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PREDICTIONS TO UNDERLYING COMPONENT

RELIABILITY ESTIMATES

THESIS

James R. Wolf
Captain, USAF

AFIT/GSO/ENS/89D-17

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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SENSITIVITY OF SPACE SYSTEM AVAILABILITY

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RELIABILITY ESTIMATES

THESIS

Presented to tne Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Space Operations

James R. Wolf, B.S., M.B.A.

Captain, USAF

December 1989

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AFIT/GSO/ENS/89D-17

Abstract

Space system availability prediction is the process of estimating the likelihood that a space system will be available to perform its assigned mission, as a function of time. The ability to make these predictions accurately is fundamental to the efficient employment of Air Force resources.

Availability prediction is based on the estimated reliability of individual spacecraft and the components of which they are comprised. This study made use of response surface methodology to determine the sensitivity of the system availability prediction to the estimated reliabilities of individual spacecraft components.

The study was conducted in two steps. First a coarse screening was conducted to identify components which significantly influenced the parameters of a best-fit Weibull approximation to the spacecraft reliability function. Then the Weibull parameters and the availability prediction itself were regressed against the reliabilities of the critical components and the results were used to quantify the effects of uncertainty in the reliability estimates.

For the spacecraft and mission models investigated, the screening technique was extremely successful, identifying 5 of 100 components at the box level as critical to the spacecraft reliability function. Availability, however, was found to be relatively insensitive to component reliability. In particular, the uncertainty failed to account for the fact that observed space system availability usually ... exceeds

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the prediction. This may be due to overly-conservative factors in the reliability analysis such as duty cycle and stand-by redundancy correction factors, or it may be that uncertainty in the individual component reliability estimates is signifcantly greater than was assumed in the study. Further research is required to resolve this issue.

To the extent that the spacecraft reliability function can be trusted, the response surface methodology employed here provides a very useful way to quantify the benefits that might be received either by improving the reliability of critical components or by reducing the uncertainty in their reliability estimates.

SENSITIVITY OF SPACE SYSTEM AVAILABILITY

PREDICTIONS TO UNDERLYING COMPONENT

RELIABILITY ESTIMATES

I. Introduction

Background

Space system availability prediction is the process of estimating the likelihood that a space system will be available to perform its assigned mission, as a function of time. The ability to make these predictions accurately is fundamental to the efficient employment of Air Force resources. Organizations at all levels of the Air Force and the Department of Defense use availability predictions to better understand their operational readiness and to develop and implement sound procurement policy.

The future availability of a space system is based on the reliability of the individual components of which it is comprised, and on the time intervals required for the procurement, launch, and testing of replenishment spacecraft. Because significant uncertainty exists in each of these areas, prediction models developed to aid decision-making must be employed with caution.

Currently, the most widely accepted method of making availability predictions is The Aerospace Corporation's Generalized Availability Program (GAP), a group of statistical computer tools developed in the

late 1960's and consolidated and significantly improved in 1981 (8:1-6).
In order to use GAP, the Air Force requires space systems contractors to
provide a reliability analysis of each spacecraft it procures. GAP
takes the results of this analysis, along with production schedules and
other data, as inputs. It then simulates a large number of missions for
the system, and uses the results to predict future availability (8:1-83;
14:1-24; 20:1-37).

Unfortunately, GAP has not proven to be a very accurate predictor
of availability. Reasons for this include large uncertainties in the
reliability analyses (6:10-37; 16:195-196), unforseen methods of
extending the useful life of individual spacecraft (15:1), fluctuations
in replenishment scheduling, and the normal difficulties of applying a
statistical analysis to the small populations commonly seen in space
systems. Of these, the uncertainty in the reliability analyses is
probably the major contributor to inaccuracy. Moreover, the magnitude
of the uncertainty -- that is, the confidence in the availability
prediction -- is unknown. In general, individual spacecraft tend to
function far longer than predicted, often by a factor of two or more
(6:114). This underestimation often leads to management decisions to
expend resources on system replenishment much earlier than necessary.

Reliability analyses are commonly reported in the form of a diagram
showing each component of a spacecraft and the connections and
dependencies between components, along with a reliability math model
showing how overall reliability is determined. Figure 1 is an example
of a typical reliability analysis of one spacecraft assembly. Each
component has a characteristic failure rate, and standard reliability

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Math Model: $P_s = P_1 P_2 P_3 P_4$

where: $P_1 = \exp(-\lambda_1 t)$

$P_2 = 1-[1-\exp(-\lambda_2 t)]^2$

$P_3 = \exp(-\lambda_3 t)\{1+(1/X)[1-\exp(-X\lambda_3 t)]\}$

X = Ratio of standby failure rate to active failure rate

$P_4 = \exp(-\lambda_4 t)$
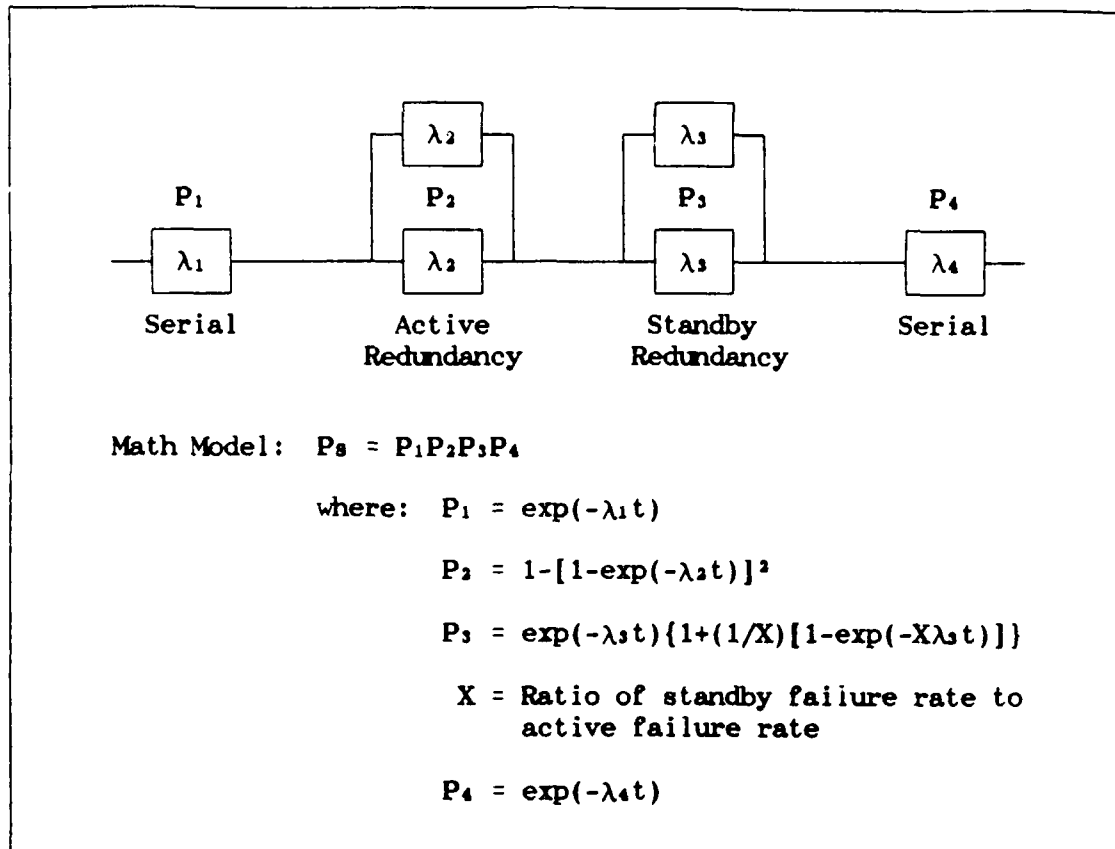
Fig. 1. Typical Reliability Diagram and Corresponding Math Model for a Simple System (14:11)

theory allows these rates to be combined according to the reliability diagram and math model into an overall reliability function for the spacecraft. For a complex system such as a satellite, with a large number of components and a high degree of redundancy, this overall reliability function is a complicated function of time. In order to make it computationally more manageable, a "best-fit" Weibull distribution is found via least-squares methodology with very little loss of accuracy. It is this Weibull function that is used by the GAP program (14:12-15).

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Component failure rates are generally assumed to be exponentially distributed:

$$P_s = \exp(-\lambda t) \qquad (1)$$

where P_s is the probability of successful operation at any given time, t, and λ is failures per unit time for the component.

This assumption has long been observed to be valid for electronic parts in ground-based applications, and, since electronics make up the vast majority of spacecraft components, the use of the exponential distribution seems reasonable. It has the advantage that a closed-form overall reliability function is achievable, but the disadvantage that component failure times, and thus system failure times, are relatively sensitive to small departures from the assumed component failure rates (11:2).

Another complication is that space systems contractors many times report "equivalent" failure rates for components at higher than the piece-part level and build the system reliability math model from these equivalent rates. This implies curve-fitting the reliability function of these intermediate level components to an exponential distribution. This will be accurate only in the case of components whose piece-parts are functionally serial and have exponentially distributed failure times themselves. For more complex components, an error is introduced into the reliability function which is greatest at the beginning and end of the expected component lifetime.

Failure rates are obtained from many sources, including piece-part and component level factory testing, subjective assignment based on

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similar components, and standard references (12:391). In some cases, these rates may be updated based on limited operational experience or new test data. But in the majority of cases, the rates are derived from the application of statistical techniques to very small populations, leading to a very low level of certainty about their accuracy. Furthermore, this uncertainty increases with the complexity of the system until, at the spacecraft level, the accuracy of the reliability function is both uncertain and very sensitive. The greater the uncertainty in the reliability function, the more limited is availability prediction as a management tool.

Objective

The objective of this research was to investigate the sensitivity of space system availability predictions to uncertainties in contractor-supplied reliability data. Components whose reliability strongly influences availability are identified as potential candidates for further investigation, and the effects on availability of improving the reliability of these critical components is quantified.

The investigation is conducted conceptually in two steps; first the sensitivity of the Weibull approximation of the spacecraft reliability function to component failure rates is determined, and then the effect of the possible ranges of the Weibull parameters on the availability prediction is assessed.

Sub-objectives. The following are sub-objectives of this research:
1. Identify an appropriate space system to use as a subject of the sensitivity investigation. The system should be reasonably simple, it

should have complete and easily available reliability data, and it must be unclassified.

2. A spacecraft may be conceptually broken down successively from the spacecraft level to the subsystem level, to the "box" level, to the assembly level, to the subassembly level and, finally, to the piece-part level. Determine the lowest level at which sensitivity can realistically be evaluated.

3. Formulate an experimental design to determine the sensitivity of the parameters of the Weibull approximation to failure rates at the lowest practical level.

4. Apply the GAP program to predict the availability of a system of spacecraft based on the chosen spacecraft model. Determine the sensitivity of the prediction to the previously determined range of the Weibull function and, thus, on the input component failure rates. Use this information to evaluate the confidence one may have in the GAP prediction.

5. Determine the usefulness of this type of analysis to a procurement agency in the efficient employment of resources, either to increase confidence in the reliability estimates of those components to which availability is most sensitive, or to improve their reliability.

6. Determine the usefulness of this type of analysis to an operational agency as a decision tool in scheduling system replenishment and in assessing operational readiness.

Scope

This research does not attempt to validate component failure rates, but investigates the changes in predicted system availability with

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chan__s in the supposed individual component rates. It was anticipated that the results would indicate that the predictions are considerably more sensitive to failure rates in some components than in others. This would, in turn, allow recommendations to be made regarding the efficient employment of effort during reliability analysis to be sure that the failure distributions of those components were known with confidence. It would also identify the most critical components as possible candidates for further research to improve their reliability.

Furthermore, an understanding of the sensitivity of availability predictions to component failure rates is a first step toward understanding the degree of confidence one may have in the predictions. This, in turn, allows a manager to make a better assessment of system status and operational readiness.

The input component failure rates are not the only potential source of uncertainty in availability prediction. There are at least three others; the approximation of the satellite reliability function by a Weibull function, variance internal to the GAP s_mulation, and uncertainty of the time intervals required for the procurement, launch, and testing of replenishment spacecraft.

The Weibull approximation is addressed briefly in this research and the uncertainty due to its use is believed to be generally negligible. The variance internal to GAP is not addressed but is assumed by regular users to be small when the number of simulations is large (8:15; 20:27-28).

Uncertainty of replacement time intervals is not addressed. GAP provides for replenishment based on need (the failure of an operational

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satellite) or on schedule (the preplanned delivery and launch of a new spacecraft). In both cases, perfect knowledge of the production schedule is required, both for satellites and launch vehicles (8:33-36). If these change at a later date, a new GAP availability prediction will be required.

Summary

Space system availability predictions are used routinely throughout the Air Force and the Department of Defense to assess readiness and to schedule procurement of replenishment and follow-on systems. Yet, the underlying component reliability estimates from which the system availability is predicted may be highly uncertain, making it impossible to assess the degree of confidence one may have in the prediction.

II. Literature Review

Introduction

The following is a brief review of the professional literature relevant to space systems availability. The discussion includes a short recapitulation of the history of reliability as a discipline and its application to space systems availability prediction, current paths of research into better ways to predict the reliability of space systems, and the need to better understand the effect of reliability analysis uncertainties on availability predictions.

Discussion

Historical Perspective. Until about 40 years ago, no formal engineering reliability discipline existed. In the late 1940's and early 50's, the concept of "reliability" slowly emerged from a general understanding that better-made equipment lasted longer, to the beginning of the field we know today. Perrotta and Somma give credit for the first qualitative definition of reliability to Robert Lusser, in 1952: "The reliability of an object is the probability that it will perform correctly for an assigned period of time and under specific conditions" (16:189). The use of the word "probability" in this definition is significant, as reliability theory leans heavily on probability theory. We will define the time-dependent reliability, R, of a system simply as the probability of successful operation:

$$R(t) = P_s(t) \qquad (2)$$

As systems increased in complexity and cost during World War II and the post-war period, reliability became more important to the efficient employment of resources, at both the national and commercial levels. During this time, much previous literature which had gone under such headings as failure statistics, life testing, fatigue, maintenance, and duty cycles, was grouped together into the field of reliability (16:189-190).

At about this same time, the United States began to design and build space systems. These systems were not only some of the most complex and costly conceived to date but had the nearly unique problem of having to operate with no maintenance at all. Clearly, the reliability of these systems was of the utmost importance. Shooman noted that the percentage of successful NASA space launches increased from 62 to 83 percent in the short period from 1961 to 1964, indicating that this fact was not lost on the space community, and that ". . . in space programs reliability engineering is not a costly extra but the only possible way to try and keep the tremendous costs within bounds by making every rocket shot count" (18:8-9).

The predicted reliability of early space systems was nothing more than an extrapolation of the ground operating characteristics of parts similar to those used on spacecraft to the expected operating conditions in space, along with the liberal statistical manipulation of some limited laboratory test data. This technique, although somewhat refined, is still a major source of reliability predictions today.

In the middle 1960's, the Air Force and the U.S. Navy began to plan space missions in terms of constellations of satellites, rather than a

single vehicle at a time. In this context, reliability is even more important, since the predictions and observations of one satellite's performance can be directly applied to the entire constellation.

Also, it is at this point that the concept of "availability" becomes important. Availability refers to the probability, as a function of time, that a space system is available to perform its assigned mission, where the "system" may include several satellites, as well as ground-based support, launch facilities, production lines for replenishment satellites and launch vehicles, etc.

The underlying problem in space system reliability calculations is that a prediction, not a demonstration, is usually the most that can be hoped for. It would be very nice to have the time and resources to fully test systems at the piece-part, assembly, "box," subsystem, and system levels, to remove all doubts about the true reliability, but this is seldom practical. This leaves only predictions of reliability, the quality of which must rest on the quality of the assumptions implicit in the analysis. As Hiltz observed:

> . . . these estimates are based upon a priori knowledge without which no estimate would be possible. Unfortunately, a prediction is not a demonstration. It might be postulated that equipment reliability can be demonstrated if (and only if) sufficient test data can be accumulated to provide irrefutable evidence that the failures encountered during the tests are consistently characteristic of equipment failures. . . The risk associated with the decision will be a function of the assumptions made and the degree of conservatism employed. If gross assumptions are made, the prediction is also gross. (7:19)

Under these conditions, The Aerospace Corporation developed GAP to support Air Force Systems Command's acquisition of military space systems. Although GAP does not calculate reliability itself,

reliability is an important input to the availability prediction
algorithm (8:1-83; 14:1-24; 20:1-37).

Figure 2 is a conceptual diagram of the GAP simulation program,
showing its inputs and outputs. To predict system availability, one
inputs, as a minimum, the reliability of each spacecraft, the spacecraft
production and delivery schedule, the launch schedule, the launch
success probability, and the spacecraft orbital test timeline. The
basic methodology used by GAP has been widely disseminated and used
(4:1021-1025; 9:3-17).
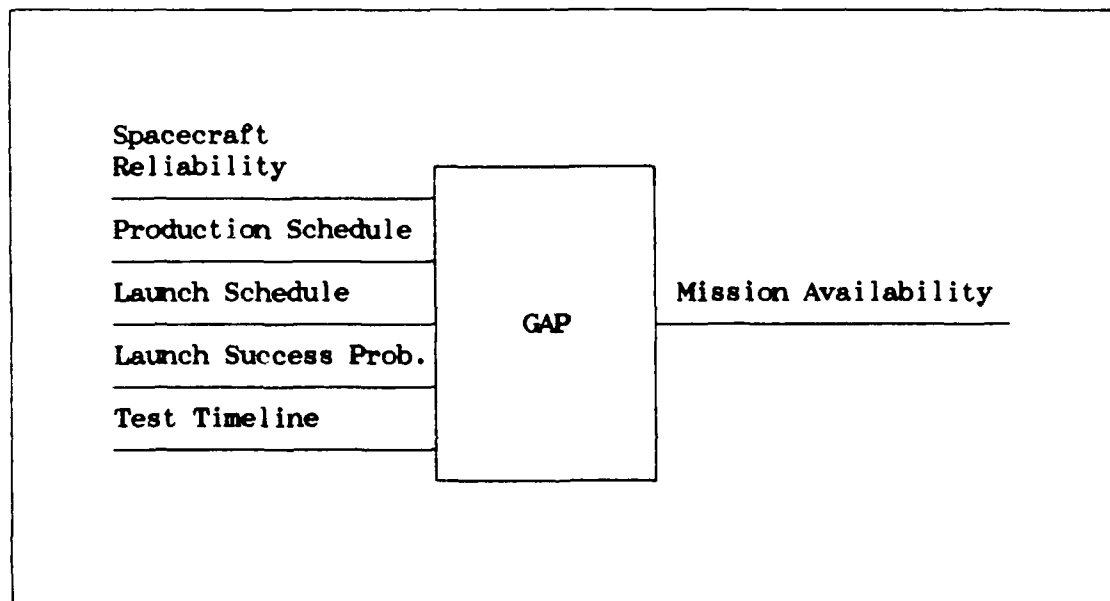
Fig. 2. Conceptual Diagram of the Aerospace Corporation's Generalized
Availability Program (GAP) Simulation Model

For more complex scenarios, GAP is capable of handling a variety of
satellite reliability inputs, requirements ˙)r orbiting and ground-based
spare spacecraft, and truncation of individual satellite lifetimes due
to fuel depletion or other cause.

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But, for all its flexibility, GAP does not accurately predict the availability of space systems. The typical experience, in both the Department of Defense and in the commercial world, is that individual spacecraft survive far longer than predicted. The only GAP input that can account for the discrepency is spacecraft reliability. Some method of improving the reliability estimate is clearly needed.

In the last few years, sufficient orbital experience has been accumulated to seriously begin adapting prediction methods to more closely match observed spacecraft reliability. In 1984, Bloomquist reported on the results that could be achieved by analyzing Planning Research Corporation's On-Orbit Spacecraft Reliability (OOSR) database (then consisting of 374 spacecraft, 2500 anomalies, and over 3.75 million spacecraft operating hours) to categorize anomalies and identify trends (2:186-191).

In 1985, Hecht and Hecht used both the OOSR database and The Aerospace Corporation's Orbital Data Acquisition Program (ODAP) database to put together anomaly data on ". . . over 300 satellites comprising 96 programs which were launched between the early 1960s through January of 1984" (6:1). They used the data to develop two separate methods by which space system reliability prediction could be improved to more closely correspond to on-orbit observations.

These are welcome accomplishments and, although the methods have not yet become widely accepted, capability exists in GAP and similar models to incorporate them through the use of correction factors. Their weakness is that they attempt to modify predictions for individual systems to fit the observed reliability of the entire population of

historical spacecraft. Any attempt to distinguish newer programs from older, or to categorized spacecraft reliability by mission type, much less individual spacecraft type, rapidly diminishes the available database to the point where there can be little statistical confidence in the results obtained.

The current state of space system reliability prediction, then, is dominated by two factors: an analytical approach to prediction which does not correlate well to observation, and observations which, although very valuable, cannot be employed with high confidence to individual spacecraft.

Current Research. Reliability analysis is based on the fact that, at any given time, a system can be described as set of exhaustive and mutually exclusive states, where each state is a vector whose elements are the operating status of each component of the system. Usually, a vector element is set equal to "1" if the corresponding component is operable and "0" if it has failed. For instance, the vector $\underset{\sim}{S}$ = $\{1,1,1,\ldots,1\}$ would represent the state where all components are operable.

For a system made up of k components then, there are 2^k mutually exclusive states that the system may occupy. At any given time, there is a probability associated with each state that the system will occupy that state. In this way, calculation of reliability can be accomplished through the computation of probabilities associated with each state, as functions of time, and summing of the probabilities associated with those states that correspond to satisfactory operating conditions of the

system as a whole. If n out of the 2^k possible states represent

satisfactory operating conditions then, at any time of interest:

$$P_s = \sum_{i=1}^{n} P_i \qquad (3)$$

Also, the probability of failure, Q_s, is given by:

$$Q_s = 1 - P_s \qquad (4)$$

The following methods of making these calculations, based on

different assumptions, are taken primarily from a 1983 paper by Perrotta

and Somma (16:192-196).

The Combinatorial Approach. This is the simplest and most

widely used method of calculating reliability. Its basis is the

calculation of state probabilities from a functional diagram of the

system and known failure rates of individual components. A functional

diagram is nothing more than a representation of the system as a path,

or paths, from one component to another, at least one of which must be

fully operable in order for the system to operate (Figure 1).

The system diagram, as complicated as it may be, is built up of

combinations of serial and parallel component paths, the reliability of

which can easily be calculated from basic reliability theory (18:120-

124).

For n components in series:

$$P_s = P_1(P_2 \mid P_1)(P_3 \mid P_1,P_2) . . . (P_n \mid P_1,P_2, . . . ,P_{n-1}) \qquad (5)$$

where P_i is the probability that the ith component is operating correctly. For independent failures:

$$P_s = \prod_{i=1}^{n} P_i \qquad (6)$$

or, for identical components:

$$P_s = (P)^n \qquad (7)$$

For n components in parallel:

$$P_s = 1 - Q_1(Q_2|Q_1)(Q_3|Q_1,Q_2)\ldots(Q_n|Q_1,Q_2,\ldots,Q_{n-1}) \qquad (8)$$

where, from Eq (4), $Q_i = 1 - P_i$. For independent failures:

$$P_s = 1 - \prod_{i=1}^{n} Q_i \qquad (9)$$

or, for identical components:

$$P_s = 1 - (Q)^n \qquad (10)$$

System reliability calculation are commonly simplified further by making the assumption that the failure rates of individual components are constant with time, as given in Eq (1) (5:1). This implies that times between component failures can be modeled using an exponential distribution, and allows the computation of a system level reliability function fairly easily, since:

$$P_i = \exp(-\lambda_i t) \qquad (11)$$

The constant failure rate assumption has long been observed to be valid for electronic parts in ground-based applications. Since electronics make up the majority of spacecraft components, the extension

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of the assumption to spacecraft seems natural on the surface. As more actual observation data is accumulated, however, it is beginning to appear that other factors may dominate (6:10; 11:8-9).

Nevertheless, the combinatorial method and its derivative, fault tree analysis, are widely used. Government space system contractors use combinatorial methods almost exclusively to calculate system reliability. Current effort is primarily directed toward more efficient algorithms for analyzing the reliability of complex systems.

The Markov Approach. The Markov method of reliability prediction has been applied to space systems because, in general, failures of components are not entirely independent for systems with redundancies. When this is the case, the combinatorial method cannot be applied without some a priori knowledge of the system conditional failure probabilities -- knowledge that is seldom practical to obtain.

The Markov method, on the other hand does not require this knowledge. The method rests on the Markovian assumption that the probability of transition from one state to another is constant, regardless of how the system reached the first state. It is then possible to examine and sum the probabilities of transitioning to states which allow the system to operate, given any initial state.

The disadvantages of this method are that it can be computationaly impractical for complex systems and that it includes an implicit assumption that a failed component will be replaced, if at all, with a redundant component of the same age, rather than one which is essentially new. No mathematical development of the Markov approach is

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given here because it is not used in the reporting of space system reliability analyses by government contractors.

Current research efforts on Markovian reliability methods are concerned with both problems. In the case of the replacement assumptions, "renewal theory" attempts to make the non-Markovian process of replacement with a new unit into a Markovian process through the introduction either of artificial state vector elements or of artificial transitory states. While mathematically appealing, these methods serve to separate the analysis from reality, in a sense, and have not been widely accepted.

Empirical. Empirical methods are becoming available as data on observed orbital reliability is accumulated. An empirical method is merely the application of past observations of reliability to present or future systems. Although it is sometimes difficult to intuitively justify the application of past reliability observations to new and different systems, the evidence indicates that much greater accuracy can be obtained using empirical data (6:112-126).

One of the most useful improvements obtained from empirical data may be an improved correction factor for failure rates of stand-by, powered down, redundant components. The government requires contractors to use a factor of 0.5 when estimating these rates, meaning the assumed failure rates of these components are half those of identical active units. In contrast, the commercial world uses a factor of 0.1. This represents a significant difference for these systems which have extensive redundancy, and the 0.1 factor appears to correspond more closely to reality (5:3).

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Uncertainty. Although reliability is only one of several factors included in the prediction of system availability, errors in its computation have a disproportionately large effect on overall accuracy. This is due to the multiplicative effect of errors on the overall reliability function of complex systems, the sensitivity of the reliability function to departures from the assumption of exponentially distributed failures at the component level, and the fact that reliability is a factor over the entire mission duration for most spacecraft components, not just before and during launch.

One of the most useful results of a thorough reliability analysis can be an understanding of the relative importance of system components to total system reliability (1:11). This allows a decision-maker to efficiently allocate resources to more fully understand the failure rates of critical components, thus improving the overall reliability estimate, and to improve those rates. Moreover, availability analysis is a management tool, and an understanding and a consciousness of the uncertainty in any management tool aids in its employment.

Summary

Space system reliability is, perhaps, the most important aspect of predicting system availability. As an engineering discipline, reliability is about 40 years old -- not much older than its application to space systems -- and room exists for improvement.

The techniques of reliability analysis developed to date do not accurately predict the on-orbit reliability of space systems. When combined with approaches based on empirical reliability data, however,

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much improvement can be made, although the confidence in applying these approaches to any given satellite is not high.

An understanding of the sensitivity of reliability and availability to errors in assumed component failure rates is essential in order to fully exploit the uses of availability prediction as a management tool.

III. Methodology

The Space System Model

While the methods developed here may be applied to any satellite or constellation of satellites, it was necessary to choose a particular system as an initial subject and to use the Generalized Availability Program (GAP) to predict its availability. The system chosen is a single communications satellite and a 15-year mission. In order to perform the mission, one fully operational spacecraft is required at all times and the designated 15-year mission begins at the time the first spacecraft is launched.

Along with individual spacecraft reliabilities, GAP requires the following additional inputs: number of satellites produced (two), and launch schedule (satellites will be launched at t = 0 and 72 months).

The actual satellite model chosen is the NATO III D communications satellite. Reliability information on NATO III D is taken directly from the satellite contractor's report to the Air Force (5:3-80). This spacecraft was chosen for its relative simplicity and because the data is easily available, is unclassified, and is reasonably complete.

The NATO III D satellite is broken down into seven subsystems: communications payload (COMM); telemetry, tracking, and command (TTC); attitude and antenna control (AAC); electrical power subsystem (EPS); reaction contol equipment (RCE); structure (STRUC); and apogee kick motor (AKM). Details on the model, including functional diagrams and the associated math model, are provided in Appendix A.

Only the first five subsystems are of immediate interest, since their reliabilities are functions of time. The AKM subsystem is used only for orbit injection at the beginning of the spacecraft's life, and it's reliability can be included with and input to GAP as probability of launch success. The satellite structure is stressed only by launch loads and operates thereafter in a nearly benign environment. Structual reliability, also, can be included with launch success probability.

System Level of Interest

A satellite may be conceptually broken down first into subsystems, then "boxes," assemblies, subassemblies, and piece-parts. An average satellite may have several tens of thousands of parts and, in fact, the NATO III D spacecraft has just over 43,000. Clearly, it is not practical to determine the effect of varying the assumed reliability of each part on the overall system availability prediction. Nor is it necessary since, at the piece-part level, the effects of very few, if any, components would have measurable effects.

The method of investigation presented here is to determine first, which subsystems most significantly affect system-level reliability, then which boxes are critical to these important subsystems. Further investigation -- what assemblies affect box reliability, what subassemblies affect the assemblies, etc. -- is not performed for several reasons.

First, it is not important in demonstrating the methodology. All techniques and known pitfalls can be shown by investigating to the box level.

Second, a point of diminishing returns is reached, where changes in the spacecraft reliability function are only marginally observable as the reliabilities of assembly and lower level components are varied. This is related both to the relative homogeneity of NATO III D assembly level failure rates and the nature of the Weibull parameter outputs of interest. For other systems and applications, a deeper level investigation may be required.

Third, the box level is the lowest level at which a spacecraft contractor commonly performs any life testing. Lower level life testing, if it is done at all, is done by vendors. Here, then, is a level at which reliability may be based, in a few cases, directly on test results and not on lower level failure rates and a math model.

