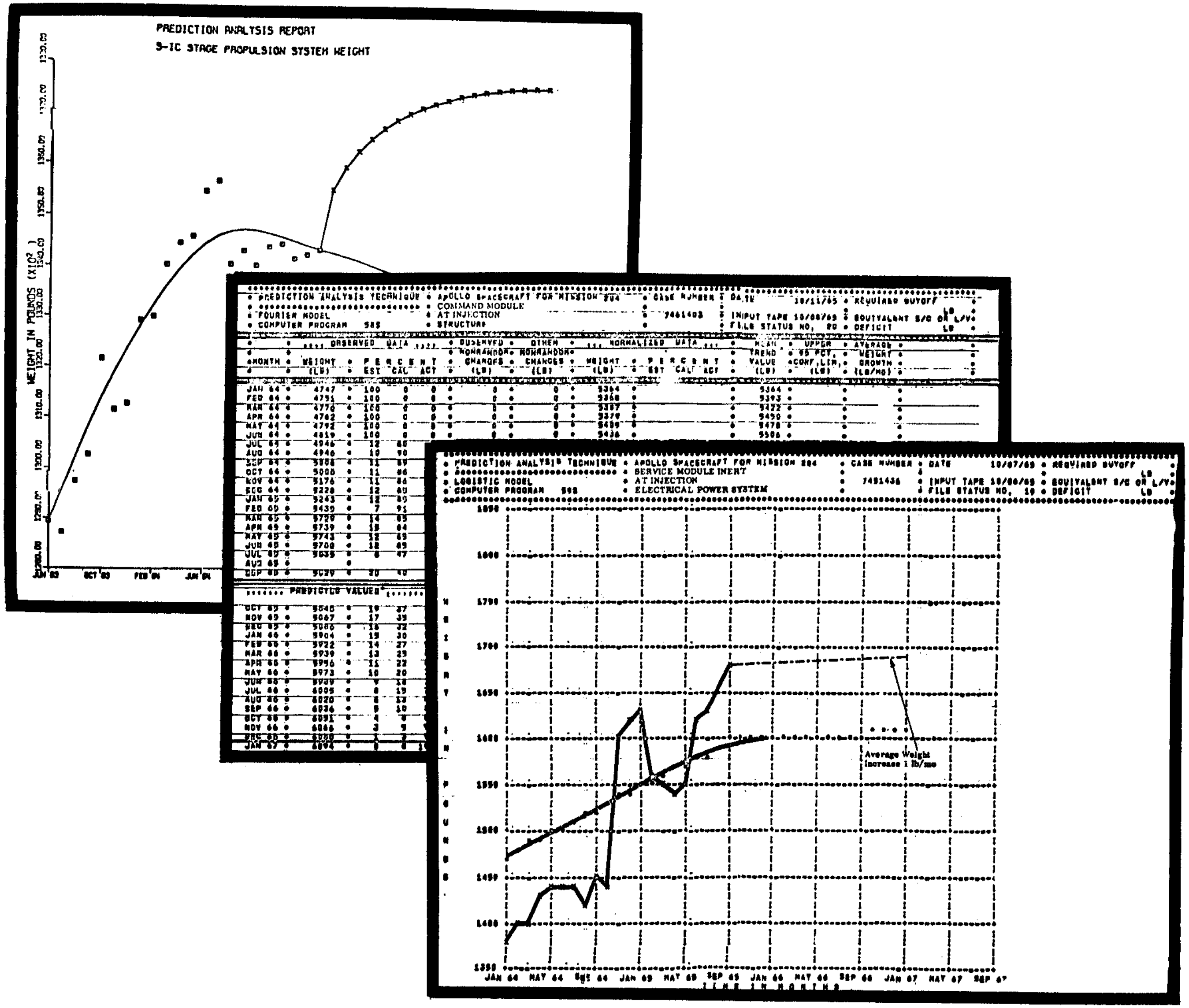


Figure 4-3. Automated Results Presentation

Zone 1

PREDICTION ANALYSIS TECHNIQUE
FOURIER MODEL
COMPUTER PROGRAM 58S

APOLLO SPACECRAFT FOR MISSION 204
COMMAND MODULE
AT INJECTION
STRUCTURE

CASE NUMBER 7461403

DATE 10/11/65
INPUT TAPE 10/08/65
FILE STATUS NO. 20

REQUIRED BUYOFF LB
EQUIVALENT S/C OR L/V DEFICIT LB

Zone 2

MONTH	.... OBSERVED DATA .... WEIGHT (LB)	PERCENT EST	PERCENT CAL	PERCENT ACT	OBSERVED NONRANDOM CHANGES (LB)	OTHER NONRANDOM CHANGES (LB)	... NORMALIZED DATA ... WEIGHT (LB)	PERCENT EST	PERCENT CAL	PERCENT ACT	MEAN TREND VALUE (LB)	UPPER 95 PCT. CONF. LIM. (LB)	AVERAGE WEIGHT GROWTH (LB/MO)
Zone 3													
JAN 64	4747	100	0	0	0	0	5364				5364		
FEB 64	4751	100	0	0	0	0	5368				5393		
MAR 64	4770	100	0	0	0	0	5387				5422		
APR 64	4762	100	0	0	0	0	5379				5450		
MAY 64	4792	100	0	0	0	0	5409				5478		
JUN 64	4819	100	0	0	0	0	5436				5506		
JUL 64	4946	12	88	0	0	0	5563				5533		
AUG 64	4946	10	90	0	0	0	5563				5560		
SEP 64	5008	11	89	0	0	0	5625				5586		
OCT 64	5008	11	86	3	0	0	5625				5611		
NOV 64	5176	11	86	3	-166	0	5627				5635		
DEC 64	5228	12	85	3	0	0	5679				5659		
JAN 65	5243	12	85	3	0	0	5694				5682		
FEB 65	5435	7	91	2	-174	0	5712				5704		
MAR 65	5729	14	85	1	0	-255	5730				5726		
APR 65	5739	15	84	1	0	0	5740				5747		
MAY 65	5743	12	85	3	0	0	5744				5768		
JUN 65	5780	12	85	3	0	0	5801				5789		
JUL 65	5835	8	47	45	-5	0	5851				5809		
AUG 65													
SEP 65	5829	20	40	40	-16	0	5829				5829		17
Zone 4	.... PREDICTED VALUES*												
OCT 65	5848	19	37	44			5848				5848	5983	16
NOV 65	5867	17	35	47			5867				5867	5944	16
DEC 65	5886	16	32	51			5886				5886	5980	16
JAN 66	5904	15	30	55			5904				5904	6013	16
FEB 66	5922	14	27	59			5922				5922	6043	16
MAR 66	5939	13	25	62			5939				5939	6072	16
APR 66	5956	11	22	66			5956				5956	6100	15
MAY 66	5973	10	20	70			5973				5973	6126	15
JUN 66	5989	9	18	74			5989				5989	6152	15
JUL 66	6005	8	15	77			6005				6005	6177	15
AUG 66	6020	6	13	81			6020				6020	6201	15
SEP 66	6036	5	10	85			6036				6036	6224	15
OCT 66	6051	4	8	89			6051				6051	6247	14
NOV 66	6066	3	5	92			6066				6066	6269	14
DEC 66	6080	1	3	96			6080				6080	6291	14
Zone 5													
JAN 67	6094	0	0	100			6094				6094	6312	0

Figure 4-4. Tabular Results Presentation

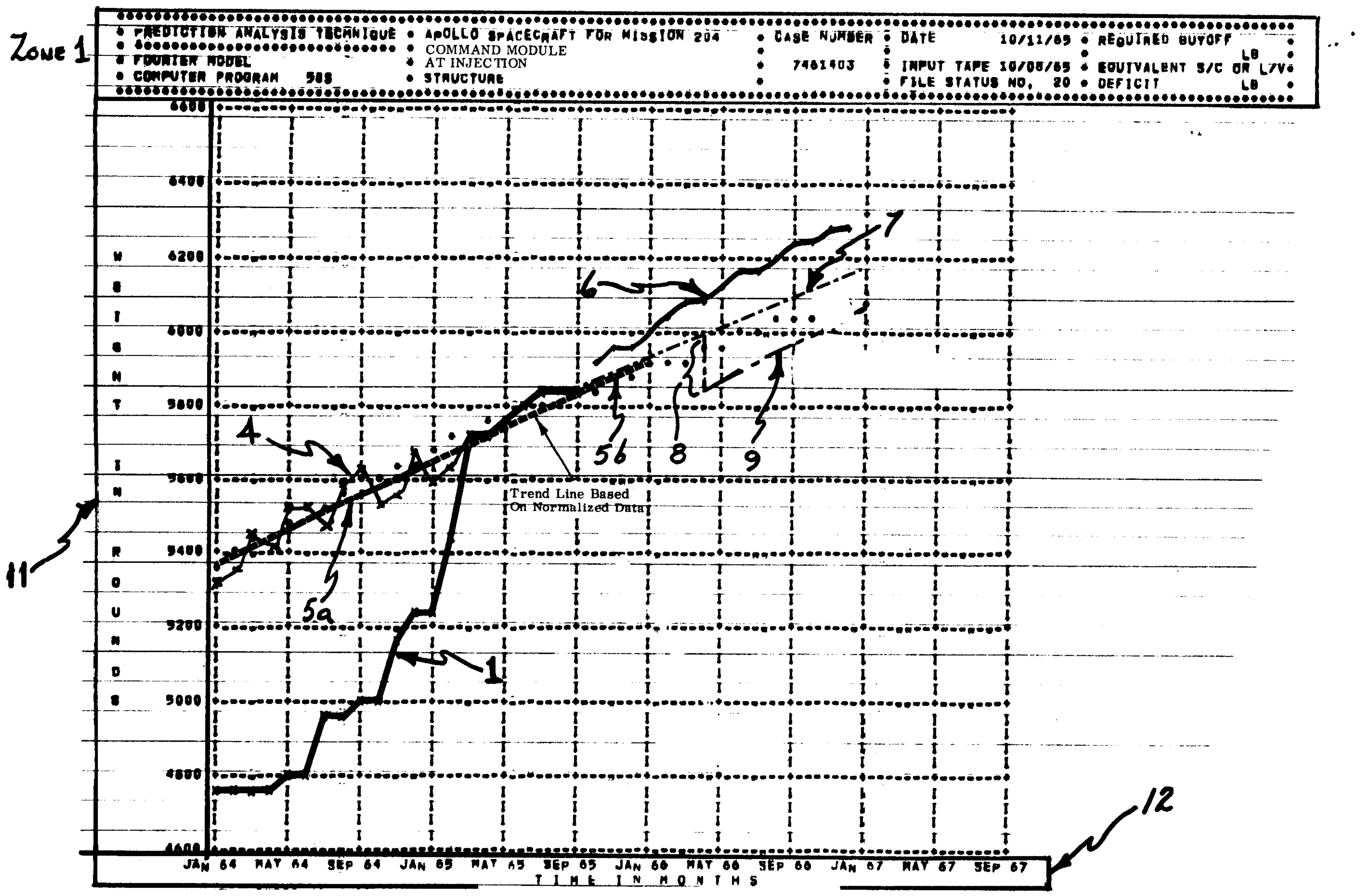


Figure 4-5. Graphic Results Presentation

Functional system plots, Zone 1 of Figure 4-5 corresponds directly to Zone 1 of Figure 4-4. Since this figure is a plot of the data tabulated in Figure 4-4, use of the same identification number serves as an aid to clarity. The numbers on the figure relate to the following:

1. Plot of the observed weight data.
2. The non-random changes incorporated into the data will not be seen on the plots.
3. The normalized data is not a portion of the digital computer plot, but is shown here to illustrate how their values influence the trend line.
4. Plot of the mean trend line in the observed range.
5. Plot of the mean trend line in the forecast range.
6. Plot of the upper 95 percent confidence limit in the forecast range.
7. The normalized data in the forecast range is plotted from the last observed point, using the mean trend line slope.
8. No non-random changes are shown on the tabulation of results. To show their effect on the plots an arbitrary value has been included.
9. Forecast line showing effect of the non-random change in the forecast range.
10. The average weight growth, like the non-random changes in the observed range, is not a portion of the digital computer plot.
11. The vertical scale, elected by the computer on functional system plots, is the weight of the system in pounds.
12. The horizontal scale, which is dependent on a specified plot size, is the time in months.

CALCOMP PLOTS

The Calcomp graphical plotter produces output, (Figure 4-6) which has much better resolution than the digital plotter. This better resolution on plots is highly desirable. The Calcomp plotter is also capable of producing all the desired information. Symbols are utilized to represent different curves and these symbols are connected by straight lines, dashed lines, or dotted lines. Schedules and Key Events are simulated on the Calcomp plotter by overlapping symbols. Any information to be printed on the surface of the plot can be plotted, along with the points and lines. Using the Calcomp plotter to produce functional system plots will yield a sharp, clear graphical plot of the output data. However, one drawback is apparent. The time to produce these plots is excessive when compared to the time it

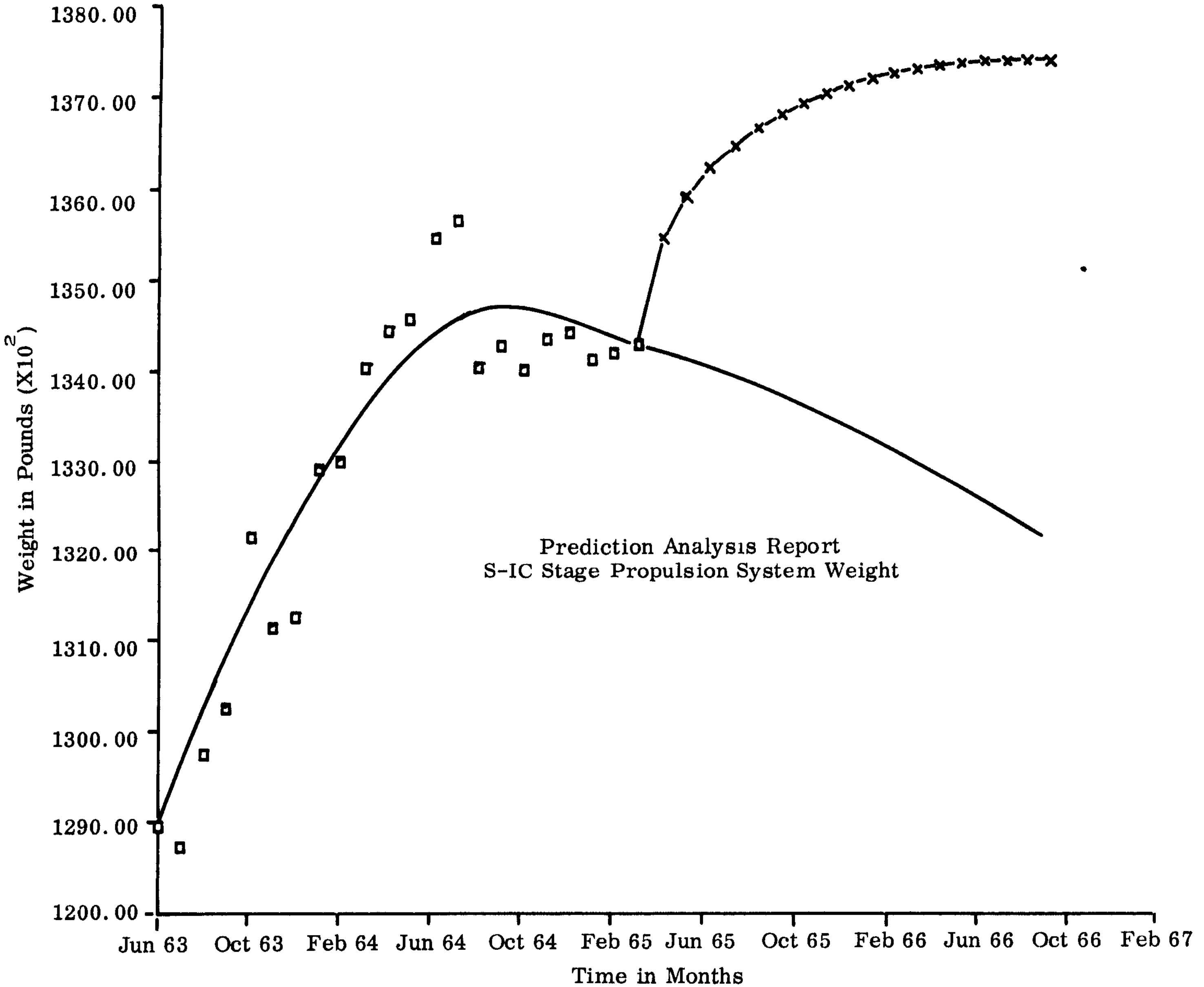


Figure 4-6. Calcomp Graphical Plotter Output

takes to produce a digital plot. The digital plots are produced at high speed, but the Calcomp plotter. The actual time it takes to plot each graph is a function of the amount of information to be plotted, roughly 5 minutes each. Output formats for launch vehicle reliability, costs, and utilization areas for appraisals are covered in later chapters of this book.

CHAPTER 5

REPORTING TO MANAGEMENT

5.1 PURPOSE

The whole purpose of FAME, as stated in Chapter 1, is to provide meaningful information of management planning and control. To be useful, the information transmitted to management must meet certain predetermined requirements. The starting point is, of course, to have a clear definition of what information is wanted. This seem obvious enough until it is recalled that many organizations generate information which is not useful, needed, or wanted.

Assuming a clear-cut need for certain types of information, several questions need to be resolved. For simplicity, these questions can be stated as: What? When? How? Who? Answers to these questions may not be simple. Taking them in order, the first question is: What kind of information is needed or wanted? The answer will come out of the nature of the subject being controlled and the depth of information wanted. In some cases, there may be a requirement not only for information about current status and for conditional forecasts, but also about possible remedial actions and their consequences, such as the time and money involved in each alternative. This brief elaboration will serve to illustrate that the answer to what kind of information is wanted deserves careful definition. Not only does the final decision on this question influence the type of data flow to be established it influences the selection of math models and their utilization.

The matter of when information is needed usually is resolved by the nature of the program being controlled. Feedback may be needed every day, every month, every quarter -- at any interval, depending upon how soon adjustments must be made to prevent a sequence of compounded error. Since Forecast Analysis has the capability for looking ahead to see what is likely to happen unless corrective action is taken, the reporting interval should be on a timely basis in order to capitalize on the intrinsic value of the system.

The question of how the information yielded by FAME is to be transmitted refers to the form to be employed rather than the channel to be used. The form requirements are that the information be clear, concise, complete and undistorted. Clarity is obtained usually by employing on a continuing basis those graphic devices which convey meaning quickly. They can employ words, numbers, pictures, symbols, lines, bars, etc., arranged into charts, tables, pictograms, and the like. Usually information will be presented on a comparative basis; for instance, with the last reporting period and in relationship to ultimate goal. And the base chosen should be such that variations and disturbances are not smoothed out, magnified, or distorted, either deliberately or unintentionally.

The question of who is to receive the information is not a concern about protocol but about the level of refinement and the depth of detail needed in the reports. If, for example, the report is for top management only, the inclusion of details of value only to department managers merely introduces "noise" into the communication system. Very often, the question of who is to be on the distribution list is related to the time factor. If early action is a requirement in the program, a wide distribution to various levels can expedite program adjustment or adaptation. Sometimes this matter is resolved by providing monthly reports to one distribution list and quarterly reports to another, again depending upon the nature of the programs.

Many of the questions which may arise about the reporting phase of FAME can be answered by returning to a definition of the basic purposes of this system, which are: to provide management with a means for determining whether a program is progressing in accordance with established goals; to supply timely predictions of possible future developments based upon current trends, and to furnish estimates of the probable consequences of alternative actions. It is worth mentioning that one additional yield could be evidence of program planning errors or inadequacies.

The information which can be transmitted to management by the FAME system is as follows (both for the over-all project and major individual elements):

a. Current Status Review.
b. Predicted Status.
c. Problem Areas.
d. Criticalities.
e. Buyoffs (together with estimated costs in dollars and anticipated schedule slippage).

This information can be graphically displayed in easily read charts. Figure 5-1 illustrates an idealized representation of a program which progressed according to plan. The abscissa is usually time, the ordinate can be weight, power, dollars, etc. The curve shown is the one which best fits the plot of data points (indicated by x's) versus time.

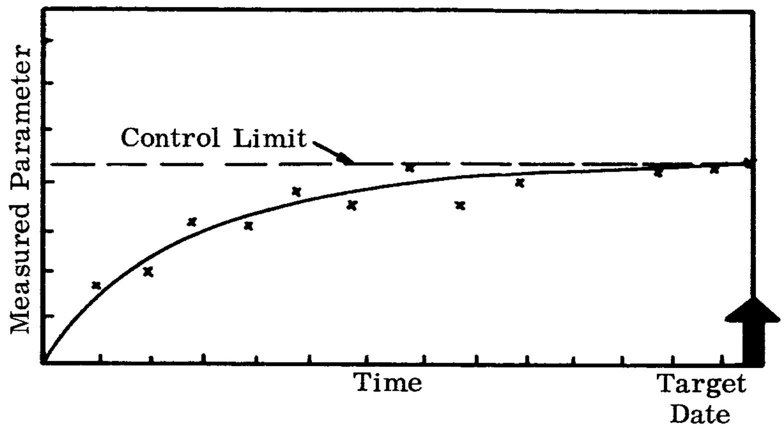


Figure 5-1. Program Status Presentation Idealized Program

Figure 5-2 represents an actual progress report at some stage in a program. The solid line represents the reported values plotted versus time. The dotted line is the trend line, and in this illustration it predicts that the parameter will exceed its control limit before the target date. Charts of this type are used to transmit FAME information to management.