Lastly, the box level is normally the level at which commandable redundancy is provided on a spacecraft. In the design phase, impact of box level reliability on system availability can directly bear on the redundancy and multiple-path circuitry provided in the final product. In the operational phase, changes in predicted system availability can easily be determined when on-orbit failures of redundant components do occur.

Experimental Design

Input failure rates at various levels for the spacecraft model are as given in Table A-1, Appendix A, and are assumed to be independent (5:1-80). This assumption of independence is common for complex systems made up primarily of electronic components and is completely valid at the piece-part level. At higher system levels, however, we must keep in mind that significant interactions between components may be present

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and, in fact, are likely to grow more pronounced with each level we move up.

Failure Rate Ranges and Variable Coding. Uncertainty in component failure rates comes, ultimately, from the limited amount of data available. For common piece-parts and simple subassemblies and assemblies, failure rates may be taken from standard references such as MIL-HDBK-217, which is a compliance document on all government space systems contracts. Other parts may be subjected to lot-testing techniques which allow fairly high confidence levels in their failure rates.

But uncertainty is much greater in the rates of more unique, and thus less exhaustively tested, components, and in components at higher levels where reliability is reported as equivalent failure rates. If a complete understanding of the effect of these uncertainties on the accuracy of the availability prediction is to be gained, one must have some prior knowledge, not just of every component's estimated failure rate, but also of the range of uncertainty in the estimate. If this information is not available, as it is not for the vast majority of components in complex systems, some subjective estimate of the likely range must be made by the investigator.

To simplify the methodology presented here, and because the investigation does not reach below the box level, a common range of plus or minus ten percent is used as the possible range over which all component failure rates may vary. The object then becomes the identification of those components which have the greatest effect on the

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system availability prediction as their failure rates, alone and in combination, are allowed to vary to these extremes.

For ease of later calculations, it is convenient to code the reliability extremes for each component so that the upper extreme transforms to 1 and the lower to -1. In general, a variable, U, may be mapped to the variable, X, ranging from -1 to 1 through the following transformation:

$$X = \frac{U - 0.5(U_{MAX} + U_{MIN})}{0.5(U_{MAX} - U_{MIN})} \tag{12}$$

In particular, the failure rate, λ, of each component will be mapped to X by:

$$X = \frac{\lambda - 0.5(\lambda_{MAX} + \lambda_{MIN})}{0.5(\lambda_{MAX} - \lambda_{MIN})} \tag{13}$$

Thus,

$$1 = \frac{\lambda_{MAX} - 0.5(\lambda_{MAX} + \lambda_{MIN})}{0.5(\lambda_{MAX} - \lambda_{MIN})} \tag{14}$$

and

$$-1 = \frac{\lambda_{MIN} - 0.5(\lambda_{MAX} + \lambda_{MIN})}{0.5(\lambda_{MAX} - \lambda_{MIN})} \tag{15}$$

μ

Table A-1 in Appendix A lists reported failure rates and failure rates corresponding to the extremes of their ranges for the NATO III D satellite model.

Two-Level Factorial and Fractional Factorial Design. Having coded the component failure rates to two levels, a maximum and a minimum, the effects of changes in these rates can be examined fairly simply via a

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two-level factorial design. This merely means observing the output of the model -- in this case, the predicted system availability -- at every possible combination of maximum and minimum component failure rate. If k components are to be considered, there will exist 2^k observations which must be taken if we are to fully understand the main effects of each component rate and all the possible interactive effects (3:105-109).

Clearly, the number of required observations rapidly becomes very large if there are more than a few components of interest. The simplest model we can hope to construct is one in which only the main effects of individual component failure rates are dominant, and that interactions among components are negligible. In this case, a much smaller number of observations may be taken. For this reason, the simple model is initially assumed and then supplemental observations are taken if it is found to be inadequate.

The number of observations required to assess only main events, given k components of interest, and the exact construction -- which component rates are set to maximum and minimum values for the observation -- can be obtained from reference tables (3:164-165). Experimental designs of this type are referred to as 2_R^{k-p} fractional factorial designs. R is the resolution of the design. To distinguish main effects only, it is necessary to construct a resolution III design, thus, 2_{III}^{k-p} designs will intially be required. If two-component interactive effects must be considered, a 2_{IV}^{k-p} design will be needed.

Regression Analysis and Response Surfaces. The general model for the effect of component reliabilities, X, on an output of interest, Y

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(to be further defined shortly), is assumed to be of the following form
when only main effects are believed to exist:

$$Y = B_0 + B_1X_1 + B_2X_2 + \ldots + B_kX_k + \epsilon \qquad (16)$$

where B_0, B_1, B_2, . . . B_k are constants to be determined and ϵ is
random error.

This is referred to as a first-order linear model with k
independent variables, meaning it is linear in the parameters, B, and
linear in the independent variables, X (13:227). Regression analysis
provides the tools whereby Y may be estimated by estimating B_0, B_1, B_2,
. . . B_k. This allows us to construct a new model:

$$\hat{Y} = \hat{B}_0 + \hat{B}_1X_1 + \hat{B}_2X_2 + \ldots + \hat{B}_kX_k \qquad (17)$$

where the hat sign ($\hat{\ }$) indicates an estimated quantity.

If two-component interactions are present, Eq (17) must be
supplemented:

$$\hat{Y} = \hat{B}_0 + \hat{B}_1X_1 + \hat{B}_2X_2 + \ldots + \hat{B}_kX_k + \hat{B}_{1,2}X_1X_2 + \hat{B}_{1,3}X_1X_3$$

$$+ \ldots + \hat{B}_{k-1,k}X_{k-1}X_k \qquad (18)$$

For a detailed presentation of regression analysis, see Neter,
Wasserman, and Kutner, 1985 (13:23-296). For the purpose at hand, it is
sufficient to note that B_0, B_1, B_2, . . . B_k may be estimated by the
following matrix equation:

$$\hat{\underset{\sim}{B}} = (\underset{\sim}{Z}'\underset{\sim}{Z})^{-1}\underset{\sim}{Z}'\underset{\sim}{Y} \qquad (19)$$

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where $\underset{\sim}{Z}$, the design matrix, is a square matrix constructed from the appropriate factorial or fractional factorial design and supplemented by a column of 1's in the first column. Other columns correspond to separate main effects or interactions and denote, by +1 or -1, whether they are at a maximum or a minimum for each run. Figure 3 shows the construction of the design matrix for a 2^3 full factorial design.

Effect/Interaction:	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$
Run: 1 $\underset{\sim}{Z}$ =	+1	-1	-1	-1	+1	+1	+1	-1
2	+1	+1	-1	-1	-1	-1	+1	+1
3	+1	-1	+1	-1	-1	+1	-1	+1
4	+1	+1	+1	-1	+1	-1	-1	-1
5	+1	-1	-1	+1	+1	-1	-1	+1
6	+1	+1	-1	+1	-1	+1	-1	-1
7	+1	-1	+1	+1	-1	-1	+1	-1
8	+1	+1	+1	+1	+1	+1	+1	+1

Fig. 3. Design Matrix for a 2^3 Full Factorial Design.

Once the coefficients, B_0, B_1, B_2, . . . B_k, have been estimated, a graphical analysis may be used to determine the appropriateness of the model given by Eq (17) by plotting the residuals, e, against the predicted values, $\hat{Y}$. Residuals are merely the difference between the observed and the expected values:

$$e = Y - \hat{Y} \tag{20}$$

If the model is appropriate, e is expected to be randomly distributed with a mean of θ. The plot, then, should show that the residuals lie in

a horizontal band centered about 0. Any systematic departure indicates that the model may not be adequate (13:111-122).

Eqs (17) and (18) describes a surface in (k+1)-space, where k, now, is the number of components that have been judged to be significant and retained in the model. This "response surface" is a geometric interpretation of the model and the methodology by which we arrive at the model, including the designing of the experiment, is known as response surface methodology.

In this work, regression analysis is accomplished with the aid of the STATISTIX II software package. In addition to performing the above calculations, this program allows easy comparison of alternate models, analysis of variance (ANOVA) and data plotting for residual analysis (19:1-66, 88-155).

The Weibull Reliability Function

For simple systems in which the components are functionally serial and have exponentially distributed failure times, the overall system reliability will be of the form given in Eq (1). This is easily seen from Eqs (1), (2), and (6):

$$R = [\exp(-\lambda_1 t)][\exp(-\lambda_2 t)] \ . \ . \ . \ [\exp(-\lambda_k t)]$$

$$= \exp(-\lambda_1 t - \lambda_2 t - \ . \ . \ . \ - \lambda_k t)$$

$$= \exp(-\Lambda t) \quad , \quad \Lambda = \lambda_1 + \lambda_2 + \ . \ . \ . \ + \lambda_k \tag{21}$$

Such a reliability model is unsatisfactory, however, for more complex systems. For the type of space system considered here, we will still be constrained by the assumption of exponentially distributed component failure times, but in constructing a system level math model

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we must also be concerned with such complicating factors as corrections for duty cycle and various functional redundancy configurations.

In this case, a more useful model is given by the two-parameter Weibull reliability function:

$$R = \exp(-t/\beta)^{\alpha} \qquad (22)$$

where α is referred to as the shape parameter and is dimensionless. β is the scale parameter and has the same units as t. For the degenerate case of $\alpha = 1$, it is easily seen that the Weibull reliability model of Eq (22) is equal to the exponential model of Eq (21) with $\Lambda = 1/\beta$. By an appropriate choice of the two parameters, α and β, a wide range of potential reliability functions can be approximated. The flexibility of the Weibull model is shown in Figure 4.
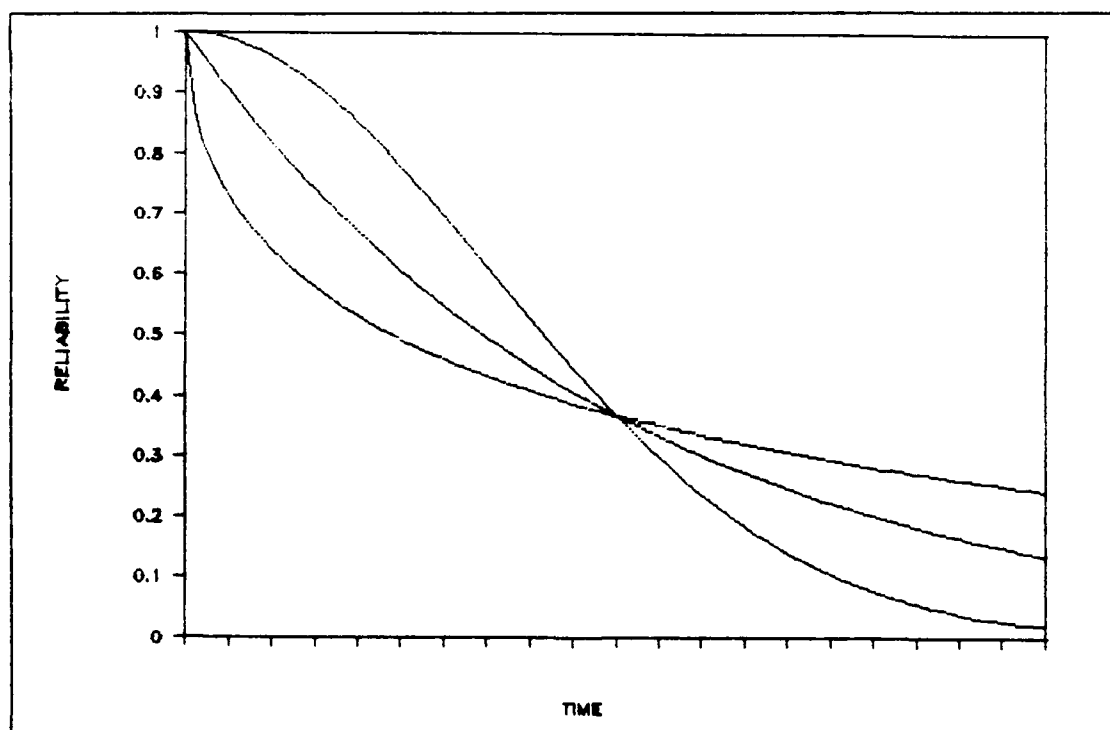
Fig. 4. The Weibull Reliability Function.

In order to evaluate availability, then, it will be necessary to perform a regression analysis to determine the effect of individual component failure rates on both α and β. Thus, we must be concerned with two separate models:

$$\hat{\alpha} = \hat{B}_{\bullet_\alpha} + \hat{B}_{1_\alpha}X_1 + \hat{B}_{2_\alpha}X_2 + \ldots + \hat{B}_{k_\alpha}X_k \tag{23}$$

and

$$\hat{\beta} = \hat{B}_{\bullet\beta} + \hat{B}_{1\beta}X_1 + \hat{B}_{2\beta}X_2 + \ldots + \hat{B}_{k\beta}X_k \tag{24}$$

Care must be taken not to eliminate without justification any components from the model which may significantly affect only one of the Weibull parameters. Again, we must be aware that this simple model may prove inadequate, and that we may be forced to adopt a more complex model of the form given in Eq (18).

Calculation of the System Reliability Function

NATO III D system reliability can be calculated for any given time, t, using the math model given in Appendix A. The parameters of a Weibull approximation to the system reliability function are estimated by evaluating the reliability at several values of t, spanning the time range of interest, and using a least-squares algorithm to curve-fit the resulting data.

This was accomplished via the Reliability Update Program (RUP), a dBASE III PLUS series of programs written for this investigation. RUP uses a Hooke-Jeeves vector search algorithm to optimize and by minimizing the square of Eq (20) (17:511-515). Other capabilities include calculation of equivalent exponential failure rates at all levels via the method of maximum likelihood (10:159) and easy editing of

individual component failure rates and the times at which reliability
will be evaluated. RUP code and data files are given in Appendix B.

The NATO III D spacecraft was designed for a seven-year life and,
in all cases for this research, system reliability was evaluated at 20
values of t spanning 156 months (13 years) to achieve a good
approximation. The resulting estimates of α and β are taken to be the
observations which are to be regressed for the models given by Eqs (23)
and (24). The NATO III D reliability function calculated by RUP for
nominal (contractor-reported) component failure rates is shown in Figure
5. Table 1 shows the accuracy of the Weibull approximation over the
156-month period, at the times that were used for all runs during this
investigation.
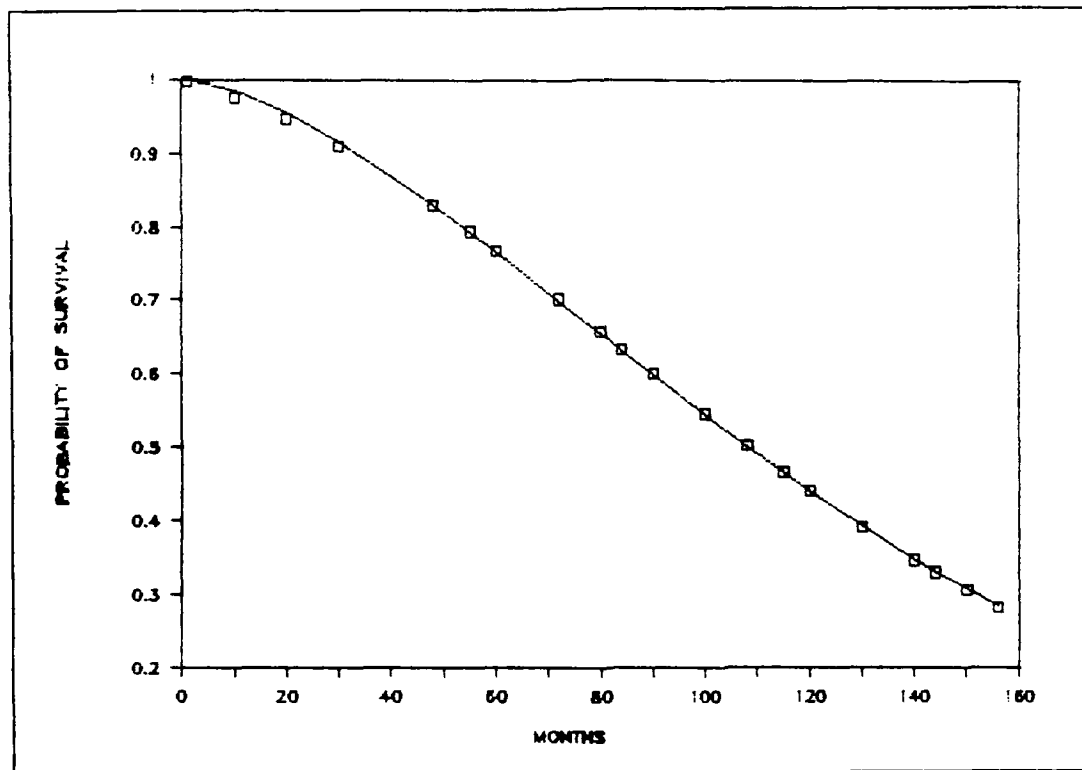
Fig. 5. NATO III D Spacecraft Reliability Function.

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Table 1. NATO III D Spacecraft Reliability and Weibull Approximation.

Time (months)	Calculated Reliability	Weibull Approximation
1	0.997848	0.999659
10	0.976314	0.985674
20	0.946534	0.956439
30	0.916169	0.917493
48	0.829648	0.831180
55	0.794156	0.793961
60	0.767749	0.766603
72	0.701910	0.699420
80	0.656950	0.654221
84	0.634388	0.631699
90	0.600643	0.598174
100	0.545200	0.543405
108	0.502071	0.500973
115	0.465539	0.465095
120	0.440255	0.440271
130	0.391958	0.392824
140	0.346963	0.348522
144	0.329940	0.331722
150	0.305475	0.307529
156	0.282304	0.284553

Calculation of the System Availability Prediction

Once the parameters of the Weibull approximation are known, they may be input to the Generalized Availability Program (GAP), along with the other inputs previously described, to predict system availability versus time. GAP is a Monte Carlo simulation model which makes entities (spacecraft in this case) available to the system according to the schedule specified by the input procurement delivery dates, launch and test delays, etc. From this point forward, the "system" will be understood to be the aggregate of the satellites being produced, rather than a single spacecraft. A random number between 0 and 1 is generated and may, with a probability equal to the input launch failure rate,

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destroy the entity before it can be made available. If a successful launch is simulated, the spacecraft's operational life begins. A second random number between 0 and 1 is generated and, through the inverse of the Weibull reliability function, a failure time is assigned to the spacecraft.

This procedure is repeated for each spacecraft and GAP keeps track of the time when the system is "available" -- that is, able to perform its mission. In the system used in this research, "available" equates to at least one operational satellite in orbit.

By making these calculations a large number of times -- typically 1000 -- GAP builds up statistics from which it calculates "probability of availability" versus time. This, finally, is the metric with which we are concerned (8:1-83; 14:1-24; 20:1-37).

This research was conducted using a personal computer version of GAP -- PC-GAP. Although much less flexible than the mainframe version, it is accurate for the simple space system postulated here. For more complex systems involving spacecraft with different reliabilities, dormant storage correction factors, wear-out reliability problems, truncation of operational life, etc., mainframe GAP is recommended.

By "availability prediction," we really mean "probability of availability versus time." For a single spacecraft with no launch success or scheduling uncertainty, the availability curve is the same as the spacecraft reliability curve. The problem is, in fact, deterministic at this point. As the overall system increases in complexity, however, due to the factors mentioned above, the complexity of a deterministic solution also increases and a simulation approach

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becomes attractive. Unfortunately, one of the main advantages of simulation -- that of easily calculating variance across the simulation runs and determining confidence intervals on the estimate under the assumption of an accurate model -- is not implemented by GAP. It is recommended that further research be conducted to incorporate these calculations.

Figure 6 shows the GAP availability prediction for the 15-year mission we have specified. As for any mission model consisting of more
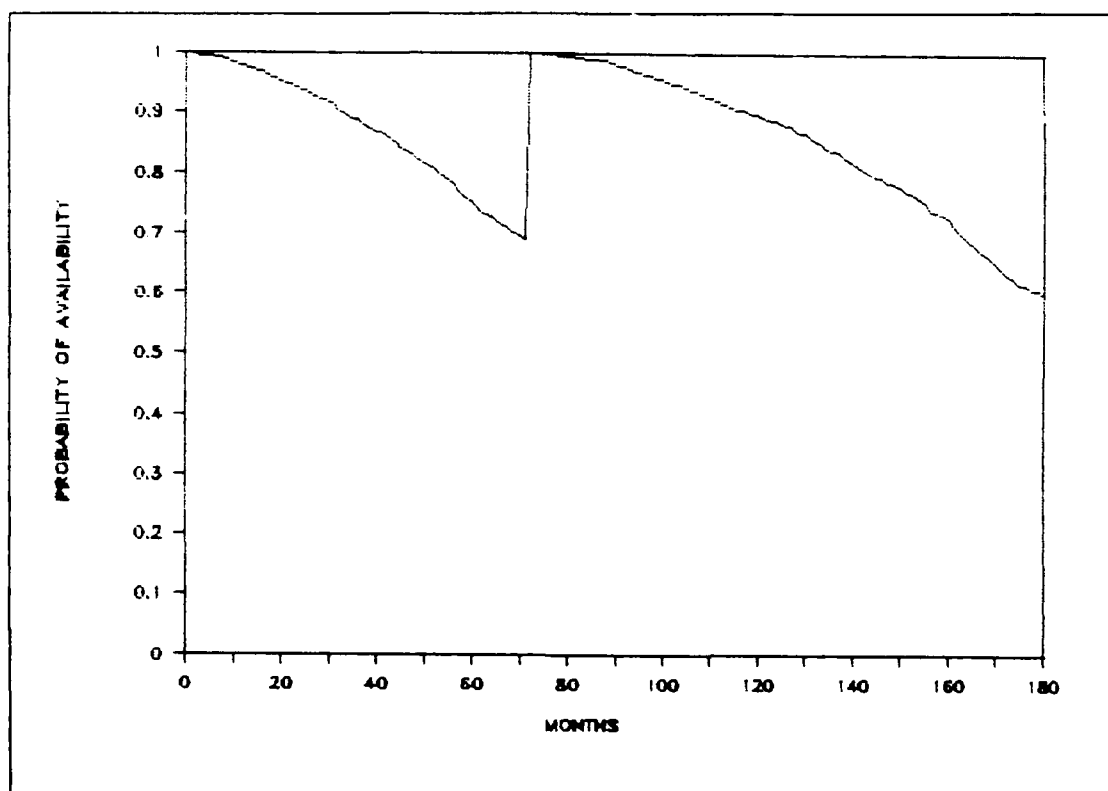
Fig. 6. GAP Availability Prediction for 15-Year NATO III D Mission

than one spacecraft, the availability prediction is a curve with discontinuities whenever a new satellite is made available to the system (launched). This curve is very useful to a system manager, and depth

and duration of its low points are of prime concern. Because only component reliability is allowed to change in this investigation, and not the mission model itself, we will take "average availability" to be a useful metric. This is nothing more than the point availability averaged across the 15-year mission duration. While this is not a commonly-used measure of mission posture, it provides us with a way to compare one prediction with another.

Summary

The end-to-end methodology applied here is as follows. First, failure rates for all components in the spacecraft are set to maximum and minimum values and the spacecraft reliability function for these two cases is determined. This provides bounds between which all subsequent runs should fall. The availability predictions associated with these runs are important in that they provide useful bounds on confidence in the baseline predictions, although they cannot be construed as confidence intervals in the normal sense.

Next, the sensitivity of the spacecraft-level Weibull reliability function approximation to subsystem-level failure rates is determined. This is done by setting the failure rates of all lower level components within a subsystem to maximum and minimum values according to an appropriate fractional factorial design and performing a regression analysis.

After those susbsystems important to the regression model are identified, a similar investigation is performed to determine which boxes within those critical subsystems are critical to the spacecraft-level reliability function.

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The adequacy of the model is assessed by performing another regression analysis where the components investigated are all those boxes determined to have been important, regardless of the subsystem to which they belong.

∴ GAF prediction is made at each design point of this final model to relate average availability directly to the failure rates of driver components.

IV. Implementation and Results

Baseline

The first step was to calculate the baseline reliability of the NATO III D satellite and the availability of the two-satellite system we specified. This was accomplished by, first, implementing the Reliability Update Program (RUP) with nominal failure rate data for all spacecraft components. Results of this stage were previously presented in Figure 5 and Table 1.

Figure 5 shows the calculated reliability of the satellite at 20 values of time spanning 156 months, as well as the RUP-fitted Weibull approximation. Table 1 lists the 20 reliability data points and the value of the Weibull approximation at the same times. The actual Weibull parameters calculated by RUP for the baseline case were: $\alpha = 1.626$, and $\beta = 135.54$ months.

Next, the baseline availability prediction was made by the Generalized Availability Program (GAP) using these calculated parameters. Other GAP input is listed in Table 2. The resulting prediction of availability versus time was shown in Figure 6 and the average availability over the 15-year mission was 0.8594. Figure 7 is a reproduction of Figure 6, with the fitted Weibull reliability function from Figure 5 superimposed to demonstrate the accuracy of the simulation. When only one satellite is present, the deterministic solution of the reliability function and the simulated availability should be identical except for the randomness of the simulation, and this is seen to be the case in the figure.

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Table 2. Baseline System GAP Inputs

Input	Value	
Duration	180	months
Time Step Size	1	months
α	1.626	
β	135.54	months
Number of Trials	1000	
Random Number Seed	1	
Single Launch Pad Constraint	YES	
Number of Constellations	1	
Active Satellites Required	1	
Spare Satellites Required	0	
Satellite 1: Production Time	0	months
Launch Delay	0	months
Launch Success Probability	1.0	
Wearout Expectation	NONE	
Truncation Expectation	NONE	
Satellite 2: Production Time	72	months
Launch Delay	0	months
Launch Success Probability	1.0	
Wearout Expectation	NONE	
Truncation Expectation	NONE	
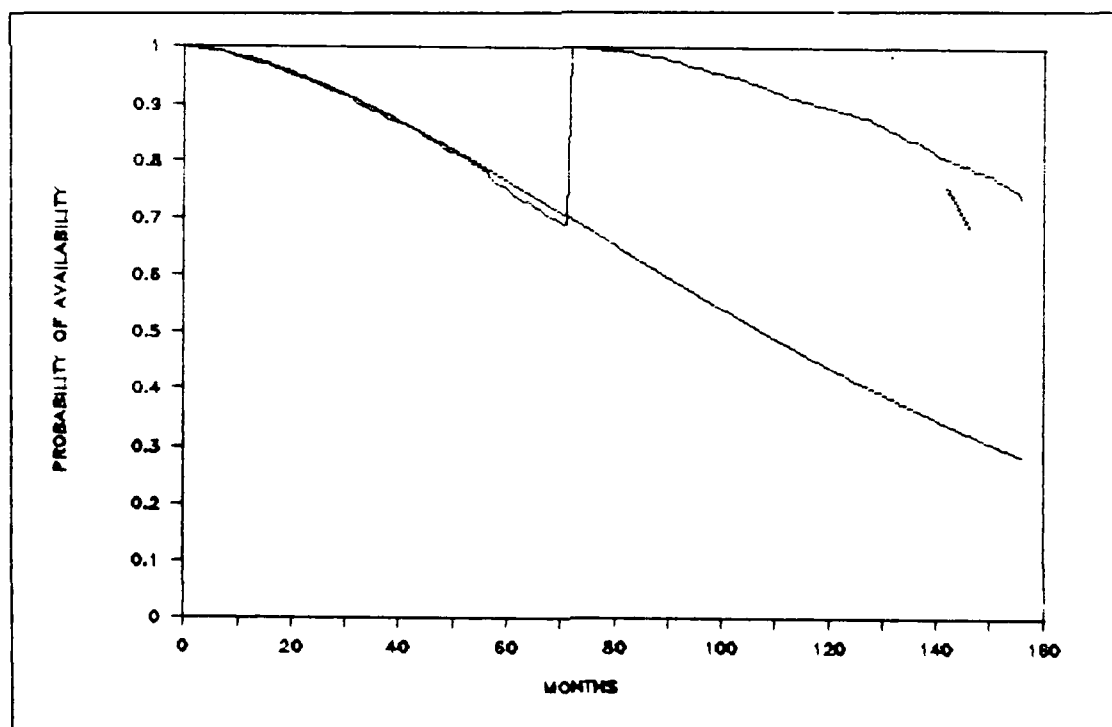
Fig. 7. Baseline NATO III D Mission Availability Prediction With First Satellite Reliability Function

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Maximum and Minimum Bounds

Once the baseline case was constructed, the possible bounds on the Weibull parameters and on system availability were explored by setting all spacecraft component failure rates to their maximum and minimum values at the same time, using RUP to estimate the Weibull parameters, and using those parameters with GAP to make availability predictions. All other GAP inputs were the same as those given in Table 2. Results are shown along with the baseline case in Table 3 and Figures 8 and 9.

Table 3. Baseline, Maximum, and Minimum Weibull Parameters and Average Availability.

Case	α	β	Avg Availability
Baseline	1.626	135.54	0.8594
Maximum Failure Rates	1.631	122.48	0.8311
Minimum Failure Rates	1.616	151.85	0.8865
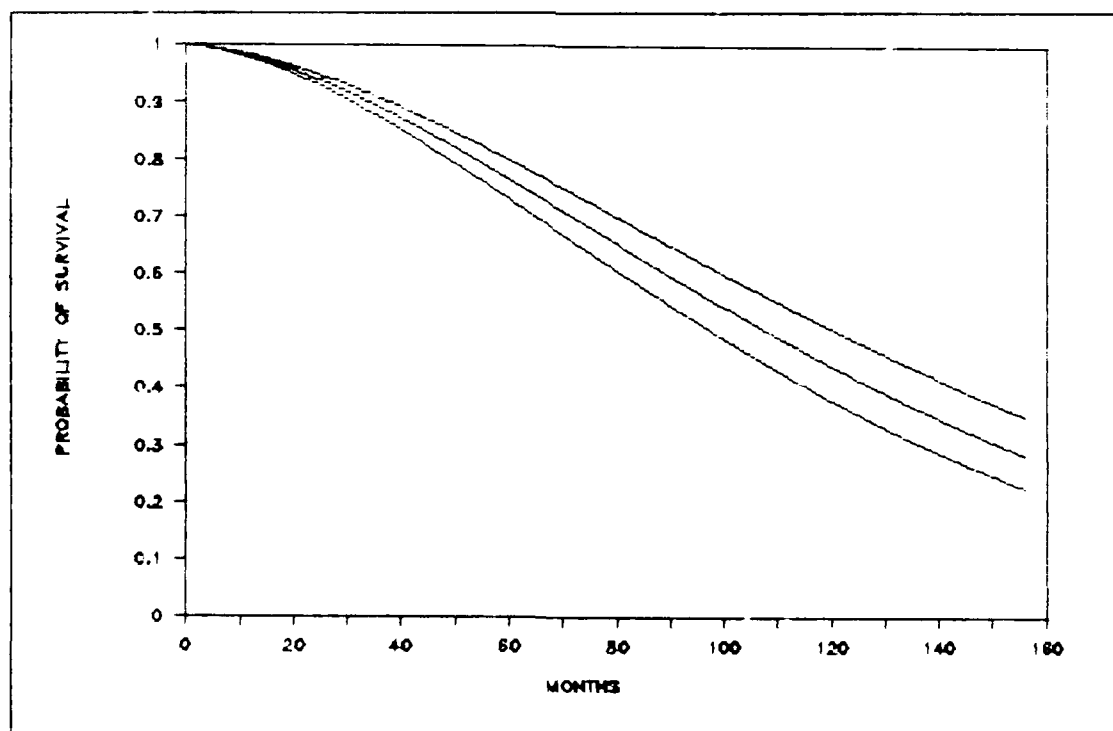
Fig. 8. Baseline, Maximum, and Minimum Weibull Reliability Functions
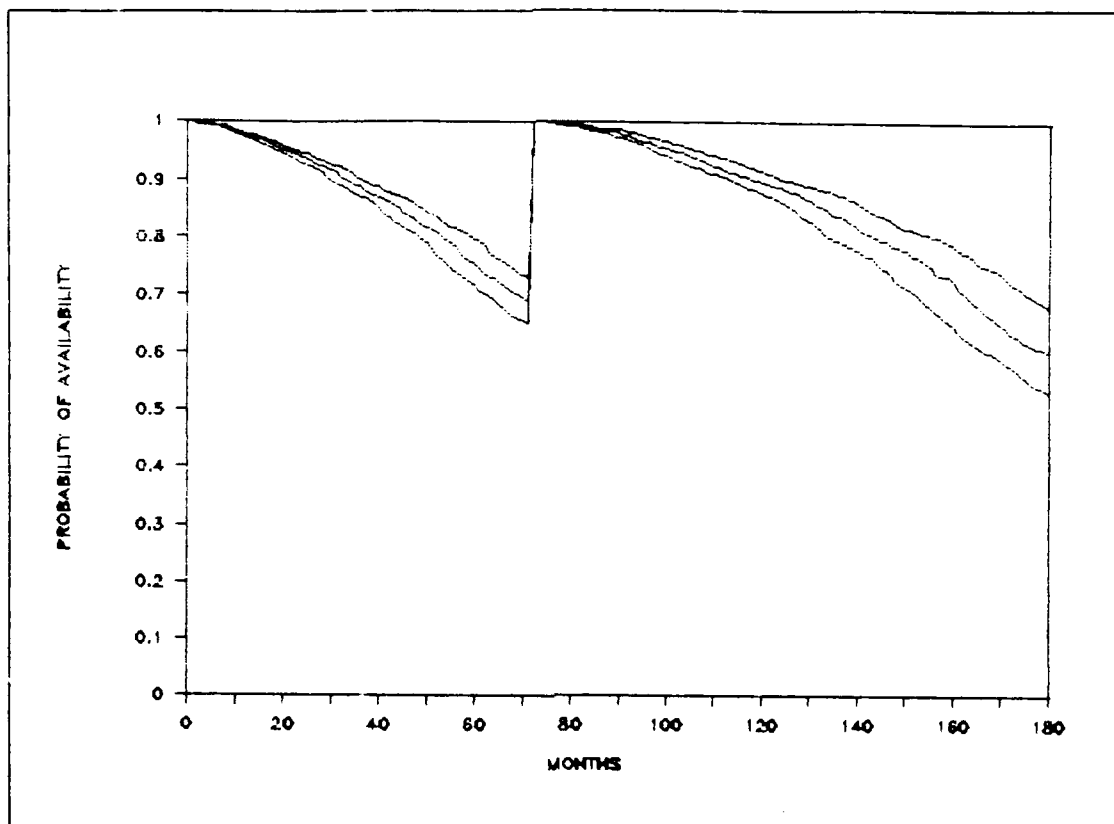
Fig. 9. Baseline, Maximum, and Minimum Availability Predictions

Two immediate observations can be made. First, a plus or minus ten percent change in system-wide failure rates does not cause a very large fluctuation in the average system availability -- only two or three percent. While somewhat of a surprise, this finding should be encouraging to system managers who use availability predictions. It indicates that the overall sensitivity of the prediction to underlying component reliability estimates is not great.

On the other hand, this effect is probably due, at least in part, to the simple mission model that has been described. For a mission involving more satellites and requiring more active satellites at all

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times, the effect is likely to be compounded. More research is required in this area.

Second, the effects in availability that can be seen appear to be due primarily to changes in β, the Weibull scale parameter. Ten percent changes in component failure rates resulted in ten to twelve percent changes in β, but changes only on the order of one-half of one percent for α. This indicates that α is very nearly a constant over the range of component reliabilities we are interested in, and regression models developed for α in the course of this work must be closely scrutinized to see if any effects at all, other than the mean of the observations, are significant. In particular, if the components driving α are found to be different than those driving β, it may be practical to accept the β model only, at least in the early part of the investigation when the main objective is merely to identify critical components.

Identification of Critical Components

Critical components are investigated by using RUP to calculate α and β for enough combinations of maximum and minimum component failure rates to satisfy the requirements of a $2_{III}{}^{k-p}$ fractional factorial design. Analysis of variance (ANOVA) is used to decide upon a model which eliminates those components which do not significantly contribute to changes in α and β. Predicted values of α and β are generated from the model and residuals are plotted against the predicted values to determine whether the model is adequate. If it is not, additional RUP runs are made to explore interactive effects via a $2_{IV}{}^{k-p}$ design.

Subsystem-Level Drivers. The NATO III D spacecraft is broken down into seven subsystems, of which two have no effect on this analysis

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because their relibilities are not functions of time. The structure subsytem, Ps = 0.9998, and the apogee kick motor, Ps = 0.9754 (5:3), are operated or stressed only during launch and orbit injection, and may normally be included with launch success probability when making a GAP prediction.

With only five remaining subsystems, it became practical to implement a full 2^5 factorial design. This was particularly appropriate because this is the highest level that can be investigated and, if interactive effects are significant anywhere, we would expect them to be so here.

32 RUP runs were made to get the responses, α and β, corresponding to the settings for maximum and minimum subsystem-wide failure rates shown, in their coded forms, in Table 4.

Table 4. Subsystem-Level Design Settings and Responses

| RUN | SUBSYSTEM | | | | | RESPONSE | |
	COMM	TTC	AAC	EPS	RCE	α	β
1	-1	-1	-1	-1	-1	1.616	151.85
2	1	-1	-1	-1	-1	1.666	133.26
3	-1	1	-1	-1	-1	1.589	140.62
4	1	1	-1	-1	-1	1.638	125.14
5	-1	-1	1	-1	-1	1.616	150.44
6	1	-1	1	-1	-1	1.666	132.28
7	-1	1	1	-1	-1	1.590	139.42
8	1	1	1	-1	-1	1.639	124.29
9	-1	-1	-1	1	-1	1.615	149.70
10	1	-1	-1	1	-1	1.664	131.76
11	-1	1	-1	1	-1	1.589	138.83
12	1	1	-1	1	-1	1.637	123.84
13	-1	-1	1	1	-1	1.616	148.32
14	1	-1	1	1	-1	1.664	130.81
15	-1	1	1	1	-1	1.590	137.67

Table 4. (Continued)

RUN	SUBSYSTEM					RESPONSE	
	COMM	TTC	AAC	EPS	RCE	α	β
16	1	1	1	1	-1	1.637	123.02
17	-1	-1	-1	-1	1	1.608	151.09
18	1	-1	-1	-1	1	1.659	132.65
19	-1	1	-1	-1	1	1.583	139.92
20	1	1	-1	-1	1	1.632	124.58
21	-1	-1	1	-1	1	1.609	149.66
22	1	-1	1	-1	1	1.658	131.67
23	-1	1	1	-1	1	1.583	138.74
24	1	1	1	-1	1	1.633	123.74
25	-1	-1	-1	1	1	1.608	148.93
26	1	-1	-1	1	1	1.657	131.16
27	-1	1	-1	1	1	1.583	138.12
28	1	1	-1	1	1	1.631	123.30
29	-1	-1	1	1	1	1.608	147.57
30	1	-1	1	1	1	1.657	130.21
31	-1	1	1	1	1	1.583	137.00
32	1	1	1	1	1	1.631	122.48

Note that runs 1 and 32 are identical to those performed earlier, in which all component failure rates were set to their maximum and minimum values. Also, for all other runs the values of β stay between the bounds set by the earlier runs, but values of α do not. The range of α is now seen to be plus or minus two or three percent -- a much more significant range than seen before -- and this may make it more difficult to eliminate components which drive α but not β.

Eq (19) now allows calculation of all component effects and interactions. Because β still has a greater potential range, it is preferable to work with β first and then α when selecting a model. Table C-1, in Appendix C, is a STATISTIX II-formatted coefficient table

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for the main effects and two-component interactions. Table C-2 is a STATISTIX II ANOVA table for the same model.

From the high values of the adjusted R^2 statistic, it seems likely that this is an acceptable model for β -- there is little need to look for three-component and higher interactions. In fact, the model is overspecified, and there are many effects and interactions which don't significantly drive it.

It appears that the COMM and TTC subsystems are the most significant drivers of β, so the logical course of action now is to form a new model with only these two regressors. The coefficient and ANOVA tables for this new model are shown below in Tables C-3 and C-4, respectively.

This model appears to be quite good. The difference between the new adjusted R^2 (0.9803) and the old is small enough to suggest that the new model accounts for most of quality that was present in the old one.

This model is tentatively accepted, then, and an attempt is made to prove its adequacy via residual analysis. Residuals, given by Eq (20), and values of β predicted by the new model are tabulated in Table C-5 with the observations of β from Table 4. The residuals are plotted against the predicted values in Figure C-1.

Here, a problem arises. The residuals clearly show a nonlinear tendancy, indicating that the model is not adequate and that one or more interaction terms is present. Referring back to the original model in Tables C-1 and C-2, it appears that the CT interaction (COMM-TTC) is the most likely prospect if, indeed, a single interaction term will allow an adequate model.

If the CT interaction is added back into the model, the EPS main effect must also be added, since it is about the same magnitude. The subsystem-level model for β will then have four regressors: COMM, TTC, EPS, and CT. Subsequent analysis of the coefficient table, Table C-6, the ANOVA table, Table C-7, the table of predicted values and residuals, Table C-8, and the residual plot, Figure C-2, show this model to be satisfactory and the model is adopted in the following form:

$$\hat{\beta} = 136.00 - 8.2403(COMM) - 4.7078(TTC) - 0.8322(EPS)$$
$$+ 0.7447(COMM)(TTC) \quad (25)$$

The independent variables, COMM, TTC, and EPS, in Eq (25) do not represent the lowest level components for which failure rate data is available, so it is not appropriate to attempt to use this equation by assigning values to them. Rather, they represent a scale of relibility and Eq (25) is properly used by scaling all the lower level components of which they are comprised, together, through the transformation given by Eq (13).

The same procedure must now be followed to develop a model for α at the subsystem level. First, the coefficient and ANOVA tables for a model which contains all main effects and two-component interactions is considered. These are presented, respectively, in Tables C-9 and C-10.

Again, the model is overspecified and several noncritical subsystems can be eliminated. The objective is to keep the simplest model which adequately explains the variation in α. As before, the obvious model to try contains only COMM and TTC. If this is inadequate, the next logical addition is not EPS or the COMM-TCC interaction, as was

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the case in the β model, but RCE -- the reaction control equipment subsystem. It is preferable to avoid this, if possible, because RCE was eliminated from the β model. Coefficient and ANOVA tables for the new model are presented in Tables C-11 and C-12.

From the small change in adjusted R^2, this appears to be quite a good model and it shows marked improvement in the F-statistic due to the increase in the model's degrees of freedom. The proof that the model is adequate must come from residual analysis -- residuals and predicted values of α are tabulated in Table C-13 and Figure C-3 is the residual plot.

While the residual plot shows a slight downward trend, it is fairly safe to ignore it, first, because it is not very great and, second, because this type of trend is an indicator that a mathematical transformation of the observations, rather than addition of interactive terms, is probably needed to adjust the model. Since, at this level, the objective is to identify the driver subsystems, this type of discrepency can be accepted. The following subsystem-level model for α is therefore accepted:

$$\hat{\alpha} = 1.6222 + 0.0259(\text{COMM}) - 0.0145(\text{TTC}) \tag{26}$$

Box-Level Drivers. The two subsystem-level models that have been adopted, Eqs (25) and (26), include only three of the original five subsystems: COMM, TTC, and EPS. Because these three have been found to significantly influence the parameters of the satellite reliability function, the next step is to consider what components within each of these subsystems are influential. They are considered one at a time.

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Communications Payload Subsystem (COMM). The communications
subsystem is has 28 different components at the box level. Clearly, it
is not practical to perform the 2^{28} RUP runs required for a full
factorial design. A fractional factorial experiment must be designed
and, in keeping with the stated strategy of first implementing a
resolution III design, the 28 boxes were grouped into 11 groups, and the
groups were tested for main effects. This was accomplished in 16 runs
via a 2_{III}^{11-7} design. Table 5 lists the components in each of the
groups.

Table 5. COMM Subsystem Groups

GROUP	CLASS	COMPONENTS
A	Low Failure Rate, Serial Components	Test Coupler Preselector Band Pass Filter Coax Switch Equalizer Band Pass Filter Output Filter Low Pass Filter Beacon Inject Filter Beacon Reject Filter Coupler Detector
B	Medium Failure Rate, Serial, Similar Components	Wide Beam Receive Antenna Wide Beam Transmit Antenna Narrow Beam Transmit Antenna
C	High Failure Rate, Parallel Component	Limiter
D	Medium Failure Rate, Serial Components	Redundancy Control Unit Preamplifier Port Circulator Switch Circulator Switch Wave Guide Switch
E	Low Failure Rate, Parallel Components	Attenuator Downconverter

Table 5. (Continued)

GROUP	CLASS	COMPONENTS
F	Low Failure Rate, Parallel Components	Hybrid Splitter Local Oscillator Hybrid
G	Low Failure Rate, Mixed-Use Components	Equalizer Isolator
H	High Failure Rate, Parallel Component	Local Oscillator
I	High Failure Rate, Parallel Component	Driver Amplifier
J	High Failure Rate, Parallel Component	Traveling Wave Tube Amlifier
K	High Failure Rate Parallel Component	Beacon

The testing was conducted by setting all components in a group to maximum and minimum failure rates according to the coded pattern given in Table 6. Setting the failure rate of a box implies setting the failure rates of all lower level components if data is available at the lower levels. Responses, α and β, at the system level are given in Table 7 for each run.

Main effects of the groups are now calculated using Eq (19) and a model is selected. The purpose here is to eliminate enough groups that the overall number of boxes remaining is more manageable. One would not normally expect to identify the critical components at this stage unless the only groups not eliminated from the model have a single component in them. As before, a model for β is determined first.

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Table 6. COMM Subsystem Design Settings

RUN	A	B	C	D	E	F	G	H	I	J	K
1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1
2	1	-1	-1	-1	1	-1	1	1	-1	-1	-1
3	-1	1	-1	-1	1	1	-1	1	-1	-1	1
4	1	1	-1	-1	-1	1	1	-1	1	1	-1
5	-1	-1	1	-1	1	1	1	-1	-1	1	-1
6	1	-1	1	-1	-1	1	-1	1	1	-1	1
7	-1	1	1	-1	-1	-1	1	1	1	-1	-1
8	1	1	1	-1	1	-1	-1	-1	-1	1	1
9	-1	-1	-1	1	-1	1	1	1	-1	1	1
10	1	-1	-1	1	1	1	-1	-1	1	-1	-1
11	-1	1	-1	1	1	-1	1	-1	1	-1	1
12	1	1	-1	1	-1	-1	-1	1	-1	1	-1
13	-1	-1	1	1	1	-1	-1	1	1	1	-1
14	1	-1	1	1	-1	-1	1	-1	-1	-1	1
15	-1	1	1	1	-1	1	-1	-1	-1	-1	-1
16	1	1	1	1	1	1	1	1	1	1	1

Table 7. COMM Subsystem Responses

RUN	α	β	RUN	α	β
1	1.654	128.85	9	1.649	128.67
2	1.594	143.32	10	1.598	143.28
3	1.596	142.98	11	1.598	142.68
4	1.649	128.79	12	1.645	128.83
5	1.652	129.17	13	1.651	128.53
6	1.598	142.44	14	1.597	142.90
7	1.596	142.85	15	1.596	143.56
8	1.650	128.57	16	1.648	127.75

The coefficient and ANOVA tables for the full model with all group main effects included, Tables C-14 and C-15, respectively, are presented in Appendix C. One group, J, clearly stands out as a likely driver, so a new model should be constructed with J being the only regressor. If the new model is acceptable, no further investigation of the COMM subsystem will be required because J is a single-box group. Group J

will be redesignated TWTA at this point -- the mnemonic for traveling wave tube amplifier, the only box in the group. New coefficient and ANOVA tables are given in Tables C-16 and C-17.

The new model appears to be very good and to confirm it, residuals and predicted values are tabulated in Table C-18 and plotted in Figure C-4.

Again, the model appears adequate and is adopted in the following form:

$$\hat{\beta} = 135.82 - 7.1781(\text{TWTA}) \tag{27}$$

Next, the identical procedure is followed to determine an appropriate model for α. First, all the main effects are studied via the coefficient table, Table C-19, and the ANOVA table, Table C-20. As with β, group J, or TWTA, appears to be the dominant influence. A new model with TWTA as the only regressor is shown in Tables C-21 and C-22.

Again the model appears to be adequate, and this is confirmed with residual analysis, Table C-23 and Figure C-5.

As at the subsystem level, the residual plot for α shows an unwanted trend. In this case, it is a definite indication of nonconstant variance in the residuals at different levels of $\hat{\alpha}$. If the variance is, indeed, not constant, it may be an indication that the Weibull prediction model we are trying to fit may not be entirely adequate.

The assumption of constant variance in the residuals is fundamental to linear regression analysis. As previously stated, however, accepting less than a perfect model for α is justified, because the total range over which α can vary is relatively much smaller than that of β.

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The following model for α is tentatively accepted, then, realizing that a less than ideal model has been accepted at both the subsystem level and the COMM subsystem box level:

$$\hat{\alpha} = 1.6232 + 0.0266(\text{TWTA}) \tag{28}$$

This means putting increasing faith in the assumption that β, and not α, will ultimately be most important in describing a useful model of system reliability. If this later turns out not to be the case, then the models accepted for α will have to be revisted.

This completes the investigation of the COMM subsystem. Only one box-level component, TWTA, has been found to have significant influence on the system-level reliability function. Eqs (27) and (28) describe this effect.

Reasons were given previously for not investigating below the box level. It is impossible in this case anywav, because TWTA is a subcontracted box and the NATO III D contractor did not supply lower-level component failure rate data to the Air Force (5:25-43).

Telemetry, Tracking, and Command Subsystem (TTC). The TTC subsystem has 13 box-level components. As with the COMM subsystem, these were broken down into seven groups for screening, the idea being to eliminate some groups and work with a reduced number of individual boxes. Table 8 lists the TTC components by group.

A 2_{III}^{7-4} design of only eight runs was implemented to test for main effects of the groups. Group failure rate settings and responses, α and β, for each run are shown together in Table 9.

Table 8. TTC Subsystem Groups

GROUP	CLASS	COMPONENTS
A	Low Failure Rate, Serial Components	TTC Diplexer Hybrid
B	Common-Function, Parallel Components	Receiver DC/DC Converter S-Band Receiver
C	High Failure Rate, Parallel Component	Command Processing Unit
D	Common-Function, Parallel Components	Beacon DC/DC Converter Beacon Telemetry Unit
E	Common-Function, Parallel Components	Telemetry DC/DC Converter Telemetry Generator Telemetry Interface Unit
F	Common-Function, Parallel Components	Transmitter DC/DC Converter S-Band Transmitter
G	Complex Component	S-Band Antenna

Table 9. TTC Subsystem Group Design Settings and Responses

RUN	A	B	C	D	E	F	G	α	β
1	-1	-1	-1	1	1	1	-1	1.620	137.46
2	1	-1	-1	-1	-1	1	1	1.625	138.77
3	-1	1	-1	-1	1	-1	1	1.625	137.69
4	1	1	-1	1	-1	-1	-1	1.642	138.86
5	-1	-1	1	1	-1	-1	1	1.631	133.90
6	1	-1	1	-1	1	-1	-1	1.622	133.45
7	-1	1	1	-1	-1	1	-1	1.626	133.03
8	1	1	1	1	1	1	1	1.613	130.99

The full, overspecified models are not presented here. Instead, the models judged to be adequate to explain group effects are considered directly. Tables C-24 and C-25 in Appendix C are the coefficient and ANOVA tables, respectively, in which groups A and G have been eliminated

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from the model. Residuals are not tabulated, but are plotted in Figure C-6.

This model seems, clearly, to be adequate and may even be overspecified. But, by eliminating groups A and G, we have already reduced the total number of components to 10, a slightly more manageable number. Because the next four groups one might consider eliminating -- B, D, E, and F -- appear to have effects of roughly the same magnitude, it seems prudent to leave them all in the group screening model. The group screening step has been only moderately successful for β.

Next, a model for α must be developed. Again, the full, overspecified model is not presented, and a more compact version is considered directly. Tables C-26 and C-27 and Figures C-7 present data on a model for α which retains only groups C, E, and F, a subset of the groups retained in the β model. Again, the residual plot, Figure C-7, shows that there may be nonconstant variances in the residuals and, again, the penalty of a less than ideal α model is accepted in order to preserve the β model. In fact, the residual data is not conclusive because it is so sparse and the scale of the residual axis is so small.

Next, the remaining 10 boxes in the TTC subsystem must be investigated in detail. This is accomplished using a 32-run 2_{IV}^{10-5} experimental design. A resolution IV experiment allows two-component interactions to be identified and, while none were expected (none were present at the box level in the COMM subsystem), this is a convenient and logical place to check the assumption.

The 10 TTC boxes remaining will be identified in the following analysis either by their mnemonics or by alphabetical codes: RCVCON

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(A), RCVR (B), CMDU (C), BCONV (D), BTU (E), TLMCON (F), TLMGEN (G), TLMINF (H), XMTCON (I), and SXMTR (J). Design settings and responses are shown in Tables 10 and 11, respectively.

The full model for β is shown in Tables C-28 and C-29. A good reduced model can be constructed by regressing only against components C, G, and J (CMDU, TLMGEN, and SXMTR), as shown in Tables C-30 and C-31.

The adequacy of the reduced model is confirmed by analyzing the residuals. Table C-32 lists the residuals and predicted values and they are plotted in Figure C-8.

The TTC subsystem model for β is now accepted:

$$\hat{\beta} = 135.59 - 2.6100(\text{CMDU}) - 0.6662(\text{TLMGEN}) - 0.4944(\text{SXMTR}) \qquad (29)$$

The same three regressors also form a satisfactory model for α, as seen in Tables C-33 and C-34 (the full model for α is not shown). Again, this is confirmed in the residual listing, Table C-35, and the residual plot, Figure C-9. The TTC subsystem model for α is:

$$\hat{\alpha} = 1.6257 - 0.0026(\text{CMDU}) - 0.0053(\text{TLMGEN}) - 0.0040(\text{SXMTR}) \qquad (30)$$

This completes the investigation of the TTC subsystem. Three common components, CMDU, TLMGEN, and SXMTR, have been found to be the dominant influences on both β and α, as given in Eqs (29) and (30). These are added to TWTA from the COMM subsystem as box-level drivers of the spacecraft-level reliability function.

Table 10. TTC Subsystem Design Settings

RUN	A	B	C	D	E	F	G	H	I	J
1	-1	-1	-1	-1	-1	1	1	1	1	1
2	1	-1	-1	-1	-1	-1	-1	-1	-1	1
3	-1	1	-1	-1	-1	-1	-1	-1	1	-1
4	1	1	-1	-1	-1	1	1	1	-1	-1
5	-1	-1	1	-1	-1	-1	-1	1	-1	-1
6	1	-1	1	-1	-1	1	1	-1	1	-1
7	-1	1	1	-1	-1	1	1	-1	-1	1
8	1	1	1	-1	-1	-1	-1	1	1	1
9	-1	-1	-1	1	-1	-1	1	-1	-1	-1
10	1	-1	-1	1	-1	1	-1	1	1	-1
11	-1	1	-1	1	-1	1	-1	1	-1	1
12	1	1	-1	1	-1	-1	1	-1	1	1
13	-1	-1	1	1	-1	1	-1	-1	1	1
14	1	-1	1	1	-1	-1	1	1	-1	1
15	-1	1	1	1	-1	-1	1	1	1	-1
16	1	1	1	1	-1	1	-1	-1	-1	-1
17	-1	-1	-1	-1	1	1	-1	-1	-1	-1
18	1	-1	-1	-1	1	-1	1	1	1	-1
19	-1	1	-1	-1	1	-1	1	1	-1	1
20	1	1	-1	-1	1	1	-1	-1	1	1
21	-1	-1	1	-1	1	-1	1	-1	1	1
22	1	-1	1	-1	1	1	-1	1	-1	1
23	-1	1	1	-1	1	1	-1	1	1	-1
24	1	1	1	-1	1	-1	1	-1	-1	-1
25	-1	-1	-1	1	1	-1	-1	1	1	1
26	1	-1	-1	1	1	1	1	-1	-1	1
27	-1	1	-1	1	1	1	1	-1	1	-1
28	1	1	-1	1	1	-1	-1	1	-1	-1
29	-1	-1	1	1	1	1	1	1	-1	-1
30	1	-1	1	1	1	-1	-1	-1	1	-1
31	-1	1	1	1	1	-1	-1	-1	-1	1
32	1	1	1	1	1	1	1	1	1	1

Table 11. TTC Subsystem Responses

RUN	α	β	RUN	α	β
1	1.617	137.71	17	1.637	139.40
2	1.629	139.12	18	1.627	138.22
3	1.638	139.12	19	1.621	136.73
4	1.627	137.80	20	1.630	137.62
5	1.631	134.51	21	1.614	132.10
6	1.619	133.11	22	1.624	133.12
7	1.614	131.72	23	1.632	133.15
8	1.625	132.85	24	1.624	132.22
9	1.627	138.77	25	1.629	138.59
10	1.635	139.69	26	1.619	137.27
11	1.630	138.17	27	1.627	137.28
12	1.619	137.00	28	1.640	138.69
13	1.622	133.45	29	1.621	132.79
14	1.614	132.52	30	1.632	133.95
15	1.622	132.53	31	1.627	132.55
16	1.635	136.10	32	1.613	130.99

Electrical Power Subsystem (EPS). The EPS subsystem has 33 box-level components which are divided into 11 groups for screening according to Table 12. As before, an attempt is made to eliminate some groups in order to reduce the total number of observations required. A $2_{111}{}^{11-7}$ experiment was performed with group maximum and minimum failure rate settings as indicated in Table 13. α and β responses are listed in Table 14.

The full models for α and β are not presented and those judged to be adequate to explain the observations are examined directly. Tables C-36 and C-37 show a model for β based only on three groups: A, G, and J. The model seems adequate from the values of the F-statistic and adjusted R^2, and this is confirmed by the residual plot shown in Figure C-10.

Table 12. EPS Subsystem Groups

GROUP	CLASS	COMPONENTS
A	Serial Components	Main Solar Cell Array Battery Solar Cell Array Solar Array Relay Battery Relay AGE/RCE Circuit Circuit Breaker Reset Relay Circuit Breaker Relay
B	Low Failure Rate, Multiple-Copy Components	Resistor Set A Resistor Set B Resistor Set C Capacitor Assembly 1 Capacitor Assembly 2
C	High Failure Rate, Multiple-Copy Component	Fuse
D	Low Failure Rate, Parallel Components	Error Amplifier Majority-Voter Boost Converter Electronic Compiler Assembly
E	Medium Failure Rate Components	Shunt Driver Shunt Set TWTA Circuit Breaker AKM Circuit AKM Igniter Squibs
F	Medium Failure Rate Miscellaneous	Misc Chassis Components Battery Charge Sequencer
G	Medium Failure Rate Serial Components	Current Telemetry Circuit Voltage Telemetry Circuit Fuse Block
H	High Failure Rate, Common-Function	Automatic Disconnector Automatic Reconnector
I	High Failure Rate Component	Pulse-Width Modulator
J	High Failure Rate Component	Battery
K	Medium Failure Rate, Common-Function	Battery Charge Controller Undervoltage Controller

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Table 13. EPS Subsystem Group Design Settings

RUN	A	B	C	D	E	F	G	H	i	J	K
1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1
2	1	-1	-1	-1	1	-1	1	1	-1	-1	-1
3	-1	1	-1	-1	1	1	-1	1	-1	-1	1
4	1	1	-1	-1	-1	1	1	-1	1	1	-1
5	-1	-1	1	-1	1	1	1	-1	-1	1	-1
6	1	-1	1	-1	-1	1	-1	1	1	-1	1
7	-1	1	1	-1	-1	-1	:	1	1	-1	-1
8	1	1	1	-1	1	-1	-1	-1	-1	1	1
9	-1	-1	-1	1	-1	1	1	1	-1	1	1
10	1	-1	-1	1	1	1	-1	-1	1	-1	-1
11	-1	1	-1	1	1	-1	1	-1	1	-1	1
12	1	1	-1	1	-1	-1	-1	1	-1	1	-1
13	-1	-1	1	1	1	-1	-1	1	1	1	-1
14	1	-1	1	1	-1	-1	1	-1	-1	-1	1
15	-1	1	1	1	-1	1	-1	-1	-1	-1	-1
16	1	1	1	1	1	1	1	1	1	1	1

Table 14. EPS Group Subsystem Responses

RUN	α	β	RUN	α	β
1	1.632	135.49	9	1.628	134.93
2	1.620	135.52	10	1.624	136.09
3	1.627	136.15	11	1.623	135.63
4	1.625	134.88	12	1.630	135.41
5	1.627	135.09	13	1.632	135.61
6	1.625	135.96	14	1.620	135.43
7	1.623	135.73	15	1.626	136.31
8	1.630	135.27	16	1.626	134.69

The same three groups are seen to provide a good model for α, provided one is still willing to accept a slight trend in the residuals, in Tables C-38 and C-39 and Figure C-11.