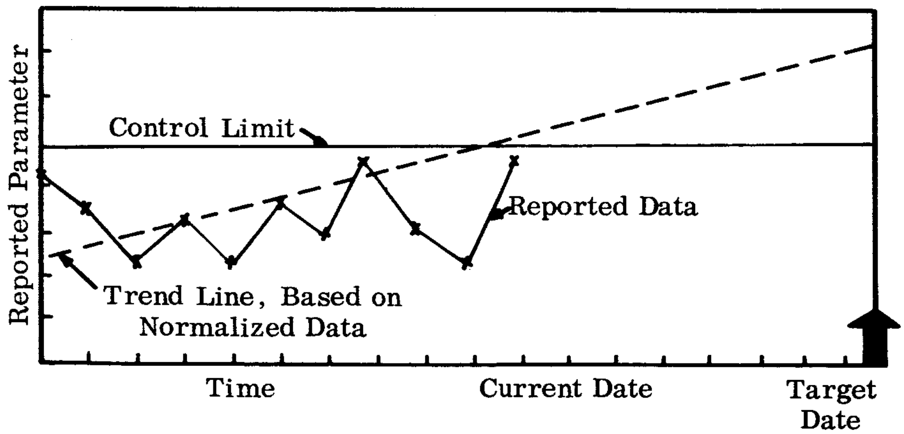


Figure 5-2. Program Status Presentation Representative Program

An additional report to management, shown in Figure 5-3, pinpoints specific problems and indicates the degree of criticality. In this illustration current and predicted expenditures are shown in relation to budgeted amounts.

Expenditures versus Budget				Required Buy-off
Item	Budget	Current Expend.	Predicted	
Mark B	32.5	25.9	30.6	0
Mark C	33.9	30.4	42.6	8.7
Mod. I	20.1	19.6	25.1	5.0
Mod. IV	22.2	16.7	20.9	0

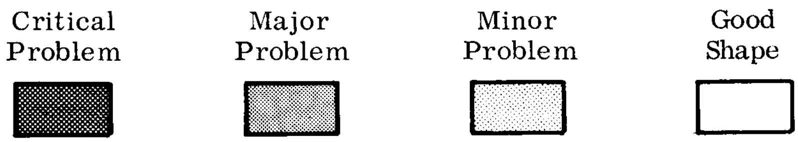


Figure 5-3. One Method for Indicating Criticality by Use of Shaded Areas

In many cases established control limits are based upon capabilities which may change during the course of the program. Figure 5-4 shows two plots of reported values over some time period. Line A, which, let us say, is power source capability shows progress related to the Control Limit, which in this illustration represents minimum acceptable capability. Line B, representing total power load, rises throughout the program, perhaps necessitating an increased control limit, but in any case diminishing the criticality of a possible increased demand for electrical power relative to forecasted capability.

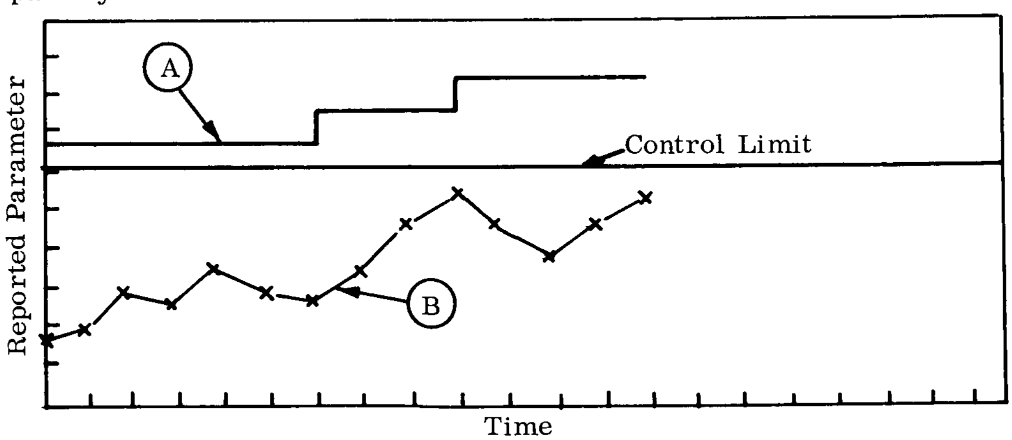


Figure 5-4. Graphic Illustrations for Program Visibility

The graphic devices used to provide visibility for program managers can very in accordance with the particular needs of a specific program. The essential requirement is, of course, to utilize graphics which are easily read, accurate, and timely. The remainder of this section describes how these requirements are met for weight/performance control of a major aerospace program.

For Apollo weight/performance control, the report to management is a monthly publication entitled Apollo Space Vehicle Weight/Performance Forecast and Analysis Status Transmittal Report (U) (FAST), internally referred to as "the PAM." This publication presents weight/performance comparisons down to the stage and module level. Once every three months current and forecast status are presented down to the functional system level. Summary charts are used to present for each space vehicle a composite picture of current weight/performance relationships, forecasts relationships, required buyoffs, criticalities, and possible trade-offs with cost, schedules, and reliability.

To assure maximum utilization, the FAST is divided into three volumes which are separately routed to top management, system managers, and section chiefs. Needed information is presented in charts, graphs, and tabulations which not only point up current and potential problems but indicate the degree of criticality involved. A detailed description of the FAST follows.

5.2 FORECASTS AND APPRAISALS FOR MANAGEMENT EVALUATION MEMORANDA

The results obtained from Forecast Analysis can be presented in many ways. For the Apollo weight/performance data, the form used in the Forecast and Appraisals for Management Evaluation Memoranda (Acronym FAST). These memoranda graphically present to Apollo program management the predicted values obtained each month from data reported by contractors and the NASA Centers. The monthly issue of FAST presents the current status and predicted values for weight/performance parameters to the stage and module level. Once every three months, current and predicted data are presented down to the functional system level. Summary charts present a composite picture of today's weight/performance status, predicted weight/performance values, and required buyoffs. The summary charts are supplemented by weight/performance deficiency matrices and trade-off summaries for cost, reliability, and schedules. Each space vehicle is described on a status chart. This chart presents first-order mission objectives, engine performance status, summarized weight prediction data, stage and module trade-off factors, and primary weight/performance highlights and problems.

To assure maximum usage at all levels of management, Forecasts and Appraisals for Management Evaluation (U), (FAST) is divided into three volumes. Volume I contains summaries for use by top-level management. Volumes II and III contain launch vehicle and spacecraft weight/performance data respectively in summary and detail form. The latter two volumes are directed primarily to system managers and section chiefs.

5.2.1 VOLUME I - SUMMARY

This volume summarizes in concise fashion the weight/performance status of the Apollo/Saturn space vehicles up to and including the current month. Salient facts are highlighted in summaries and in deficiency and trade-off matrices. Background information is also provided on a vehicle-by-vehicle basis by means of status charts.

5.2.1.1 Weight/Performance Summary Chart

The first data shown in Volume I is the Summary Chart, shown in Figure 5-5. (All numbers shown in figures in this chapter are fictitious.) The summary chart presents current, control, and predicted values of spacecraft weight and launch vehicle payload capability. This chart pinpoints weight/performance trouble spots at the stage and module level, then at the launch vehicle and spacecraft level, and finally at the total space vehicle level. Such a presentation allows management to focus attention on major problems only. The shaded patterns indicate the probable impact of critical vehicle deficiencies on specific missions and on over-all program objectives. Special situations not covered by the established form of the charts are emphasized by adding explanatory notes where needed.

5.2.1.2 Trade-Off Summary Chart

Volume I of the PAM also includes trade-off summary charts, represented in Figure 5-6. All values on this chart are predicted values at the designated shipping date. A weight/performance deficiency is shown in terms of equivalent payload pounds for each launch vehicle and spacecraft. The launch vehicle values represent payload capability, while the spacecraft values represent payload weight. A deficiency with a positive (+) value represents increased payload weight or decreased payload capability and so indicates an unhealthy condition. A negative (-) value indicates a weight reduction or a payload capability increase; both are healthy conditions. The cost shown is an estimate of dollars required to remove, by major hardware redesign, weight deficits in individual stages and modules. These cost estimates are based on stage or module inert weights, not on equivalent payload pounds. The probability of mission success

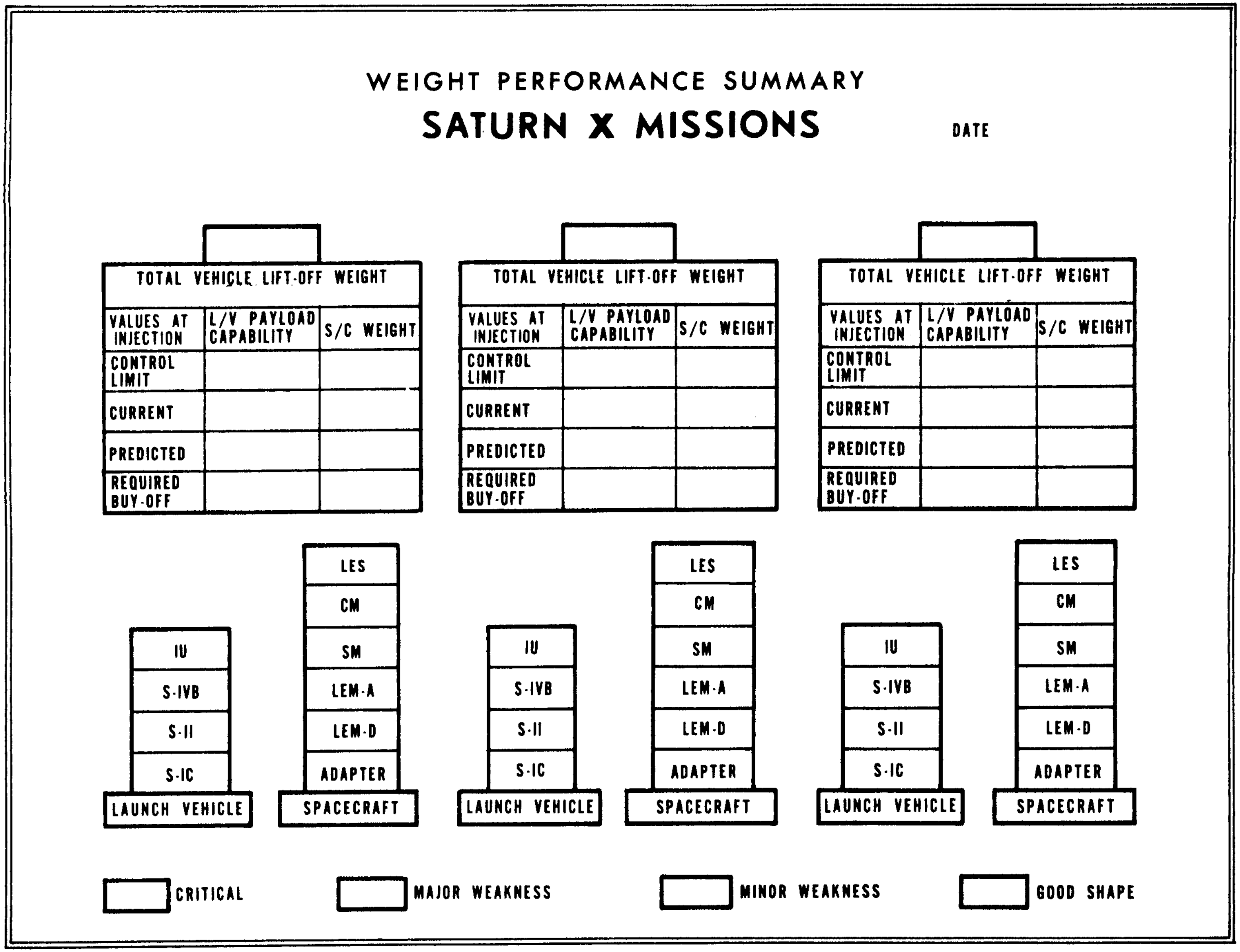


Figure 5-5. A Typical Weight/Performance Summary Chart for Volume I

TRADEOFF SUMMARY

(Positive signs indicate that buyoffs are required, negative signs indicate that values are within control limits)

Saturn X Space Vehicle			Weight/Performance Deficiency Equivalent Payload (pounds)			Cost (Millions of Dollars)			Reliability (Mission Success Probability)			Schedule Change (Months)			Pacing Action Date
LV No.	S/C Numbers CSM	S/C Numbers LEM	LV	S/C	Total Space Vehicle	LV	S/C	Total Space Vehicle	LV	S/C	Total Space Vehicle	LV	S/C	Total Space Vehicle	
															Today
															Aug 75
															July 76
															Sept 67
															Nov 53
															Today

Figure 5-6. A Typical Trade-Off Summary for Volume I

for the launch vehicle, the spacecraft, and the total space vehicle also can be shown. The schedule change column indicates the estimated number of months required to incorporate any predicted weight buyoffs. Schedule change predictions are based on the level of effort currently being expended on each stage or module. The values given do not illustrate program status, but indicate the additional months required to maintain a stage within the control limit. The Pacing Action date shown is the long-range procurement date or "Today," if long-range procurement has already started.

5.2.1.3 Weight/Performance Deficiency Summary Chart

The summary shown in Figure 5-7 gives deficiencies down to the stage and module level. The predicted deficiencies for stages and modules of the launch vehicle and the spacecraft are provided along with current and control limit values for payload capability and spacecraft weight. The deficiencies for launch vehicle stages represent the loss of payload capability caused by weight growth or by performance changes in the individual stages. The spacecraft stage or module deficiencies represent weight growth of the total spacecraft due to weight growth or performance changes in the individual stages or modules. Again, positive deficiencies indicate unhealthy situations; negative deficiencies indicate no corrective action is necessary.

5.2.1.4 Weight/Performance Status Chart

This chart is shown in two halves which face each other in the published memorandum. Both halves are prepared for each space vehicle. In Figure 5-8, first order mission objectives, mission requirements, and mission status are presented, along with weight and performance status information for the launch vehicle and the spacecraft. Brief statements describing primary problems with a specific space vehicle are made. Unusual or outstanding circumstances are discussed briefly. The arrangement of the chart is such that it presents all data necessary for comparison of launch vehicle and spacecraft weight/performance status, on both a current and a predicted basis.

The other half of the weight/performance status chart is shown in Figure 5-9. This chart presents the various trade-off factors associated with each stage and module, plus a graphic portrayal of the weight growth prediction for launch vehicle capability and spacecraft weight. The plot on this chart illustrates the weight/performance interface between the launch vehicle and the spacecraft and tells what its status is now and will be later. Schedule data is shown at the top of the plot for launch vehicles and at the bottom for spacecraft.

WEIGHT/PERFORMANCE DEFICIENCY SUMMARY

(Positive signs indicate that buyoffs are required, negative signs indicate that values are within control limits)

Saturn V Space Vehicle						Predicted Deficiency											
	S/C Numbers					Launch Vehicle Equivalent Payload (lb)					Spacecraft Equivalent Spacecraft Weight (lb)						
LV No.	CSM	LEM	Current LV Cap	Control Limit	Current S/C Weight	S-IC	S-II	S-IVB	IU	Total LV	CM, SM and Adapter	LES	Total NAA S/C	LEM A	LEM D	Total LEM	Total S/C

Figure 5-7. A Typical Weight/Performance Deficiency Summary for Volume I

WEIGHT/PERFORMANCE STATUS

LV No. ____________
CSM No. ____________
LEM No. ____________

DATE: ____________
MISSION TYPE: ____________
MONTHS TO LAUNCH: ____________

FIRST ORDER MISSION OBJECTIVES	MISSION REQUIREMENTS	MISSION STATUS

LAUNCH VEHICLE					CONTROL LIMITS			SPACECRAFT				
ENGINE ISP		ISP CHANGE IN TERMS OF LBS PAYLOAD	STAGE	WEIGHT TREND LBS PAYLOAD/MO	LV CAP	LES WT	S/C WT	WEIGHT TREND LBS PAYLOAD/MO	STAGE	ISP CHANGE IN TERMS OF LBS PAYLOAD	ENGINE ISP AT VACUUM	
REQM'T	STATUS										REQM'T	STATUS
					CURRENT STATUS							
					LV CAP	LES WT	S/C WT					
					PRIMARY PROBLEMS							

HIGHLIGHTS

Figure 5-8. A Typical Weight/Performance Status Chart (First Half) for Volume I

WEIGHT/PERFORMANCE STATUS

DATE: ______________

LV No. ______________
CSM No. ______________
LEM No. ______________

MISSION TYPE: ______________
MONTHS TO LAUNCH: ______________

LAUNCH VEHICLE TRADEOFF FACTORS						SPACECRAFT TRADEOFF FACTORS					
		PERFORMANCE	COST*	SCHEDULE	RELIABILITY			PERFORMANCE	COST*	SCHEDULE	RELIABILITY
STAGE	LBS/LB PAYLOAD	LBS PAYLOAD/ PERF	$$/LB	LBS PAYLOAD/ (NO.) MO	LBS PAYLOAD/ % RELIB	STAGE OR MODULE	LB of S/C per LB	LBS PAYLOAD/ PERF	$$/LB	LBS PAYLOAD/ (NO.) MO	LBS PAYLOAD/ % RELIB
S-IC Sep.											
S-IC/S-II Interstage											
S-II Sep.											
S-II/S-IVB Interstage											
S-IVB Sep.											
IU											

LAUNCH VEHICLE/SPACECRAFT PREDICTIONS

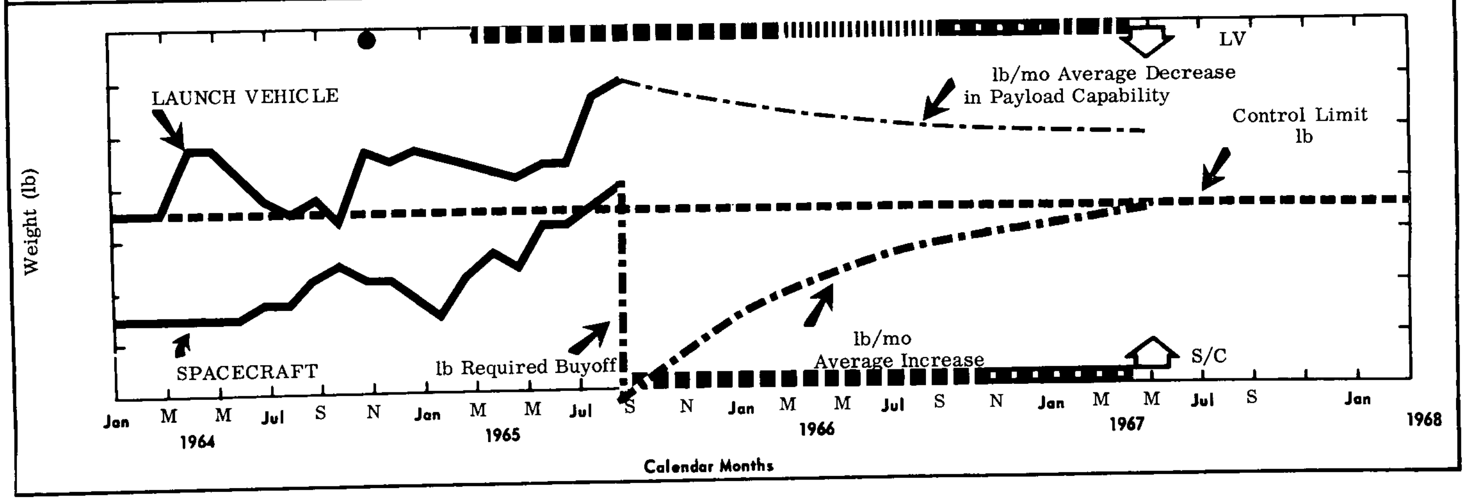


Figure 5-9. A Typical Weight/Performance Status Chart (2nd Half) for Volume I

5.2.2 VOLUME II - LAUNCH VEHICLES

This volume presents, in a concise fashion, the weight/performance status of the Saturn IB and Saturn V launch vehicles. Also presented are Forecast Analysis results for the complete launch vehicles, their individual stage and modules, and typical first-level functional systems. The weight/performance facts are set forth in convenient prediction charts and numerical matrices. The prediction charts reflect predicted weight values, authorized weight buyoffs, propulsion system performance changes, and required buyoffs. The numerical matrices include trade-off factors for weight/performance, cost, schedule, and reliability, as well as weight/performance deficiencies.

5.2.2.1 Weight/Performance Summary Chart

The weight/performance summary chart, Figure 5-10, is the first presentation of data in Volume II. This chart is very similar to the weight/performance summary chart described in paragraph 5.2.1.1 except that it only goes as high as the launch vehicle level.

5.2.2.2 Trade-Off Summary Chart

Trade-off summary charts (Figure 5-11) are used in Volume II to present data on the cost, reliability, and schedule aspects of weight/performance deficiencies. This chart is similar to the trade-off summary chart described in paragraph 5.2.1.2, but gives deficiencies and trade-off data at the stage and module level and includes both weight deficits and performance deficits.

5.2.2.3 Weight/Performance Deficiency Summary Chart

In Volume II, the weight/performance deficiency summary chart (Figure 5-12) gives deficiencies for launch vehicle stages and modules. The values are given in terms of both inert weight and equivalent payload weight. They represent the loss of payload capability caused by weight growth. Loss of payload capability due to performance changes in the individual stages is also shown.