At this point, 8 of the 11 groups in the EPS subsytem have been screened out, reducing the number of components that must be further investigated from 33 to 11. This further investigation is accomplished

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by subjecting the remaining 11 components to another 2_{III}^{11-7}

experiment.

The components will be identified either by their mnemonics or
their alphabetic codes: ARRAY1 (A), ARRAY2 (B), SAREL (C), BATR (D),
AGERCE (E), CBRR (F), CBR (G), ITLM (H), VTLM (I), FUSEBL (J), and BAT
(K). The component maximum and minimum failure rate settings used are
the same as were used for the group screening and are shown in Table 13.
The observations of α and β taken are listed in Table 15, below.

Table 15.   EPS Subsystem Responses

RUN	α	β	RUN	α	β
1	1.631	135.37	9	1.628	135.07
2	1.621	135.65	10	1.624	135.94
3	1.628	135.16	11	1.631	135.45
4	1.625	135.84	12	1.621	135.56
5	1.628	136.14	13	1.623	135.67
6	1.625	134.89	14	1.630	135.35
7	1.622	135.76	15	1.627	136.22
8	1.630	135.27	16	1.625	134.79

The full model for β is shown in Tables C-40 and C-41, and a
reduced model with only three regressors, ARRAY1, ITLM, and BAT, is
shown in Tables C-42 and C-43. This second model appears to be
adequate, as seen by the residuals in Table C-44 and Figure C-12. The
following EPS subsystem model for β is then accepted:

$$\hat{\beta} = 135.51 - 0.0969(ARRAY1) - 0.1894(ITLM) - 0.3394(BAT) \qquad (31)$$

Next, the same process must be implemented to find a model for α.
Tables C-45 and C-46 are the coefficient table and the ANOVA table.

respectively, for the full α model. Tables C-47 and C-48 show that the same three regressors as used in the β model, ARRAY1, ITLM, and BAT, form a good model for α. Again, the adequacy of the model is confirmed with residual analysis, Table C-49 and Figure C-13.

Thus an EPS subsystem model for α may be adopted:

$$\hat{\alpha} = 1.6262 - 0.0011(ARRAY1) - 0.0021(ITLM) + 0.0023(BAT) \qquad (32)$$

and ARRAY1, ITLM, and BAT are added to the list of box-level drivers.

Box-Level Response Surface

At this point, seven potentially critical components at the box level have been identified: TWTA, CMDU, TIMGEN, SXMTR, ARRAY1, ITLM, and BAT. These seven have been identified while working separately with three different subsystems and, in order to model the system as a whole, they must now be considered together. Thus, the interim models developed for β and α, Eqs (27) - (32), cannot be used for anything beyond the identification of the independent variables (components) that will now be of further interest.

Instead, another regression analyis must be performed, using the seven remaining components as regressors. This gives a system-wide response to box-level regressors. Remembering from Eq (25) two-component interactions need to be considered at the system level, a 2_{IV}^{7-3}, 16-run experiment is implemented and the observations regressed against, not just main effects, but also all interactions between components of the COMM and TTC subsystems. Explicitly, the TWTA-CMDU (TC), TWTA-TIMGEN (TT), AND TWTA-SXMTR (TS) interactions must be considered.

Tables C-50 and C-51, Appendix C, are the coefficient and ANOVA tables for the full box-level model for β.

A reduced model with only six regressors is shown in Tables C-52 and C-53 and its adequacy is confirmed by analysis of the residuals in Table C-54 and Figure C-14. These six regressors, then, give the final response surface for β:

$$\hat{\beta} = 135.82 - 7.1875(\text{TWTA}) - 2.7187(\text{CMDU}) - 0.5888(\text{TLMGEN})$$
$$- 0.4162(\text{SXMTR}) - 0.3525(\text{BAT}) + 0.4075(\text{TWTA})(\text{CMDU}) \quad (33)$$

Similarly, the box-level model for α must be determined. The full model showing all main effects and the previously specified two-component interactions is shown in Tables C-55 and C-56. A good reduced model for α can be found using the same five main effects as for β, but without the TWTA-CMDU interaction. This is as expected, remembering from Eq (26) that, at the subsystem level, no interactions were required in the model for α.

Tables C-57 and C-58 show the reduced model and analysis of the residuals in Table C-59 and Figure C-15 shows the model to be adequate. Thus, the final box-level response surface for α is:

$$\hat{\alpha} = 1.6231 + 0.0266(\text{TWTA}) - 0.0022(\text{CMDU}) - 0.0051(\text{TLMGEN})$$
$$- 0.0036(\text{SXMTR}) - 0.0024(\text{BAT}) \quad (34)$$

Availability Response Surface

The objective of this research is to understand the effect of changes in component reliability on overall system availability. A necessary intermediate step is to understand the effect of component

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reliability on the parameters of a fitted Weibull reliability function at the spacecraft level, and this has now been accomplished.

To investigate further, two methods suggest themselves. First, knowing the effect of critical components on α and β, average availability could be regressed against these two parameters and, assuming an adequate model could be found, the availability-to-failure rate expressions could be derived by combining the two models. This new regression could be accomplished by determining average availability via the GAP program for any reasonably-sized subset of the combinations of α and β already collected in the course of this research.

Alternatively, average availability could be regressed directly against component failure rates using the Weibull parameter responses (Tables C-54 and C-59). This may be done merely by evaluating average availability via GAP for each of the 16 combinations of α and β listed and treating these as the responses for a new regression analysis.

Either of these approaches is acceptable. The latter is chosen because it avoids the possiblity of introducing higher-order models than have so far been required and because it may reasonably be assumed that any lack of fit in the model derived this way is of the same order of magnitude as the lack of fit error in the α and β response surfaces, whereas mathematically combining two models might multiply any lack of fit error.

To proceed, then, 16 GAP runs are made using the values of β from Table C-54 and α from Table C-59 associated with each prior RUP run. All other GAP inputs are the same as shown in Table 2. Average availability, A, responses are listed in Table 16 below. These are

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Table 16. Inputs and Average Availability Responses

RUN	α	β	A	RUN	α	β	A
1	1.608	148.08	0.8801	9	1.601	145.79	0.8757
2	1.665	131.64	0.8547	10	1.649	131.15	0.8523
3	1.598	141.05	0.8672	11	1.600	139.78	0.8651
4	1.656	126.83	0.8435	12	1.649	126.98	0.8433
5	1.596	145.16	0.8742	13	1.587	145.52	0.8740
6	1.648	131.01	0.8519	14	1.649	129.99	0.8499
7	1.599	139.62	0.8647	15	1.583	139.09	0.8623
8	1.644	126.53	0.8418	16	1.638	124.96	0.8376

the responses for a 2_{IV}^{7-3}, 16-run experiment with the same maximum and minimum failure rate settings as were used to formulate the box-level response surfaces for α and β.

Tables C-60 and C-61 illustrate a full model of the main effects of all seven potential driver components, as well as the TC, TT, and TS interactions. As before, a reduced model is possible and, in fact, the model can easily be reduced to four regressors, less than for either the β or α models from of Eqs (33) and (34). This reduced model is illustrated in Tables C-62 and C-63. As always, the adequacy of the model must be demonstrated through residual analysis. Residuals are listed in Table C-64 and plotted in Figure C-16.

Now the box-level response surface model for availability may be written:

$$\hat{A} = 0.8586 - 0.01177(TWTA) - 0.005456(CMDU) - 0.001594(TLMGEN)$$

$$- 0.001119(SXMTR) \qquad (35)$$

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Reverse Variable Transformations

All response surface models developed so far have been stated in terms of coded component failure rates. Substitution of actual component failure rates for the coded values must now be made. From Eq (13) and Table A-1, Appendix A:

$$\text{TWTA} = \frac{\lambda_{\text{TWTA}}(10^9) - 8880}{888.0} \tag{36}$$

$$\text{CMDU} = \frac{\lambda_{\text{CMDU}}(10^9) - 1390}{139.0} \tag{37}$$

$$\text{TLMGEN} = \frac{\lambda_{\text{TLMGEN}}(10^9) - 1277}{127.7} \tag{38}$$

$$\text{SXMTR} = \frac{\lambda_{\text{SXMTR}}(10^9) - 921.0}{92.10} \tag{39}$$

$$\text{BAT} = \frac{\lambda_{\text{BAT}}(10^9) - 620.9}{62.09} \tag{40}$$

Therefore, Eqs (33), (34), and (35) may be rewritten as:

$$\hat{\beta} = 289.21 - 1.268(10^7)(\lambda_{\text{TWTA}}) - 4.888(10^7)(\lambda_{\text{CMDU}})$$
$$- 4.611(10^6)(\lambda_{\text{TLMGEN}}) - 4.519(10^6)(\lambda_{\text{SXMTR}}) - 5.677(10^6)(\lambda_{\text{BAT}})$$
$$+ 3.301(10^{12})(\lambda_{\text{TWTA}})(\lambda_{\text{CMDU}}) \tag{41}$$

$$\hat{\alpha} = 1.4901 + 2.9955(10^4)(\lambda_{\text{TWTA}}) - 1.5827(10^4)(\lambda_{\text{CMDU}})$$
$$- 3.9937(10^4)(\lambda_{\text{TLMGEN}}) - 3.9088(10^4)(\lambda_{\text{SXMTR}})$$
$$- 3.8654(10^4)(\lambda_{\text{BAT}}) \tag{42}$$

$$\hat{A} = 1.0580 - 1.3255(10^4)(\lambda_{\text{TWTA}}) - 3.9252(10^4)(\lambda_{\text{CMDU}})$$
$$- 1.2482(10^4)(\lambda_{\text{TLMGEN}}) - 1.2150(10^4)(\lambda_{\text{SXMTR}}) \tag{}$$

With Eq (43), the objective has been accomplished. The NATO III D spacecraft reliability model in Appendix A identifies 100 components at the box level. This number has been reduced to only four critical boxes and the parameters of the spacecraft-level reliability function and the availability of the two-satellite, 15-year mission have been described in terms of the failure rates of these four components.

Validation

The response surfaces given by Eqs (41), (42), and (43) were briefly tested by choosing four combinations of reliability for the five critical components in the equations. Table 17, below, shows these four combinations (in percentage change from nominal failure rates), and Table 18 gives the values of α, β, and A predicted by the response surfaces, and corresponding values determined by actually making the necessary RUP and GAP computer runs. Clearly, the surfaces predict the actual values quite well -- at least to the third significant figure.

Table 17. Response Surface Validation Test Settings

Test	TWTA	CMDU	TLMGEN	SXMTR	BAT
1	+ 5%	0%	+10%	+10%	+10%
2	+ 5%	+ 5%	+ 5%	+ 5%	+ 5%
3	- 5%	- 5%	- 5%	- 5%	- 5%
4	0%	-10%	-10%	-10%	-10%

Table 18. Response Surface Validation Test Results

Test	$\hat{\alpha}$	α	$\hat{\beta}$	β	$\hat{A}$	A
1	1.625	1.633	130.87	130.76	0.850	0.850
2	1.630	1.634	130.09	130.17	0.849	0.849
3	1.616	1.616	141.35	141.37	0.869	0.869
4	1.636	1.635	139.90	139.60	0.867	0.868

V. Conclusions and Recommendations

Interpretation of Response Surfaces

The reponse surfaces that have been generated identify the components at the box level that are most critical to mission success, and quantify the effects that uncertainties in their failure rates have on that success. In general, the components identified as critical are among those with the highest individual failure rates, but this is not always the case. In fact, three of the five boxes shown in Appendix A to have the highest failure rates were not selected as critical to the response surface models developed here. This occurs because redundancy configurations, duty cycle and other factors affect the requirements of a component in a complex system.

The mere identification of critical components can be important to a system manager. In design and manufacturing, these components may receive special attention and resources, if not to improve their reliability, at least to make sure their reliability is known with a high degree of certainty. In the operational phase of a space mission, particular care may be taken to update their reliability estimates as more data becomes available, in order to better understand current and future mission status.

The response surfaces derived here provide a way to quantify the benefits of improvement in component reliabilities. For instance, if a program director believes he can spend a certain amount of money and obtain a ten percent decrease in TWTA and CMDU failure rates, Eq 43 (or

Eq 35, if it is preferable to work in coded variables) shows an increase in average mission availability from 0.859 to 0.876 can be expected.

If this doesn't seem like much, consider the director whose program management directive includes, as a goal, the maintenance of 0.8 probability of availability. Using Eqs (41) and (42) (or (33) and (34)), we can quickly generate new Weibull parameters and make a GAP run to compare point availabilities. Figure 77 shows that the time during the 15-year mission when the objective is not met has been reduced from 54 months to 43 months. Average availbility was determined by GAP to be 0.8760 for this case, confirming the expected result obtained from the model of Eq (43).
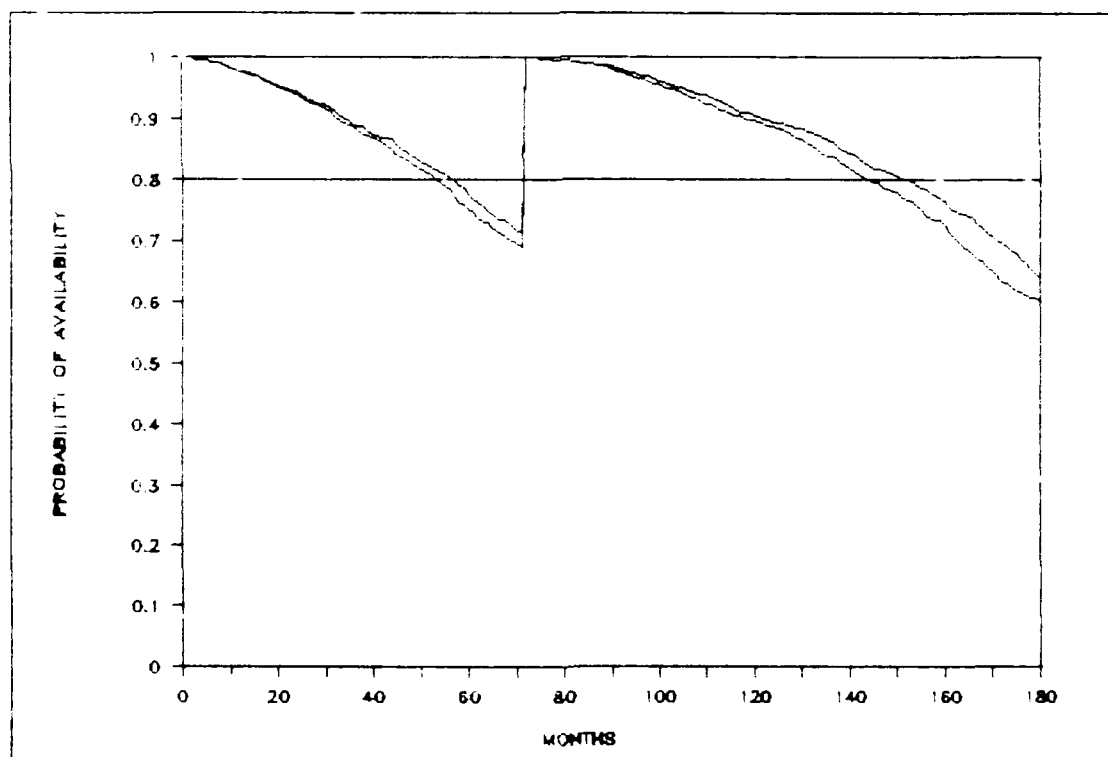
Fig. 10. NATO Mission Availabilty: Baseline Case and With 10% Improvement in TWTA and CMCU Reliability

The response surface for average availability, Eq (43), is specific to the NATO satellite and the mission model described. Eqs (41) and (42) describe the parameters of the satellite reliability, and so are not dependent on any particular mission model. Because point availability and not average availability is a more commonly used metric, Eqs (41) and (42) are probably of the most use. As indicated, it is a simple matter to use these response surface equations to generate Weibull parameters, make a GAP prediction, and analyze the results graphically.

Conclusions

Response surface methodology is a useful tool in making space system availability predictions. It provides two major advantages to a system manger: it aids in the identification of components whose reliability is most critical to overall system availability, and it allows quantification of the benefits to be had by increasing the reliability of those critical components.

In general, the sensitivity of the predicted system availability to component failure rates does not seem to be very great. For the mission model specified, a simultaneous increase or decrease of ten percent in all system components only causes a two or three percent change in average availability. Possible reasons for this low sensitivity include the relatively simple mission model selected, the robustness of the NATO III D spacecraft in terms of redundancy, and the choice of average availability as the response metric.

There is significant uncertainty in current methods of making space systems availability predictions, and the underlying component

reliability estimates are only one source of this uncertainty. By using the methodology presented here, one can identify critical components, derive a response surface describing the effects of those components' failure rates on reliability parameters of interest, and, by considering what the bounds on those failure rates might reasonably be, place subjective bounds on the confidence one has in an availability prediction.

Recommendations

Much room exists for improvement in the way the availability of space systems is predicted. In particular, uncertainty in the prediction is rarely addressed. A prediction with no way to measure the level of confidence one may have in it is a poor management tool, and a real need exists for a way to put true confidence intervals on the predictions. This thesis has begun to address one area of uncertainty, that of the underlying component reliability estimates, but much remains to be done.

The current work is fairly narrow in that it applies to only one type of spacecraft and one mission model. It is recommended that the results obtained be confirmed by further applications. Investigation of other mission models would be particularly easy because only availability predictions -- GAP runs -- need be made. No new calculations of Weibull parameters are required.

The ultimate goal in the field of availability prediction should be that anyone who works with space systems be able to quickly and accurately make predictions, given that the system reliability model is available, and attach a confidence level to it. Quantifying confidence

means quantifying uncertainty, and that is where further research must be directed.

Appendix A: <u>NATO III D Spacecraft Reliability Model</u>

Components Listing

Table A-1 is a listing of all NATO III D spacecraft components used in the math model from which reliability calculations are made for this investigation. Given are the baseline failure rates for each component, the system level the component falls in, and the uncoded maximum and minimum failure rates used in the various experimental designs.

Equivalent failure rates for components whose reliability is calculated by RUP from the rates of lower level components are marked with an asterisk (*). No coded maximum and minimum rates are applicable for these components.

All failure rates are given in terms of number of failures per 10^9 operating hours.

Table A-1. NATO III D Spacecraft Components Listing and Failure Rates (Ford:3-80)

Component Name	λ	Level	λ_{MAX}	λ_{MIN}
COMMUNICATIONS SUBSYSTEM	2981.20*	SSYS		
REDUNDANCY CONTROL UNIT	20.81*	BOX		
RCU POWER SELECTOR	6.48*	ASM		
RCU PS RELAY	1.10	PART	1.21	0.99
RCU PS DC/DC CONVERTER	142.00	PART	156.20	127.80
RCU COMPONENT SELECTOR	0.25*	ASM		
RCU CS LOCAL OSC SELECTOR	6.20	PART	6.82	5.58
RCU CS BEACON SELECTOR	10.00	PART	11.00	9.00
RCU CS PREAMP SELECTOR	10.00	PART	11.00	9.00
RCU CS LIMITER SELECTOR	12.40	PART	13.64	11.16
RCU TWTA SELECTOR	0.37*	ASM		
RCU TS MODE SELECTOR	112.00	PART	123.20	100.80
RCU TS TWTA SELECTOR	15.00	PART	16.50	13.50
RCU TS WB/NB SELECTOR	15.00	PART	16.50	13.50

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Table A-1 (Continued)

Component Name	λ	Level	λ_{MAX}	λ_{MIN}
RCU TS DRIVER SELECTOR	12.40	PART	13.64	11.16
RCU LIMITER GAIN SELECTOR	4.38*	ASM		
RCU LGS RELAY TYPE 1	1.06	PART	1.17	0.95
RCU LGS RELAY TYPE 2	1.16	PART	1.28	1.04
RCU LGS RESISTOR	0.02	PART	0.02	0.02
RCU DIRECT BUS CONNECTION	0.57*	ASM		
RCU DBC RESISTOR TYPE 1	0.05	PART	0.06	0.04
RCU DBC RESISTOR TYPE 2	0.10	PART	0.11	0.09
WB RECEIVE ANTENNA	38.30*	BOX		
WB RECEIVE ANT ASSEMBLY	8.48*	ASM		
WBR HORN SECTION	0.10	PART	0.11	0.09
WBR HORN JOINT	0.10	PART	0.11	0.09
WBR HORN COVER	0.10	PART	0.11	0.09
WBR THERMAL FINISH	0.10	PART	0.11	0.09
WBR MODE GENERATOR	1.00	PART	1.10	0.90
WBR WG TRANSITION	1.00	PART	1.10	0.90
WBR WG FLANGE	0.50	PART	0.55	0.45
WBR WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBR WG BRAZED JOINT	0.20	PART	0.22	0.18
WBR UPPER WG RUN	8.10*	ASM		
WBR W1 WG FLANGE	0.50	PART	0.55	0.45
WBR W1 WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBR W1 WG SECTION	0.10	PART	0.11	0.09
WBR W1 WG RUN	0.10	PART	0.11	0.09
WBR W1 WG FLEX SECTION	1.00	PART	1.10	0.90
WBR W1 WG 30 D BEND	0.20	PART	0.22	0.18
WBR W1 WG 45 D BEND	0.20	PART	0.22	0.18
WBR W1 WG 60 D BEND	0.20	PART	0.22	0.18
WBR W1 WG 90 D BEND	0.20	PART	0.22	0.18
WBR W1 WG BRAZED JOINT	0.20	PART	0.22	0.18
WBR REJECT WG RUN	2.51*	ASM		
WBR W2 WG FLANGE	0.50	PART	0.55	0.45
WBR W2 WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBR W2 WG SECTION	0.10	PART	0.11	0.09
WBR W2 WG 45 D BEND	0.20	PART	0.22	0.18
WBR W2 WG BRAZED JOINT	0.20	PART	0.22	0.18
WBR OUTER REJECT CHANNEL	14.27*	ASM		
WBR ORC WG FLANGE	0.50	PART	0.55	0.45
WBR ORC FLANGE FASTENER	0.10	PART	0.11	0.09

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Table A-1 (Continued)

Component Name	λ	Level	λMAX	λMIN
WBR ORC TRANSFORMER	1.00	PART	1.10	0.90
WBR ROTARY COAX CHOKE	1.00	PART	1.10	0.90
WBR REJECT COAX SECTION	1.00	PART	1.10	0.90
WBR HORN JOINT SPACER	0.10	PART	0.11	0.09
WBR ORC WG HYBRID	1.00	PART	1.10	0.90
WBR ORC WG BRAZED JOINT	0.20	PART	0.22	0.18
WBR LOWER WG RUN	4.93*	ASM		
WBR W3 WG FLANGE	0.50	PART	0.55	0.45
WBR W3 WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBR W3 WG SECTION	0.10	PART	0.11	0.09
WBR W3 WG RUN	0.10	PART	0.11	0.09
WBR W3 WG FLEX SECTION	1.00	PART	1.10	0.90
WBR W3 WG 60 D BEND	0.20	PART	0.22	0.18
WBR W3 WG BRAZED JOINT	0.20	PART	0.22	0.18
TEST COUPLER	1.00	BOX	1.10	0.90
PRESELECTOR BP FILTER	13.00	BOX	14.30	11.70
COAX SWITCH	25.00	BOX	27.50	22.50
PREAMP	81.00	BOX	89.10	72.90
ATTENUATOR	13.00	BOX	14.30	11.70
HYBRID SPLITTER	17.00	BOX	18.70	15.30
PORT CIRCULATOR SWITCH	30.00	BOX	33.00	27.00
BAND PASS FILTER	13.00	BOX	14.30	11.70
EQUALIZER	13.00	BOX	14.30	11.70
LIMITER	383.00	BOX	421.30	344.70
LOCAL OSCILLATOR	591.00	BOX	650.10	531.90
LOCAL OSCCILLATOR HYBRID	37.00	BOX	40.70	33.30
DOWN CONVERTER	128.00	BOX	140.80	115.20
ISOLATOR	13.00	BOX	14.30	11.70
CIRCULATOR SWITCH	50.00	BOX	55.00	45.00
DRIVER AMPLIFIER	222.00	BOX	244.20	199.80
TWT AMPLIFIER	8880.00	BOX	9768.00	7992.00
WAVE GUIDE SWITCH	20.00	BOX	22.00	18.00
OUTPUT FILTER	5.00	BOX	5.50	4.50
LOW PASS FILTER	5.00	BOX	5.50	4.50
BEACON INJECT FILTER	5.00	BOX	5.50	4.50
BEACON REJECT FILTER	13.00	BOX	14.30	11.70
COUPLER DETECTOR	32.00	BOX	35.20	28.80
BEACON GENERATOR	1454.00	BOX	1599.40	1308.60
WB TRANSMIT ANTENNA	28.51*	BOX		

Table A-1 (Continued)

Component Name	λ	Level	λMAX	λMIN
WB TRANSMIT ANT ASSEMBLY	8.48*	ASM		
WBT HORN SECTION	0.10	PART	0.11	0.09
WBT HORN JOINT	0.10	PART	0.11	0.09
WBT HORN COVER	0.10	PART	0.11	0.09
WBT THERMAL FINISH	0.10	PART	0.11	0.09
WBT MODE GENERATOR	1.00	PART	1.10	0.90
WBT WG TRANSITION	1.00	PART	1.10	0.90
WBT WG FLANGE	0.50	PART	0.55	0.45
WBT WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBT WG BRAZED JOINT	0.20	PART	0.22	0.18
WBT UPPER WG RUN	7.82*	ASM		
WBT W1 WG FLANGE	0.50	PART	0.55	0.45
WBT W1 WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBT W1 WG SECTION	0.10	PART	0.11	0.09
WBT W1 WG RUN	0.10	PART	0.11	0.09
WBT W1 WG FLEX SECTION	1.00	PART	1.10	0.90
WBT W1 WG 30 D BEND	0.20	PART	0.22	0.18
WBT W1 WG 60 D BEND	0.20	PART	0.22	0.18
WBT W1 WG 90 D BEND	0.20	PART	0.22	0.18
WBT W1 WG BRAZED JOINT	0.20	PART	0.22	0.18
WBT REJECT WG RUN	2.23*	ASM		
WBT W2 WG FLANGE	0.50	PART	0.55	0.45
WBT W2 WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBT W2 WG SECTION	0.10	PART	0.11	0.09
WBT W2 WG 30 D BEND	0.20	PART	0.22	0.18
WBT W2 WG BRAZED JOINT	0.20	PART	0.22	0.18
WBT CENTRL REJECT CHANNEL	4.48*	ASM		
WBT CRC WG FLANGE	0.50	PART	0.55	0.45
WBT CRC FLANGE FASTENER	0.10	PART	0.11	0.09
WBT ROTARY COAX CHOKE	1.00	PART	1.10	0.90
WBT REJECT COAX SECTION	1.00	PART	1.10	0.90
WBT HORN JOINT SPACER	0.10	PART	0.11	0.09
WBT CRC WG BRAZED JOINT	0.20	PART	0.22	0.18
WBT LOWER WG RUN	5.50*	ASM		
WBT W3 WG FLANGE	0.50	PART	0.55	0.45
WBT W3 WG FLANGE FASTENER	0.10	PART	0.11	0.09
WBT W3 WG SECTION	0.10	PART	0.11	0.09
WBT W3 WG RUN	0.10	PART	0.11	0.09
WBT W3 WG FLEX SECTION	1.00	PART	1.10	0.90

Table A-1 (Continued)