5.2.2.4 Launch Vehicle Payload Capability Plot

The many aspects of the launch vehicle payload capability are presented in launch vehicle payload capability plots (Figure 5-13). Each plot consists of a computer printout or history plot upon which is mounted a stage and module Prediction Analysis summary form which gives a complete picture of the status and predictions for a particular launch

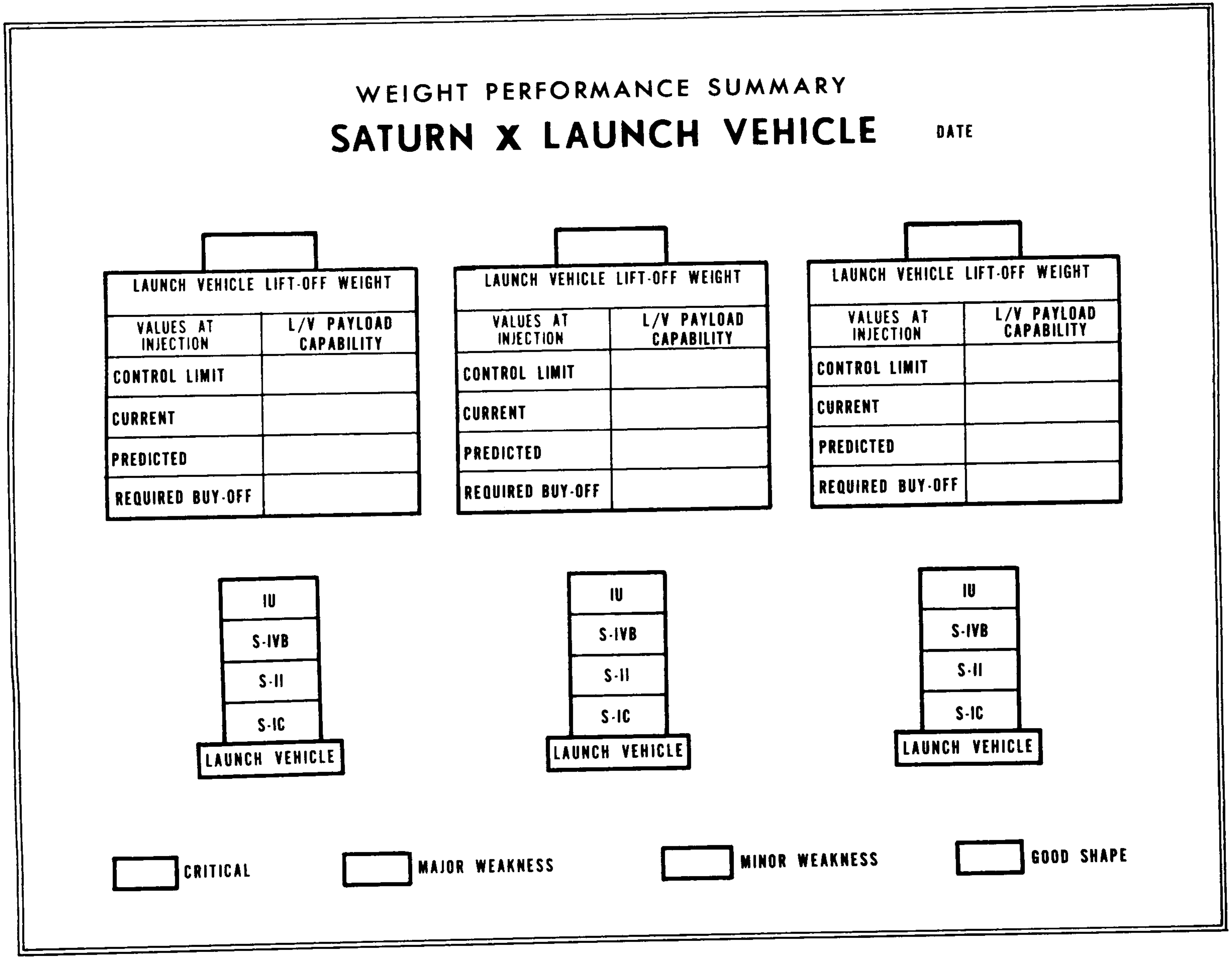


Figure 5-10. A Typical Weight/Performance Summary Chart for Volume II

SATURN X TRADEOFF SUMMARY

(Positive signs indicate that buyoffs are required, negative signs indicate that values are within control limits.)

Saturn X Launch Vehicle		Weight/Performance Deficiency Equivalent Payload (Pounds)			Cost (Millions of Dollars)			Reliability (Mission Success Probability)			Schedule Change (Months)			Pacing Action Date
Mission No.	Stage or Module	Weight Deficit	Perf. Deficit	Total	Weight Deficit	Perf. Deficit	Total	Weight Deficit	Perf. Deficit	Total	Weight Deficit	Perf. Deficit	Total	
	S-IA													
	S-IIB													
	S-VG													
	IU													
	Total LV													
	S-IA													
	S-IIB													
	S-VG													
	IU													
	Total LV													

Figure 5-11. A Typical Trade-Off Summary for Volume II

SATURN X WEIGHT/PERFORMANCE DEFICIENCY SUMMARY

(Positive signs indicate that buyoffs are required, negative signs indicate that values are within control limits)

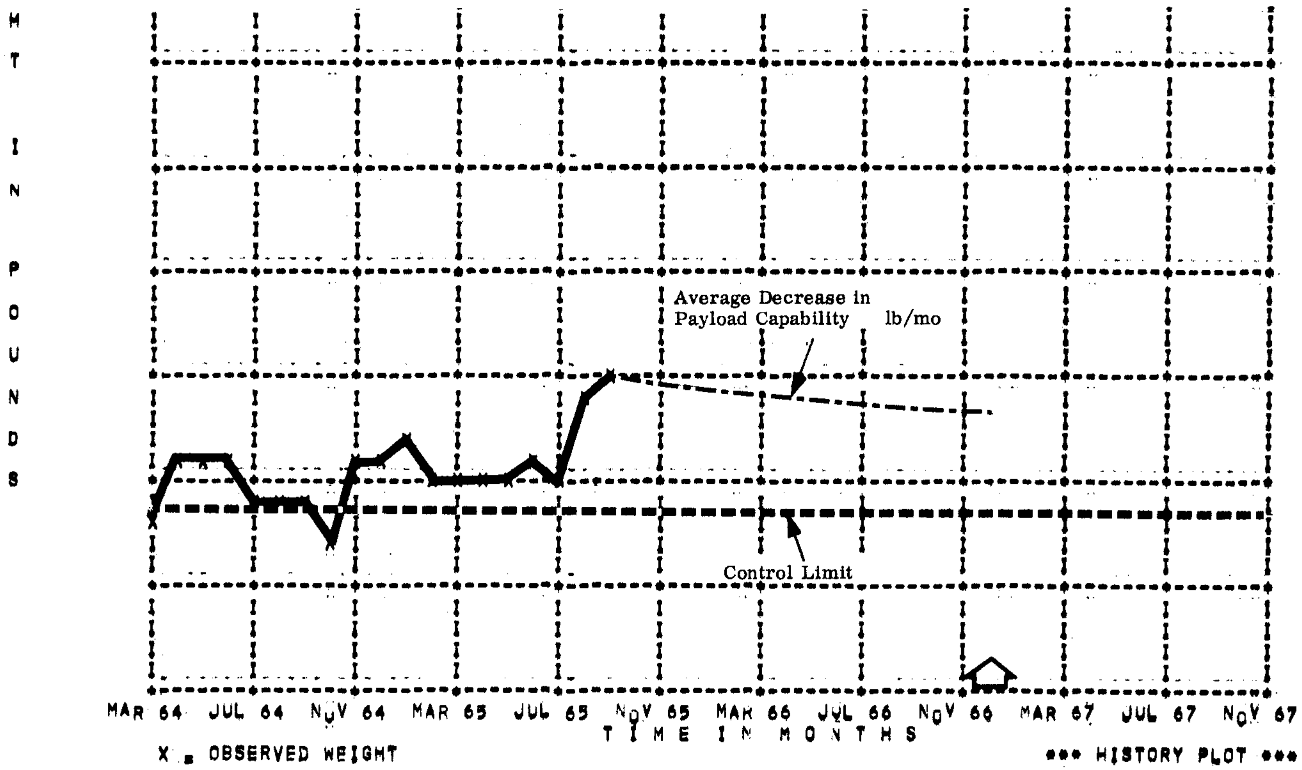
Saturn X Launch Vehicle				Predicted Deficiency										Total Performance Variation		
					S-IA		S-IIB		S-VG		IU		S-IA	S-IIB	S-VG
Mission	Current Payload Capability	Control Limit	Predicted Payload Capability	Total Launch Vehicle	Inert Wt.	Equiv. Payload	Inert Wt.	Equiv. Payload	Inert Wt.	Equiv. Payload	Inert Wt.	Equiv. Payload	Equiv. Payload	Equiv. Payload	Equiv. Payload

Figure 5-12. A Typical Weight/Performance Deficiency Summary for Volume II

PREDICTION ANALYSIS TECHNIQUE • SATURN X LAUNCH VEHICLE SA307 • CASE NUMBER • DATE • REQUIRED BUYOFF LB
HISTORY PLOT • LAUNCH VEHICLE • 5200500 • INPUT TAPE • EQUIVALENT S/C OR L/V
COMPUTER PROGRAM 61S • PAYLOAD • FILE STATUS NO • DEFICIT LB

Mission 307 Launch Vehicle Stages	Current Weight (Lb)	Control Weight (Lb)	Avg. Weight Growth (Lb/Mo)	Predicted at Launch: Weight (Lb)	Predicted at Launch: Probable Error (1)	Required Buyoff (Lb)	Sched Ship Date	Weight Changes Reported This Date: Auth	Pend	Poten	Prop
Total LV											
S-IC Separation											
S-IC/S-II Interstage											
S-II Separation											
S-II/S-IVB Interstage											
S-IVB Separation											
IU at Ground Ignition											

(1) One chance in 20 that the Probable Error will be exceeded.



DATE	WEIGHT EST	CAL	ACT
MAR 64			
APR 64			
MAY 64			
JUN 64			
JUL 64			
AUG 64			
SEP 64			
OCT 64			
NOV 64			
DEC 64			
JAN 65			
FEB 65			
MAR 65			
APR 65			
MAY 65			
JUN 65			
JUL 65			
AUG 65			
SEP 65			

Figure 5-13. A Typical Launch Vehicle Payload Capability Plot for Volume II

vehicle at the stage and module level, as well as current, control limit, and predicted values, growth rates and required buyoffs. Four classes of weight change are reported: authorized, pending, potential, and proposed.

5.2.2.5 Stage and Module Prediction Chart

This chart (Figure 5-14) gives the results of Forecast Analysis for each stage and module of each launch vehicle. It consists of a computer printout (history plot) upon which is mounted a summary of the functional system data for the stage or module. For purposes of comparison weight and growth rates from the previous month are also shown.

5.2.2.6 Functional System Prediction Data

The final form of data presentation in Volume II involves the functional system data. Once every three months additional books of Volume II are published which contain tabulations of data and computer printouts of every functional system involved in the Forecast Analysis calculations. These tabulations and printouts are illustrated in Figures 5-15 and 5-16.

5.2.3 VOLUME III - SPACECRAFT

This volume presents the weight/performance status and the results of Forecast Analysis for the spacecraft. It is entirely similar in form and make-up to Volume II, just described in the preceding paragraphs. The only difference between the two volumes is that Volume II discusses or presents launch vehicle payload capability while Volume III presents the total spacecraft weight (at injection). Volume III, of course, also presents data on spacecraft stages and modules rather than launch vehicle stages and modules. Since the two volumes are so similar, a detailed discussion of Volume III is not necessary.

5.3 INTEGRATED WEIGHT/ PERFORMANCE STATUS AND ANALYSIS

5.3.1 GENERAL DISCUSSION OF THE "STATUS AND ANALYSIS" DOCUMENT

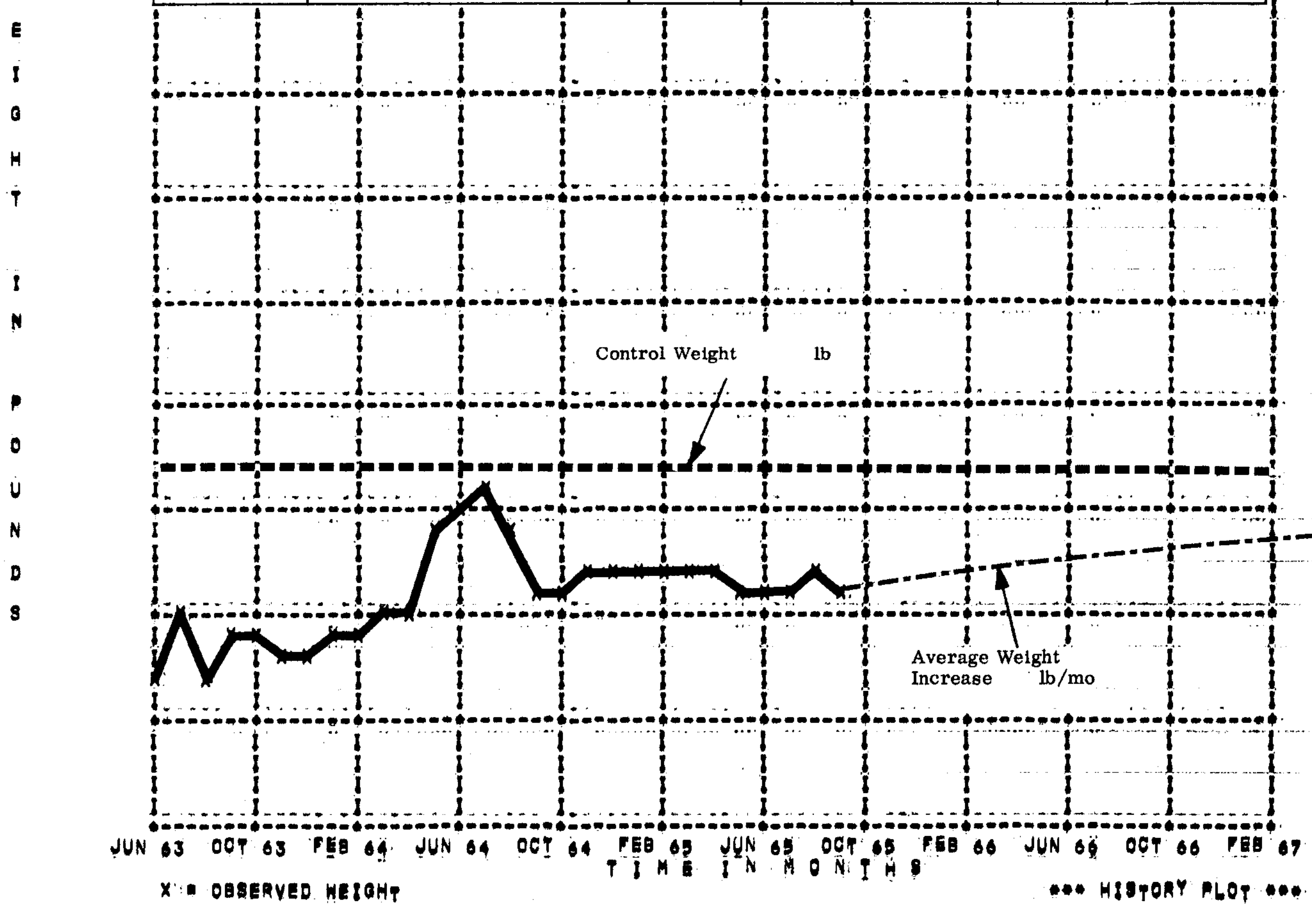
The Apollo Space Vehicles Integrated Weight/Performance Status and Analysis (U), is a document prepared and published in the interim between issues of the Forecast Analysis Memoranda. It presents only the most salient facts of the latest Apollo weight/performance developments. Issued each month, as soon as possible after receipt of current data from the individual contractors, the document is published

PREDICTION ANALYSIS TECHNIQUE
HISTORY PLOT
COMPUTER PROGRAM 61S

CASE NUMBER 5611200
DATE
INPUT TAPE
FILE STATUS NO.

REQUIRED BUYOFF LB
EQUIVALENT S/C OR L/V
DEFICIT LB

Stage	System	System Current Weight (lb)	Predicted Weight (lb)	System Average Weight Growth (lb/mo)	System Weight Last Month (lb)	System Average Weight Growth Last Month (lb/mo)
S-IC Stage at Separation	Structure Propulsion System Equipment and Instrumentation Residual and Reserve Propellant Total					



DATE	WEIGHT	EST	CAL	ACT
JUN 63	349430	59	30	11
JUL 63	354402	54	35	11
AUG 63	348059	39	49	12
SEP 63	353799	37	51	12
OCT 63	352262	38	50	12
NOV 63	350403	38	50	12
DEC 63	350976	34	54	12
JAN 64	352964	34	54	12
FEB 64	353352	34	54	12
MAR 64	354416	34	54	12
APR 64	354728	26	62	12
MAY 64	362450	25	60	15
JUN 64	365615	27	61	12
JUL 64	366576	28	60	12
AUG 64	363903	28	60	12
SEP 64	357364	27	61	12
OCT 64	357830	26	61	13
NOV 64	358439	25	60	15
DEC 64	358470	24	58	18
JAN 65	358710	23	59	18
FEB 65	358758	24	49	27
MAR 65	358521	24	49	27
APR 65	358456	24	49	27
MAY 65	357948	24	42	34
JUN 65	357812	23	55	22
JUL 65	357634	23	54	23
AUG 65	358310	23	54	23
SEP 65	357861	22	54	24

Figure 5-14. A Typical Stage Prediction Chart for Volume II

PREDICTION ANALYSIS TECHNIQUE
FOURIER MODEL
COMPUTER PROGRAM 58S

PROPULSION SYSTEM

CASE NUMBER: 5650104
DATE
INPUT TAPE
FILE STATUS NO.

REQUIRED BUYOFF LB
EQUIVALENT S/C OR L/V DEFICIT LB

MONTH	.... OBSERVED DATA .... WEIGHT (LB)	PERCENT EST	PERCENT CAL	PERCENT ACT	OBSERVED NONRANDOM CHANGES (LB)	OTHER NONRANDOM CHANGES (LB)	... NORMALIZED DATA ... WEIGHT (LB)	PERCENT EST	PERCENT CAL	PERCENT ACT	MEAN TREND VALUE (LB)	UPPER 95 PCT. CONF. LIM. (LB)	AVERAGE WEIGHT GROWTH (LB/MO)
JUN 63	5688	48	30	22	0	0	6382				6382		
JUL 63	5688	48	30	22	0	0	6382				6412		
AUG 63	6796	70	30	0	-181	-864	6444				6442		
SEP 63	6668	70	30	0	0	0	6316				6472		
OCT 63	6550	60	40	0	145	0	6343				6503		
NOV 63	6470	70	30	0	92	0	6355				6533		
DEC 63	6482	70	30	0	0	0	6367				6563		
JAN 64	6585	60	40	0	0	0	6470				6593		
FEB 64	6746	60	40	0	-143	0	6488				6623		
MAR 64	6801	40	60	0	0	0	6543				6654		
APR 64	6855	30	70	0	0	0	6605				6684		
MAY 64	6865	23	33	44	0	0	6615				6714		
JUN 64	6912	20	34	46	0	0	6662				6744		
JUL 64	7084	21	33	46	0	0	6834				6774		
AUG 64	7106	21	33	46	0	0	6856				6804		
SEP 64	7143	34	14	52	0	0	6893				6835		
OCT 64	7191	21	24	55	0	0	6941				6865		
NOV 64	7114	17	30	53	0	0	6864				6895		
DEC 64	6944	19	28	53	211	0	6905				6925		
JAN 65	6946	19	17	64	0	0	6907				6955		
FEB 65	6993	18	17	65	32	0	6986				6986		
MAR 65	6965	18	12	70	-3	0	6955				7016		
APR 65	7158	18	9	73	9	0	7157				7046		
MAY 65	7129	18	10	72	1	0	7129				7076		
JUN 65	7120	17	9	74	0	0	7120				7106		
JUL 65	7153	17	9	74	0	0	7153				7137		
AUG 65	7199	17	9	74	0	0	7199				7167		
SEP 65	7197	18	8	74	0	0	7197				7197		30
.... PREDICTED VALUES													
OCT 65	7227	17	8	75			7227				7227	7334	30
NOV 65	7257	16	7	76			7257				7257	7408	30
DEC 65	7288	16	7	77			7288				7288	7473	30
JAN 66	7318	15	7	78			7318				7318	7531	30
FEB 66	7348	14	6	79			7348				7348	7587	30
FINAL PREDICTED VALUES													
SEP 67	7922	0	0	100			7922				7922	8445	0

Figure 5-15. A Typical Functional System Data Tabulation for Volume II

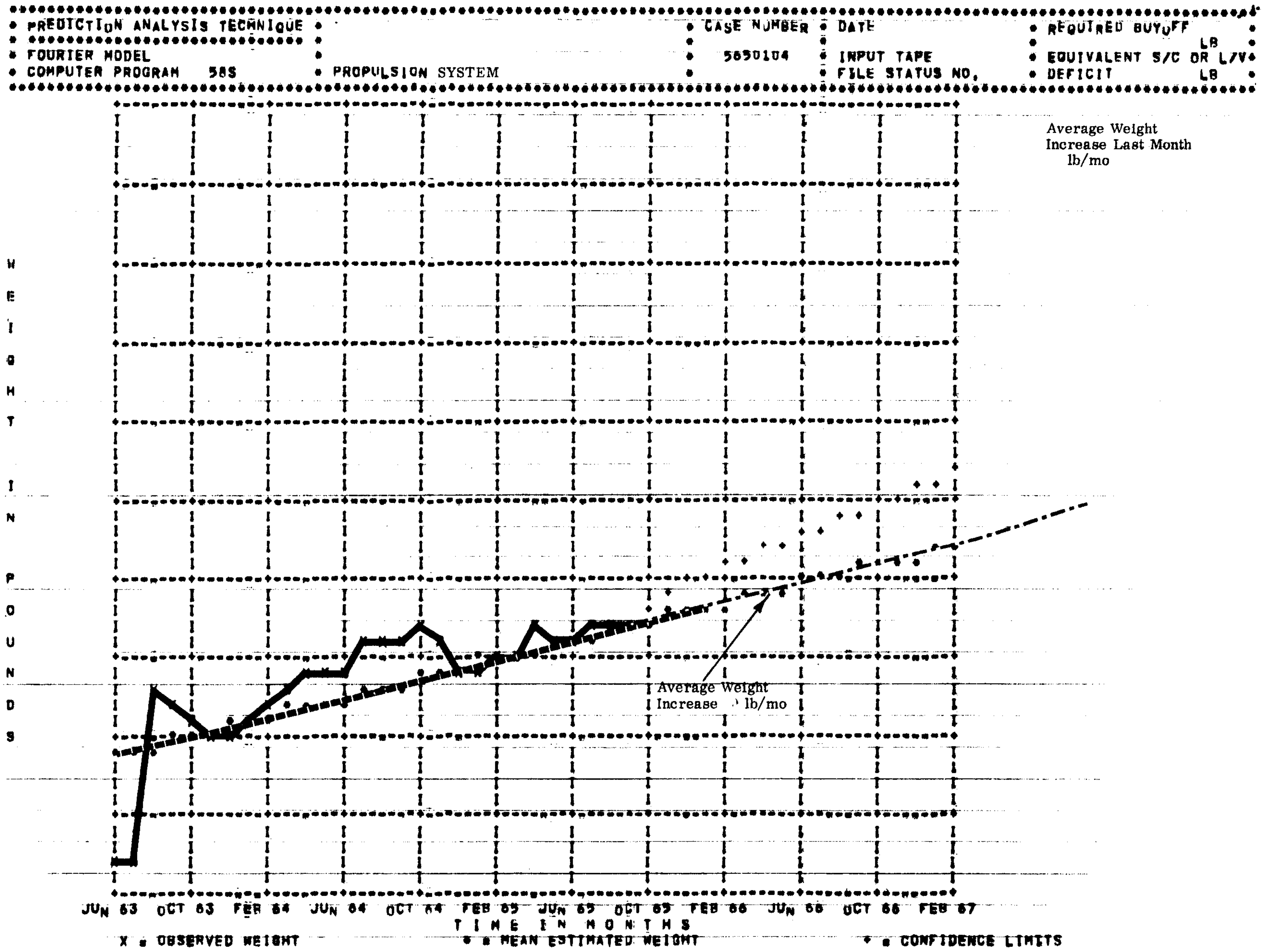


Figure 5-16. A Typical Functional System Plot for Volume II

prior to the completion of the Forecast Analysis computer runs which form the basis for the detailed Forecast Analysis Memorandum.