Component Name	λ	Level	λ_{MAX}	λ_{MIN}
WBT W3 WG 60 D BEND	0.20	PART	0.22	0.18
WBT W3 WG 90 D TWIST	0.40	PART	0.44	0.36
WBT W3 WG BRAZED JOINT	0.20	PART	0.22	0.18
NB TRANSMIT ANTENNA	39.61*	BOX		
NB TRANSMIT ANT ASSEMBLY	14.18*	ASM		
NBT HORN SECTION	0.10	PART	0.11	0.09
NBT HORN JOINT	0.10	PART	0.11	0.09
NBT HORN COVER	0.10	PART	0.11	0.09
NBT THERMAL FINISH	0.10	PART	0.11	0.09
NBT MODE GENERATOR	1.00	PART	1.10	0.90
NBT WG TRANSITION	1.00	PART	1.10	0.90
NBT WG FLANGE	0.50	PART	0.55	0.45
NBT WG FLANGE FASTENER	0.10	PART	0.11	0.09
NBT WG SECTION	0.10	PART	0.11	0.09
NBT WG BRAZED JOINT	0.20	PART	0.22	0.18
NBT POLARIZER	1.00	PART	1.10	0.90
NBT UPPER WG RUN	7.19*	ASM		
NBT W1 WG FLANGE	0.50	PART	0.55	0.45
NBT W1 WG FLANGE FASTENER	0.10	PART	0.11	0.09
NBT W1 WG SECTION	0.10	PART	0.11	0.09
NBT W1 WG RUN	0.10	PART	0.11	0.09
NBT W1 WG FLEX SECTION	1.00	PART	1.10	0.90
NBT W1 WG 30 D BEND	0.20	PART	0.22	0.18
NBT W1 WG 90 D BEND	0.20	PART	0.22	0.18
NBT W1 WG BRAZED JOINT	0.20	PART	0.22	0.18
NBT REJECT WG RUN	2.51*	ASM		
NBT W2 WG FLANGE	0.50	PART	0.55	0.45
NBT W2 WG FLANGE FASTENER	0.10	PART	0.11	0.09
NBT W2 WG SECTION	0.10	PART	0.11	0.09
NBT W2 WG 30 D BEND	0.20	PART	0.22	0.18
NBT W2 WG BRAZED JOINT	0.20	PART	0.22	0.18
NBT INNER REJECT CHANNEL	9.50*	ASM		
NBT IRC WG FLANGE	0.50	PART	0.55	0.45
NBT IRC FLANGE FASTENER	0.10	PART	0.11	0.09
NBT IRC TRANSFORMER	1.00	PART	1.10	0.90
NBT ROTARY COAX CHOKE	1.00	PART	1.10	0.90
NBT REJECT COAX SECTION	1.00	PART	1.10	0.90
NBT HORN JOINT SPACER	0.10	PART	0.11	0.09
NBT IRC WG BRAZED JOINT	0.20	PART	0.22	0.18

Table A-1 (Continued)

Component Name	λ	Level	λ_{MAX}	λ_{MIN}
NBT LOWER WG RUN	6.23*	ASM		
NBT W3 WG FLANGE	0.50	PART	0.55	0.45
NBT W3 WG FLANGE FASTENER	0.10	PART	0.11	0.09
NBT W3 WG SECTION	0.10	PART	0.11	0.09
NBT W3 WG RUN	0.10	PART	0.11	0.09
NBT W3 WG FLEX SECTION	1.00	PART	1.10	0.90
NBT W3 WG 60 D BEND	0.20	PART	0.22	0.18
NBT W3 WG 90 D BEND	0.20	PART	0.22	0.18
NBT W3 WG 90 D TWIST	0.40	PART	0.44	0.36
NBT W3 WG BRAZED JOINT	0.20	PART	0.22	0.18
TELEM TRACK CMD SUBSYSTEM	3192.18*	SSYS		
TTC DIPLEXER	21.00	BOX	23.10	18.90
TTC HYBRID	15.00	BOX	16.50	13.50
RECEIVER DC/DC CONVERTER	98.00	BOX	107.80	88.20
S BAND RECEIVER	1672.00	BOX	1839.20	1504.80
COMMAND UNIT	1390.23*	BOX		
COMMAND DC/DC CONVERTER	128.00	ASM	140.80	115.20
COMMAND BIT DETECTOR	397.00	ASM	436.70	357.30
COMMAND DECODER	947.00	ASM	1041.70	852.30
COMMAND DECRYPTER	1114.00	ASM	1225.40	1002.60
LOW SIDE DRIVER	819.00	ASM	900.90	737.10
HIGH SIDE DRIVER	88.00	ASM	96.80	79.20
COMMAND COMBINER RELAYS	0.00	BOX	0.00	0.00
BEACON DC/DC CONVERTER	107.00	BOX	117.70	96.30
BEACON TELEMETRY UNIT	1380.00	BOX	1518.00	1242.00
TELEMETRY DC/DC CONVERTER	106.00	BOX	116.60	95.40
TELEMETRY GENERATOR	1277.00	BOX	1404.70	1149.30
TELEMETRY INTERFACE UNIT	87.00	BOX	95.70	78.30
TRANSMIT DC/DC CONVERTER	103.00	BOX	113.30	92.70
S BAND TRANSMITTER	921.00	BOX	1013.10	828.90
S BAND ANTENNA	251.99*	BOX		
RF SWITCH	34.00	ASM	37.40	30.60
POWER DIVIDER	25.00	ASM	27.50	22.50
ANTENNA POWER DIVIDER	21.00	ASM	23.10	18.90
ANTENNA ELEMENT	5.00	ASM	5.50	4.50
ANT ATT CNTRL SUBSYSTEM	290.96*	SSYS		
EARTH SENSOR	390.00	BOX	429.00	351.00
SUN SENSOR	5.00	BOX	5.50	4.50
AAC DC/DC CONVERTER	114.00	BOX	125.40	102.60

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Table A-1 (Continued)

Component Name	λ	Level	λ_{MAX}	λ_{MIN}
AAC ELECTRONICS	1998.00	BOX	2197.80	1798.20
MAGNETIC PICKUP	15.00	BOX	16.50	13.50
MTR DRIVE DC/DC CONVERTER	80.00	BOX	88.00	72.00
MOTOR DRIVE AMP	160.00	BOX	176.00	144.00
RESOLVER WINDING	100.00	BOX	110.00	90.00
MOTOR BEARINGS	100.00	BOX	110.00	90.00
MOTOR WINDINGS	100.00	BOX	110.00	90.00
NUTATION DAMPER	10.00	BOX	11.00	9.00
ELECTRIC POWER SUBSYSTEM	569.40*	SSYS		
MAIN SOLAR CELL ARRAY	117.00	BOX	128.70	105.30
BATTERY SOLAR CELL ARRAY	2.00	BOX	2.20	1.80
SA RELAY	9.00	BOX	9.90	8.10
CRNT SENSING RESIST SET A	0.00*	BOX		
CRNT SENSING RESISTOR	0.85	ASM	0.94	0.76
FUSE	100.00	BOX	110.00	90.00
BATTERY CHARGE CONTROLLER	92.00	BOX	101.20	82.80
CRNT SENSING RESIST SET C	3.00	BOX	3.30	2.70
UNDERVOLTAGE CONTROLLER	96.00	BOX	105.60	86.40
BATTERY	620.88*	BOX		
BATTERY CELL	150.00	ASM	165.00	135.00
BATTERY RELAY	10.00	BOX	11.00	9.00
ERROR AMPLIFIER	13.00	BOX	14.30	11.70
MAJORITY VOTER	13.00	BOX	14.30	11.70
PULSE WIDTH MODULATOR	117.00	BOX	128.70	105.30
BOOST CONVERTER	38.00	BOX	41.80	34.2
ELECTRONIC COMPILER ASSM	2.00	BOX	2.20	1.80
CAPACITOR ASSEMBLY 1	0.00*	BOX		
CAPACITOR	0.75	ASM	0.82	0.68
SHUNT DRIVER	39.00	BOX	42.90	35.10
SHUNT SET	13.00	BOX	14.30	11.70
AUTOMATIC DISCONNECTOR	120.00	BOX	132.00	108.00
AUTOMATIC RECONNECTOR	126.00	BOX	138.60	113.40
AGE RCE CIRCUIT	82.00	BOX	90.20	73.80
CIRCUIT BRKR RESET RELAY	8.00	BOX	8.80	7.20
TWTA CIRCUIT BREAKER	34.00	BOX	37.40	30.60
CRNT SENSING RESIST SET B	6.00	BOX	6.60	5.40
CIRCUIT BREAKER RELAY	8.00	BOX	8.80	7.20
CAPACITOR ASSEMBLY 2	0.00*	BOX		
CAPACITOR	0.75	ASM	0.82	0.68

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Table A-1 (Continued)

Component Name	λ	Level	λMAX	λMIN
CURRENT TELEMETRY	115.00	BOX	126.50	103.50
VOLTAGE TELEMETRY	52.00	BOX	57.20	46.80
FUSE BLOCK	100.00	BOX	110.00	90.00
MISC CHASSIS COMPONENTS	88.00	BOX	96.80	79.20
AKM CIRCUIT	30.00	BOX	33.00	27.00
AKM INITIATOR SQUIB	30.00	BOX	33.00	27.00
BATTERY CHARGE SEQUENCER	102.00	BOX	112.20	91.80
RCTN CNTRL EQUP SUBSYSTEM	398.33*	SSYS		
FUEL TANK	150.00	BOX	165.00	135.00
WET LINES AND FITTINGS	19.00	BOX	20.90	17.10
FILL/DRAIN VALVE	70.00	BOX	77.00	63.00
PRESSURE TRANSDUCER	157.00	BOX	172.70	141.30
AXIAL VALVE DRIVERS	21.00	BOX	23.10	18.90
AXIAL THRUST CHMBR ASSEM	3.00	BOX	3.30	2.70
AXIAL TCA HEATER	14.00	BOX	15.40	12.60
RADIAL VALVE DRIVERS	21.00	BOX	23.10	18.90
RADIAL THRUST CHMBR ASSEM	19.00	BOX	20.90	17.10
RADIAL TCA HEATER	14.00	BOX	15.40	12.60
FUEL TANK HEATERS	42.00	BOX	46.20	37.80
FUEL LINE HEATERS	20.00	BOX	22.00	18.00
VALVE DRIVER HEATERS	28.00	BOX	30.80	25.20
RCE THERMOSTAT	200.00	BOX	220.00	180.00

Reliability Math Model

The NATO III D reliability math model elements are presented below in a series of figures, beginning at the system level and descending to the lowest level for which data is available, taking each subsystem in turn. Each figure consists of a portion of the math model associated with the subsystem or component named in the figure caption and a reference list relating component names to the index numbers used in the math model (5:3-80).

$$P_S = P_1 P_2 P_3 P_4 P_5$$

1 = COMM Subsystem   4 = EPS Subsystem
2 = TTC Subsystem   5 = RCE Subsystem
3 = AAC Subsystem

Fig. A-1. Spacecraft-Level Math Model

$$P_S = P_1 P_2 P_3 P_4 (P_5)^X P_6 P_7 \{1+[1-(P_6 P_7)^X]/X\} P_8 P_9 (P_{10})^2 (P_{11})^2 (P_8)^2 P_A$$

$$\times \ \{1+[1-(P_A)^X]/X\} P_{10} (P_{11})^2 P_8 P_B \{1+[1-(P_B)^X]/X\} P_{13} P_7$$

$$\times \ [1+(1-P_{13} P_7)^X/X] P_{14} (P_8)^2 (P_C)^2 \{2(K+2)(2K+2)/[2(K)^2]\}$$

$$\times \ \{0.5-[2(P_C)^K/(K+2)]+[(P_C)^{2K}/(2K+2)]\} (P_{20})^{2X} P_{21} P_{22} P_{23} P_3 P_{27}$$

$$\times \ P_{21} P_{22} P_{24} P_3 P_{28} P_{26} \{1+[1-(P_{26})^X]/X\} (P_5)^X$$

$X = 0.5$ Ratio of standby to active reliabilities

$$P_A = (P_7)^5 (P_{12})^2 P_8 P_{15} P_{16}$$

$$P_B = (P_7)^3 P_{12} P_{15} P_{16}$$

$$P_C = (P_7)^2 P_{18} P_{19} P_{16}$$

$$K = [(\lambda_{17}+2\lambda_7+\lambda_{18}+\lambda_{19}+\lambda_{16}+\lambda_{20}-7250)+1000]/[2(2\lambda_7+\lambda_{18}+\lambda_{19}+\lambda_{16})]$$

 1 = Redundancy Control Unit   15 = Down-Converter
 2 = WB Receive Antenna   16 = Isolator
 3 = Test Coupler   17 = Circulator Switch
 4 = Preselector Band Pass Filter   18 = Driver Amplifier
 5 = Coax Switch   19 = TWT Amplifier
 6 = Preamplifier   20 = Wave Guide Switch
 7 = Attenuator   21 = Output Filter
 8 = Hybrid Splitter   22 = Low Pass Filter
 9 = Port Circulator Switch   23 = Beacon Inject Filter
10 = Band Pass Filter   24 = Beacon Reject Filter
11 = Equalizer   25 = Coupler Detector
12 = Limiter   26 = Beacon
13 = Local Oscillator   27 = WB Transmit Antenna
14 = Local Oscillator Hybrid   28 = NB Transmit Antenna

Fig. A-2. Communications Payload Subsystem Math Model

$$P_s = P_1 P_2 P_3 (P_4)^3 P_5$$

1 = RCU Power Selector   4 = RCU Limiter Gain Controller
2 = RCU Component Selector   5 = RCU Dirrect Bus Connection
3 = RCU TWTA Selector

Fig. A-3. Redundancy Control Unit Math Model

$$P_s = (P_1)^3 P_2 \{1 + [1 - ((P_1)^3 P_2)^{0.5}]/0.5\}$$

1 = PS Relay   2 = PS DC/DC Converter

Fig. A-4. RCU Power Selector Math Model

$$P_s = 2[P_1 P_2 P_3 (P_4)^3] - [P_1 P_2 P_3 (P_4)^3]^2$$

1 = CS Local Oscillator Selector   3 = CS Preamplifier Selector
2 = CS Beacon Selector   4 = CS Limiter Selector

Fig. A-5. RCU Component Selector Math Model

$$P_s = 2[P_1 P_2 P_3 (P_4)^2]^{0.5} - P_1 P_2 P_3 P_4$$

1 = TS Mode Selector   3 = TS TWTA Selector
2 = TS WB/NB Selector   4 = TS Driver Selector

Fig. A-6. RCU TWTA Selector Matn Model

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$$P_8 = P_2(P_1)^3(P_3)^3\{1-[1-(P_1)^3]^2\}$$

1 = LGS Type 1 Relay   3 = LGS Resistor
2 = LGS Type 2 Relay

Fig. A-7. RCU Limiter Gain Selector Math Model

$$P_8 = \{P_1[2P_2-(P_2)^2]\}^2$$

1 = DBC Type 1 Resistor   2 = DBC Type 2 Resistor

Fig. A-8. RCU Direct Bus Connection Math Model

$$P_8 = P_1P_2P_3P_4P_5$$

1 = Receive Antenna Assembly   4 = Outer Reject Channel
2 = WBR Upper Wave Guide Run   5 = WBR Lower Wave Guide Run
3 = WBR Reject Wave Guide Run

Fig. A-9. Wide Beam Receive Antenna Math Model

$$P_8 = (P_1)^4(P_2)^5P_3(P_4)^2P_5P_6(P_7)^5(P_8)^{2\bullet}(P_9)^4$$

1 = Horn Section   6 = Wave Guide Transition
2 = Horn Joint   7 = Wave Guide Flange
3 = Horn Cover   8 = Flange Fastener
4 = Thermal Finish   9 = Brazed Joint
5 = Mode Generator

Fig. A-10. WB Receive Antenna Assembly Math Model

$$P_s = (P_1)^2(P_2)^8(P_3)^4 P_4(P_5)^2 P_6 P_7 P_8(P_9)^3(P_{10})^{13}$$

1 = Wave Guide Flange   6 = 30 Deg Wave Guide Bend
2 = Flange Fastener   7 = 45 Deg Wave Guide Bend
3 = Wave Guide Section   8 = 60 Deg Wave Guide Bend
4 = Wave Guide Run   9 = 90 Deg Wave Guide Bend
5 = Wave Guide Flex Section   10 = Brazed Joint

Fig. A-11. WBR Upper Wave Guide Run Math Model

$$P_s = P_1(P_2)^4(P_3)^2(P_4)^2(P_5)^5$$

1 = Wave Guide Flange   4 = 45 Deg Wave Guide Bend
2 = Flange Fastener   5 = Brazed Joint
3 = Wave Guide Section

Fig. A-12. WBR Reject Wave Guide Run Math Model

$$P_s = P_1(P_2)^4(P_3)^8(P_4)^4 P_5(P_6)^2(P_7)^2 P_8$$

1 = Wave Guide Flange   5 = Reject Coax Section
2 = Flange Fastener   6 = Horn Joint Spacer
3 = Transformer   7 = Wave Guide Hybrid
4 = Rotary Coax Choke   8 = Brazed Joint

Fig. A-13. WBR Outer Reject Channel Math Model

$$Ps = (P_1)^2(P_2)^8(P_3)^2 P_4 P_5 (P_6)^2 (P_7)^7$$

1 = Wave Guide Flange   5 = Wave Guide Flex Section
2 = Flange Fastener   6 = 60 Deg Wave Guide Bend
3 = Wave Guide Section   7 = Brazed Joint
4 = Wave Guide Run

Fig. A-14. WBR Lower Wave Guide Run Math Model

$$Ps = P_1 P_2 P_3 P_4 P_5$$

1 = WB Transmit Antenna Assembly   4 = Central Reject Channel
2 = WBT Upper Wave Guide Run   5 = WBT Lower Wave Guide Run
3 = WBT Reject Wave Guide Run

Fig. A-15. Wide Beam Transmit Antenna Math Model

$$Ps = (P_1)^4(P_2)^5 P_3 (P_4)^2 P_5 P_6 (P_7)^5 (P_8)^{28} (P_9)^4$$

1 = Horn Section   6 = Wave Guide Transition
2 = Horn Joint   7 = Wave Guide Flange
3 = Horn Cover   8 = Flange Fastener
4 = Thermal Finish   9 = Brazed Joint
5 = Mode Generator

Fig. A-16. WB Transmit Antenna Assembly Math Model

$$P_8 = (P_1)^2(P_2)^6(P_3)^3P_4(P_5)^2(P_6)^2P_7(P_8)^3(P_9)^{12}$$

1 = Wave Guide Flange   6 = 30 Deg Wave Guide Bend
2 = Flange Fastener   7 = 60 Deg Wave Guide Bend
3 = Wave Guide Section   8 = 90 Deg Wave Guide Bend
4 = Wave Guide Run   9 = Brazed Joint
5 = Wave Guide Flex Section

Fig. A-17. WBT Upper Wave Guide Run Math Model

$$P_8 = P_1(P_2)^4P_3(P_4)^2(P_5)^4$$

1 = Wave Guide Flange   4 = 30 Deg Wave Guide Bend
2 = Flange Fastener   5 = Brazed Joint
3 = Wave Guide Section

Fig. A-18. WBT Reject Wave Guide Run Math Model

$$P_8 = P_1(P_2)^4(P_3)^2P_4(P_5)^4P_6$$

1 = Wave Guide Flange   4 = Reject Coax Section
2 = Flange Fastener   5 = Horn Joint Spacer
3 = Rotary Coax Choke   6 = Brazed Joint

Fig. A-19. WBT Central Reject Channel Math Model

$$P_S = (P_1)^2(P_2)^8(P_3)^2P_4P_5(P_6)^4P_7(P_8)^8$$

1 = Wave Guide Flange	5 = Wave Guide Flex Section
2 = Flange Fastener	6 = 60 Deg Wave Guide Bend
3 = Wave Guide Section	7 = 90 Deg Wave Guide Twist
4 = Wave Guide Run	8 = Brazed Joint

Fig. A-20. WBT Lower Wave Guide Run Math Model

$$P_S = P_1P_2P_3P_4P_5$$

1 = NB Transmit Antenna Assembly	4 = Inner Reject Channel
2 = NBT Upper Wave Guide Run	5 = NBT Lower Wave Guide Run
3 = NBT Reject Wave Guide Run	

Fig. A-21. Narrow Beam Transmit Antenna Math Model

$$P_S = (P_1)^4(P_2)^5P_3(P_4)^2P_5P_6(P_7)^7(P_8)^{52}P_9(P_{10})^6P_{11}$$

1 = Horn Section	7 = Wave Guide Flange
2 = Horn Joint	8 = Flange Fastener
3 = Horn Cover	9 = Wave Guide Section
4 = Thermal Finish	10 = Brazed Joint
5 = Mode Generator	11 = Polarizer
6 = Wave Guide Transition	

Fig. A-22. NB Transmit Antenna Assembly Math Model

$$P_8 = (P_1)^2(P_2)^8 P_3 P_4 (P_5)^2 (P_6)^2 (P_7)^3 (P_8)^{11}$$

1 = Wave Guide Flange	5 = Wave Guide Flex Section
2 = Flange Fastener	6 = 30 Deg Wave Guide Bend
3 = Wave Guide Section	7 = 90 Deg Wave Guide Bend
4 = Wave Guide Run	8 = Brazed Joint

Fig. A-23. NBT Upper Wave Guide Run Math Model

$$P_8 = P_1 (P_2)^4 (P_3)^2 (P_4)^2 (P_5)^5$$

1 = Wave Guide Flange	4 = 30 Deg Wave Guide Bend
2 = Flange Fastener	5 = Brazed Joint
3 = Wave Guide Section	

Fig. A-24. NBT Reject Wave Guide Run Math Model

$$P_8 = P_1 (P_2)^4 (P_3)^3 (P_4)^4 P_5 (P_6)^4 P_7$$

1 = Wave Guide Flange	5 = Reject Coax Section
2 = Flange Fastener	6 = Horn Joint Spacer
3 = Transformer	7 = Brazed Joint
4 = Rotary Coax Choke	

Fig. A-25. NBT Inner Reject Channel Math Model

$$P_B = (P_1)^2(P_2)^8(P_3)^3 P_4 P_5(P_6)^2 P_7 P_8(P_9)^{10}$$

1 = Wave Guide Flange   6 = 60 Deg Wave Guide Bend
2 = Flange Fastener   7 = 90 Deg Wave Guide Bend
3 = Wave Guide Section   8 = 90 Deg Wave Guide Twist
4 = Wave Guide Run   9 = Brazed Joint
5 = Wave Guide Flex Section

Fig. A-26. NBT Lower Wave Guide Run Math Model

$$P_B = P_1 P_2[2P_3P_4 - (P_3P_4)^2]P_5P_6P_7P_8\{1+[1-(P_7P_8)^{0.5}]/0.5\}P_9P_{10}$$
$$\times \; \{1+[1-(P_9P_{10})^{0.5}]\}P_{11}P_{12}P_{13}\{1+[1-(P_{12}P_{13})^{0.5}]\}P_{14}$$

1 = TTC Diplexer   8 = Beacon Telemetry Unit
2 = Hybrid   9 = TLM DC/DC Converter
3 = Receiver DC/DC Converter   10 = Telemetry Generator
4 = S-Band Receiver   11 = TLM Interface Unit
5 = Command Processing Unit   12 = Xmtr DC/DC Converter
6 = Command Combiner Relays   13 = S-Band Transmitter
7 = Beacon DC/DC Converter   14 = S-Band Antenna Assembly

Fig. A-27 Telemetry, Tracking, and Command Subsystem Math Model

$$P_B = 2P_A(1-P_A)(P_B)^{120}(P_C)^8 + (P_A)^2[2P_B - (P_B)^2]^{120}[2P_C - (P_C)^2]^8$$

$$P_A = P_1 P_2(P_3 P_4)^{0.525}$$

$$P_B = (P_6)^{0.525}$$

$$P_C = (P_5)^{0.525}$$

1 = Command DC/DC Converter   4 = Command Decrypter
2 = Command Bit Detector   5 = Low Side Drivers
3 = Command Decoder   6 = High Side Drivers

Fig. A-28. Command Processing Unit Math Model

$$P_S = P_1(P_2)^2(P_3)^8 \left[\sum_{i=0}^{4} \binom{64}{i} (P_4)^{64-i}(1-P_4)^i \right]$$

1 = RF Switch	3 = Antenna Power Divider
2 = Power Divider	4 = Antenna Element

Fig. A-29.   S-Band Antenna Assembly Math Model

$$P_S = [3(P_1)^4 - 8(P_1)^3 + 6(P_1)^2][2P_2 - (P_2)^2]P_3P_4P_5P_6P_7P_8P_9P_{10}$$

$$\times [3-2(P_3P_4P_5)^{0.5}][3-2(P_6P_7)^{0.5}][3-2(P_8)^{0.5}][3-2(P_{10})^{0.5}]$$

$$\times [2P_{11}-(P_{11})^2]$$

1 = Earth Sensor	7 = Motor Drive Amplifier
2 = Sun Sensor	8 = Resolver Windings
3 = AAC DC/DC Converter	9 = Motor Bearings
4 = AAC Electronics	10 = Motor Windings
5 = Magnetic Pickup	11 = Nutation Damper
6 = Motor Drive DC/DC Converter	

Fig. A-30   Attitude and Antenna Control Subsystem Math Model

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$$P_S = P_1 P_2 [2P_3 - (P_3)^2](P_E)^3$$

$$\times \{3[(P_F)^2 P_6 P_7 P_8 P_B P_E P_{10}]^2 - 2[(P_F)^2 P_6 P_7 P_8 P_B P_E P_{10}]^3\}$$

$$\times [2P_F P_{33} - (P_F P_{33})^2][3(P_{11})^2 P_{12} - 3(P_{11})^3(P_{12})^2 + (P_{11})^3(P_{12})^3]$$

$$\times [2P_C - (P_C)^2][2P_{17} - (P_{17})^2][12(P_{18})^{11} - 11(P_{18})^{12}]$$

$$\times [P_{19} + P_D - P_{19}P_D]^2[P_F P_{20} + P_D - P_F P_{20}P_D]P_{21}P_{22}$$

$$\times [P_{23}P_{24}P_{25} + P_D - P_{23}P_{24}P_{25}P_D]^4 P_F$$

$$\times [351(P_{26})^{28} - 728(P_{26})^{27} + 378(P_{26})^{26}](P_{27})^2 P_{28}[2P_{29} - (P_{29})^2]$$

$$\times [2(P_{30})^{0.5} - P_{30}][2(P_{31})^{0.5} - P_{31}][2P_{32} - (P_{32})^2]$$

$$P_B = (P_9)^3[20(P_9)^{16.15} - 19(P_9)^{17}]$$

$$P_C = P_{13}[3(P_5)^2 - 2(P_5)^3]P_{14}P_{15}[253(P_{16})^{24} - 528(P_{16})^{23} + 276(P_{16})^{22}]$$

$$\times (P_E)^2$$

$$P_D = exp[-330(10^{-9})t]$$

$$P_E = 20(P_4)^{19} - 19(P_4)^{20}$$

$$P_F = 2P_5 - (P_5)^2$$

1 =	Main Solar Cell Array	18 =	Shunt Set
2 =	Battery Solar Cell Array	19 =	Automatic Disconnector
3 =	Solar Array Relay	20 =	Automatic Reconnector
4 =	Current Sensing Resistor A	21 =	AGE/RCE Circuit
5 =	Fuse	22 =	Circuit Breaker Reset
6 =	Battery Charge Controller	23 =	TWTA Circuit Breaker
7 =	Current Sensing Resistor C	24 =	Current Sensing Resistor B
8 =	Undervoltage Controller	25 =	Circuit Breaker Relay
9 =	Battery Cell	26 =	Capacitor 2
10 =	Battery Relay	27 =	Current Telemetry
11 =	Error Amplifier	28 =	Voltage Telemetry
12 =	Majority Voter	29 =	Fuse Block
13 =	Pulse Width Modulator	30 =	Misc Chassis Components
14 =	Boost Converter	31 =	AKM Circuit
15 =	Electronics Compiler Assm	32 =	AKM Initiator Squib
16 =	Capacitor 1	33 =	Battery Charge Sequencer
17 =	Shunt Driver		

Fig. A-31. Electrical Power Subsystem Math Model

$$P_S = P_1 P_2 P_3 P_4 P_5 P_6 P_7 \{1+[1-(P_5 P_6 P_7)^X]/X\} P_8 P_9 P_{10} \{1+[1-(P_8 P_9 P_{10})^X]/X\}$$

$$\times [P_A + P_A P_B - (P_A)^2 P_B]$$

$$X = 0.5$$

$$P_A = P_{11} P_{12} P_{13}$$

$$P_B = 2(P_{14})^2 - (P_{14})^4$$

1 = Fuel Tanks		8 =	Radial Valve Drivers
2 = Wet Lines and Fittings		9 =	Radial Thrust Chamber
3 = Fill/Drain Valve		10 =	Radial TCA Heater
4 = Pressure Transducer		11 =	Fuel Tank Heaters
5 = Axial Valve Drivers		12 =	Fuel Line Heaters
6 = Axial Thrust Chamber		13 =	Valve Driver Heaters
7 = Axial TCA Heater		14 =	RCE Thermostat

Fig. A-32. Reaction Control Equipment Subsystem Math Model

Appendix B: NATO III D Reliability Update Program (RUP)

The Reliability Update Program (RUP) is a group of dBASE III PLUS
programs and data files that calculates the reliability of the NATO
spacecraft and estimates the parameters of a Weibull reliability
function that best approximates the spacecraft reliability function.

Normally, files which contain user-specified failure rates for each
component are accessed to calculate reliability from the lowest level
for which data is available. Alternatively, RUP can be used to
calculate equivalent failure rates at any level and then calculate the
Weibull system reliability function from whatever level is desired.

The user creates a data file which contains the values of time, t
(in months), for which system reliability will be calculated. RUP
calculates reliability according to the math model given in Appendix A
at each of these times and then fits an optimum Weibull reliability
curve to the resulting data via a Hooke-Jeeves vector search algorithm
(17:511-515). RUP's calculation of equivalent constant failure rates
instead of a Weibull function involves fitting a curve (the exponential
failure curve) with only one parameter and is more efficiently
accomplished using the method of maximum likelihood estimators (10:159).

RUP includes seven program files and two data files as shown in
Figure B-1. Editing of data files is best accomplished by creating and
editing alternate files of the same format and using RUP's on-screen
menus to load these files for a RUP application. The following pages
contain a listing of all RUP program and data files.