5.3.2 PURPOSE AND PREPARATION OF THE "STATUS AND ANALYSIS" DOCUMENT

The primary purpose of the "Status and Analysis" document is to give on a quick response basis a clear, concise, and integrated summary of the current Apollo/Saturn mission-by-mission status, together with an approximate analysis of probable future trends. In the interest of time no effort is made to incorporate the newly received data into the prediction trends. Instead, predictions are made by taking the current data points and using them to project the previous month's growth rates. This method gives a fairly good approximation to the true prediction because the latest point generally has a relatively minor effect on the growth rate when incorporated into a prediction already based on a large number of history points.

5.3.3 DESCRIPTION OF THE "STATUS AND ANALYSIS" DOCUMENT

The Apollo Space Vehicles Integrated Weight/Performance Status and Analysis (U) document briefly summarizes the weight/performance analysis of the complete spacecraft, and the over-all launch vehicle payload capability required to accomplish the specified mission. Details and analyses of second generation mission components are purposely omitted and left to the more extensive Forecast Analysis Memorandum. The "Status and Analysis" document consists primarily of three parts, the introductory letter, the trade-off summary, and the weight/performance summary. Each part is designed for a specific function.

The introductory letter tells the purpose and intent of the document and refers to the source of a more detailed analysis, if desired. The trade-off summary (Figure 5-18) shows the weight/performance deficiency for the spacecraft, the launch vehicle and the over-all mission. It interprets the deficiencies in terms of probable cost, loss of reliability, and schedule changes which may be involved in their elimination. Areas of particular interest and importance are outlined by notes under "Highlights and Problem Areas," as a supplement to the trade-off summary.

The weight performance summary (Figure 5-19) identifies the type of mission to be accomplished and gives the current, control limit, and forecast values for both spacecraft weight and launch vehicle capability. The entire history and forecast lines for spacecraft weight and launch vehicle payload capability are plotted versus time, along

SATURN X TRADE-OFF SUMMARY

(Positive signs indicate that buyoffs are required, negative signs indicate that values are within control limits)

Space Vehicle			Weight/Performance Deficiency Equivalent Payload (pounds)			Cost (Millions of Dollars)			Reliability (Mission Success Probability)			Schedule Change (Months)			Pacing Action Date
LV No.	S/C Numbers CSM	S/C Numbers LEM	LV	S/C	Total Space Vehicle	LV	S/C	Total Space Vehicle	LV	S/C	Total Space Vehicle	LV	S/C	Total Space Vehicle	

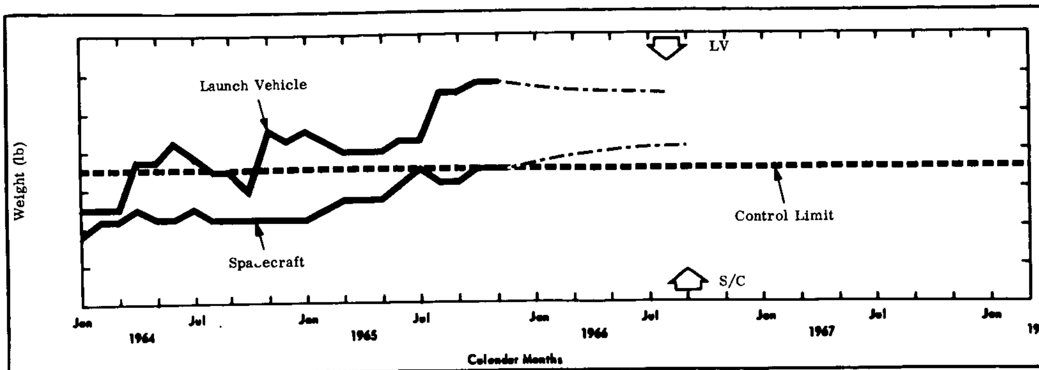
HIGHLIGHTS AND PROBLEM AREAS

- Weight reduction programs are underway at GAEC and NAA. Initial results of these programs are reflected in a 12 lb. reduction in the LEM separation weight and a 283 lb. decrease in the LOR spacecraft injected weight.
- The Block II service module current weight exceeds its control weight. Weight reduction measures to offset this growth trend are being studied.

Figure 5-18. Typical Overall Summary Tabulation

WEIGHT PERFORMANCE SUMMARY

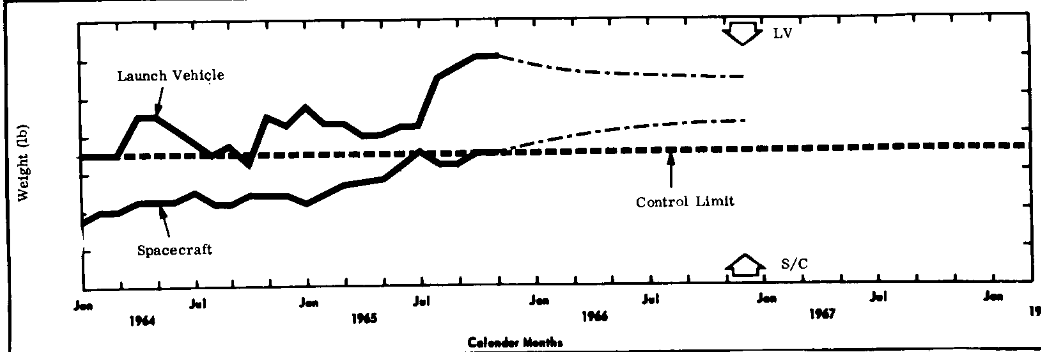
SATURN x MISSIONS



VALUES AT INJECTION	L/V PAYLOAD CAPABILITY	S/C WEIGHT
CONTROL LIMIT		
CURRENT		
PREDICTED		

LV No. ______
CSM No. ______
LEM No. ______

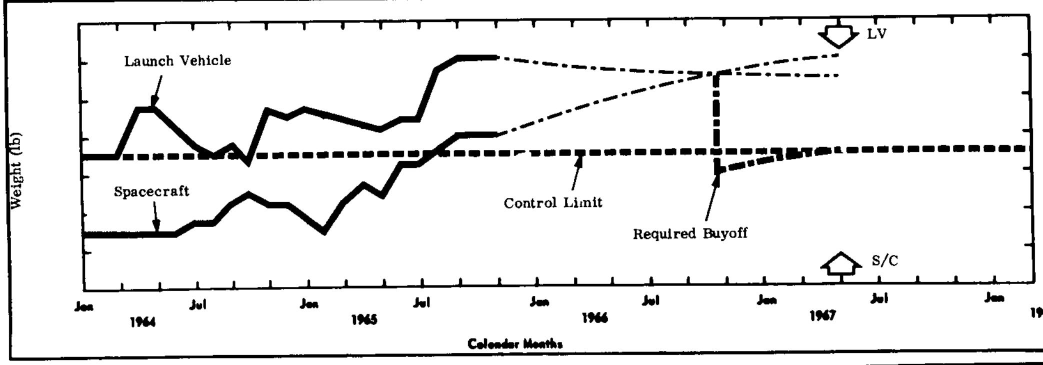
MISSION TYPE: ______
MONTHS TO LAUNCH: ______



VALUES AT INJECTION	L/V PAYLOAD CAPABILITY	S/C WEIGHT
CONTROL LIMIT		
CURRENT		
PREDICTED		

LV No. ______
CSM No. ______
LEM No. ______

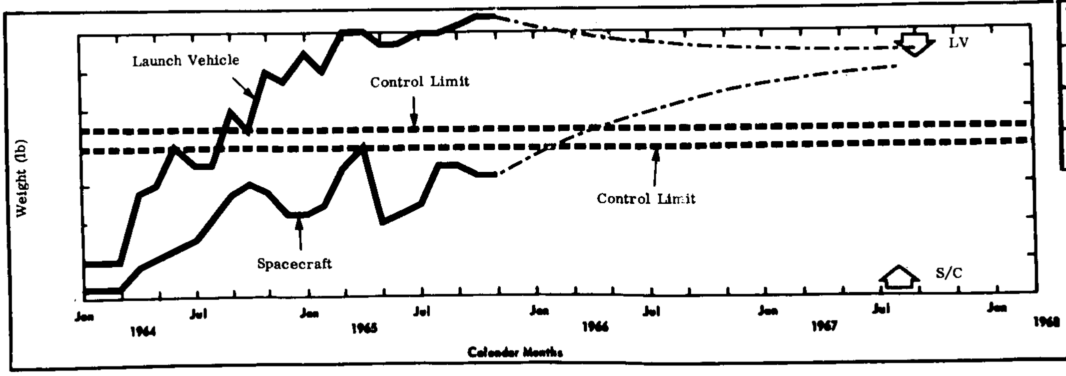
MISSION TYPE: ______
MONTHS TO LAUNCH: ______



VALUES AT INJECTION	L/V PAYLOAD CAPABILITY	S/C WEIGHT
CONTROL LIMIT		
CURRENT		
PREDICTED		

LV No. ______
CSM No. ______
LEM No. ______

MISSION TYPE: ______
MONTHS TO LAUNCH: ______



VALUES AT INJECTION	L/V PAYLOAD CAPABILITY	S/C WEIGHT
CONTROL LIMIT		
CURRENT		
PREDICTED		

LV No. ______
CSM No. ______
LEM No. ______

MISSION TYPE: ______
MONTHS TO LAUNCH: ______

Figure 5-19. Typical Mission Summary Plots with their control limits. The forecast lines are extended out to the shipping dates of the spacecraft and launch vehicle. This graph shows not only the relation of the units to their control limits, but also their relation to each other. Areas are highlighted where future trade-offs might profitably be considered.

5.4 OTHER TYPES OF OUTPUTS

5.4.1 INTRODUCTION

Publication of the Forecast Analysis Memoranda and the integrated weight/peformance status and analysis requires the compilation and integration of a large amount of data. A long working involvement with this data and component relationships of the Apollo missions leads to insights into facets of the weight/performance area that suggest the need for a special analysis of an area of interest of the generation of a report on a particular aspect of the mission. Examples of such special applications follow.

5.4.2 INDIVIDUAL VEHICLE/STAGE/DRY WEIGHT SUMMARIES

Many of the inert weights used in the analysis of mission capabilities and performance include a certain amount of fluids in the form of residual and reserve propellants. Certain types of studies, however, require a knowledge of the dry (or hardware) weights of individual stages and modules. For example, an analysis may be made of production costs in relation to total hardware weight. The Dry Weights Report (Figures 5-20 and 5-21) fills this need by listing total hardware weights for the stages and modules of each mission.

5.4.3 SUMMARY BY DESIGN RESPONSIBILITIES FOR PROGRAM CONTROL

The Apollo Program Control Office has final responsibility for coordinating and controlling individual contractor performance on the program. Contractors are held to rigid weight control specifications. It is necessary that program control be made aware at the earliest possible time of any deviations or of any trend that may indicate future deviation. Therefore, the stages and modules are summarized by design responsibility in the Dry Weights Report. Notes are used in the FAST to serve the same function, particularly in those areas which seem headed for trouble.

5.4.4 SPECIFIC AREA COMPARISON - INTERFACE CHARTS

Reporting and trending individual components of a complex and integrated system does not give the whole story without a presentation of the relation between those components.

Manufacturer	Module	Block I	Block II
NAA	Command Module*		
NAA	Service Module*		
Total			
GAEC	LEM Ascent		
GAEC	LEM Descent		
Total			
NAA	Adapter		
NAA	Launch Escape System**		

Figure 5-20. Spacecraft Dry Weights Summary

Manufacturer	Launch Vehicle Stage	Mission			
Boeing	S-1A Stage				
NAA	S-1A/S-II Interstage				
NAA	S-II Stage				
Total					
Douglas	S-II/S-IVB Interstage				
Douglas	S-IVB Stage				
Total					
IBM	Instrumentation Unit				

Figure 5-21. Launch Vehicle Dry Weights Summary

This need is met in part by interface charts. The function of the interface chart is to present the components of a system as integrated whole rather than as individual stages and modules plotted against their specified control limit as isolated cases. These charts display the capability of each system to perform its specified function.

To show the importance of this interface data the following questions might be asked. Is the S-IB stage of the SA-504 launch vehicle capable of achieving the necessary velocity to perform its function considering its own weight plus the weight of the stages and modules it must carry? Is the LEM-Descent stage capable of performing its specified mission in light of the fact that the LEM-Ascent stage, which is must carry to the lunar surface, is predicted to exceed its control limit? Does the predicted capability requirement for any stage indicate a need for more propellant than its tanks will hold?

An integrated picture is achieved by plotting the forecasted capability of each component against the trend of the total requirement. The point at which these lines cross (i.e., the point at which the requirements exceed the capability) indicates a potential source of problems. These plots may also reveal possible trade-offs. For instance, even though a system may not meet its control limit value or may not be capable of meeting the capability specified for it, it is possible that the requirements are not as rigorous as supposed or specified. In this case, an analysis should be made to determine if a trade-off is possible.

5.4.5 WEIGHT DATA COMPILATION

One of the most useful results of Forecast Analysis is the Weight Data File. This file is a by-product of the Forecast Analysis effort and is not issued as an official report. Publication of the FAST involves collecting and recording extensive amounts of data over extended periods of time. This data is summarized and stored in one central location, the Weight Data File. This file is simply a printout of the recorded values for each individual component of the Apollo missions. Each component is identified by a code number and the recorded values of that component are listed by month throughout the period of time for which data is available. This data is stored on computer tapes and is printed out each month after the latest data has been added. By this means, the complete history, or the specific value at any point in time, is readily available for any system in question. The Weight Data File makes no attempt at analysis or explanation, but simply serves as a central data collection point and ready reference for recorded and reported data.

5.4.6 NOTES ON PROBLEM AREAS

The presentation of data and the results of calculations in the form of tables, charts, and graphs does not in itself present the complete picture of the problems which may be involved on any Apollo mission. To tie the various components into a comprehensive picture and to present and explain specific problem areas, extensive use must be made of explanatory notes. These notes are another by-product of Forecast Analysis. They may be derived directly from contractor reports or they may be the result of insights gained through processing of reported data. Such notes are a useful and necessary part of the effort to present an effective and comprehensive summary of a system which is as complex and interrelated as the Apollo system.

CHAPTER 6

APPLICATION OF FAME TO OTHER TECHNICAL AREAS

6.1 GENERAL APPLICABILITY

This chapter discusses the application of FAME to areas such as cost, schedule, vehicle performance, and electrical power surveillance. It is suggested that techniques described in this manual may be used wherever the following elements are available:

a. Measurable requirements.

b. Status information flow.

c. Measurable status.

When these three elements are present, patterns of data behavior may be measured and assessed. The measured status compared with measurable requirements forms the basis for forecasting deficiencies which require managerial analysis and action.

Through the Forecast Analysis computational system, which uses elements a, b, and c above, the decision-maker is provided with information in an effective, formal output. The Forecast Analysis computational system considers the relationships, interdependencies and interactions between the elements listed above. These relationships are shown pictorially in Figure 6-1. Historical values of the measured parameters form the basis for forecast values. They also give confidence limits for the predicted values. As a program matures FAME techniques provide consistent data in usable form for managerial action. Thus, by using a formal evaluation program, the gap is closed between the information specialist's capacity to understand the information for assessment and decision making.

6.2 APPLICATION TO COST AND SCHEDULE MONITORING

Launch vehicle or spacecraft weight growth is usually paralleled by increased expenditures and schedule modifications. It seems apparent that a FAME system can be devised for cost and schedule control by utilizing the same basic approach now in effect for weight control. FAME offers several advantages not provided by present methods of control. This section discusses the basic requirements for instituting a FAME system for cost and schedule control to obtain these advantages.

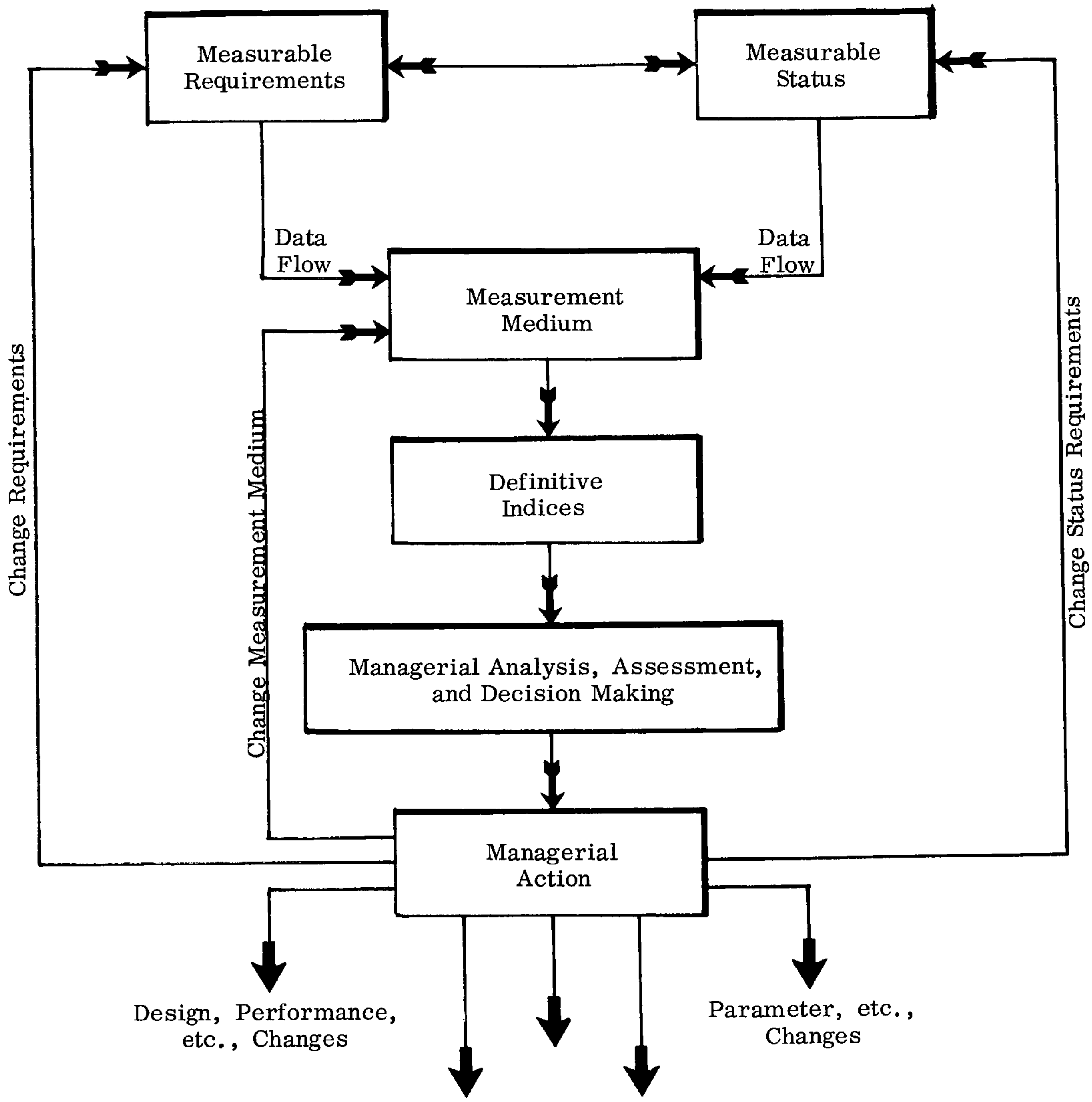


Figure 6-1. FAME Computational System Elements

6.2.1 THE IMPORTANCE OF COST AND SCHEDULE MONITORING TO MANAGEMENT CONTROL

During a development program of any type, management control is particularly important in the area of program cost and schedule. Budgets, profits, and reputations are all sensitive to the ability of management to meet schedule and cost commitments. Money is supposedly spent at allocated rates during the progress of a program. Similarly, schedule milestones are established to set and measure the program's pace. If, at some point in time, progress begins to lag in a certain area, schedules begin to slip and invariably costs will mount. Any delay in pointing out such problem areas to management permits additional slip and involves greater expenditure. Once alerted, management can initiate corrective action immediately. But harm has already been done, for money once spent cannot be "unspent" -- at least not without degrading equipment quality elsewhere. Schedule slips usually can be made up, but only if sufficient funds are available. The problem thus becomes a multi-parameter trade-off.

6.2.2 PRESENT COST AND SCHEDULE TECHNIQUES

For the analysis of cost and schedule performance, it is necessary to organize a means for obtaining necessary data. Several excellent program management techniques are presently available which provide the necessary data. These can be roughly classified as control or forecasting techniques. A brief look at some of these techniques will help determine what information is or is not presently available to management.

Probably the most widely accepted and successful means for controlling schedules and costs in PERT (Program Evaluation and Review Techniques). PERT permits accurate planning, indicates current progress, and provides a certain degree of advance warning for potential trouble areas. This technique is especially applicable to non-repetitive operations such as construction and development programs. However, the objective in most development programs is to produce a product which is competitively superior in three respects; cost, delivery time, and quality or reliability. PERT aids mainly in meeting delivery dates. It has little effect on cost and quality factors. PERT is an excellent tool for realistic, advanced planning of program schedules. It provides an adequate means of monitoring schedule progress. It can also point out potential weaknesses. However, a FAME system can draw attention to schedule problems at an earlier point in time, thus improving management control.

A more serious need for control exists in the area of cost. PERT does not provide an early indication of increasing cost trends. FAME on the other hand, offers the same distinct advantages gained in weight control -- early problem indication, a measure of the severity of problems, and quick reaction capability.

Such techniques as NASA's "Program Analyses and Evaluation Procedure (PAEP)" or "Launch Vehicle Cost Model" are invaluable for establishing long-range plans. Many of the mathematical techniques developed for them will be of value in FAME techniques.

6.2.3 COST AND SCHEDULE MODEL FOR FORECAST ANALYSIS

The needs of management and some of the gaps left by present systems indicate that a mathematical model for Forecast Analysis must be developed which can be applied to the control of costs and schedules. The data retrieval and processing system required to implement the analysis must also be considered during the development.

6.2.3.1 Model Objectives

The primary purpose of the cost and schedule model is to yield information which will in turn provide management with a program control system that will:

a. Evaluate the program status.
b. Forecast values for cost and schedule factors.
c. Detect areas of potential weakness at the earliest possible moment.
d. Determine the seriousness of problem areas.

To accomplish this, a number of specific items must be fulfilled. Periodic reporting procedures must be established to insure data for current and adequate evaluations. The model to be developed should be capable of monitoring the growth of expenditures and the schedule status as the program progresses. The model should contain the schedule milestones and the cost budget figures under which the program is constrained to operate. Based on the data reported, forecasts of the most likely future trends can be made. The development of forecasting procedures involves the analysis of past data to determine the relationships between cost or schedule factors and the pertinent parameters in the environment. It also involves the development of mathematical forecasting techniques which adequately represent these relationships. The model must have the capability of parametric variation. This requirement is necessary to provide management with sufficient data to trade-off one course of action against another. If desired, the model might be expanded to conduct a certain amount of trade-off analysis internally, thus limiting the decision making to those alternatives which hold the most promise for success. The cost and schedule program structure is represented graphically in Figure 6-2.

6.2.3.2 Scope of Model

The number of functions within the scope of the model is related to the responsibilities of the managers who will use the results obtained. All functions over which management has responsibility or a need for control should be included. Additional functions related to the primary functions should be included when they reveal significant patterns of dependency with the system.

6.2.3.3 Level of Analysis

The level of complexity at which the model will be constructed is itself a subject for trade-off analysis. Models of lower-level activity provide more direct control over operating performance. However, conclusions drawn from such models are more susceptible to error. Models at higher levels generally can be developed and implemented more quickly and with less expense, but they are less specific. The model should be developed to provide a sufficient amount of control at the management level for which it is intended.

6.2.3.4 Selection of Variables

Once the scope of the model and the level of its analysis have been decided upon, the variables to be included then must be defined. They may have been fairly well defined when the model scope was decided upon. In any case, elements which contribute to program cost and all scheduled milestones in the program must be included.

The cost of a development program may be divided into several parts, each requiring different treatment in the forecasting procedures. The following categories should be included in program cost definition:

a. Research and development costs: The hardware items involved in a research and development program may be classified as state-of-art items (to be acquired "as is"), items which require modification, and items which require complete development. Growth models for costs of the first and second type might be satisfied by linear characteristics. Costs of the last type might be described by the familiar exponential growth models. Investigations into growth characteristics of past programs should aid in establishing appropriate models.

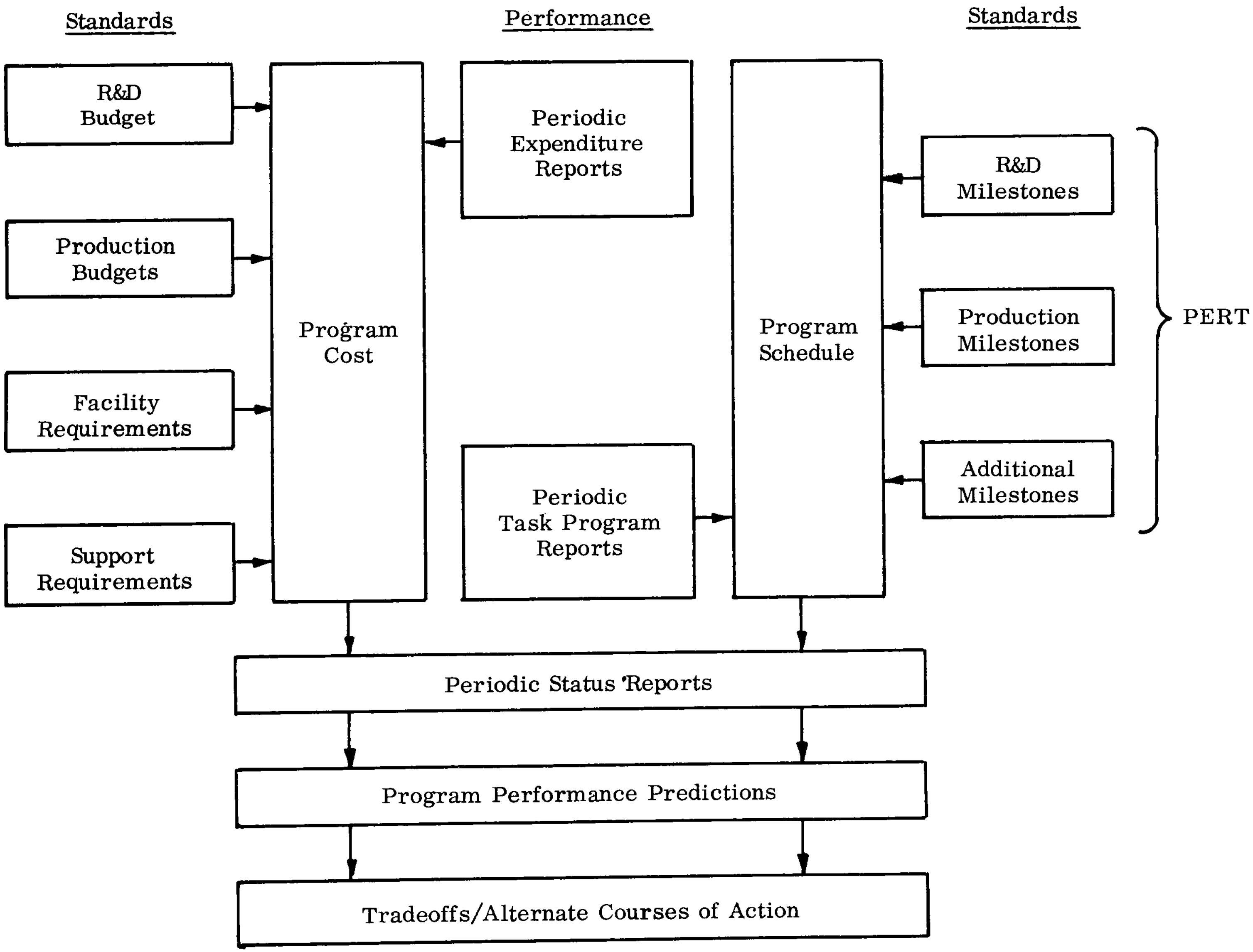


Figure 6-2. Cost/Schedule Program Structure

b. Production cost: This category includes such areas as fabrication, assembly, system testing, and all other costs which follow after completion of the initial design cycle. These are costs which are directly attributable to the hardware.

c. Facility development cost: This category describes the cost of any expansion, modification, or construction of facilities required to attain the objectives of the program. In some cases this cost may be prorated over a number of other programs.

d. Support costs: All costs normally classified as "overhead" are included in this category. It might be considered one of marginal importance and included only if a specific need exists.

It appears to be advantageous to select variables for the schedule model which are based upon present PERT networks. PERT networks used by a particular level of management usually represent the depth of analysis and the degree of control which are desired. A schedule status and trend forecasting model could then be based upon scheduled PERT events.

6.2.3.5 Establishing the Relationships

Once the variables of the model have been settled upon, it is necessary to establish the relationships which exist between them. It is this step which distinguishes a cost model from an accountant's ledger. The increased cost of one subsystem may either increase or decrease the cost of some other. The relationships between subsystems can be arrived at only through a knowledge of other system parameters such as weight, schedule, and reliability. But it is these very subtleties which make forecasting models more accurate and valuable tools. The relationships between the selected variables can be established by analyzing historical data from present and past programs. Appropriate mathematical trending models then can be selected to describe the growth with time. In addition to historical data on the parameter itself, several other potential areas exist for determining growth characteristics. Among these are the correlation between weight growth and schedule progress, and between expenditure of funds and schedule progress. Once established, the relationships serve as a new source of data, supplementing present sources and providing additional trade-off capability.

The use of PERT networks as the basis for the schedule model can provide the necessary relationships between events in time. The effect of late or early completion of one event on the over-all program completion can then readily be observed. The established relationships would also illustrate various alternatives.

6.2.3.6 Control Limits

The progress of a program with respect to schedule and cost is judged by comparing their status with some predetermined criteria. In this case, the criteria are budgets and schedule milestones. These criteria are similar to the control limits placed upon spacecraft weight. Just as weight must be kept below some maximum value, so must cost and time. Any values in excess of these limits must be reduced, or increased limits must be provided. Therefore, the limits included in the model must be capable of changing with time.

6.2.3.7 Methods of Control

The model might also be used to evaluate the various alternatives available. The model itself describes the interactions and dependencies present in the real system. Presumably, the result of any change made in the model is indicative of the expected result in the real system. Thus when unfavorable trends are noted, the model could be further exercised to determine the effect of resources reallocated in different manners. The alternatives could then be presented to management in a quantitative fashion for their evaluation and action.

6.2.3.8 Mathematical Techniques

The use of mathematical techniques is required for the analysis of past data to determine suitable forms for extrapolation into the future. Two areas in particular are of interest:

a. The analysis of past data to determine the mathematical form of growth characteristics.
b. The analysis of past data to determine the functional relationship between variables.

The techniques available range from graphical methods, when few variables are present, to sophisticated multiple regression curve-fitting methods. These techniques are well documented in later chapters. Thus the techniques required to apply FAME techniques to the control of costs and schedules are available.

6.2.4 DATA RETRIEVAL AND PROCESSING SYSTEM

An important factor in determining the ultimate worth of the output of an information system is the data retrieval and processing system on which it is based. The information system should be capable of detecting areas of potential weakness at an early date. The speed of a data retrieval and processing system must be an area of vital concern. The data being reported must be accurate and current. Present schedule reporting techniques, such as PERT, go to great extremes to insure accuracy of the reports. Cost reporting is a record of actual spending and is usually quite accurate. In Forecast Analysis, emphasis should be placed upon obtaining current data.

6.2.5 COST AND SCHEDULE RESULTS

The remaining step is to present the results to management in a form which will aid in the decision-making process. Total harmony between the system and the user can be obtained only after consultation, trial, and feedback. A lot of information is available from the computer program itself. The computer information may result from a number of different methods. It may be available at various levels of system complexity. Therefore, it is the user who must ultimately determine the type and quantity of information which is of greatest benefit. Some typical results of Forecast Analysis for cost and schedule are shown in Figures 6-3 through 6-9.

6.3 APPLICATION TO RELIABILITY MONITORING

6.3.1 RELIABILITY ESTIMATES

Reliability is defined as "the probability that a system, subsystem, component, or part will perform its required function under defined conditions at a designated time and for a specified operating period." The reliability estimates made at any time during equipment development are really forecasts of the reliability at a specific future date. They are based on an evaluation of the current system and its components. Any changes in the system or its mission results in a change in reliability estimate values. Because reliability estimates are forecasts the estimates are based not on the methods of calculating reliability, but rather on those phenomena which cause the reliability estimates to change.