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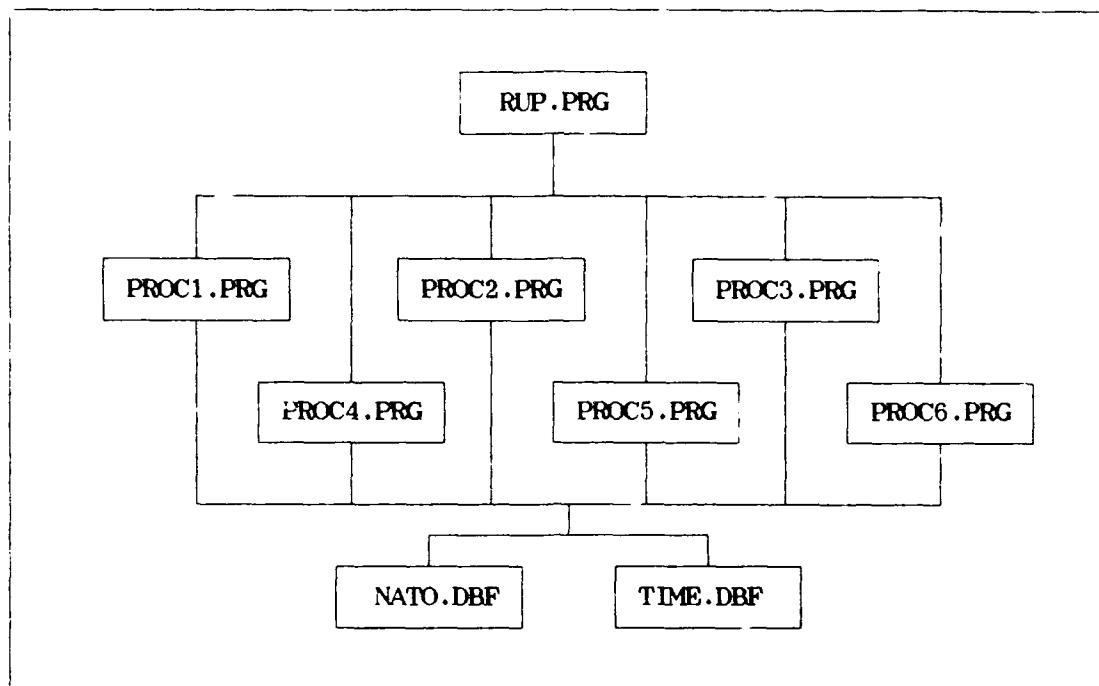
Fig. B-1. Reliability Update Program (RUP) File Structure

RUP.PRG File Listing

```
SET COLOR TO BG+/N,B/W,B
CLEAR
SET TALK OFF
SET SAFETY ON
STORE ' ' TO MOPT
STORE SPACE(7) TO MFILE
TEXT


Choose one of the following options...


        1)   Edit reliability database

        2)   Fdit time(s) for reliability calculations

        3)   Calculate reliability

        4)   Estimate system Weibull parameters

        5)   Quit
ENDTEXT
```

```
@ 22,0 SAY 'OPTION'
DO WHILE .NOT. MOPT $ '12345'
MOPT = ' '
@ 22,8 GET MOPT
READ
ENDDO
CLEAR
DO CASE
CASE MOPT = '1'
STORE 0 TO MSYS
STORE ' ' TO ML1
DIR
@ 20,0 SAY 'What file contains the reliability data you wish to i
use (no ext.)?'
@ 20,68 GET MFILE
READ
SELECT 2
USE &MFILE
DO WHILE .NOT. MSYS > 7
CLEAR
TEXT

What subsystem do you wish to edit?


        1)   Communications

        2)   Telemetry Tracking & Command

        3)   Antenna & Attitude Control

        4)   Electrical Power

        5)   Reaction Control Equipment

        6,7,8,9,0)  Quit to Main Menu
ENDTEXT
@ 24,0 SAY 'OPTION'
@ 24,8 GET MSYS PICTURE '9'
READ
IF MSYS > 7 .OR. MSYS = 0
CLEAR ALL
DO RUP
ENDIF
LOCATE FOR SSYS = MSYS .AND. BOX = 0
BROWSE
@ 2,0 SAY 'The data file has been updated.  Do you wish to load i
it (Y/N)?'
DO WHILE .NOT. ML1 $ 'YN'
ML1 = ' '
@ 2,61 GET ML1 PICTURE '!'
```

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```
READ
ENDDO
IF ML1 = 'Y'
COPY TO NATO
ENDIF
ENDDO
CLEAR ALL
CASE MOPT = '2'
STORE ' ' TO ML2
DIR
@ 20,0 SAY 'What file contains the time data you wish to use (no i
ext.)?'
@ 20,61 GET MFILE
READ
SELECT 2
USE &MFILE
BROWSE
@2,0 SAY 'The data file has been updated.  Do you wish to load it i
(Y/N)?'
DO WHILE .NOT. ML2 $ 'YN'
ML2 = ' '
@ 2,61 GET ML2 PICTURE '!'
READ
ENDDO
IF ML2 = 'Y'
COPY TO TIME
ENDIF
CLEAR ALL
DO RUP
CASE MOPT = '3'
STORE 0 TO MCHS
PUBLIC MSUM, MCNT, MPUBC, MPUBT
STORE 0 TO MSUM, MCNT, MPUBC, MPUBT
PUBLIC MPUBE, MPUBB, MPUBA, MPUBG
STORE 0 TO MPUBE, MPUBB, MPUBA, MPUBG
TEXT
        1)  Calculate R from component level to system level

        2)  Estimate failure rates at assembly level
            (Run (1) first)

        3)  Calculate R from assembly level to system level
            (Run (2) first)

        4)  Estimate failure rates at box level
            (Run (1) or (3) first)

        5)  Calculate R from box level to system level
            (Run (4) first)

        6)  Estimate failure rates at subsystem level
            (Run (1), (3), or (5) first)
```

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```
          7)   Calculate R from subsystem level to system level
               (Run (6) first)

          8)   Estimate failure rates at system level
               (Run (1), (3), (5), or (7) first)
ENDTEXT
@ 24,0 SAY 'OPTION'
@ 24,8 GET MCHS PICTURE '9'
READ
CLEAR
USE NATO
SELECT 2
USE TIME
STORE 0 TO MT, MPS
PUBLIC MC
STORE 1000000000 TO MC
COUNT TO MCNT
IF MCHS = 1
GO TOP
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
@ 12,0 SAY 'Calculating probabilities for TIME ='
@ 12,37 SAY MT/730.5
@ 12,57 SAY 'months'
SELECT 1
SET PROCEDURE TO PROC1
DO PS
DO CS
DO TS
DO LGS
DO DBC
DO WRA
DO WBRW1
DO WBRW2
DO WBRORC
DO WBRW3
DO WTA
DO WBTW1
DO WBTW2
CLOSE PROCEDURE
SET PROCEDURE TO PROC2
DO WBTCRC
DO WBTW3
DO NTA
DO NBTW1
DO NBTW2
DO NBTIRC
DO NBTW3
SELECT 2
DO RCU
DO WBRA
```

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```
DO WBTA
DO NBTA
SELECT 1
DO CMDU
DO SANT
DO CSRA
DO BAT
CLOSE PROCEDURE
SET PROCEDURE TO PROC3
DO CAP1
DO CAP2
DO COMM
DO TTC
DO AAC
CLOSE PROCEDURE
SET PROCEDURE TO PROC4
DO EPS
DO RCE
SELECT 2
DO SYSTEM
SELECT 1
CLOSE PROCEDURE
SELECT 2
SKIP
ENDDO
CLEAR ALL
DO RUP
ENDIF
SET PROCEDURE TO PROC5
IF MCHS = 2
DO STORAGE
DO ASSEMBLY
ENDIF
IF MCHS = 4
DO STORAGE
DO BOX
ENDIF
IF MCHS = 6
DO STORAGE
DO SUBSYS
ENDIF
IF MCHS = 8
DO SYS
ENDIF
CLOSE PROCEDURE
IF MCHS = 3
GO TOP
SET PROCEDURE TO PROC4
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
@ 12,0 SAY 'Calculating probabilities for TIME ='
@ 12,37 SAY MT/730.5
```

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```
@ 12,57 SAY 'months'
SELECT 1
DO XRCU
DO XWBRA
DO XWBTA
DO XNBTA
CLOSE PROCEDURE
SET PROCEDURE TO PROC3
DO COMM
CLOSE PROCEDURE
SET PROCEDURE TO PROC4
SELECT 2
DO SYSTEM
SKIP
ENDDO
CLOSE PROCEDURE
CLEAR ALL
ENDIF
IF MCHS = 5
GO TOP
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
@ 12,0 SAY 'Calculating probabilities for TIME ='
@ 12,37 SAY MT/730.5
@ 12,57 SAY 'months'
SELECT 1
SET PROCEDURE TO PROC6
DO XEPS
CLOSE PROCEDURE
SET PROCEDURE TO PROC3
DO COMM
DO TTC
CLOSE PROCEDURE
SET PROCEDURE TO PROC5
DO XCOMM
DO XTTC
CLOSE PROCEDURE
SET PROCEDURE TO PROC4
DO EPS
SELECT 2
DO SYSTEM
CLOSE PROCEDURE
SKIP
ENDDO
CLEAR ALL
RELEASE ALL
ENDIF
IF MCHS = 7
GO TOP
SET PROCEDURE TO PROC6
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
```

```
@ 12,0 SAY 'Calculating probabilities for TIME ='
@ 12,37 SAY MT/730.5
@ 12,57 SAY 'months'
SELECT 1
DO XSYSTEM
SELECT 2
SKIP
ENDDO
CLOSE PROCEDURE
ENDIF
CASE MOPT = '4'
SET PROCEDURE TO PROC6
DO WEIBULL
CLOSE ALL
DO RUP
CASE MOPT = '5'
CLOSE ALL
CANCEL
ENDCASE
CLOSE ALL
DO RUP
```

PROC1.PRG File Listing

```
PROCEDURE PS
LOCATE FOR MNEM = 'PSK'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE LAMBDA/MC TO MSASM2
STORE MSASM2 + (3 * MSASM1) TO MSASM2
STORE MSASM1 * 5 TO MSASM1
STORE EXP(-MSASM2*MT)*(3-2*EXP(-.5*MSASM2*MT))*EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE PS WITH MPS
SELECT 1
RETURN

PROCEDURE CS
LOCATE FOR MNEM = 'CSLOS'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1 + LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1 + LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1 + 3*LAMBDA/MC TO MSASM1
STORE 2*EXP(-MSASM1*MT)-(EXP(-MSASM1*MT)^2) TO MPS
SELECT 2
REPLACE CS WITH MPS
SELECT 1
RETURN
```

```
PROCEDURE TS
LOCATE FOR MNEM = 'TSMS'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1 + LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1 + LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1 + LAMBDA/MC TO MSASM1
STORE 2*(EXP(-MSASM1*MT))^.5-EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE TS WITH MPS
SELECT 1
RETURN

PROCEDURE LGS
LOCATE FOR MNEM = 'LGSK1'
STORE 3*LAMBDA/MC TO MSASM1
SKIP
STORE LAMBDA/MC TO MSASM2
SKIP
STORE MSASM2 + 3*LAMBDA/MC TO MSASM2
STORE EXP(-(MSASM1+MSASM2)*MT)*(1-(1-EXP(-MSASM1*MT))^2) TO MPS
SELECT 2
REPLACE LGS WITH MPS
SELECT 1
RETURN

PROCEDURE DBC
LOCATE FOR MNEM = 'DBCR1'
STORE 6*LAMBDA/MC TO MSASM1
SKIP
STORE LAMBDA/MC TO MSASM2
STORE EXP(-MSASM1*MT) TO MPS
STORE MPS*(2*EXP(-MSASM2*MT)-EXP(-2*MSASM2*MT)) TO MPS
STORE MPS^2 TO MPS
SELECT 2
REPLACE DBC WITH MPS
SELECT 1
RETURN

PROCEDURE WRA
LOCATE FOR MNEM = 'WBRHS'
STORE 4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+5*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
```

```
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+5*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+20*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WRA WITH MPS
SELECT 1
RETURN

PROCEDURE WBRW1
LOCATE FOR MNEM = 'WRW1F'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+3*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+13*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBRW1 WITH MPS
SELECT 1
RETURN

PROCEDURE WBRW2
LOCATE FOR MNEM = 'WRW2F'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
```

```
STORE MSASM1+5*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBRW2 WITH MPS
SELECT 1
RETURN

PROCEDURE WBRORC
LOCATE FOR MNEM = 'WRRCF'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+6*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBRORC WITH MPS
SELECT 1
RETURN

PROCEDURE WBRW3
LOCATE FOR MNEM = 'WRW3F'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+7*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBRW3 WITH MPS
SELECT 1
RETURN

PROCEDURE WTA
```

```
LOCATE FOR MNEM = 'WBTHS'
STORE 4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+5*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+5*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+20*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WTA WITH MPS
SELECT 1
RETURN

PROCEDURE WBTW1
LOCATE FOR MNEM = 'WTW1F'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+3*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+3*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+12*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBTW1 WITH MPS
SELECT 1
RETURN

PROCEDURE WBTW2
LOCATE FOR MNEM = 'WTW2F'
STORE LAMBDA/MC TO MSASM1
```

```
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBTW2 WITH MPS
SELECT 1
RETURN


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PROCEDURE WBTCRC
LOCATE FOR MNEM = 'WTRCF'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBTCRC WITH MPS
SELECT 1
RETURN

PROCEDURE WBTW3
LOCATE FOR MNEM = 'WTW3F'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
```

```
STORE MSASM1+8*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBTW3 WITH MPS
SELECT 1
RETURN

PROCEDURE NTA
LOCATE FOR MNEM = 'NBTHS'
STORE 4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+5*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+7*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+52*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+6*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE NTA WITH MPS
SELECT 1
RETURN

PROCEDURE NBTW1
LOCATE FOR MNEM = 'NTW1F'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+3*LAMBDA/MC TO MSASM1
SKIP
```

```
STORE MSASM1+11*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE NBTW1 WITH MPS
SELECT 1
RETURN

PROCEDURE NBTW2
LOCATE FOR MNEM = 'NTW2F'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+5*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE NBTW2 WITH MPS
SELECT 1
RETURN

PROCEDURE NBTIRC
LOCATE FOR MNEM = 'NTRCF'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+3*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+4*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE NBTIRC WITH MPS
SELECT 1
RETURN

PROCEDURE NBTW3
LOCATE FOR MNEM = 'NTW3F'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+3*LAMBDA/MC TO MSASM1
```

```
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+10*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE NBTW3 WITH MPS
SELECT 1
RETURN

PROCEDURE RCU
STORE PS*CS*TS*(LGS^3)*DBC TO MPS
REPLACE RCU WITH MPS
RETURN

PROCEDURE WBRA
STORE WRA*WBRW1*WBRW2*WBRORC*WBRW3 TO MPS
REPLACE WBRA WITH MPS
RETURN

PROCEDURE WBTA
STORE WTA*WBTW1*WBTW2*WBTCRC*WBTW3 TO MPS
REPLACE WBTA WITH MPS
RETURN

PROCEDURE NBTA
STORE NTA*NBTW1*NBTW2*NBTIRC*NBTW3 TO MPS
REPLACE NBTA WITH MPS
RETURN

PROCEDURE CMDU
LOCATE FOR MNEM = 'CMDCON'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+.525*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+.525*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPSA
SKIP
STORE .525*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPSC
SKIP
```

```
STORE .525*LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPSB
STORE 2*MPSA*(1-MPSA)*(MPSB^120)*(MPSC^8) TO MPS
STORE (2*MPSB-(MPSB^2))^120 TO MSASM1
STORE (2*MPSC-(MPSC^2))^8 TO MSASM2
STORE MPS+(MPSA^2)*MSASM1*MSASM2 TO MPS
SELECT 2
REPLACE CMDU WITH MPS
SELECT 1
RETURN

PROCEDURE SANT
LOCATE FOR MNEM = 'RFSWT'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+8*LAMBDA/MC TO MSASM1
SKIP
STORE LAMBDA/MC TO MSASM2
STORE EXP(-MSASM2*MT) TO MSASM2
STORE 64*(MSASM2^63)*(1-MSASM2) TO MPS
STORE MPS+2016*(MSASM2^62)*((1-MSASM2)^2) TO MPS
STORE MPS+41664*(MSASM2^61)*((1-MSASM2)^3) TO MPS
STORE MPS+635376*(MSASM2^60)*((1-MSASM2)^4) TO MPS
STORE (MPS+(MSASM2^64))*EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE SANT WITH MPS
SELECT 1
RETURN

PROCEDURE CSRA
LOCATE FOR MNEM = 'CSR'
STORE LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
STORE 20*(MPS^19)-19*(MPS^20) TO MPS
SELECT 2
REPLACE CSRA WITH MPS
SELECT 1
RETURN

PROCEDURE BAT
LOCATE FOR MNEM = 'CELL'
STORE LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
STORE (MPS^3)*(20*(MPS^16.15)-19*(MPS^17)) TO MPS
SELECT 2
REPLACE BAT WITH MPS
SELECT 1
RETURN
```

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PROC3.PRG File Listing

```
PROCEDURE CAP1
LOCATE FOR MNEM = 'C1'
STORE LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
STORE 253*(MPS^24)-528*(MPS^23)+276*(MPS^22) TO MPS
SELECT 2
REPLACE CAP1 WITH MPS
SELECT 1
RETURN

PROCEDURE CAP2
LOCATE FOR MNEM = 'C2'
STORE LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
STORE 351*(MPS^28)-728*(MPS^27)+378*(MPS^26) TO MPS
SELECT 2
REPLACE CAP2 WITH MPS
SELECT 1
RETURN

PROCEDURE COMM
STORE 0 TO MPUBC
LOCATE FOR MNEM = 'ATTEN'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE LAMBDA/MC TO MSASM2
LOCATE FOR MNEM = 'LIMIT'
STORE LAMBDA/MC TO MSASM3
LOCATE FOR MNEM = 'DC'
STORE LAMBDA/MC TO MSASM4
SKIP
STORE LAMBDA/MC TO MSASM5
SKIP
STORE LAMBDA/MC TO MSASM6
SKIP
STORE LAMBDA/MC TO MSASM7
SKIP
STORE LAMBDA/MC TO MSASM8
SKIP
STORE LAMBDA/MC TO MSASM9
STORE 5*MSASM1+2*MSASM3+MSASM2+MSASM4+MSASM5 TO MPSA
STORE EXP(-MPSA*MT) TO MPSA
STORE 3*MSASM1+MSASM3+MSASM4+MSASM5 TO MPSB
STORE EXP(-MPSB*MT) TO MPSB
STORE 2*MSASM1+MSASM5+MSASM7+MSASM8 TO MPSC
STORE EXP(-MPSC*MT) TO MPSC
STORE MSASM6+2*MSASM1+MSASM7+MSASM8+MSASM5+MSASM9 TO MPSK
STORE .5*(MPSK-7250/MC)+.000001 TO MPSK
STORE MPSK/(2*MSASM1+MSASM7+MSASM8+MSASM5) TO MPSK
LOCATE FOR MNEM = 'TESTC'
```

```
STORE MSASM1+3*LAMBDA/MC TO MSASM10
SKIP
STORE MSASM10+LAMBDA/MC TO MSASM10
SKIP
STORE MSASM10+LAMBDA/MC TO MSASM10
SKIP
STORE MSASM10+LAMBDA/MC TO MSASM10
STORE EXP(-MSASM10*MT) TO MPS
STORE MSASM1+LAMBDA/MC TO MSASM10
STORE EXP(-MSASM10*MT) TO MSASM10
STORE (1+(1-(MSASM10^.5))/.5)*MPS TO MPS
LOCATE FOR MNEM = 'PCS'
STORE 3*MSASM2+LAMBDA/MC TO MSASM10
SKIP
STORE MSASM10+2*LAMBDA/MC TO MSASM10
SKIP
STORE MSASM10+2*LAMBDA/MC TO MSASM10
STORE MPS*EXP(-MSASM10*MT)*MPSA TO MPS
STORE MPS*(1+(1-(MPSA^.5))/.5) TO MPS
STORE MSASM2+2*LAMBDA/MC TO MSASM10
SKIP -1
STORE MSASM10+LAMBDA/MC TO MSASM10
STORE MPS*EXP(-MSASM10*MT)*MPSB TO MPS
STORE MPS*(1+(1-(MPSB^.5))/.5)*EXP(-MSASM1*MT) TO MPS
LOCATE FOR MNEM = 'LO'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MPS*EXP(-LAMBDA*MT/MC)*(1+(1-(MSASM1^.5))/.5) TO MPS
STORE MPS*EXP(-2*MSASM2*MT)*(MPSC^2) TO MPS
SKIP
STORE MPS*EXP(-LAMBDA*MT/MC) TO MPS
STORE (MPSC^(2*MPSK))/(2*MPSK+2) TO MSASM1
STORE .5+MSASM1-(2*(MPSC^MPSK))/(MPSK+2) TO MSASM1
STORE MSASM1*2*(MPSK+2)*(2*MPSK+2)/(2*(MPSK^2)) TO MSASM1
STORE MPS*MSASM1*EXP(-MSASM9*MT) TO MPS
LOCATE FOR MNEM = 'OUTF'
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP 2
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPS*EXP(-MSASM1*MT) TO MPS
STORE EXP(-.5*LAMBDA*MT/MC) TO MSASM1
STORE MPS*(1+(1-MSASM1)/.5) TO MPUBC
SELECT 2
STORE MPUBC*RCU*WBRA*WBTA*NBTA TO MPS
REPLACE COMM WITH MPS
SELECT 1
```

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```
RETURN

PROCEDURE TTC
STORE 0 TO MPUBT
LOCATE FOR MNEM = 'DIPLEX'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MPS*(2*MSASM1-(MSASM1^2)) TO MPS
LOCATE FOR MNEM = 'CMDREL'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPS*EXP(-MSASM1*MT) TO MPS
STORE LAMPDA/MC TO MSASM1
SKIP -1
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MPS*(1+(1-(MSASM1^.5))/.5) TO MPS
SKIP 2
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MPS*MSASM1*(1+(1-(MSASM1^.5))) TO MPS
SKIP 2
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MPS*MSASM1*(1+(1-(MSASM1^.5))) TO MPUBT
SELECT 2
STORE MPUBT*CMDU*SANT TO MPS
REPLACE TTC WITH MPS
SELECT 1
RETURN

PROCEDURE AAC
LOCATE FOR MNEM = 'ES'
STORE EXP(-LAMBDA*MT/MC) TO MPS
STORE 3*(MPS^4)-8*(MPS^3)+6*(MPS^2) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(2*MSASM1-(MSASM1^2)) TO MPS
```

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```
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPS*EXP(-MSASM1*MT)TO MPS
STORE EXP(-.5*LAMBDA*MT/MC)TO MSASM1
STORE MPS*(3-2*MSASM1) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(2*MSASM1-(MSASM1^2)) TO MPS
LOCATE FOR MNEM = 'AACCON'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPS*(3-2*EXP(-.5*MSASM1*MT)) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPS*(3-2*EXP(-.5*MSASM1*MT)) TO MPS
SKIP
STORE MPS*(3-2*EXP(-.5*LAMBDA*MT/MC)) TO MPS
SELECT 2
REPLACE AAC WITH MPS
SELECT 1
RETURN


PROC4.PRG File Listing

PROCEDURE EPS
LOCATE FOR MNEM = 'ARRAY1'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
```

```
STORE MPS*(2*MSASM1-(MSASM1^2)) TO MPS
SELECT 2
STORE CSRA TO MPSE
STORE BAT TO MPSB
STORE CAP1 TO MPSA
STORE CAP2 TO MPSG
SELECT 1
IF MPUBB > 0
STORE MPUBE TO MPSE
STORE MPUBB TO MPSB
STORE MPUBA TO MPSA
STORE MPUBG TO MPSG
ENDIF
STORE EXP(-330*MT/MC) TO MPSD
STORE MPS*(MPSE^3) TO MPS
SKIP 3
STORE EXP(-LAMBDA*MT/MC) TO MPS5
STORE 2*MPS5-(MPS5^2) TO MPSF
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP 3
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE (MPSF^2)*MPSB*MPSE*EXP(-MSASM1*MT) TO MSASM1
STORE MPS*(3*(MSASM1^2)-2*(MSASM1^3)) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM2
STORE 3*((MSASM1^2)*MSASM2-(MSASM1^3)*(MSASM2^2)) TO MSASM3
STORE MPS*(MSASM3+(MSASM1^3)*(MSASM2^3)) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MSASM1*MPSA*(MPSE^2)*(3*(MPS5^2)-2*(MPS5^3)) TO MPSC
SKIP 3
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(2*MSASM1-(MSASM1^2)) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(12*(MSASM1^11)-11*(MSASM1^12)) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*((MSASM1+MPSD-(MSASM1*MPSD))^2) TO MPS
SKIP
```

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```
STORE MPSF*EXP(-LAMBDA*MT/MC) TO MSASM1
STORE .999988*MPS*(MSASM1+MPSD-(MSASM1*MPSD)) TO MPS
SKIP 2
STORE MPS*EXP(-LAMBDA*MT/MC) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MSASM1
STORE MPS*((MSASM1+MPSD-(MSASM1*MPSD))^4) TO MPS
STORE MPS*MPSF*MPSG TO MPS
SKIP 3
STORE 2*LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPS*EXP(-MSASM1*MT) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*((2*MSASM1-(MSASM1^2))^29) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(2*(MSASM1^.5)-MSASM1) TO MPS
SKIP 2
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(2*MSASM1-(MSASM1^2)) TO MPS
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MSASM1
STORE MPS*(2*MPSF*MSASM1-((MPSF*MSASM1)^2)) TO MPS
SELECT 2
REPLACE EPS WITH MPS
SELECT 1
RETURN

PROCEDURE RCE
LOCATE FOR MNEM = 'TANK'
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE .99898*EXP(-MSASM1*MT) TO MSASM1
```

```
STORE MPS*MSASM1*(1+(1-(MSASM1^.5))/.5) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE .996*EXP(-MSASM1*MT) TO MSASM1
STORE MPS*MSASM1*(1+(1-(MSASM1^.5))/.5) TO MPS
SKIP
STORE LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
SKIP
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPSA
SKIP
STORE EXP(-LAMBDA*MT/MC) TO MPSB
STORE 2*(MPSB^2)-(MPSB^4) TO MPSB
STORE MPS*MPSA*(1+MPSB-(MPSA*MPSB)) TO MPS
SELECT 2
REPLACE RCE WITH MPS
SELECT 1
RETURN

PROCEDURE SYSTEM
STORE COMM*TTC*AAC*EPS*RCE TO MPS
REPLACE SYSTEM WITH MPS
RETURN

PROCEDURE XRCU
LOCATE FOR MNEM = 'PS'
STORE LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'CS'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'TS'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'LGS'
STORE MSASM1+3*LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'DBC'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE RCU WITH MPS
SELECT 1
RETURN

PROCEDURE XWBRA
LOCATE FOR MNEM = 'WRA'
STORE LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBRW1'
STORE MSASM1+LAMBDA/MC TO MSASM1
```

```
LOCATE FOR MNEM = 'WBRW2'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBRORC'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBRW3'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBRA WITH MPS
SELECT 1
RETURN

PROCEDURE XWBTA
LOCATE FOR MNEM = 'WTA'
STORE LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBTW1'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBTW2'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBTCRC'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBTW3'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE WBTA WITH MPS
SELECT 1
RETURN

PROCEDURE XNBTA
LOCATE FOR MNEM = 'NTA'
STORE LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'NBTW1'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'NBTW2'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'NBTIRC'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'NBTW3'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE NBTA WITH MPS
SELECT 1
RETURN
```

PROC5.PRG File Listing

```
PROCEDURE STORAGE
PUBLIC M1, M2, M3, M4, M5, M6, M7, M8, M9, M10
PUBLIC M11, M12, M13, M14, M15, M16, M17, M18, M19, M20
```

```
STORE 0 TO M1, M2, M3, M4, M5, M6, M7, M8, M9, M10
STORE 0 TO M11, M12, M13, M14, M15, M16, M17, M18, M19, M20
RETURN

PROCEDURE ASSEMBLY
GO TOP
CLEAR
@ 12,0 SAY 'Estimating assembly level failure rates.  Standby...'
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
STORE M1+LOG(PS)/MT TO M1
STORE M2+LOG(CS)/MT TO M2
STORE M3+LOG(TS)/MT TO M3
STORE M4+LOG(LGS)/MT TO M4
STORE M5+LOG(DBC)/MT TO M5
STORE M6+LOG(WRA)/MT TO M6
STORE M7+LOG(WBRW1)/MT TO M7
STORE M8+LOG(WBRW2)/MT TO M8
STORE M9+LOG(WBRORC)/MT TO M9
STORE M10+LOG(WBRW3)/MT TO M10
STORE M11+LOG(WTA)/MT TO M11
STORE M12+LOG(WBTW1)/MT TO M12
STORE M13+LOG(WBTW2)/MT TO M13
STORE M14+LOG(WBTCRC)/MT TO M14
STORE M15+LOG(WBTW3)/MT TO M15
STORE M16+LOG(NTA)/MT TO M16
STORE M17+LOG(NBTW1)/MT TO M17
STORE M18+LOG(NBTW2)/MT TO M18
STORE M19+LOG(NBTIRC)/MT TO M19
STORE M20+LOG(NBTW3)/MT TO M20
SKIP
ENDDO
GO TOP
SELECT 1
LOCATE FOR MNEM = 'PS'
REPLACE LAMBDA WITH -M1*MC/MCNT
LOCATE FOR MNEM = 'CS'
REPLACE LAMBDA WITH -M2*MC/MCNT
LOCATE FOR MNEM = 'TS'
REPLACE LAMBDA WITH -M3*MC/MCNT
LOCATE FOR MNEM = 'LGS'
REPLACE LAMBDA WITH -M4*MC/MCNT
LOCATE FOR MNEM = 'DBC'
REPLACE LAMBDA WITH -M5*MC/MCNT
LOCATE FOR MNEM = 'WRA'
REPLACE LAMBDA WITH -M6*MC/MCNT
LOCATE FOR MNEM = 'WBRW1'
REPLACE LAMBDA WITH -M7*MC/MCNT
LOCATE FOR MNEM = 'WBRW2'
REPLACE LAMBDA WITH -M8*MC/MCNT
LOCATE FOR MNEM = 'WBRORC'
REPLACE LAMBDA WITH -M9*MC/MCNT
```