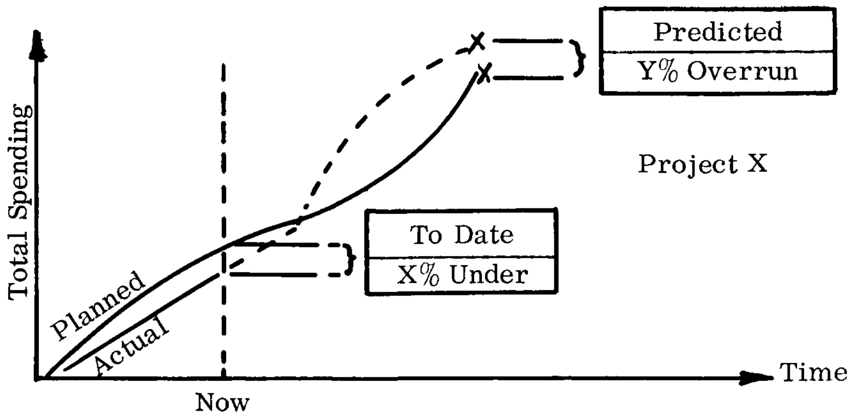


Figure 6-3. Top Level Program Control of Over-all Spending

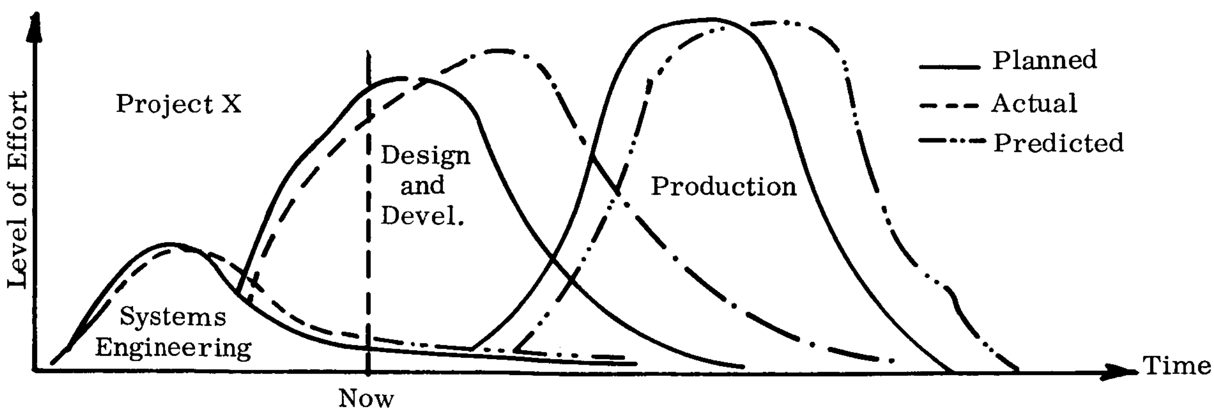


Figure 6-4. Spending Rate and Function Control

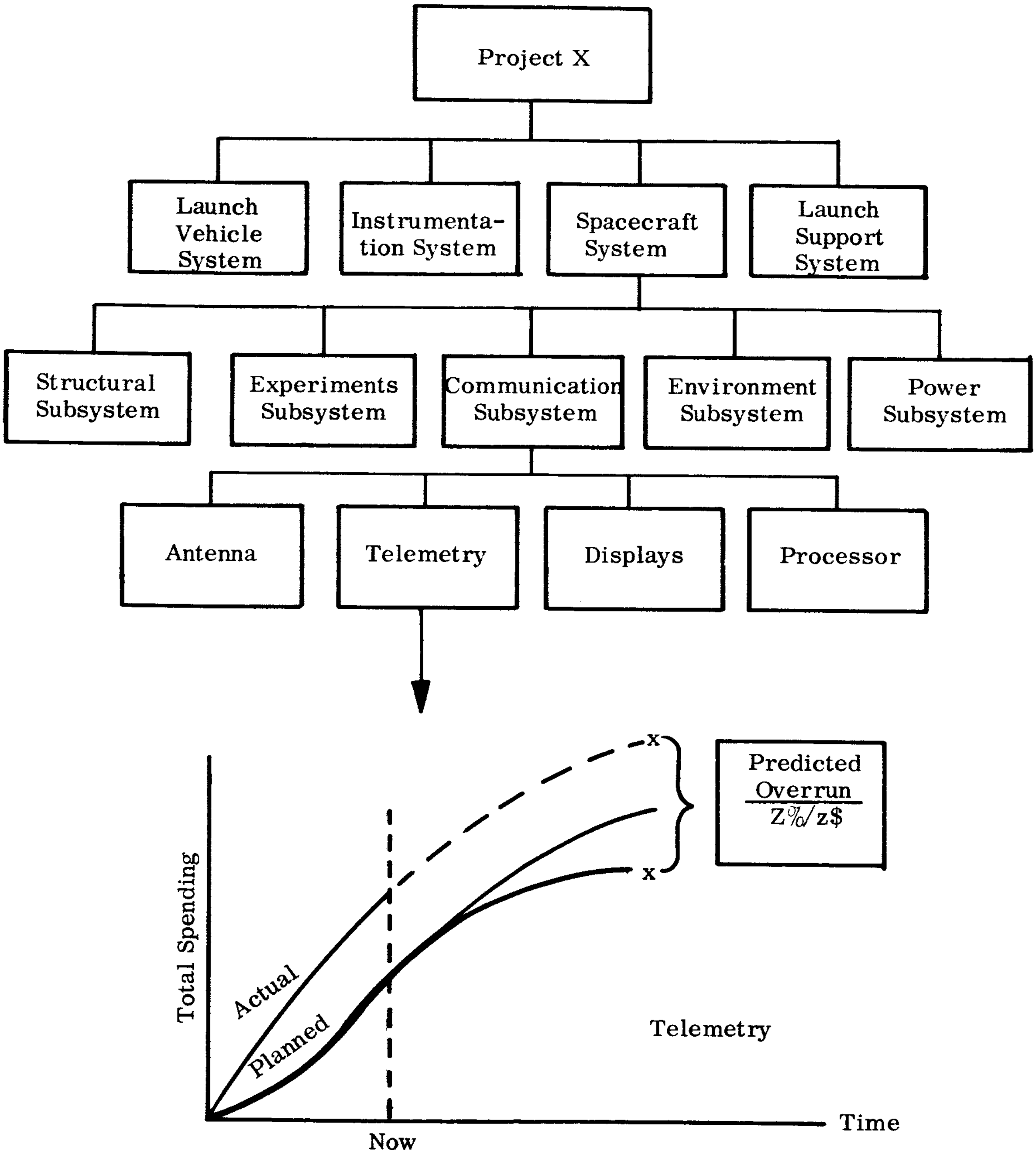


Figure 6-5. Isolating the Problem

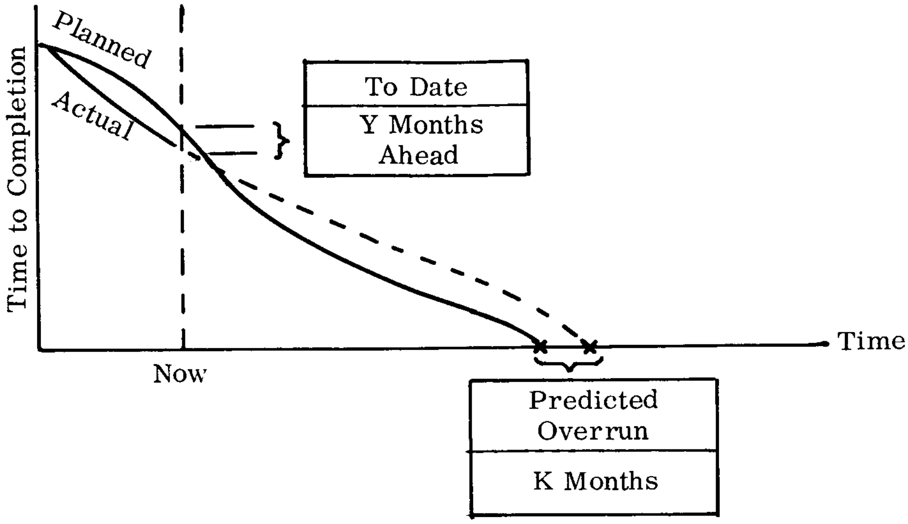


Figure 6-6. Program Progress

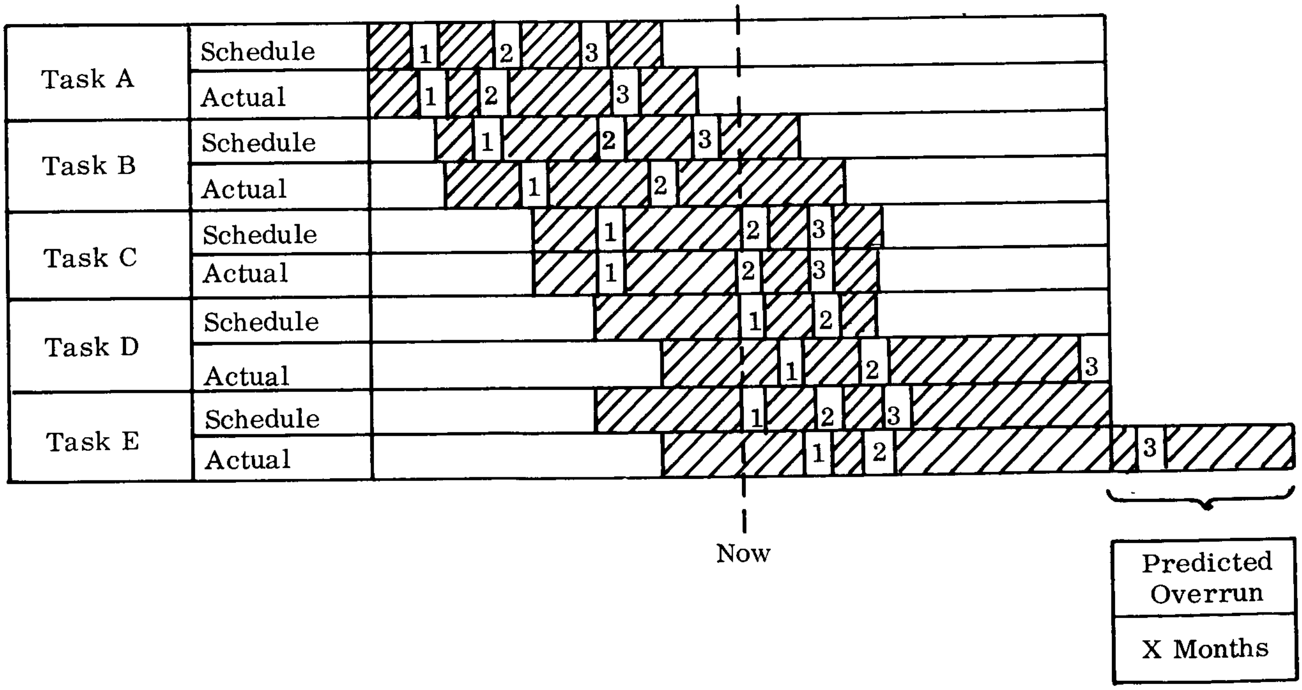


Figure 6-7. Milestone Completion

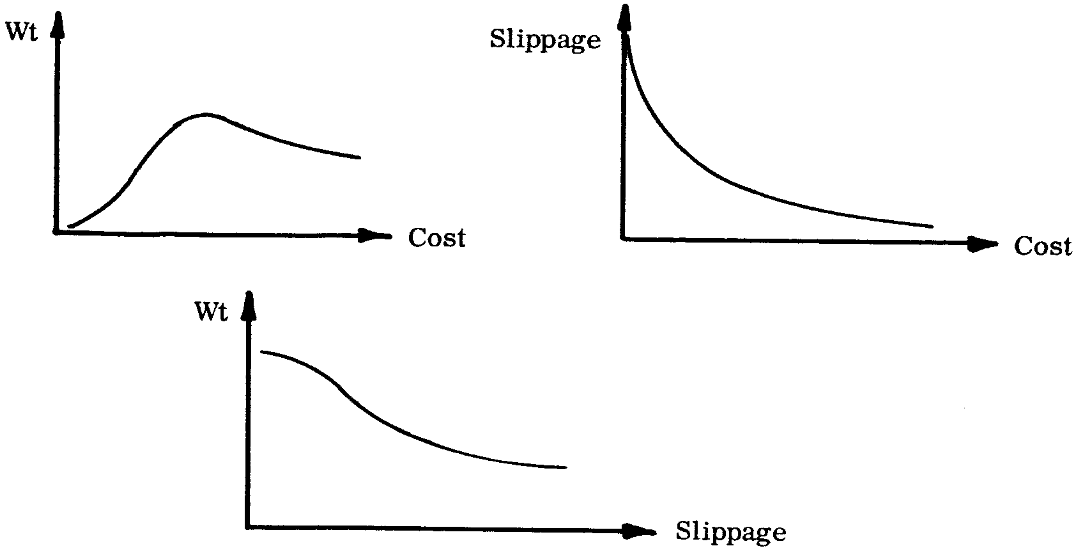


Figure 6-8. Parametric Variation

Weight Change	Cost	Slippage	$\frac{\Delta Wt}{Cost}$	$\frac{\Delta Wt}{Slip}$	$\frac{\Delta Wt}{Cost \cdot Slip}$

Figure 6-9. Trade-Off Summaries

6.3.2 THE PURPOSE OF RELIABILITY PREDICTION ANALYSIS

Current reliability programs which estimate the completed system reliability performance are based on:

a. A topological system model.

b. Subsystem and component current reliability estimates.

c. Historical component reliability data.

These measures of reliability performance are based on the current system configuration and on the current status of system components. As system development progresses, the reliability estimates will change. These changes are due to several causes:

a. Component reliabilities become better defined.

b. Estimates show deficiencies which are corrected.

c. The system reliability model is improved as system definition progresses.

Reliability Forecast Analysis involves the application of techniques which predict the future value of reliability estimates. The forecasts are based on three fundamental considerations:

a. Historical reliability trends of similar systems.

b. The growth of reliability estimates from system inception to completion.

c. The mechanisms of reliability growth.

Reliability Forecast Analysis activities are not a duplication of current reliability programs. Instead, they use the results of these programs to achieve their objectives. Reliability Forecast Analysis provides a method of extrapolating past and current reliability estimates to give future reliability estimates. In this way, Forecast Analysis provides a basis for anticipating future deficiencies and so provides another factor for management decisions. Trends and forecasts of reliability, weight, cost, and schedule, coupled with trade-off analysis, provide program management with a comprehensive overview of system development and a comparative basis for resource allocation.

6.3.3 THE PRESENT RELIABILITY ESTIMATION PROGRAM

Because testing of a large system during design and development is not always possible, the reliability of the system is determined by using a mathematical model. The model simulates the reliability requirements of the system in a phase-by-phase mission sequence. In the Apollo program the primary model used is SOAR III (Simulation of Apollo Reliability). SOAR is a system of computer programs developed to aid in the reliability estimation work on the Apollo Mission. SOAR combines analytical and Monte Carlo techniques to provide the speed and versatility necessary for detailed analysis of large, complex systems such as Apollo. The application of SOAR requires an accurate representation of the system. This representation takes the form of a reliability model showing the functional relationships of the equipment making up the system. The reliability model may vary with time to reflect the variations in equipment while in operation. The model also provides a means for representing several characteristics of manned space flight. At present, no attempt is made to trend data or to otherwise forecast future estimates.

6.3.4 USING ESTIMATION RESULTS FOR FORECAST ANALYSIS

Reliability estimation for the Apollo program has been in operation for over two years. The mathematical models have been extended and improved to increase both efficiency and scope. Reliability estimates constitute the primary input data for Forecast Analysis of weight growth as it affects reliability. The past estimates of reliability could provide background data to develop trends of the estimates. The past estimates could also be used to determine reliability growth and to forecast future reliability estimates.

The SOAR III model records the results of the trials in each element of the model for each phase of the mission. Therefore, information on mission reliability for each functional subsystem is available for use in estimate forecasting. Also recorded is data which can be used to compute the effect of functional system reliability on mission reliability.

6.3.5 RELIABILITY GROWTH

Methodologies for estimating reliability growth involve the following three elements:

a. System reliability description.
b. Reliability growth mechanisms.
c. Mathematical techniques.

The system reliability description is largely available for the Apollo program. However, it will be necessary to collect and supplement the background data for the description.

There are many different reliability growth mechanisms. Reliability growth occurs when increased equipment information causes subsystem and unit reliability estimates to be revised upward, or when the increased knowledge causes improvements to be made. The increases in system knowledge which change reliability estimates directly are typified by a new circuit which has a higher inherent reliability (fewer parts, more conservative power rating, etc.) than previous circuits on which earlier estimates had been based. Increased system knowledge might also result from tests which indicate that original estimates of reliability had been too conservative.

Another source of reliability estimate improvement is the indirect effects of system knowledge. Increases in system knowledge which produce improvements may evolve from criticality analyses which show that certain units are principal contributors to unreliability and so result in upgraded modifications. Another possibility which leads to corrections include unit and subsystem testing. Some other factors which lead to reliability growth are:

Removal of defects.
Insertion of redundancies.
State-of-the-art advances.
Redesign of critical elements.
Substitution of more reliable devices.
Upward revision of estimates.

As a program progresses through the development cycle, reliability continues to grow. Reliability estimates do not stop growing until efforts to improve reliability stop. The prediction of reliability growth, therefore, must be based on a situation which changes during the development cycle. Figure 6-10 shows a curve shape which might be expected for a plot of reliability versus time. During the early stages of development the estimates will tend to be low as in Zone A. As the equipment definition becomes more complete and deficiencies are corrected, the curve will rise more sharply over a time period. This is shown in Zone B. Then, as the system matures and reliability goals are approached or met and emphasis on reliability improvement decreases, the curve will level off, as in Zone C. At the end of the cycle, the system configuration is firm and all units approach the state-of-the-art in a reliability sense.

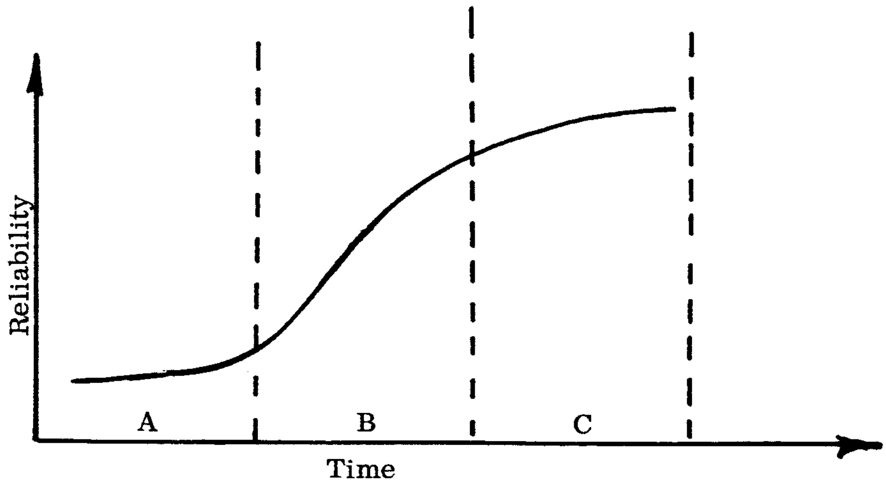


Figure 6-10. Reliability Estimate Growth

Much of the literature on reliability estimation describes reliability growth from the viewpoint of two types of failure, inherent unreliability, and transient unreliability. These are defined as follows:

a. Inherent unreliability - that portion of unreliability which cannot be eliminated by corrective engineering action due to the state-of-the-art or over-all design philosophy limitations.

b. Transient unreliability - that portion of initial unreliability amenable to modification or elimination by engineering change.

The inherent unreliabilities establish an upper bound on system growth. Transient reliabilities are detected and corrected at a rate proportional to their number. As the equipment is tested its reliability grows exponentially. Its reliability therefore approaches the upper bound asymptotically. While this approach intuitively seems good for reliability growth, we are interested in the growth of reliability estimates. The principle difference is that reliability growth is based on the removal of weaknesses as detected, while reliability estimate growth results from the reduction in the effects of known weaknesses. Therefore, we must consider also the nature of the estimates which are being used.

In Forecast Analysis techniques used for weight forecasting, estimates are modified according to the percentages of the estimate attributable to Estimated, Calculated, and Actual (E/C/A) weights. This technique is also applicable to reliability estimate growth. Certainly, the estimates made before and after fabrication and testing of equipment can be expected to differ. Even if improvements are not made a certain increase in confidence should lessen the conservatism of the estimate. Corrections made during test will result in improved test results and hence improve estimates. Thus, the refinement or growth potential of any estimate is a function of the point in the development cycle at which the estimate is made. It follows that a weighting process, akin to E/C/A technique should be used in forecasting reliability estimate growth.

This manual discusses math models used in weight growth forecasting. A math model of particular interest here is the exponential model, of the form

$$y = a - be^{-ct}$$

The observed value $\underline{w}_i$ is assumed to have the form

$$\underline{w}_i = y_i + \underline{e}_i$$

where $\underline{w}_i$ is composed of three parts, Estimated, Calculated, and Actual. Then the derivation continues to produce maximum likelihood estimators for a, b, and c based on measurements to date.

This estimation model can be adapted to the reliability estimate growth forecast by replacing the E/C/A with an N part representation of system maturity. For example, take N = 2 and let D = percent of estimate based on design and H = percent of estimate based on hardware. This seems to be a logical starting point. The use of these weighting functions should permit curves having the general shape shown in Figure 6-3 to be fitted to past estimates. Once the curve is fitted and the parameters of the model determined, forecasts can be made. The model above may not be the best technique available. Other methods and models should be considered for applicability.

6.3.6 IMPLEMENTATION

Reliability estimate information can be obtained from the current Apollo Reliability and Quality Assurance Program. This information is contained in either the quarterly status reports or is available from the SOAR III output data files. The status of the equipment at the time past estimates were made, i.e., the values for D and H is available for reliability estimation purposes. Other useful information is available also such as from MPC250-1 and from the R&QA quarterly reports. Obtaining meaningful estimates of D and H (or whatever N part description is used) for forecasting purposes appears to be feasible. The quarterly frequency of reliability estimation reports, precludes monthly updating of reliability estimation forecasts. A quarterly cycle would be required. The estimate forecasting output would yield management information having the same general character as that in the current Apollo weight/ performance reports. The reliability information would include:

a. Current reliability estimates for the functional subsystems over complete mission.
b. Current reliability estimates of mission success.
c. Forecast reliability estimate growth curve for functional subsystems.
d. Forecast reliability estimate growth curve for total mission success.

6.4 APPLICATION TO GROUND FACILITIES UTILIZATION

FAME is applicable where time-varying status is to be compared against preset requirements. There are numerous potential applications of FAME to the utilization of ground facilities. Typical applications include:

a. Utilization of test facilities and equipment.
b. Real time transmission and delayed transmission of data.
c. Processing of data, including monitoring.
d. Incorporating Forecast Analysis techniques directly within the checkout equipment for improved performance and reliability enhancement.

Two of these areas, c and d, are discussed below.

6.4.1 DATA PROCESSING

Because of the mounting complexity of test measurements and instrumentation, automated checkout and acceptance test equipment has been developed for the Apollo program (see Figure 6-11). This computerized equipment facilitates rapid and accurate testing of flight equipment. The resulting increase in the amount and rate of data flow, however, has been substantial. Surveillance of total data processing appears to be "a must" for the successful management of test data and for pinpointing problem areas revealed by the test. Surveillance would seem to be valuable in both input and output data handling requirements now that the number and rate of input sensory stations is increasing and huge amounts of output data have to be processed and stored. For these reasons it appears worthwhile to consider Forecast Analysis techniques for test data processing, particularly during the planning stages when data processing can be factored into program management.

6.4.2 CHECKOUT EQUIPMENT

Improving testing techniques and enhancing their reliability is another possible application of Forecast Analysis. Checkout equipment could presumably use appropriately

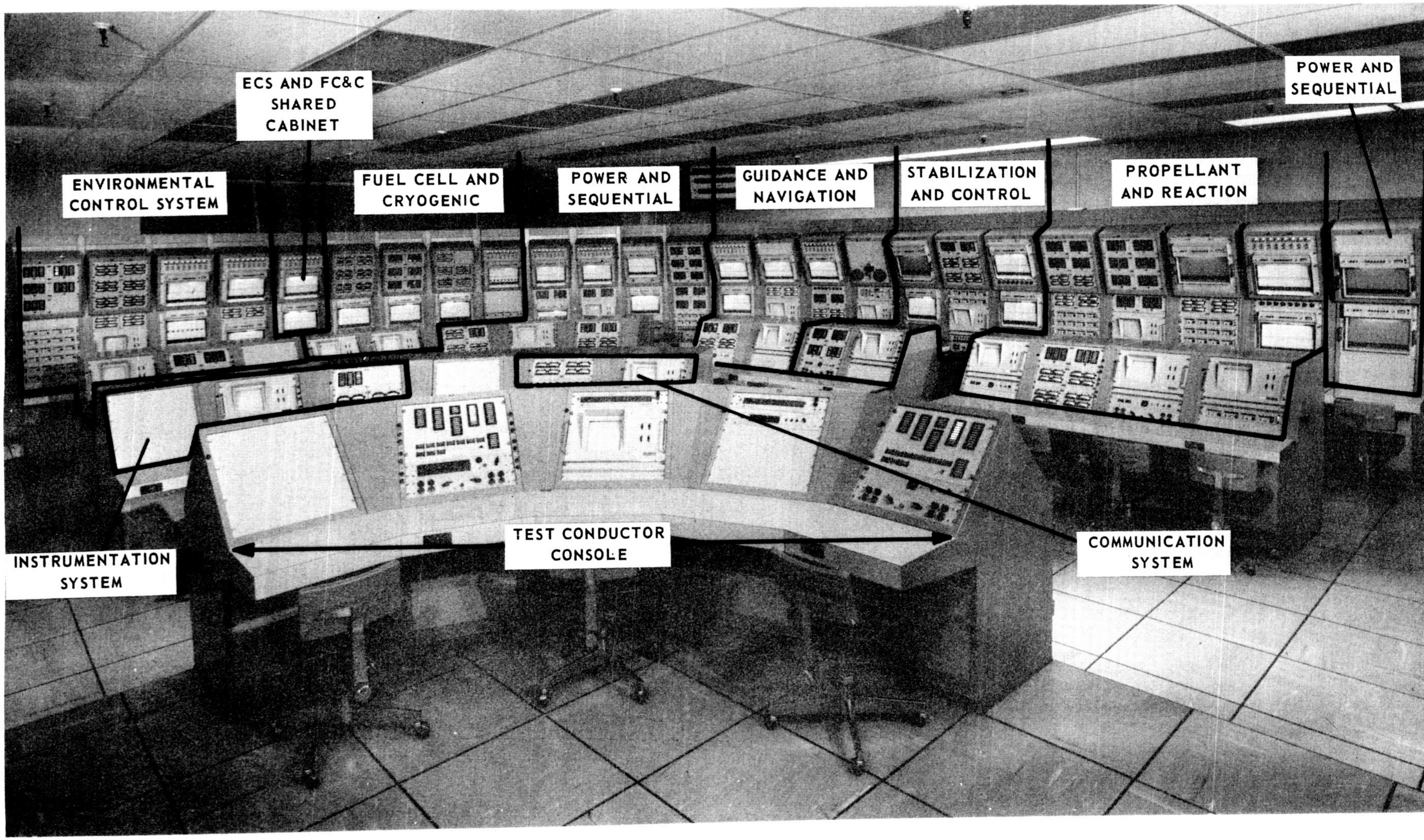


Figure 6-11. Typical ACE-S/C Control Room

modified Forecast Analysis techniques to sense trends in aerospace equipment performance. This appears to have value not only for acceptance testing, but also in determining the expected life or the time required for a critical measurement to exceed its control limits. In many components measurements of performance can be made more accurately and precisely than required by operating tolerances. Using such measurements, trends within the control bounds can be sensed and assessed by Forecast Analysis. These trend appraisals can be used to select equipment with very narrow operating limits. This would have the same saluatory effect on reliability as though the control limit band had been narrowed. In addition, better predictions about when failure will occur can be made simply by tracking the actual performance parameters and applying standard Forecast Analysis techniques. The improved reliability data comes, potentially, from the improved understanding of the behavior of a specific element measured against its requirements. Pre-flight performance assessment might also be enhanced by improved prediction of performance at the time of shipping. Both a performance prediction and an associated probable error could be obtained by Forecast Analysis derived from data on the behavior of systems during ground checkout and acceptance testing.

6.5 APPLICATION TO PERFORMANCE ASSESSMENT

The application of FAME to weight/performance data is primarily based on the assessment of weight. Performance effects are included only by the use of control weights which are derived from performance assessments. This has merit in that the principal effects of weight changes can be studied on a constant performance basis, reflected by constant control limits. Buyoffs for launch vehicle payload capability and spacecraft total weight are calculated using the control limits, predicted spacecraft weight and predicted launch vehicle performance. When comparing total vehicle buyoffs with the sum of stage or module buyoffs some inconsistencies appear, but they are usually small. Thus current techniques appear to be capable of monitoring both weight and performance, but only when performance is included as a constraint on weight.

Weight/performance control techniques can be improved by more thorough surveillance and interpretation of performance parameters. There are several ways this surveillance and improved prediction analysis of performance might be achieved. These include:

a. Compare the expected performance with requirements at the stage or module level (for which control weights are established). That is, can the vehicle perform the designated mission using both current and predicted performance factors and assuming the weights to be equal to the control limits.

b. Monitor performance values and compare them to their specific control limits, e.g., compare current and predicted Isp to the control Isp values which are used for mission determination.

c. Assess the current and predicted over-all mission performance versus requirements by a comprehensive trajectory calculation. This would require two long computer runs for each comparison, using current values and predicted values, and a third run for reference using control values.

d. Approximate c (above) using performance trade-off factors which represent combinations of performance effects on the over-all mission. New factors would be obtained each month for current and predicted status by differential methods discussed in Appendix D. These factors would be compared to the required performance factors.