```
LOCATE FOR MNEM = 'WBRW3'
REPLACE LAMBDA WITH -M10*MC/MCNT
LOCATE FOR MNEM = 'WTA'
REPLACE LAMBDA WITH -M11*MC/MCNT
LOCATE FOR MNEM = 'WBTW1'
REPLACE LAMBDA WITH -M12*MC/MCNT
LOCATE FOR MNEM = 'WBTW2'
REPLACE LAMBDA WITH -M13*MC/MCNT
LOCATE FOR MNEM = 'WBTCRC'
REPLACE LAMBDA WITH -M14*MC/MCNT
LOCATE FOR MNEM = 'WBTW3'
REPLACE LAMBDA WITH -M15*MC/MCNT
LOCATE FOR MNEM = 'NTA'
REPLACE LAMBDA WITH -M16*MC/MCNT
LOCATE FOR MNEM = 'NBTW1'
REPLACE LAMBDA WITH -M17*MC/MCNT
LOCATE FOR MNEM = 'NBTW2'
REPLACE LAMBDA WITH -M18*MC/MCNT
LOCATE FOR MNEM = 'NBTIRC'
REPLACE LAMBDA WITH -M19*MC/MCNT
LOCATE FOR MNEM = 'NBTW3'
REPLACE LAMBDA WITH -M20*MC/MCNT
SELECT 2
RELEASE ALL
RETURN

PROCEDURE BOX
GO TOP
CLEAR
@ 12,0 SAY 'Estimating box level failure rates.  Standby...'
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
STORE M1+LOG(RCU)/MT TO M1
STORE M2+LOG(WBRA)/MT TO M2
STORE M3+LOG(WBTA)/MT TO M3
STORE M4+LOG(NBTA)/MT TO M4
STORE M5+LOG(CMDU)/MT TO M5
STORE M6+LOG(SANT)/MT TO M6
STORE M7+LOG(CSRA)/MT TO M7
STORE M8+LOG(BAT)/MT TO M8
STORE M9+LOG(CAP1)/MT TO M9
STORE M10+LOG(CAP2)/MT TO M10
SKIP
ENDDO
GO TOP
SELECT 1
LOCATE FOR MNEM = 'RCU'
REPLACE LAMBDA WITH -M1*MC/MCNT
LOCATE FOR MNEM = 'WBRA'
REPLACE LAMBDA WITH -M2*MC/MCNT
LOCATE FOR MNEM = 'WBTA'
REPLACE LAMBDA WITH -M3*MC/MCNT
```

```
LOCATE FOR MNEM = 'NBTA'
REPLACE LAMBDA WITH -M4*MC/MCNT
LOCATE FOR MNEM = 'CMDU'
REPLACE LAMBDA WITH -M5*MC/MCNT
LOCATE FOR MNEM = 'SANT'
REPLACE LAMBDA WITH -M6*MC/MCNT
LOCATE FOR MNEM = 'CSRA'
REPLACE LAMBDA WITH -M7*MC/MCNT
LOCATE FOR MNEM = 'BAT'
REPLACE LAMBDA WITH -M8*MC/MCNT
LOCATE FOR MNEM = 'CAP1'
REPLACE LAMBDA WITH -M9*MC/MCNT
LOCATE FOR MNEM = 'CAP2'
REPLACE LAMBDA WITH -M10*MC/MCNT
SELECT 2
RELEASE ALL
RETURN

PROCEDURE SUBSYS
GO TOP
CLEAR
@ 12,0 SAY 'Estimating subsystem level failure rates.  Standby..'
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
STORE M1+LOG(COMM)/MT TO M1
STORE M2+LOG(TTC)/MT TO M2
STORE M3+LOG(AAC)/MT TO M3
STORE M4+LOG(EPS)/MT TO M4
STORE M5+LOG(RCE)/MT TO M5
SKIP
ENDDO
GO TOP
SELECT 1
LOCATE FOR MNEM = 'COMM'
REPLACE LAMBDA WITH -M1*MC/MCNT
LOCATE FOR MNEM = 'TTC'
REPLACE LAMBDA WITH -M2*MC/MCNT
LOCATE FOR MNEM = 'AAC'
REPLACE LAMBDA WITH -M3*MC/MCNT
LOCATE FOR MNEM = 'EPS'
REPLACE LAMBDA WITH -M4*MC/MCNT
LOCATE FOR MNEM = 'RCE'
REPLACE LAMBDA WITH -M5*MC/MCNT
SELECT 2
RELEASE ALL
RETURN

PROCEDURE SYS
STORE 0 TO M1
GO TOP
CLEAR
@ 12,0 SAY 'Estimating system level failure rate.  Standby...'
```

```
DO WHILE .NOT. EOF()
STORE 730.5*TIME TO MT
STORE M1+LOG(SYSTEM)/MT TO M1
SKIP
ENDDO
GO TOP
STORE -M1*MC/MCNT TO M1
CLEAR
@ 12,0 SAY 'System failure rate (LAMBDA) ='
@ 12,32 SAY M1
@ 12,52 SAY 'per billion hours.'
@ 20,0 say ' '
WAIT 'Hit any key to continue...'
RETURN


PROCEDURE XCOMM
LOCATE FOR MNEM = 'RCU'
STORE LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBRA'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'WBTA'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'NBTA'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPUBC*EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE COMM WITH MPS
SELECT 1
RETURN


PROCEDURE XTTC
LOCATE FOR MNEM = 'CMDU'
STORE LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'SANT'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE MPUBT*EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE TTC WITH MPS
SELECT 1
RETURN



PROC6.PRG File Listing

PROCEDURE XEPS
LOCATE FOR MNEM = 'CSRA'
STORE EXP(-LAMBDA*MT/MC) TO MPUBE
LOCATE FOR MNEM = 'BAT'
STORE EXP(-LAMBDA*MT/MC) TO MPUBB
LOCATE FOR MNEM = 'CAP1'
STORE EXP(-LAMBDA*MT/MC) TO MPUBA
LOCATE FOR MNEM = 'CAP2'
```

```
STORE EXP(-LAMBDA*MT/MC) TO MPUBG
RETURN

PROCEDURE XSYSTEM
LOCATE FOR MNEM = 'COMM'
STORE LAMBD/./MC TO MSASM1
LOCATE FOR MNEM = 'TTC'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'AAC'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'EPS'
STORE MSASM1+LAMBDA/MC TO MSASM1
LOCATE FOR MNEM = 'RCE'
STORE MSASM1+LAMBDA/MC TO MSASM1
STORE EXP(-MSASM1*MT) TO MPS
SELECT 2
REPLACE SYSTEM WITH MPS
SELECT 1
RETURN

PROCEDURE SSE
GO TOP
DO WHILE .NOT. EOF()
STORE (SYSTEM-EXP(-((TIME/MB)^MA)))^2 TO MTEMP
REPLACE TEMP WITH MTEMP
SKIP
ENDDO
SUM TEMP TO MSSE
RETURN

PROCEDURE WEIBULL
USE TIME
SET DECIMALS TO 4
CLEAR
@ 1, 5 SAY '   ALPHA        BETA        SSE        ITERATION'
STORE 0 TO MIT
PUBLIC MA, MB, MSSE
STORE 1.62 TO MA0, MA
STORE 135.5 TO MB0, MB
STORE .01 TO MDA
STORE .1 TO MDB
DO SSE
STORE MSSE TO MREF
DO WHILE .NOT. (MDA < .0001 .AND. MDB < .001)
STORE MIT+1 TO MIT
? MA, MB, MREF, MIT
STORE MB0+MDB TO MB
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MB TO MB1
ELSE
```

```
STORE MB0-MDB TO MB
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MB TO MB1
ELSE
STORE MB0 TO MB1
ENDIF
ENDIF
STORE MB1 TO MB
STORE MA0+MDA TO MA
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MA TO MA1
ELSE
STORE MA0-MDA TO MA
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MA TO MA1
ELSE
STORE MA0 TO MA1
ENDIF
ENDIF
STORE MA1 TC MA
IF MA1 = MA0 .AND. MB1 = MB0
STORE MDA/2 TO MDA
STORE MDB/2 TO MDB
LOOP
ENDIF
STORE 0 TO MFAIL
DO WHILE MFAIL <> 1
STORE MIT+1 TO MIT
STORE 2*MB1-MB0 TO MB2
STORE 2*MA1-MA0 TO MA2
STORE MB2+MDB TO MB
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MB TO MB3
ELSE
STORE MB2-MDB TO MB
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MB TO MB3
ELSE
STORE MB2 TO MB3
ENDIF
ENDIF
STORE MB3 TO MB
```

```
STORE MA2+MDA TO MA
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MA TO MA3
ELSE
STORE MA2-MDA TO MA
DO SSE
IF MSSE < MREF
STORE MSSE TO MREF
STORE MA TO MA3
ELSE
STORE MA2 TO MA3
ENDIF
ENDIF
STORE MA3 TO MA
? MA, MB, MREF, MIT
IF MB3 <> MB2 .OR. MA3 <> MA2
STORE MA1 TO MA0
STORE MB1 TO MB0
STORE MA3 TO MA1
STORE MB3 TO MB1
LOOP
ENDIF
STORE 1 TO MFAIL
ENDDO
STORE MA1 TO MA0, MA
STORE MB1 TO MB0, MB
DO SSE
STORE MSSE TO MREF
ENDDO
```

NATO.DBF File Listing

The NATO.DBF listing given here is the unedited baseline case where
all component failure rates are at their nominal (contractor-reported)
values.

Column headings are: MNEM, NAME, SSYS, BOX, ASM, SASM, and LAMBDA.

```
COMM    COMMUNICATIONS SUBSYSTEM 1 00 0     0.00
RCU     REDUNDANCY CONTROL UNIT  1 10 0     0.00
PS      RCU POWER SELECTOR       1 11 0     0.00
PSK     RCU PS RELAY             1 11 1     1.10
PSCON   RCU PS DC/DC CONVERTER    1 11 2   142.00
CS      RCU COMPONENT SELECTOR   1 12 0     0.00
CSLOS   RCU CS LOCAL OSC SELECTOR1 12 1     6.20
CSBS    RCU CS BEACON SELECTOR   1 12 2    10.00
CSPS    RCU CS PREAMP SELECTOR   1 12 3    10.00
CSLS    RCU CS LIMITER SELECTOR  1 12 4    12.40
```

```
TS      RCU  TWTA SELECTOR           1 13 0      0.00
TSMS    RCU  TS MODE SELECTOR        1 13 1    112.00
TSTS    RCU  TS TWTA SELECTOR        1 13 2     15.00
TSWNS   RCU  TS WB/NB SELECTOR       1 13 3     15.00
TSDS    RCU  TS DRIVER SELECTOR      1 13 4     12.40
LGS     RCU  LIMITER GAIN SELECTOR1  14 0       0.00
LGSK1   RCU  LGS RELAY TYPE 1        1 14 1      1.06
LGSK2   RCU  LGS RELAY TYPE 2        1 14 2      1.16
LGSR    RCU  LGS RESISTOR            1 14 3      0.02
DBC     RCU  DIRECT BUS CONNECTION1  16 0       0.00
DBCR1   RCU  DBC RESISTOR TYPE 1     1 16 1      0.05
DBCR2   RCU  DBC RESISTOR TYPE 2     1 16 2      0.10
WBRA    WB   RECEIVE ANTENNA         1 20 0      0.00
WRA     WB   RECEIVE ANT ASSEMBLY    1 21 0      0.00
WBRHS   WBR  HORN SECTION            1 21 1      0.10
WBRHJ   WBR  HORN JOINT              1 21 2      0.10
WBRHC   WBR  HORN COVER              1 21 3      0.10
WBRTH   WBR  THERMAL FINISH          1 21 4      0.10
WBRMG   WBR  MODE GENERATOR          1 21 5      1.00
WBRWGTWBR  WG TRANSITION             1 21 6      1.00
WBRF    WBR  WG FLANGE               1 21 7      0.50
WBRFF   WBR  WG FLANGE FASTENER      1 21 8      0.10
WBRWGJWBR  WG BRAZED JOINT           1 21 9      0.20
WBRW1   WBR  UPPER WG RUN            1 22 0      0.00
WRW1F   WBR  W1 WG FLANGE            1 22 1      0.50
WRW1FFWBR  W1 WG FLANGE FASTENER1    22 2       0.10
WRW1S   WBR  W1 WG SECTION           1 22 3      0.10
WRW1R   WBR  W1 WG RUN               1 22 4      0.10
WRW1FSWBR  W1 WG FLEX SECTION        1 22 5      1.00
WRW130WBR  W1 WG 30 D BEND           1 22 6      0.20
WRW145WBR  W1 WG 45 D BEND           1 22 7      0.20
WRW160WBR  W1 WG 60 D BEND           1 22 8      0.20
WRW190WBR  W1 WG 90 D BEND           1 22 9      0.20
WRW1J   WBR  W1 WG BRAZED JOINT      1 2210      0.20
WBRW2   WBR  REJECT WG RUN           1 23 0      0.00
WRW2F   WBR  W2 WG FLANGE            1 23 1      0.50
WRW2FFWBR  W2 WG FLANGE FASTENER1    23 2       0.10
WRW2S   WBR  W2 WG SECTION           1 23 3      0.10
WRW245WBR  W2 WG 45 D BEND           1 23 4      0.20
WRW2J   WBR  W2 WG BRAZED JOINT      1 23 5      0.20
WBRORCWBR  OUTER REJECT CHANNEL      1 24 0      0.00
WRRCF   WBR  ORC WG FLANGE           1 24 1      0.50
WRRCFFWBR  ORC FLANGE FASTENER       1 24 2      0.10
WRRCT   WBR  ORC TRANSFORMER         1 24 3      1.00
WRRCC   WBR  ROTARY COAX CHOKE       1 24 4      1.00
WRRCS   WBR  REJECT COAX SECTION     1 24 5      1.00
WRHJS   WBR  HORN JOINT SPACER       1 24 6      0.10
WRRCH   WBR  ORC WG HYBRID           1 24 7      1.00
WRRCJ   WBR  ORC WG BRAZED JOINT     1 24 8      0.20
WBRW3   WBR  LOWER WG RUN            1 25 0      0.00
WRW3F   WBR  W3 WG FLANGE            1 25 1      0.50
WRW3FFWBR  W3 WG FLANGE FASTENER1    25 2       0.10
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WRW3S  WBR W3 WG SECTION          1 25 3      0.10
WRW3R  WBR W3 WG RUN              1 25 4      0.10
WRW3FSWBR W3 WG FLEX SECTION      1 25 5      1.00
WRW360WBR W3 WG 60 D BEND         1 25 6      0.20
WRW3J  WBR W3 WG BRAZED JOINT     1 25 7      0.20
TESTC  TEST COUPLER               1 30 0      1.00
PSBPF  PRESELECTOR BP FILTER      1 40 0     13.00
COAXS  COAX SWITCH                1 50 0     25.00
PREAMPPREAMP                      1 60 0     81.00
ATTEN  ATTENUATOR                 1 70 0     13.00
HYBRIDHYBRID SPLITTER             1 80 0     17.00
PCS    PORT CIRCULATOR SWITCH     1 90 0     30.00
BPF    BAND PASS FILTER           1100 0     13.00
EQUAL  EQUALIZER                  1110 0     13.00
LIMIT  LIMITER                    1120 0    383.00
LO     LOCAL OSCILLATOR           1130 0    591.00
LOH    LOCAL OSCCILLATOR HYBRID   1140 0     37.00
DC     DOWN CONVERTER             1150 0    128.00
ISO    ISOLATOR                   1160 0     13.00
CIRC   CIRCULATOR SWITCH          1170 0     50.00
DRVAMPDRIVER AMPLIFIER            1180 0    222.00
TWTA   TWT AMPLIFIER              1190 0   8880.00
WGSWT  WAVE GUIDE SWITCH          1200 0     20.00
OUTF   OUTPUT FILTER              1210 0      5.00
LPF    LOW PASS FILTER            1220 0      5.00
BIF    BEACON INJECT FILTER       1230 0      5.00
BRF    BEACON REJECT FILTER       1240 0     13.00
CDET   COUPLER DETECTOR           1250 0     32.00
BEACONBEACON GENERATOR            1260 0   1454.00
WBTA   WB TRANSMIT ANTENNA        1270 0      0.00
WTA    WB TRANSMIT ANT ASSEMBLY   1271 0      0.00
WBTHS  WBT HORN SECTION           1271 1      0.10
WBTHJ  WBT HORN JOINT             1271 2      0.10
WBTHC  WBT HORN COVER             1271 3      0.10
WBTTH  WBT THERMAL FINISH         1271 4      0.10
WBTMG  WBT MODE GENERATOR         1271 5      1.00
WBTWGTWBT WG TRANSITION           1271 6      1.00
WBTF   WBT WG FLANGE              1271 7      0.50
WBTFF  WBT WG FLANGE FASTENER     1271 8      0.10
WBTWGJWBT WG BRAZED JOINT         1271 9      0.20
WBTW1  WBT UPPER WG RUN           1272 0      0.00
WTW1F  WBT W1 WG FLANGE           1272 1      0.50
WTW1FFWBT W1 WG FLANGE FASTENER   1272 2      0.10
WTW1S  WBT W1 WG SECTION          1272 3      0.10
WTW1R  WBT W1 WG RUN              1272 4      0.10
WTW1FSWBT W1 WG FLEX SECTION      1272 5      1.00
WTW130WBT W1 WG 30 D BEND         1272 6      0.20
WTW160WBT W1 WG 60 D BEND         1272 7      0.20
WTW190WBT W1 WG 90 D BEND         1272 8      0.20
WTW1J  WBT W1 WG BRAZED JOINT     1272 9      0.20
WBTW2  WBT REJECT WG RUN          1273 0      0.00
WTW2F  WBT W2 WG FLANGE           1273 1      0.50
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WTW2FFWBT  W2 WG FLANGE FASTENER1273  2     0.10
WTW2S WBT  W2 WG SECTION         1273  3     0.10
WTW230WBT  W2 WG 30 D BEND       1273  4     0.20
WTW2J WBT  W2 WG BRAZED JOINT    1273  5     0.20
WBTCRCWBT  CENTRL REJECT CHANNEL 1274  0     0.00
WTRCF WBT  CRC WG FLANGE         1274  1     0.50
WTRCFFWBT  CRC FLANGE FASTENER   1274  2     0.10
WTRCC WBT  ROTARY COAX CHOKE     1274  3     1.00
WTRCS WBT  REJECT COAX SECTION   1274  4     1.00
WTHJS WBT  HORN JOINT SPACER     1274  5     0.10
WTRCJ WBT  CRC WG BRAZED JOINT   1274  6     0.20
WBTW3 WBT  LOWER WG RUN          1275  0     0.00
WTW3F WBT  W3 WG FLANGE          1275  1     0.50
WTW3FFWBT  W3 WG FLANGE FASTENER1275  2     0.10
WTW3S WBT  W3 WG SECTION         1275  3     0.10
WTW3R WBT  W3 WG RUN             1275  4     0.10
WTW3FSWBT  W3 WG FLEX SECTION    1275  5     1.00
WTW360WBT  W3 WG 60 D BEND       1275  6     0.20
WTW3T WBT  W3 WG 90 D TWIST      1275  7     0.40
WTW3J WBT  W3 WG BRAZED JOINT    1275  8     0.20
NBTA  NB TRANSMIT ANTENNA        1280  0     0.00
NTA   NB TRANSMIT ANT ASSEMBLY   1281  0     0.00
NBTHS NBT  HORN SECTION          1281  1     0.10
NBTHJ NBT  HORN JOINT            1281  2     0.10
NBTHC NBT  HORN COVER            1281  3     0.10
NBTTH NBT  THERMAL FINISH        1281  4     0.10
NBTMG NBT  MODE GENERATOR        1281  5     1.00
NBTWGTNBT  WG TRANSITION         1281  6     1.00
NBTF  NBT  WG FLANGE             1281  7     0.50
NBTFF NBT  WG FLANGE FASTENER    1281  8     0.10
NBTWGSNBT  WG SECTION            1281  9     0.10
NBTWGJNBT  WG BRAZED JOINT       128110      0.20
NBTP  NBT  POLARIZER             128111      1.00
NBTW1 NBT  UPPER WG RUN          1282  0     0.00
NTW1F NBT  W1 WG FLANGE          1282  1     0.50
NTW1FFNBT  W1 WG FLANGE FASTENER1282  2     0.10
NTW1S NBT  W1 WG SECTION         1282  3     0.10
NTW1R NBT  W1 WG RUN             1282  4     0.10
NTW1FSNBT  W1 WG FLEX SECTION    1282  5     1.00
NTW130NBT  W1 WG 30 D BEND       1282  6     0.20
NTW190NBT  W1 WG 90 D BEND       1282  7     0.20
NTW1J NBT  W1 WG BRAZED JOINT    1282  8     0.20
NBTW2 NBT  REJECT WG RUN         1283  0     0.00
NTW2F NBT  W2 WG FLANGE          1283  1     0.50
NTW2FFNBT  W2 WG FLANGE FASTENER1283  2     0.10
NTW2S NBT  W2 WG SECTION         1283  3     0.10
NTW230NBT  W2 WG 30 D BEND       1283  4     0.20
NTW2J NBT  W2 WG BRAZED JOINT    1283  5     0.20
NBTIRCNBT  INNER REJECT CHANNEL  1284  0     0.00
NTRCF NBT  IRC WG FLANGE         1284  1     0.50
NTRCFFNBT  IRC FLANGE FASTENER   1284  2     0.10
NTRCT NBT  IRC TRANSFORMER       1284  3     1.00
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NTRCC  NBT ROTARY COAX CHOKE      1284 4      1.00
NTRCS  NBT REJECT COAX SECTION    1284 5      1.00
NTHJS  NBT HORN JOINT SPACER      1284 6      0.10
NTRCJ  NBT IRC WG BRAZED JOINT    1284 7      0.20
NBTW3  NBT LOWER WG RUN           1285 0      0.00
NTW3F  NBT W3 WG FLANGE           1285 1      0.50
NTW3FFNBT W3 WG FLANGE FASTENER1285 2         0.10
NTW3S  NBT W3 WG SECTION          1285 3      0.10
NTW3R  NBT W3 WG RUN              1285 4      0.10
NTW3FSNBT W3 WG FLEX SECTION      1285 5      1.00
NTW360NBT W3 WG 60 D BEND         1285 6      0.20
NTW390NBT W3 WG 90 D BEND         1285 7      0.20
NTW3T  NBT W3 WG 90 D TWIST       1285 8      0.40
NTW3J  NBT W3 WG BRAZED JOINT     1285 9      0.20
TTC    TELEM TRACK CMD SUBSYSTEM2 00 0        0.00
DIPLEXTTC DIPLEXER                2 10 0     21.00
TTCHYBTTC HYBRID                  2 20 0     15.00
RCVCONRECEIVER DC/DC CONVERTER    2 30 0     98.00
RCVR   S BAND RECEIVER            2 40 0   1672.00
CMDU   COMMAND UNIT               2 50 0      0.00
CMDCONCOMMAND DC/DC CONVERTER     2 51 0    128.00
BITDETCOMMAND BIT DETECTOR        2 52 0    397.00
CMDDECCOMMAND DECODER             2 53 0    947.00
CMDDCRCOMMAND DECRYPTER           2 54 011140.00
LSD    LOW SIDE DRIVER            2 55 0    819.00
HSD    HIGH SIDE DRIVER           2 56 0     88.00
CMDRELCOMMAND COMBINER RELAYS     2 60 0      0.00
BCONV  BEACON DC/DC CONVERTER     2 70 0    107.00
BTU    BEACON TELEMETRY UNIT      2 80 0   1380.00
TLMCONTELEMETRY DC/DC CONVERTER2 90 0       106.00
TLMGENTELEMETRY GENERATOR         2100 0   1277.00
TLMINFTELEMETRY INTERFACE UNIT 2110 0        87.00
XMTCONTRANSMIT DC/DC CONVERTER 2120 0       103.00
SXMTR  S BAND TRANSMITTER         2130 0    921.00
SANT   S BAND ANTENNA             2140 0      0.00
RFSWT  RF SWITCH                  2141 0     34.00
PWRD   POWER DIVIDER              2142 0     25.00
APWRD  ANTENNA POWER DIVIDER      2143 0     21.00
ANTELEANTENNA ELEMENT             2144 0      5.00
AAC    ANT ATT CNTRL SUBSYSTEM    3 00 0      0.00
ES     EARTH SENSOR               3 10 0    390.00
SS     SUN SENSOR                 3 20 0      5.00
AACCONAAC DC/DC CONVERTER         3 30 0    114.00
AACELCAAC ELECTRONICS             3 40 0   1998.00
MAGPU  MAGNETIC PICKUP            3 50 0     15.00
MDCON  MTR DRIVE DC/DC CONVERTER3 60 0       80.00
MDAMP  MOTOR DRIVE AMP            3 70 0    160.00
RESWNDRESOLVER WINDING            3 80 0    100.00
MBEAR  MOTOR BEARINGS             3 90 0    100.00
MWIND  MOTOR WINDINGS             3100 0    100.00
NDAMP  NUTATION DAMPER            3110 0     10.00
EPS    ELECTRIC POWER SUBSYSTEM 4 00 0       0.00
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ARRAY1MAIN SOLAR CELL ARRAY      4 10 0   117.00
ARRAY2BATTERY SOLAR CELL ARRAY 4 20 0     2.00
SAREL SA RELAY                   4 30 0     9.00
CSRA  CRNT SENSING RESIST SET A4 40 0     0.00
CSR   CRNT SENSING RESISTOR      4 41 0     0.85
FUSE  FUSE                       4 50 0   100.00
BCC   BATTERY CHARGE CONTROLLER4 60 0    92.00
CSRC  CRNT SENSING RESIST SET C4 70 0     3.00
UVC   UNDERVOLTAGE CONTROLLER   4 80 0    96.00
BAT   BATTERY                    4 90 0     0.00
CELL  BATTERY CELL               4 91 0   150.00
BATR  BATTERY RELAY             4100 0    10.00
EAMP  ERROR AMPLIFIER           4110 0    13.00
MAJV  MAJORITY VOTER            4120 0    13.00
PWM   PULSE WIDTH MODULATOR     4130 0   117.00
BCON  BOOST CONVERTER           4140 0    38.00
ECA   ELECTRONIC COMPILER ASSM 4150 0     2.00
CAP1  CAPACITOR ASSEMBLY 1      4160 0     0.00
C1    CAPACITOR                 4161 0     0.75
SDRIVESHUNT DRIVER              4170 0    39.00
SHUNT SHUNT SET                 4180 0    13.00
ADISC AUTOMATIC DISCONNECTOR    4190 0   120.00
ARECONAUTOMATIC RECONNECTOR     4200 0   126.00
AGERCEAGE RCE CIRCUIT           4210 0    82.00
CBRR  CIRCUIT BRKR RESET RELAY 4220 0     8.00
CBRK  TWTA CIRCUIT BREAKER      4230 0    34.00
CSRB  CRNT SENSING RESIST SET B4240 0     6.00
CBR   CIRCUIT BREAKER RELAY     4250 0     8.00
CAP2  CAPACITOR ASSEMBLY 2      4260 0     0.00
C2    CAPACITOR                 4261 0     0.75
ITLM  CURRENT TELEMETRY         4270 0   115.00
VTLM  VOLTAGE TELEMETRY         4280 0    52.00
FUSEBLFUSE BLOCK                4290 0   100.00
MISC  MISC CHASSIS COMPONENTS   4300 0    88.00
AKMCIRAKM CIRCUIT               4310 0    30.00
AKMSQUAKM INITIATOR SQUIB       4320 0    30.00
BCHGS BATTERY CHARGE SEQUENCER  4330 0   102.00
RCE   RCTN CNTRL EQUP SUBSYSTEM5 00 0     0.00
TANK  FUEL TANK                 5 10 0   150.00
LINES WET LINES AND FITTINGS    5 20 0    19.00
FDV   FILL/DRAIN VALVE          5 40 0    70.00
PRESSTPRESSURE TRANSDUCER       5 50 0   157.00
AXVD  AXIAL VALVE DRIVERS       5 60 0    21.00
AXTCA AXIAL THRUST CHMBR ASSEM  5 70 0    19.00
AXTCH AXIAL TCA HEATER          5 80 0    14.00
RAVD  RADIAL VALVE DRIVERS      5 90 0    21.00
RATCA RADIAL THRUST CHMBR ASSEM5100 0     3.00
RATCH RADIAL TCA HEATER         5110 0    14.00
TANKH FUEL TANK HEATERS         5120 0    42.00
LINEH FUEL LINE HEATERS         5130 0    20.00
VDH   VALVE DRIVER HEATERS      5140 0    28.00
RCET  RCE THERMOSTAT            5150 0   200.00
```

TIME.DBF File

The TIME.DBF file must be created by the user. Its first field
(column) is labeled TIME and contains the values of time, t (in months),
at which reliability will be calculated. As many entries as desired are
possible, although it should be remembered that the number of entries
directly affects RUP run time.

There are 37 other fields, labeled as follows: COMM, RCU, PS, CS,
TS, LGS, DBC, WBRA, WRA, WBRW1, WBRW2, WBRORC, WBRW3, WBTA, WTA, WBTW1,
WBTW2, WBTCRC, WPTW3, NBTA, NTA, NBTW1, NBTW2, NBTIRC, NBTW3, TTC, CMDU,
SANT, AAC, EPS, CSRA, BAT, CAP1, CAP2, RCE, SYSTEM, and TEMP. No values
need be initially specified in any of these field -- RUP will provide
them. Except for SYSTEM and TEMP, these are in-process storage
locations for the reliabilities of these units corresponding to the
times specified in TIME, and may be viewed at the end of a RUP run.

SYSTEM is the same thing, but for the spacecraft as a whole. TEMP
provides temporary storage during calculation of the fitted Weibull
reliability function. In the final iteration of the fitting procedure,
the solution will be less optimal than the previous iteration so, at the
end of a RUP run, viewing the TEMP column will not quite allow the user
to reconstruct the optimal solution -- this must either be taken from
the screen, or a separate dBASE III PLUS macro program must be written.

Appendix C: <u>Model Coefficient Tables, ANOVA Tables,</u>

<u>Residual Tables, and Residual Plots</u>

Table C-1. Subsystem-Level Coefficient Table for β: All Main Effects
and Two-Component Interactions