Method (b) will be used to illustrate the application of FAME. Methods (a) and (c) require rather extensive computational capabilities, including the analysis of complex trajectory phenomena, and will not be considered. Method (d) has merit, and is described, with illustrations of its use, in Appendix D.

Method (b) presupposes that management, supported by systems engineering groups of the various design agencies, can and does establish control values for the many factors that affect performance. Current status is assumed to be reported on a periodic basis. The FAME formula could then be applied to produce quantitative information about the performance values.

A list of typical performance elements which might be monitored is presented in Table 6-1. Such a list can be constructed for any aerospace program. This list includes:

a. Items which have a measurable impact on performance.
b. Items which have preset control limits.
c. Items whose status can be measured and whose future value can be predicted.

This list shows that there are a large number of performance factors, all of which are important to mission success, which could be monitored. The selected factors must be monitored for each specific vehicle and each specific mission to present the over-all

Table 6-1

Typical Performance Elements Which Could be Assessed by Forecast Analysis

A. SPACE VEHICLE PERFORMANCE FACTORS

1. Time Sequencing Performance
   - 1.1 Hold down timing
   - 1.2 LES jettison time
   - 1.3 Time in orbit
   - 1.4 Boost between stages
   - 1.5 Trip time to moon
   - 1.6 Stay time on moon
   - 1.7 Trip time to earth
2. Thrust or Total Impulse Tolerance
   - 2.1 Stage thrust profile
   - 2.2 Stage nominal thrust
   - 2.3 Programmed mixture ratio profile
   - 2.4 Variable thrust engine performance
   - 2.5 Reaction control unit thrust program
3. Specific Impulse Values
   - 3.1 Engine instantaneous I_{sp}
   - 3.2 Stage average I_{sp}
   - 3.3 Programmed mixture ratio profile
   - 3.4 Variation of I_{sp} with run time, altitude
   - 3.5 Variation of I_{sp} with trottled engines
4. Propellant Loading Tolerance
   - 4.1 Stage or module loading
   - 4.2 Boiloff and other losses
5. Propellant Residual Variations
   - 5.1 Stage or module residule propellant
   - 5.2 Stage or module pressurization gas weight variation

B. TRAJECTORY PERFORMANCE FACTORS

1. Launch Parameters
   - 1.1 Date
   - 1.2 Time
   - 1.3 Azimuth
2. Parking Orbit Parameters
   - 2.1 Altitude
   - 2.2 Ellipticity (Ephermeris)
   - 2.3 Epoch
3. Injection Parameters
   - 3.1 Position
   - 3.2 Injection velocity (trip time)
   - 3.3 Injection angle
   - 3.4 Free return characteristics
4. Planetary Arrival Parameters
   - 4.1 Arrival altitude and velocity
   - 4.2 Orbit Ephemeris
   - 4.3 Place change
   - 4.4 Descent trajectory
   - 4.5 Hover capability
5. Planetary Departure Parameters
   - 5.1 Date
   - 5.2 Time
   - 5.3 Orbit requirements
   - 5.4 Docking maneuvers
   - 5.5 De-orbit time and position
   - 5.6 Departure velocity requirement
   - 5.7 Departure angle
6. Midcourse ΔV Corrections
   - 6.1 Transplanetary requirements
   - 6.2 Transearth requirements
7. Earth Arrival Parameters
   - 7.1 Entry time
   - 7.2 Entry position
   - 7.3 Entry velocity
   - 7.4 Entry angle
   - 7.5 Entry altitude
   - 7.6 L/D ratio
   - 7.7 Landing requirements, site locations

C. GUIDANCE AND NAVIGATIONAL FACTORS

1. Launch Vehicle Guidance
   - 1.1 Platform errors
   - 1.2 Accelerometer accuracy
   - 1.3 Computer performance
   - 1.4 Vehicle variations
2. Spacecraft Guidance and Navigation
   - 2.1 Inertial measuring unit parameters
   - 2.2 Optical system performance
   - 2.3 Guidance computer performance
   - 2.4 Radar parameters
   - 2.5 Ground tracking performance
   - 2.6 Stabilization and control performance
   - 2.7 Controls and displays

program status. Clearly, the performance data handling problem could be as large or larger than weight data processing. The use of computers for performance data processing would be essential.

Data on selected individual items must be reported and monitored on a periodic basis. Status and control information would be required for each specific item. Identification numbers would be assigned to each item to assure accuracy.

A typical example of a data reporting format for a rocket engine is shown in Figure 6-12. For this figure, the status of key performance parameters is assumed to have been requested. Since these engines are used with a variety of oxidizer-to-fuel ratios (O/F), specific status is requested for three (say) measured values. For comparison of this specific engine to the class of engines, the average performance curves are superimposed on the specific curves. The average performance curves also indicate the expected standard deviation and the general variation of performance with varying O/F ratio. Other data required for the surveillance of engine status is included in Figure 6-12.

Data request forms similar to Figure 6-12 would be required for each area of performance considered. While it may be impractical to monitor all significant areas of performance, as detailed in Table 6-1, benefits could be derived from surveillance of even two or three items. Additional elements could be added as the information and control limits became available. Once the flow of status information is established, method (b) reduces to a standard application of Forecast Analysis techniques. The procedures followed would be quite similar to those being used for weight/performance on the Apollo program.

6.6 APPLICATION TO ELECTRICAL POWER SURVEILLANCE

The proper application of Forecast Analysis techniques can reduce the adverse impact of the electrical load growth on a program. Again, the problem is to select the best significant parameters to monitor and to use for predictions of electrical load growth. Experience has shown that whenever electrical power parameters, including peak power, total energy, required voltage, etc., are followed on a periodic basis from the inception of a program definite patterns of growth are exhibited by the various systems. In fact, the patterns are quite consistent from program to program. This leads to the selection of the electrical power parameters above for use in Forecast Analysis. Measurable requirements are available for these parameters and status measurements

SATURN V ROCKET ENGINE PERFORMANCE SUMMARY

Engine Serial Number ____________ Date of This Report ____________

Reporting Unit ____________

Engine Type ____________
Engine Model No. ____________

Engine Components Serial No.
Thrust Chamber ____________
Turbo-Pump ____________
Other ____________

Propellants:
Fuel ____________
Oxidizer ____________
Other ____________

Chamber Throat Area ____________ in^2
Chamber Exit Area ____________ in^2

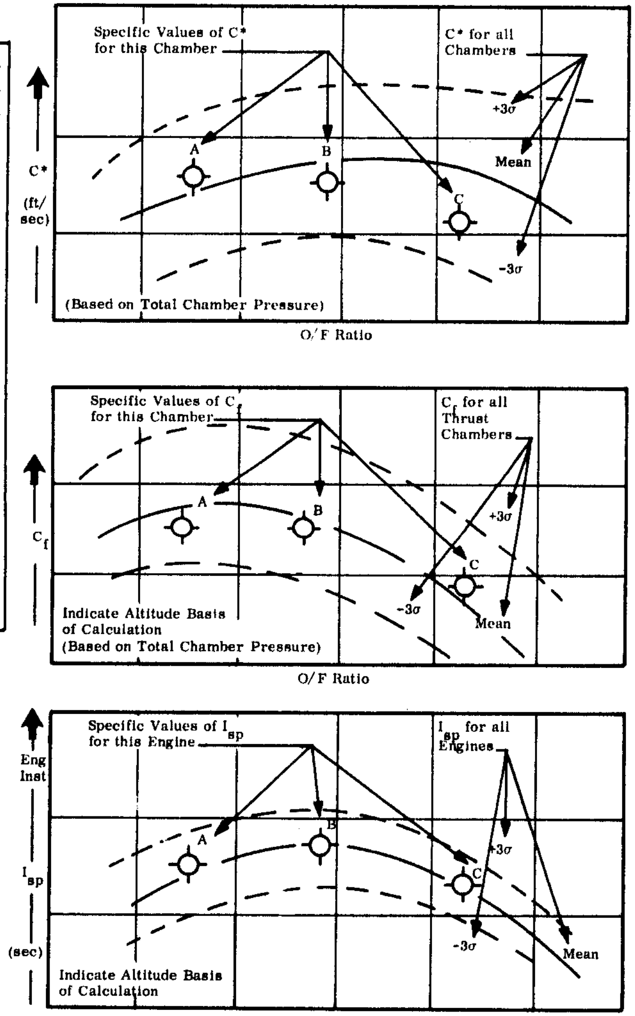
Start and Stop Losses (1)
Start-Up Losses ____________ lb

Shut Down Impulse ____________ lb-sec

Shut Down Impulse Tolerance ____________ lb-sec

Reference Source of Information ____________

(1) Include Curves versus Time if Available



Parameter	Three Specific Performance Values at Different O/F Ratios		
	A	B	C
Chamber Press (Total) (psia)			
O/F Ratio			
C*(ft/sec) (1)			
Thrust Chamber C_f			
Chamber Thrust (lb)			
Engine Thrust (lb)			
Thrust Chamber Flow Rate (lb/sec)			
Engine Flow Rate (lb/sec)			
Engine Instantaneous I_{sp} (1) (sec)			
Basic of Reported Values, A, B, C (State Whether Estimated ______, Calculated ______, or Measured ______)			

(1) Include curve versus time if available

Figure 6-12. Typical Engine Performance Chart can be made which include Estimated, Calculated, and Actual percentages, as for weight data. Once status information flow is established, standard Forecast Analysis procedures can be applied to electrical power data.

Figures 6-13 and 6-14 (taken from "Electrical Power Data Submittal Requirements," CM 006.000-1) show typical input data. The form in Figure 6-13 is designed to supply the information necessary to monitor over-all electrical load requirements and electrical source capabilities. The form in Figure 6-15 is designed to present the data needed to monitor the voltage available at a component. These forms are completed for each power source and each electrical load. Figures 6-16, 6-17, and 6-18 show typical plots resulting from the application of Forecast Analysis to the input data. Figures 6-16 and 6-17 show trend charts for electrical power parameters. An extension of a trend to the delivery date graphically shows management if corrective action is needed. The minimum load voltage data is presented typically as in Figure 6-18 in terms of the voltage margin ratio. This ratio is defined as follows:

$$\text{VOLTAGE MARGIN RATIO} = \frac{\text{MIN. VOLTAGE - MIN. SPEC. VOLTAGE}}{\text{MIN. SPEC. VOLTAGE}}$$

Forecast Analysis applies statistical techniques to the well known electrical power load growth problem. It provides predictions based on the periodically reported data and on the level of program maturity as indicated by the percentage of the reported data which is Estimated, Calculated, and Actual. It provides confidence limits on the predicted data. It quickly alerts management to any existing or potential problem areas and to any changes affecting previous predictions. Management thus has available, at all times, current data and competent predictions on which to base decisions.

Stage or Module ______ SN ______ Mission ______ Date ______
Report No. ______
Prepared By ______

Electrical Power Summary										
Power System Identification	Infor-mation Code*	Original Specified Base	Procuring Activity/GSE Changes	Revised Base	Present Data	Change from Last (+or-) Present	Present Breakdown			Note Number
							EST	CAL	ACT	
	S-WH									
	S-PP									
	L-WH									
	L-PP									
	S-WH									
	S-PP									
	L-WH									
	L-PP									
	S-WH									
	S-PP									
	L-WH									
	L-PP									
	S-WH									
	S-PP									
	L-WH									
	L-PP									

*Code S-WH = Source Capability Total Power: Watt-Hours
S-PP = Source Capability Peak Power: Watts
L-WH = Combined Loads Total Power: Watt-Hours
L-PP = Combined Loads Peak Power: Watts

Form A
Page ______

Figure 6-13. Over-all Electrical Load Requirements

Power System Mission Profile

Stage or Module ______ SN ______ Report No. ______
Mission ______ Prepared By ______
Power System ______ Date ______

Mission Phase	Source Peak Power Capability - Watts	Peak Load - Watts	Total Power for Mission Phase - Watt Hours
Launch			
Earth Orbit			
Translunar			
Lunar Orbit			
Lunar Landing			
Lunar Operations			
Lunar Launch			
Rendezvous			
Transearth			
Re-Entry			
Recovery			

Form B

Figure 6-14. Component Voltage Usage

Minimum Load Voltage

Mission ____________ Report No. ____________
Stage or Module ____________ SN ____________ Date ____________
Mission ____________ Prepared By ____________
Power System ____________

Load	Actual Min. Voltage-Volts	M or C	Specification Min. Voltage Volts

Form C
Page ____

Figure 6-15. Minimum Load Voltage Log

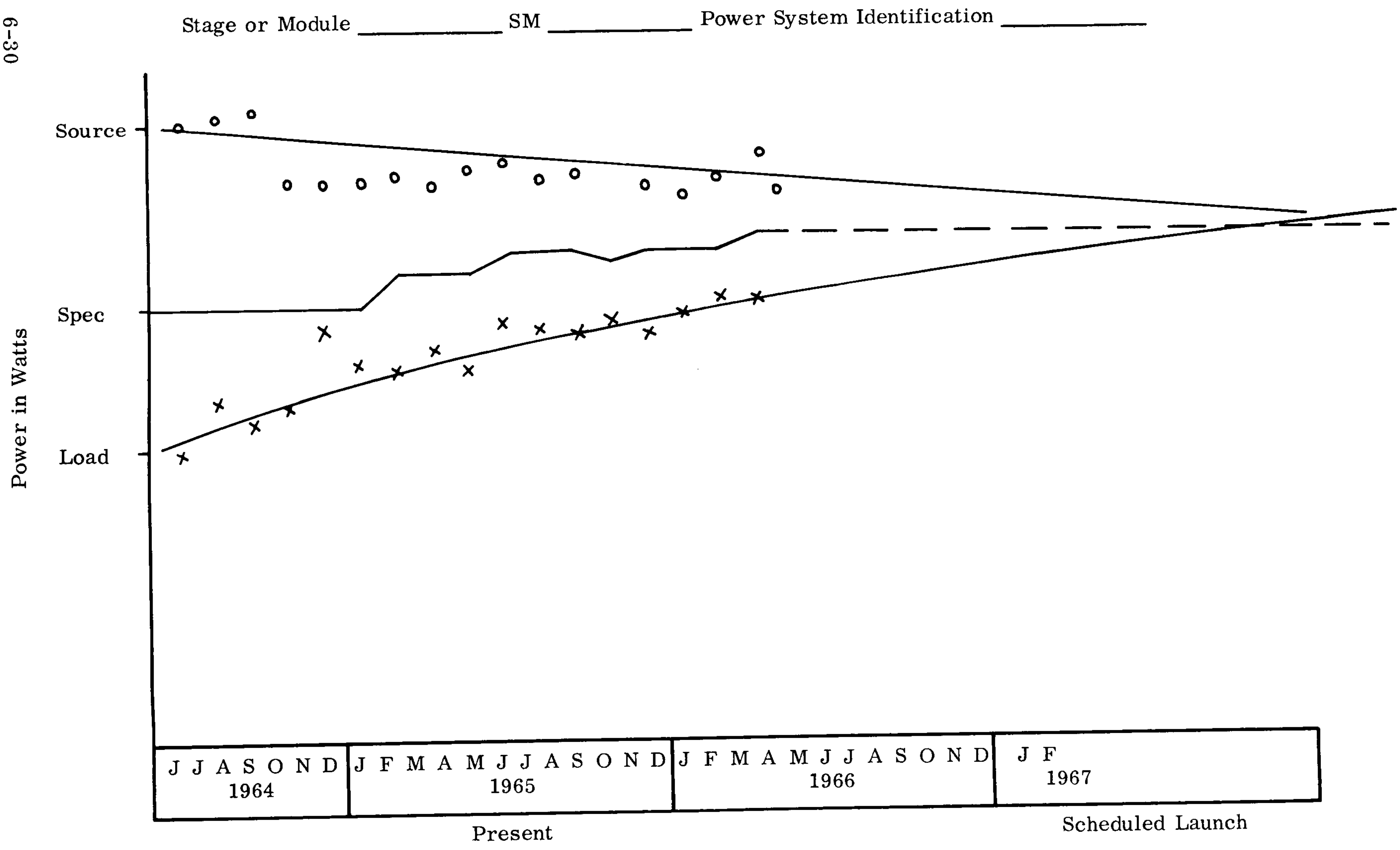


Figure 6-16. Sample Plot of Power Requirements

Stage or Module ______ SN ______ Power System Identification ______

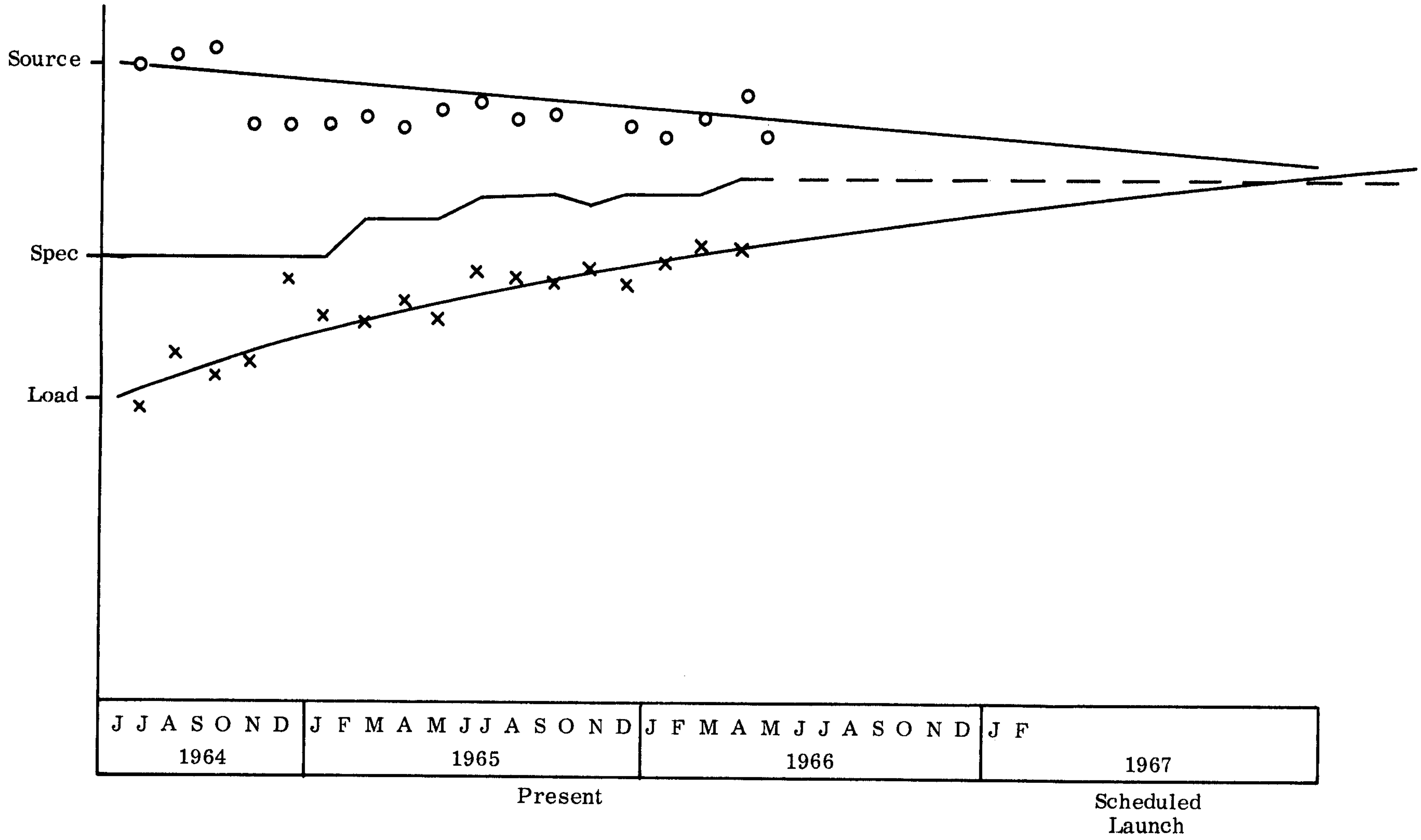


Figure 6-17. Total Power Capability and Demand Projection

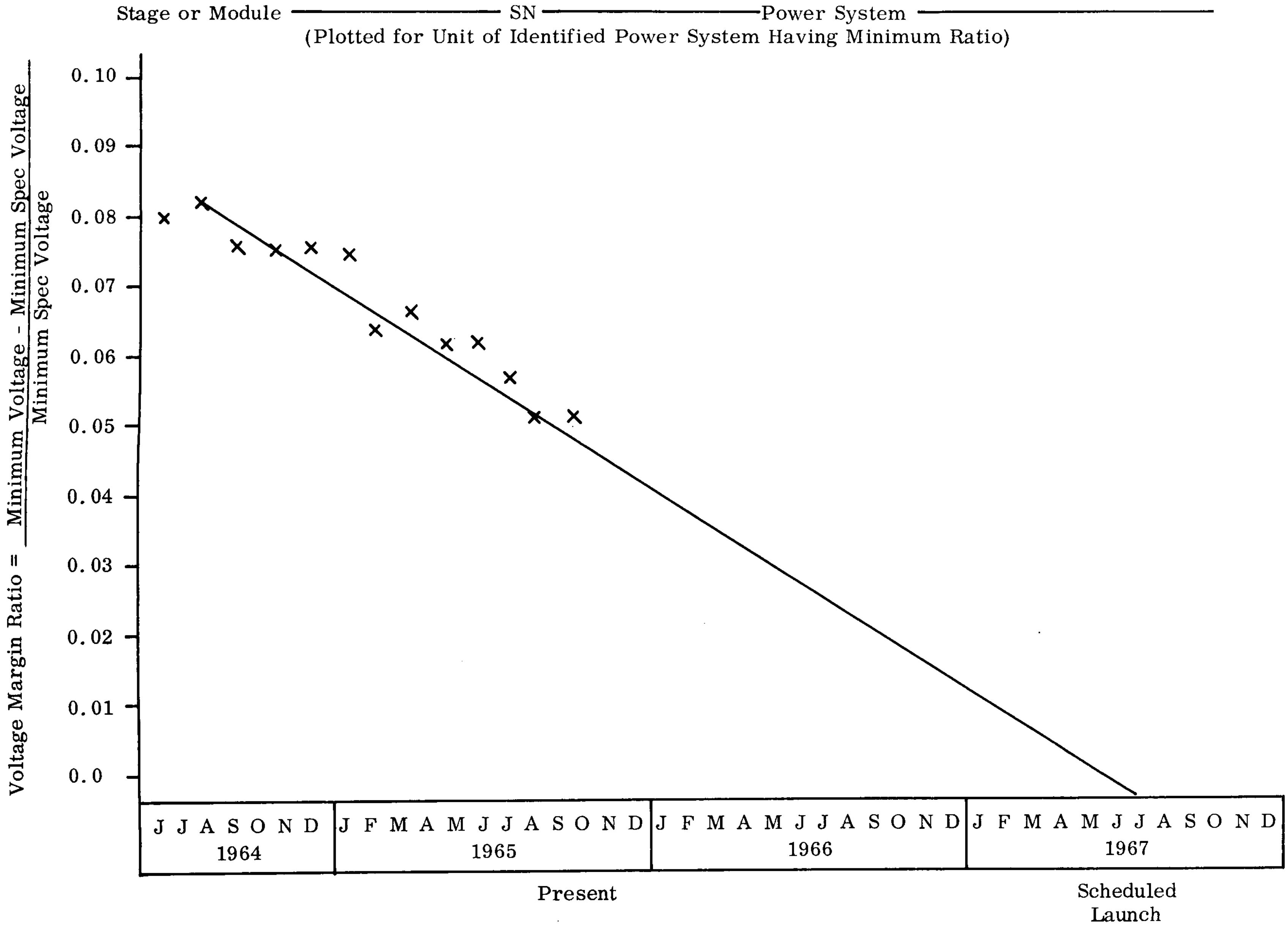


Figure 6-18. Voltage Margin Ratio Projection

NOMENCLATURE AND DEFINITIONS

There are several terms or nomenclature unique to Forecasts and Appraisals for Management Evaluation. These terms are defined below:

TERM	DEFINITION
Buyoff - Required	The actual amount, for example in pounds, which must be removed to assure that the control value or limit will not be exceeded.
Buyoffs-Authorized	Weight changes which have officially been approved but not formally implemented or incorporated in released drawings.
Buyoffs-Potential	Includes those changes which have been documented but not authorized for incorporation. Can include proposed and pending changes.
Confidence Limits	Those limits within which a predetermined percentage of reported weights will fall for a large number of observations.
Control Weight	The maximum amount of weight permissible for a stage, module, or spacecraft to be used in a specified mission.
Deficiency	The amount by which a stage, module, or vehicle exceeds its control limit, expressible as actual pounds, equivalent spacecraft weight, or payload capability.
E/C/A	Methods by which a parameter, such as weight, is determined, with E representing the percent Estimated, C representing the percent Calculated, and A the percent Actually measured.
Non-random Weight Change	A change in weight which is not mathematically considered as a part of normal weight growth.
Normalization	The process of removing the effects of non-random weight changes from data prior to trend forecasting.
Mark II	A system of computer programs written for the IBM 7044 Computer, each of which may operate as physically independent but functionally consistent units using outputs from other programs in the system and information from the Weight Data File.

TERM	DEFINITION
Model	Mathematical representation of observed behavior, used in this manual for forecasting purposes to refer to one of four different models; Linear Maximum Likelihood, Non-Linear Maximum Likelihood, Asymptotic (Logistic) Exponential, and Adaptive (Fourier) Exponential.
Forecast	A representation of the sequence of observed and probable future weights over a segment of time.
Forecast Analysis	Forecast Analysis is a process which assesses the facts of yesterday, determines the certainties of today, and forecasts the probabilistic events of the future. In so doing it provides quantitative forecasts of a stated condition, (e.g., weight growth) defines its magnitude, and describes the effects of alternate management actions or inaction.
Forecast Line	A line extending from the last real data point as dictated by the Forecast Analysis model, adjusted by logic, for purposes of forecasting a system weight.
Probable Error	The probable range of a forecast weight. This range is expected to be exceeded in no more than one case out of 20.
Performance Deficit (or Performance Variation)	The amount of equivalent payload weight attributed to deviation of performance parameters (e.g., programmed mixture ratio, Isp, etc.) from the set of values used to define control weights.
Repeating Mode Analysis	Basically, a repeating mode program is one which analyzes a sequential set of observations (five to six points beginning with time zero) and makes forecasts for the succeeding months. It then automatically adds the next observed point and makes new forecasts for succeeding months. This process is repeated until all available data is exhausted. A plot is then made of these results as a check on the attribute of consistency, i.e., targeting.
Targeting	Consistency is that attribute of PAT which is distinguished by the convergence of the estimated parameter (in this application weight) toward a final value each time an additional set of data is added to the initial set of observation. This means that as our knowledge improves the probability of forecasting another value, other than the one upon which we are converging, diminishes rapidly. We choose to refer to this attribute as "targeting."

Trade-off Results	The weighing of one alternate result against others to arrive at what may be considered the best compromise solution possible for a deficiency.
Trend	The direction which weight/performance appears to be taking.

REFERENCES

BIBLIOGRAPHY - FORECAST ANALYSIS
BOOKS AND PAPERS

1. Air Force, Department of the, MANAGEMENT ENGINEERING PROJECT ADMINISTRATION, AFP 25-3-3, May 1959.

2. Bailey, T.J., THE ELEMENTS OF STOCHASTIC PROCESSES WITH APPLICATIONS TO THE NATURAL SCIENCES, Wiley and Sons, 1964.

3. Brents, J.E., et al., "Launch Vehicle Systems Cost Model," General Dynamics, Fort Worth, FZM-4154, 15 June 1964.

4. Bresenham, J.E., "Reliability Growth Models," Stanford University Tech Report 74, 24 August 1964.

5. Brown, R., SMOOTHING, FORECASTING, AND PREDICTION OF DISCRETE TIME SERIES, Prentice-Hall Inc., 1962.

6. Cramer, H., MATHEMATICAL METHODS OF STATISTICS, Princeton University Press, Princeton, N.J., 1946.

7. Crow, Davis and Macfield, STATISTICS MANUAL, Dover Publication, 1960.

8. Dixon and Massey, AN INTRODUCTION TO STATISTICAL ANALYSIS, McGraw-Hill Co., Inc., Second Edition, 1957.

9. Enrick, N.L., "Management Operations Research," Holt, Rinehart and Winston, 1965.

10. General Electric Company, PROFESSIONAL MANAGEMENT IN GENERAL ELECTRIC, 1954.

11. Grumman Aircraft Engineering Co., "Quarterly Reliability Status Report," February 1964 (Confidential).

12. Hoel, P.G., INTRODUCTION TO MATHEMATICAL STATISTICS, 2nd Edition, John Wiley and Sons, Inc., 1956.

13. Kaufmann, A., METHODS AND MODELS OF OPERATIONS RESEARCH, Prentice-Hall, Inc., 1963.

14. Koelle, H.H., Voss, R.G., "A Procedure to Analyze and Evaluate Alternative Space Program Plans," NASA TMX53212, 3 March 1965.

15. Lesourne, J., ECONOMIC ANALYSIS AND INDUSTRIAL MANAGEMENT, Prentice-Hall, Inc., 1963.

16. Malcolm, O.G., Row, A.J., L.J. McConnel, MANAGEMENT CONTROL SYSTEMS, John Wiley and Sonc, 1960.

17. Malinvaud, E., "Estimation et Prevision Dans Les Modeles Ecónomiques Auto-regressifs," Revue de l'Institut International de Statistique, 29, 1961.

18. Mood and Graybill, INTRODUCTION TO THE THEORY OF STATISTICS, 2nd Edition, McGraw Hill Co., Inc., 1963.

19. NASA, "Apollo Terminology," SP-6001, August 1963.

20. NASA, "Apollo Reliability Estimation Guideline," RA-006-007-1, 24 Septemper 1965.

21. NASA, Office of Manned Space Flight, "Apollo Program Specification (U)," SE005-001-1.

22. NASA, Office of Manned Space Flight, "Apollo Flight Mission Assignments (U)," NPC-C500-11, SE 010-000-1.

23. NASA, Office of Manned Space Flight, Apollo Program, "Mass Properties Standard," SP-7004, CM 018-001-1.

24. NASA, Office of Manned Space Flight, Apollo Program, "Weight and Performance Data Submittal Requirements," CM-005-000-1.

25. Neuschel, R.F., MANAGEMENT BY SYSTEM, McGraw Hill Co., Inc., 1960.

26. Parzen, E., STOCHASTIC PROCESSES, Holden Day, Inc., 1962.

27. Proshan, Frank, REDUNDANCY FOR RELIABILITY IMPROVEMENT, STATISTICAL THEORY OF RELIABILITY, The University of Wisconsin Press, 1963.

28. Roth, G.L., and Leibermann, C.R., "Prediction Analysis and Management Decisions," NASA Manned Space Flight Office, 5 April 1965, Second Space Congress, Cocoa Beach, Florida.

29. Scarborough, J.B., NUMERICAL MATHEMATICAL ANALYSIS, Fifth Edition, The John Hopkins Press, 1962.

30. Zelen, M., STATISTICAL THEORY OF RELIABILITY, The University of Wisconsin Press, 1963.

BIBLIOGRAPHY - FORECAST ANALYSIS
ADDITIONAL READING

1. Anderson, R., "The Problem of Autocorrelation in Regression Analysis," American Statistical Association Journal, March 1954, pp. 113-129.

2. Anderson, T.W., "Statistical Inference About Markov Chains," Ann. Math. Statist., Volume 28, p. 89, 1957.

3. Anderson, T.W., "On Bayes Procedures for a Problem with Choice of Observations," Annals of Math. Statistics, Vol. 35, No. 3., September 1964, pp. 1128-1135.

4. Anderson, T.W., and Rubin, H., "The Asymptotic Properties of Estimates of the Parameters of a Single Equation in a Complete System of Stochastic Equations," Annals of Math. Statistics, 21, 1950, pp. 570-582.

5. Anonymous, "Statistical Analysis of Space Vehicle Performance," North American Aviation, October, 1962.

6. Anscombe, F.J., "Bayesian Statistics," The American Statistician, February 1961, pp. 21-24.

7. Bartlett, M.S., AN INTRODUCTION TO STOCHASTIC PROCESSES, Cambridge University, 1955.

8. Bartlett, M.S., ESSAYS ON PROBABILITY AND STATISTICS, John Wiley and Sons, Inc., 1962.

9. Bartlett, M.S., THE STATISTICAL ANALYSIS OF STOCHASTIC PROCESSES, Essays on Probability and Statistics, John Wiley and Sons, Inc., 1962.

10. Bayes, Rev., F.R.S., "An Essay Towards Solving a Problem in the Doctrine of Changes," Biometrika, Vol. 46, 1958, pp. 296-315.

11. Bayley, G.V., "The 'Effective' Number of Independent Observations in an Autocorrelated Time Series," Suppl. J. Roy Statist. Soc., Vol. 8, p. 184, 1946.

12. Bellman, Richard (Editor), MATHEMATICAL OPTIMIZATION TECHNIQUES, University of California Press, 1963.

13. Bendat, Julius S., PRINCIPLES AND APPLICATION OF RANDOM NOISE THEORY, John Wiley and Sonc, Inc., 1958.

14. Berkson, J., ESTIMATION BY LEAST SQUARES AND BY MAXIMUM LIKELIHOOD, Third Berkeley Symposium of Mathematical Statistics and Probability, Edited by J. Neyman, University of California Press, 1956.

15. Bharucha-Reid, A.T., ELEMENTS OF THE THEORY OF MARKOV PROCESSES AND THEIR APPLICATIONS, McGraw Hill Co., 1960.

16. Box, G.E.P. and Tiao, G.C., "A Further Look at Robustness via Bayes Theorem," Biometrika, 49; 3 and 4, 1962, pp. 419-432.

17. Buckley, M.H., and Duff, R.A., "Exponential Smoothing with Variable Alpha," General Electric Company, May 1964.

18. Cruickshank, A.J.O., "A Note on Time Series and the Use of Jump Functions in Approximate Analysis," Proc. Inst. Elec. Engrs., Vol. 102, p. 81, 1955.

19. Champernowne, D.G., "Sampling Theory Applied to Autoregressive Sequences," Journal of the Royal Statistical Society, B10, 1948, pp. 204-231.

20. Clark, C.J., "On Stochastic Processes and Their Representations," Sylvania Electric Products, Ohio, April 1964.

21. Cochrane, D. and Orcutt, G.H., "Application of Least Squares Regression to Relationships Containing Auto-Correlated Error Terms," Journal of the American Statistical Association, 44, 1949, pp. 32-61.

22. Coombs, S.R., "Three Dimensional Probable Error," January 1964.

23. Davis, H.T., "The Statistics of Time Series," Math. Monographs, Vol. 1, pp. 45-85, Northwestern Univ., Evanston, Ill., 1941.

24. Deming, L.S., "Selected Bibliography of Statistical Literature, 1930 to 1957: 11 Time Series, Journal of Research of the National Bureau of Standards, B, Mathematics and Mathematical Physics, Vol. 64B, No. 1, January - March 1960.

25. Domb, C., "The Statistics of Correlated Events," Philos, Mag., Vol. 41, p. 969, 1950.

26. Durbin, J., "Estimation of Parameters in Time-Series Regression Models," Journal of the Royal Statistic Society, Series B, 22, 1960, pp. 139-153.

27. Ezekiel, Mordeai and Karl A. Fox, <u>METHODS OF CORRELATION ANALYSIS AND REGRESSION ANALYSIS</u>, 3rd Edition, John Wiley and Sone, Inc., 1956.

28. Geisser, S., "The Modified Mean Square Successive Difference and Related Statistics," Ann. Math. Statist., Vol. 27, p. 819, 1956.

29. Ghurye, S.G., "A Method of Estimating the Parameters of an Autoregressive Time-Series," Biometrika, 37, 1950, pp. 173-178.

30. Glasser, M., "Linear Regression Analysis with Mission Observations Among the Independent Variables," Journal of American Statistical Association, Vol. 59, September 1964, pp. 834-844.

31. Grant, A.M., "Some Properties of Runs in Smoothed Random Series," Biometrika, Vol. 29, p. 198, 1952.

32. Graybill, Franklin, A., <u>AN INTRODUCTION TO LINEAR STATISTICAL MODELS</u>, Vol. 1, McGraw Hill Co., Inc., 1961.

33. Hald, <u>STATISTICAL THEORY WITH ENGINEERING APPLICATIONS</u>, John Wiley and Sons, Inc.

34. Hannan, E.J., <u>TIME SERIES ANALYSIS</u>, John Wiley and Sons, Inc., 1960.

35. Hoel, P.G., "Confidence Bands for Polynomial Curves," Ann. Math. Statist., Vol. 25, p. 534, 1954.

36. Johnson, N.L., "Alternative Systems in the Analysis of Variance," Biometrika, Vol. 35, p. 80, 1948.

37. Kemeny, John G., and J. Laurie Snell, FINITE MARKOV CHAINS, D. Van Nostrand Co., Inc., 1960.

38. Kendall, M.G., "On Autoregressive Time Series," Biometrika, 33, 1944, pp. 105-122.

39. Kendall, M.G., "Regression, Structure, and Functional Relationship," Biometrika, 38, 1951, pp. 11-25.

40. Kendall, M.G., "The Advanced Theory of Statistics," Vol. II, Charles Griffin Co., London, W.C. 2, 1946.

41. Kenney, MATHEMATICS OF STATISTICS, D. Van Nostrand Co.

42. Kudo, A., "Note of the Estimation of the Mean Value of the Stochastic Process," Bull. Math. Statist., Vol. 5, p. 53, 1953.

43. Liebermann, C.R., "Rolling Type Alighting Gear Weight Estimation," Society of Aeronautical Weight Engineers, 1960.

44. Liebermann, C.R., and Tilyou, C., "The Unity Equation and Growth Factor," Society of Aeronautical Weight Engineers, 1960.

45. Luvsanceren, S., "Maximum Likelihood Estimates and Confidence Regions for Unknown Parameters of a Stationary Gaussian Process of Markov Type," Doklady Akad. Nauk., SSSR, Vol. 98, p. 723, 1954.

46. Mann, H.B., and Wald, A., "On the Statistical Treatment of Linear Stochastic Difference Equations," Econometricia, Vol. II, Nos. 3 and 4, July-October 1943, pp. 173-220.

47. Mattila, S., "Some Tests Based on Moving Average Operations on Time Series," Ann. Acad. Sci. Fenn., Series A., p. 226, 12 pp., 1956.

48. Neyman, Jerzy (Editor), THIRD BERKELEY SYMPOSIUM OF MATHEMATICAL STATISTICS AND PROBABILITY, University of California Press, 1956.

49. Osborne, M.F.M., Reply to "Comments on 'Browian Motion in the Stock Market,' " Operational Research, Vol. 7, 1959, pp. 807-811.

50. Papoulis, PROBABILITY, RANDOM, VARIABLES, AND STOCHASTIC PROCESSES, McGraw-Hill Book Company, Inc., 1963.

51. Parzen, E., "A New Approach to the Synthesis of Optimal Smoothing and Prediction Systems," Chapter 5 of Mathematical Optimization Techniques, edited by R. Bellmann, University of California Press, 1963.

52. Parzen, E., "An Approach to Time Series Analysis," Annals. of Math. Statistics, Vol. 32b, 1961, pp. 951-989.

53. Parzen, E., "Probability Density Functionals and Reproducing Kernel Helbert Spaces," Chapter 11 of Time Series Analysis, edited by M. Rosenblatt, John Wiley and Sons, Inc., 1962.

54. Plackett, R.L., PRINCIPLES OF REGRESSION ANALYSIS, Oxford University Press, 1960.

55. Raiffa, Howard and Robert Schlaifer, "Applied Statistical Decision Theory," Harvard University, Division of Research, 1961.

56. Robbins, H., "The Empirical Bayes Approach to Statistical Decision Problems," Annals. of Math. Statistics, Vol. 35, No. 1, March 1964.

57. Rosenblatt, M., RANDOM PROCESSES, Oxford University Press, 1962.

58. Rosenblatt, Murray (Editor), TIME SERIES ANALYSIS, John Wiley and Sons, Inc., 1962.

59. Rudra, A., "A Method of Discrimination in Time Series Analysis," 1., Sankhya, Vol. 15, p. 9, 1955.

60. Rudra, A., "A Method of Discrimination in Time Series Analysis," 11., Sankhya, Vol. 17, p. 51, 1956.

61. Savage, L.J., "BAYESIAN STATISTICS," RECENT DEVELOPMENT IN INFORMATION AND DECISION PROCESSES, The Maximillan Co., 1962.

62. Scheid, F., "The Under-Over-Under Theorem," American Mathematical Monthly, Vol. 68, November 1961, pp. 862-871.

63. Schlaifer, Robert, INTRODUCTION TO STATISTICS FOR BUSINESS DECISIONS, McGraw Hill Co., Inc.

64. Schlaifer, Robert, PROBABILITY AND STATISTICS FOR BUSINESS DECISIONS, McGraw Hill Co., Inc. 1959.

65. Spiegel, Murray R., THEORY AND PROBLEMS OF STATISTICS, Schaum Pub. Co.

66. Strand, T.G., et al., "Modification to the Newton-Raphson Method for the Fitting of Non-Linear Functions by Least Squares," Indiana University, May 1963.

67. Takacs, L., STOCHASTIC PROCESSES, John Wiley and Sons, Inc., 1960.

68. Tiao, G.C., and Zellner, A., "Bayer' Theorem and the Use of Prior Knowledge in Regression Analysis," Biometrika, 51, 1 and 2, 1964, pp. 219-230.

69. Walker, A.M., "A Goodness of Fit Test for Spectral Distribution Functions of Stationary Time Series with Normal Residuals," Biometrika, Vol. 43, p. 257, 1956.

70. Whittle, P., "Some Results in Time Series Analysis," Skand. Aktaurietidskr, Vol. 35, p. 48, 1952.

71. Wiener, Norbert, EXTRAPOLATION, INTERPOLATION, AND SMOOTHING OF STATIONARY TIME SERIES, John Wiley and Sons, Inc., 1949.

72. Wilks, S.S., MATHEMATICAL STATISTICS, Princeton University Press.

73. Williams, E.J., REGRESSION ANALYSIS, John Wiley and Sons, Inc., 1959.

74. Wold, H., DEMAND ANALYSIS, John Wiley and Sons, Inc., 1962.

75. Wold, H., "A Study in the Analysis of Stationary Time Series," 2nd Edition, (Almqvist and Wiksell. Stockholm, 1954), Vol. 15, p. 118.

76. Wold, H., "Forecasting by the Chain Principle," Chapter 28 of Time Series Analysis, Edited by M. Rosenblatt, John Wiley and Sons, Inc., 1962.

77. Yaglom, A.M., AN INTRODUCTION TO THE THEORY OF STATIONARY RANDOM FUNCTIONS, Prentice-Hall, Inc., 1962.

78. Zellner, A., and Tiao, G.C., "Bayesian Analysis of the Regression Model with Auto-Correlated Errors," Journal of American Statistical Association, Vol. 59, September 1964, pp. 763-778.

NASA-Langley, 1966