```
┌─────────────────────────────────────────────────────────────────────────┐
│ UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA                       │
│                                                                          │
│ PREDICTOR                                                                │
│ VARIABLES     COEFFICIENT    STD ERROR     STUDENT'S T       P           │
│                                                                          │
│ CONSTANT       136.00        5.9621E-03    22811.04      0.0000          │
│ COMM          -8.2403        5.9621E-03    -1382.11      0.0000          │
│ TTC           -4.7078        5.9621E-03     -789.62      0.0000          │
│ AAC           -5.4469E-01    5.9621E-03      -91.36      0.0000          │
│ EPS           -8.3219E-01    5.9621E-03     -139.58      0.0000          │
│ RCE           -3.2594E-01    5.9621E-03      -54.67      0.0000          │
│ CT             7.4469E-01    5.9621E-03      124.90      0.0000          │
│ CA             9.5312E-02    5.9621E-03       15.99      0.0000          │
│ CE             1.4281E-01    5.9621E-03       23.95      0.0000          │
│ CR             3.7812E-02    5.9621E-03        6.34      0.0000          │
│ TA             4.5313E-02    5.9621E-03        7.60      0.0000          │
│ TE             7.0313E-02    5.9621E-03       11.79      0.0000          │
│ TR             1.6562E-02    5.9621E-03        2.78      0.0134          │
│ AE             9.6875E-03    5.9621E-03        1.62      0.1237          │
│ AR             2.1875E-03    5.9621E-03        0.37      0.7185          │
│ ER             2.1875E-03    5.9621E-03        0.37      0.7185          │
│ CASES  INCLUDED          32         MISSING CASES      0                 │
│ DEGREES OF FREEDOM       16                                              │
│ OVERALL F             1.721E+05     P VALUE       0.0000                 │
│ ADJUSTED R SQUARED    1.0000                                             │
│ R SQUARED             1.0000                                             │
│ RESID. MEAN SQUARE    1.137E-03                                          │
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Table C-2. Subsystem-Level ANOVA Table for β: All Main Effects and Two-Component Interactions

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	5.9189E+05				
COMM	2172.9	1	2172.9	2172.9	0.7314
TTC	709.23	2	2882.1	1441.1	0.9803
AAC	9.4939	3	2891.6	963.87	0.9832
EPS	22.161	4	2913.8	728.44	0.9912
RCE	3.3995	5	2917.2	583.43	0.9923
CT	17.746	6	2934.9	489.15	0.9995
CA	2.9070E-01	7	2935.2	419.32	0.9996
CE	6.5265E-01	8	2935.9	366.98	0.9999
CR	4.5753E-02	9	2935.9	326.21	0.9999
TA	6.5703E-02	10	2936.0	293.60	0.9999
TE	1.5820E-01	11	2936.1	266.92	1.0000
TR	8.7781E-03	12	2936.1	244.68	1.0000
AE	3.0031E-03	13	2936.1	225.86	1.0000
AR	1.5313E-04	14	2936.1	209.72	1.0000
ER	1.5313E-04	15	2936.1	195.74	1.0000
RESIDUAL	1.8200E-02	31	2936.2	94.715	

Table C-3. Subsystem-Level Coefficient Table for β: Two Regressors

	UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA			
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	136.00	2.4132E-01	563.57	0.0000
COMM	-8.2403	2.4132E-01	-34.15	0.0000
TTC	-4.7078	2.4132E-01	-19.51	0.0000

CASES INCLUDED	32	MISSING CASES	0
DEGREES OF FREEDOM	29		
OVERALL F	773.3	P VALUE	0.0000
ADJUSTED R SQUARED	0.9803		
R SQUARED	0.9816		
RESID. MEAN SQUARE	1.864		

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Table C-4. Subsystem-Level ANOVA Table for β: Two Regressors

STEPWISE ANALYSIS OF VARIANCE OF BETA					
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	5.9189E+05				
COMM	2172.9	1	2172.9	2172.9	0.7314
TTC	709.23	2	2882.1	1441.1	0.9803
RESIDUAL	54.044	31	2936.2	94.715	

Table C-5. Predicted Values and Residuals for β: Subsystem-Level with Two Regressors

RUN	β	$\widehat{\beta}$	e	RUN	β	$\widehat{\beta}$	e
1	151.85	148.95	2.8997	17	151.09	148.95	2.1397
2	133.26	132.47	0.7903	18	132.65	132.47	0.1803
3	140.62	139.53	1.0853	19	139.92	139.53	0.3853
4	125.14	123.05	2.0859	20	124.58	123.05	1.5259
5	150.44	148.95	1.4897	21	149.66	148.95	0.7097
6	132.28	132.47	-0.1897	22	131.67	132.47	-0.7997
7	139.42	139.53	-0.1147	23	138.74	139.53	-0.7947
8	124.29	123.05	1.2359	24	123.74	123.05	0.6859
9	149.70	148.95	0.7497	25	148.93	148.95	-0.0203
10	131.76	132.47	-0.7097	26	131.16	132.47	-1.3097
11	138.83	139.53	-0.7047	27	138.12	139.53	-1.4147
12	123.84	123.05	0.7859	28	123.30	123.05	0.2459
13	148.32	148.95	-0.6303	29	147.57	148.95	-1.3803
14	130.81	132.47	-1.6597	30	130.21	132.47	-2.2597
15	137.67	139.53	-1.8647	31	137.00	139.53	-2.5347
16	123.02	123.05	-0.0341	32	122.48	123.05	-0.5741
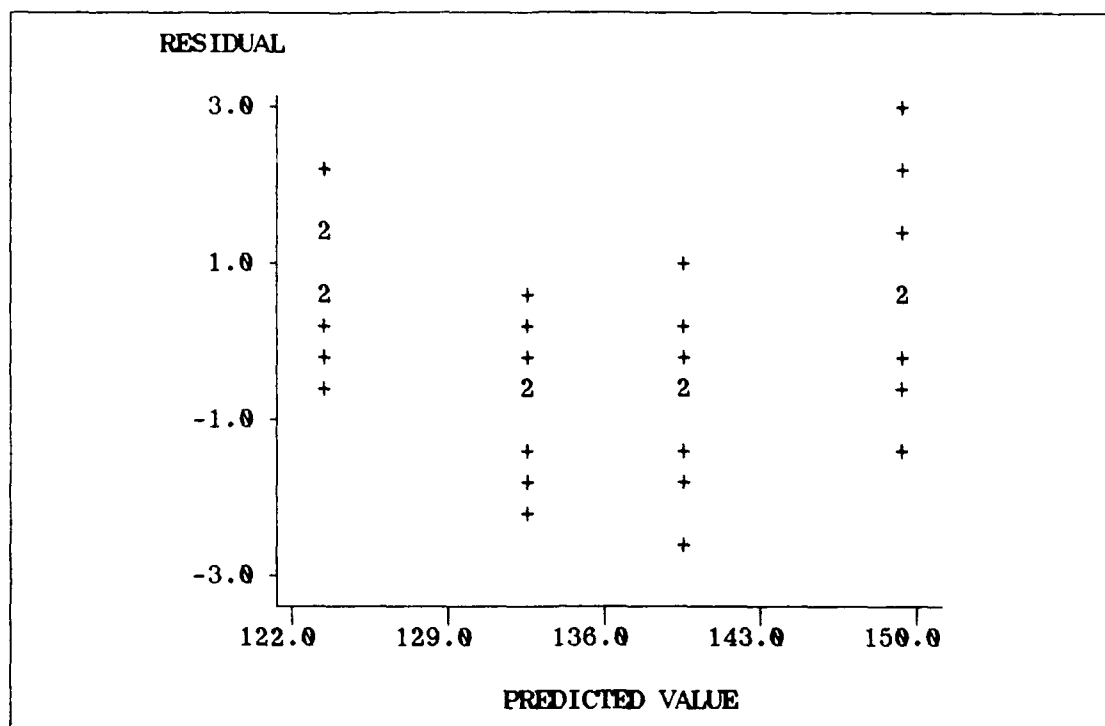
Fig. C-1.   Subsystem-Level Residual Plot for β: Two Regressors

Table C-6.   Subsystem-Level Coefficient Table for β: Four Regressors

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UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA

PREDICTOR
VARIABLES      COEFFICIENT      STD ERROR      STUDENT'S T      P

CONSTANT        136.00          1.2791E-01       1063.23      0.0000
COMM            -8.2403         1.2791E-01        -64.42      0.0000
TTC             -4.7078         1.2791E-01        -36.80      0.0000
EPS             -8.3219E-01     1.2791E-01         -6.51      0.0000
CT               7.4469E-01     1.2791E-01          5.82      0.C000


CASES INCLUDED          32       MISSING CASES       0
DEGREES OF FREEDOM      27
OVERALL F            1.395E+03   P VALUE      0.0000
ADJUSTED R SQUARED   0.9945
R SQUARED            0.9952
RESID. MEAN SQUARE   5.236E-01
```

Table C-7. Subsystem-Level ANOVA Table for β: Four Regressors

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	5.9189E+05				
COMM	2172.9	1	2172.9	2172.9	0.7314
TTC	709.23	2	2882.1	1441.1	0.9803
EPS	22.161	3	2904.3	968.09	0.9880
CT	17.746	4	2922.0	730.51	0.9945
RESIDUAL	14.137	31	2936.2	94.715	

Table C-8. Predicted Values and Residuals for : Subsystem Level with Four Regressors

RUN	β	$\widehat{\beta}$	e	RUN	β	$\widehat{\beta}$	e
1	151.85	150.53	1.3228	17	151.09	150.53	0.5628
2	133.26	132.56	0.7028	18	132.65	132.56	0.0928
3	140.62	139.62	0.9978	19	139.92	139.62	0.2978
4	125.14	124.63	0.5091	20	124.58	124.63	-0.0509
5	150.44	150.53	-0.0872	21	149.66	150.53	-0.8672
6	132.28	132.56	-0.2772	22	131.67	132.56	-0.8872
7	139.42	139.62	-0.2022	23	138.74	139.62	-0.8822
8	124.29	124.63	-0.3409	24	123.74	124.63	-0.8909
9	149.70	148.86	0.8372	25	148.93	148.86	0.0672
10	131.76	130.89	0.8672	26	131.16	130.89	0.2672
11	138.83	137.96	0.8722	27	138.12	137.96	0.1622
12	123.84	122.97	0.8734	28	123.30	122.97	0.3334
13	148.32	148.86	-0.5428	29	147.57	148.86	-1.2928
14	130.81	130.89	-0.0828	30	130.21	130.89	-0.6828
15	137.67	137.96	-0.2878	31	137.00	137.96	-0.9578
16	123.02	122.97	0.0534	32	122.48	122.97	-0.4866

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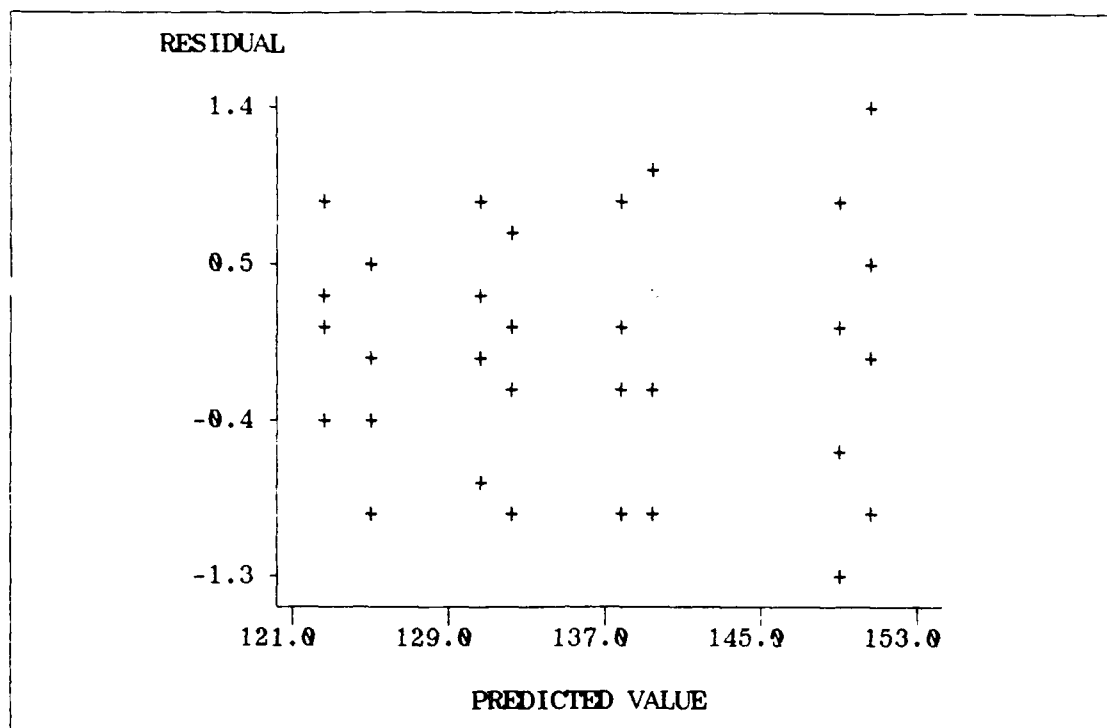
Fig. C-2.   Subsystem-Level Residual Plot for β: Four Regressors

Table C-9. Subsystem-Level Coefficient Table for α: All Main Effects and Two-Component Interactions

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.6222	1.3919E-03	1165.41	0.0000
COMM	2.5875E-02	1.3919E-03	18.59	0.0000
TTC	-1.4500E-02	1.3919E-03	-10.42	0.0000
AAC	1.5625E-03	1.3919E-03	1.12	0.2782
EPS	9.3750E-04	1.3919E-03	0.67	0.5102
RCE	-4.8125E-03	1.3919E-03	-3.46	0.0032
CT	1.1875E-03	1.3919E-03	0.85	0.4062
CA	-1.5000E-03	1.3919E-03	-1.08	0.2972
CE	-1.7500E-03	1.3919E-03	-1.26	0.2267
CR	1.5000E-03	1.3919E-03	1.08	0.2972
TA	1.5000E-03	1.3919E-03	1.08	0.2972
TE	1.5000E-03	1.3919E-03	1.08	0.2972
TR	-1.1250E-03	1.3919E-03	-0.81	0.4308
AE	-1.4375E-03	1.3919E-03	-1.03	0.3171
AR	1.3125E-03	1.3919E-03	0.94	0.3597
ER	1.4375E-03	1.3919E-03	1.03	0.3171

CASES INCLUDED   32   MISSING CASES   0
DEGREES OF FREEDOM   16
OVERALL F   31.89   P VALUE   0.0000
ADJUSTED R SQUARED   0.9373
R SQUARED   0.9676
RESID. MEAN SQUARE   6.200E-05

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Table C-10. Subsystem-Level ANOVA Table for α: All Main Effects and Two-Component Interactions

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	84.208				
COMM	2.1425E-02	1	2.1425E-02	2.1425E-02	0.6890
TTC	6.7280E-03	2	2.8152E-02	1.4076E-02	0.9129
AAC	7.8125E-05	3	2.8231E-02	9.4102E-03	0.9126
EPS	2.8125E-05	4	2.8259E-02	7.0647E-03	0.9104
RCE	7.4112E-04	5	2.9000E-02	5.8000E-03	0.9358
CT	4.5125E-05	6	2.9045E-02	4.8408E-03	0.9350
CA	7.2000E-05	7	2.9117E-02	4.1596E-03	0.9354
CE	9.8000E-05	8	2.9215E-02	3.6519E-03	0.9369
CR	7.2000E-05	9	2.9287E-02	3.2541E-03	0.9373
TA	7.2000E-05	10	2.9359E-02	2.9359E-03	0.9378
TE	7.2000E-05	11	2.9431E-02	2.6755E-03	0.9383
TR	4.0500E-05	12	2.9471E-02	2.4560E-03	0.9372
AE	6.6125E-05	13	2.9538E-02	2.2721E-03	0.9374
AR	5.5125E-05	14	2.9593E-02	2.1138E-03	0.9370
ER	6.6125E-05	15	2.9659E-02	1.9773E-03	0.9373
RESIDUAL	9.9200E-04	31	3.0651E-02	9.8874E-04	

Table C-11. Subsystem-Level Coefficient Table for α: Two Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.6222	1.6408E-03	988.66	0.0000
COMM	2.5875E-02	1.6408E-03	15.77	0.0000
TTC	-1.4500E-02	1.6408E-03	-8.84	0.0000

CASES INCLUDED	32	MISSING CASES	0
DEGREES OF FREEDOM	29		
OVERALL F	163.4	P VALUE	0.0000
ADJUSTED R SQUARED	0.9129		
R SQUARED	0.9185		
RESID. MEAN SQUARE	8.615E-05		

Table C-12. Subsystem-Level ANOVA Table for α: Two Regressors

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	84.208				
COMM	2.1425E-02	1	2.1425E-02	2.1425E-02	0.6890
TTC	6.7280E-03	2	2.8152E-02	1.4076E-02	0.9129
RESIDUAL	2.4984E-03	31	3.0651E-02	9.8874E-04	

Table C-13. Predicted Values and Residuals for α: Subsystem Level with Two Regressors

RUN	α	$\hat{\alpha}$	e	RUN	α	$\hat{\alpha}$	e
1	1.6160	1.6108	0.0052	17	1.6080	1.6108	-0.0028
2	1.6660	1.6626	0.0034	18	1.6590	1.6626	-0.0036
3	1.5890	1.5818	0.0072	19	1.5380	1.5818	-0.0438
4	1.6380	1.6336	0.0044	20	1.6320	1.6336	-0.0016
5	1.6160	1.6108	0.0052	21	1.6090	1.6108	-0.0018
6	1.6660	1.6626	0.0034	22	1.6580	1.6626	-0.0046
7	1.5900	1.5818	0.0082	23	1.5830	1.5818	0.0012
8	1.6390	1.6336	0.0054	24	1.6330	1.6336	-0.0006
9	1.6150	1.6108	0.0042	25	1.6080	1.6108	-0.0028
10	1.6640	1.6626	0.0014	26	1.6570	1.6626	-0.0056
11	1.5890	1.5818	0.0072	27	1.5830	1.5818	0.0012
12	1.6370	1.6336	0.0034	28	1.6310	1.6336	-0.0026
13	1.6160	1.6108	0.0052	29	1.6080	1.6108	-0.0028
14	1.6640	1.6626	0.0014	30	1.6570	1.6626	-0.0056
15	1.5900	1.5818	0.0082	31	1.5830	1.5818	0.0012
16	1.6370	1.6336	0.0034	32	1.6310	1.6336	-0.0026
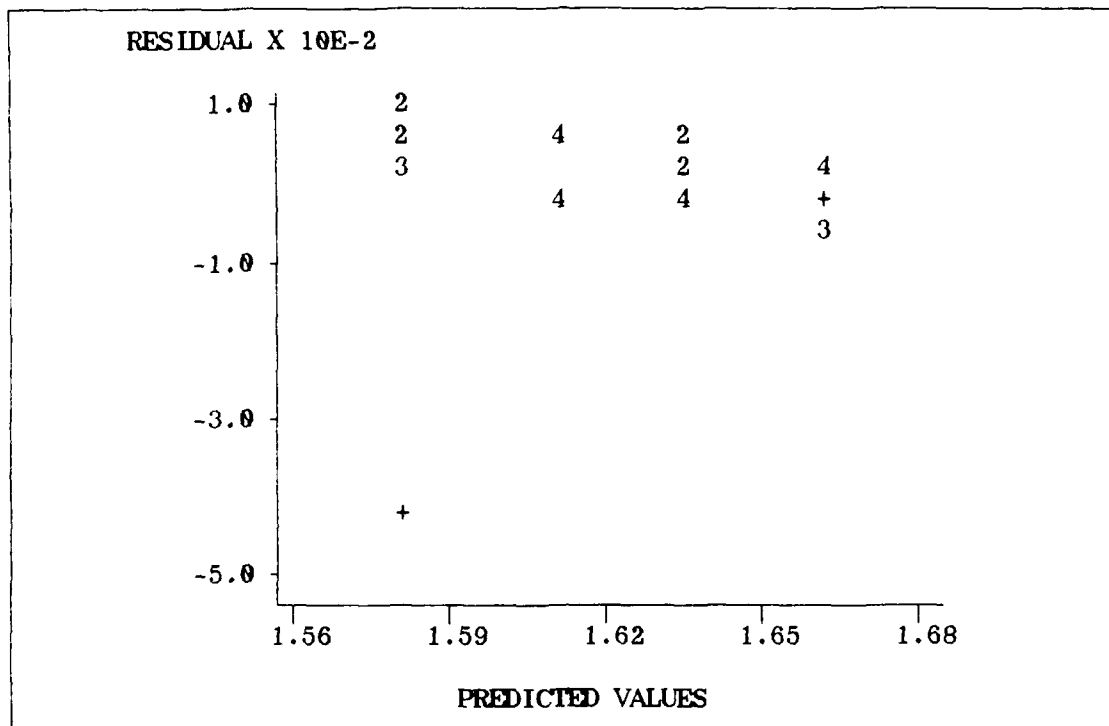
Fig. C-3.   Subsystem-Level Residual Plot for α: Two Regressors

Table C-14. COMM Subsystem Coefficient Table for β: All Main Effects

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.82	1.7689E-02	7678.52	0.0000
A	-8.8125E-02	1.7689E-02	-4.98	0.0076
B	-7.1875E-02	1.7689E-02	-4.06	0.0153
C	-1.0187E-01	1.7689E-02	-5.76	0.0045
D	-4.8125E-02	1.7689E-02	-2.72	0.0530
E	-3.8125E-02	1.7689E-02	-2.16	0.0974
F	6.8750E-03	1.7689E-02	0.39	0.7173
G	-5.6875E-02	1.7689E-02	-3.22	0.0324
H	-1.5187E-01	1.7689E-02	-8.59	0.0010
I	-1.7687E-01	1.7689E-02	-10.00	0.0006
J	-7.1781	1.7689E-02	-405.80	0.0000
K	-2.1812E-01	1.7689E-02	-12.33	0.0002

CASES INCLUDED	16	MISSING CASES	0	
DEGREES OF FREEDOM	4			
OVERALL F	1.501E+04	P VALUE	0.0000	
ADJUSTED R SQUARED	0.9999			
R SQUARED	1.0000			
RESID. MEAN SQUARE	5.006E-03			

Table C-15.   COMM Subsystem ANOVA Table for β: All Main Effects

			STEPWISE ANALYSIS OF VARIANCE OF BETA		
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9517E+05				
A	1.2426E-01	1	1.2426E-01	1.2426E-01	-0.0713
B	8.2656E-02	2	2.0691E-01	1.0346E-01	-0.1536
C	1.6606E-01	3	3.7297E-01	1.2432E-01	-0.2494
D	3.7056E-02	4	4.1002E-01	1.0251E-01	-0.3630
E	2.3256E-02	5	4.3328E-01	8.6656E-02	-0.4992
F	7.5625E-04	6	4.3404E-01	7.2340E-02	-0.6658
G	5.1756E-02	7	4.8579E-01	6.9399E-02	-0.8739
H	3.6906E-01	8	8.5485E-01	1.0686E-01	-1.1406
I	5.0056E-01	9	1.3554	1.5060E-01	-1.4959
J	824.41	10	825.76	82.576	0.9972
K	7.6126E-01	11	826.52	75.139	0.9999
RESIDUAL	2.0781E-02	15	826.54	55.103	

Table C-16. COMM Subsystem Coefficient Table for β: One Regressor

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.82	9.7667E-02	1390.68	0.0000
TWTA	-7.1781	9.7667E-02	-73.50	0.0000

CASES INCLUDED	16	MISSING CASES	0
DEGREES OF FREEDOM	14		
OVERALL F	5.402E+03	P VALUE	0.0000
ADJUSTED R SQUARED	0.9972		
R SQUARED	0.9974		
RESID. MEAN SQUARE	1.526E-01		

Table C-17. COMM Subsystem ANOVA Table for β: One Regressor

STEPWISE ANALYSIS OF VARIANCE OF BETA

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9517E+05				
TWTA	824.41	1	824.41	824.41	0.9972
RESIDUAL	2.1367	15	826.54	55.103	

Table C-18. Predicted Values and Residuals for β: COMM subsystem with One Regressor

RUN	β	$\hat{\beta}$	e	RUN	β	$\hat{\beta}$	e
1	128.85	128.64	0.2050	9	128.67	128.64	0.0250
2	143.32	143.00	0.3188	10	143.28	143.00	0.2788
3	142.98	143.00	-0.0212	11	142.68	143.00	-0.3212
4	128.79	128.64	0.1450	12	128.83	128.64	0.1850
5	129.17	128.64	0.5250	13	128.53	128.64	-0.1150
6	142.44	143.00	-0.5612	14	142.90	143.00	-0.1012
7	142.85	143.00	-0.1512	15	143.56	143.00	0.5588
8	128.57	128.64	-0.0750	16	127.75	128.64	-0.8950
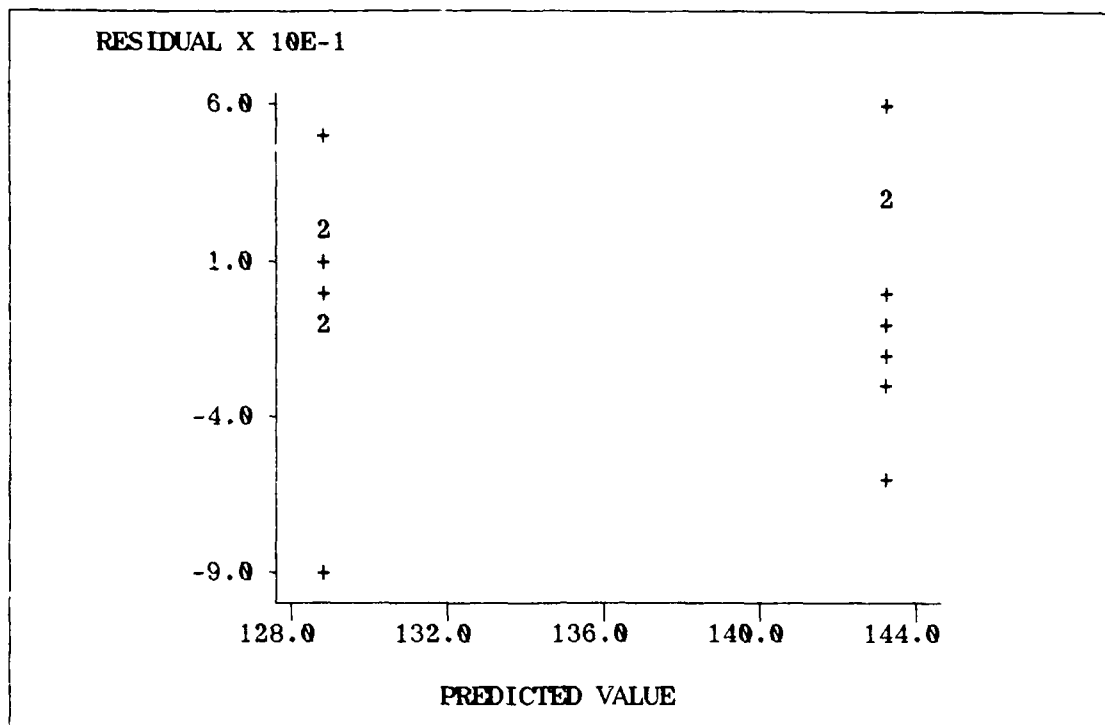
Fig. C-4.   COMM Subsystem Residual Plot for β: One Regressor

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Table C-19. COMM Subsystem Coefficient Table for α: All Main Effects

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.6232	6.2500E-05	25971.00	0.0000
A	-8.1250E-04	6.2500E-05	-13.00	0.0002
B	-9.3750E-04	6.2500E-05	-15.00	0.0001
C	3.1250E-04	6.2500E-05	5.00	0.0075
D	-4.3750E-04	6.2500E-05	-7.00	0.0022
E	1.8750E-04	6.2500E-05	3.00	0.0399
F	6.2500E-05	6.2500E-05	1.00	0.3739
G	-3.1250E-04	6.2500E-05	-5.00	0.0075
H	-1.0625E-03	6.2500E-05	-17.00	0.0001
I	8.1250E-04	6.2500E-05	13.00	0.0002
J	2.6562E-02	6.2500E-05	425.00	0.0000
K	5.6250E-04	6.2500E-05	9.00	0.0008

CASES INCLUDED 16   MISSING CASES 0
DEGREES OF FREEDOM 4
OVERALL F 1.652E+04   P VALUE 0.0000
ADJUSTED R SQUARED 0.9999
R SQUARED 1.0000
RESID. MEAN SQUARE 6.250E-08

Table C-20. COMM Subsystem ANOVA Table for α: All Main Effects

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	42.156				
A	1.0562E-05	1	1.0562E-05	1.0562E-05	-0.0704
B	1.4062E-05	2	2.4625E-05	1.2312E-05	-0.1513
C	1.5625E-06	3	2.6187E-05	8.7292E-06	-0.2471
D	3.0625E-06	4	2.9250E-05	7.3125E-06	-0.3601
E	5.6250E-07	5	2.9812E-05	5.9625E-06	-0.4961
F	6.2500E-08	6	2.9875E-05	4.9792E-06	-0.6623
G	1.5625E-06	7	3.1437E-05	4.4911E-06	-0.8698
H	1.8062E-05	8	4.9500E-05	6.1875E-06	-1.1335
I	1.0563E-05	9	6.0062E-05	6.6736E-06	-1.4868
J	1.1289E-02	10	1.1349E-02	1.1349E-03	0.9986
K	5.0625E-06	11	1.1354E-02	1.0322E-03	0.9999
RESIDUAL	3.1250E-07	15	1.1354E-02	7.5696E-04	

Table C-21. CCMM Subsystem Coefficient Table for α: One Regressor

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UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

PREDICTOR
VARIABLES    COEFFICIENT    STD ERROR    STUDENT'S T      P

CONSTANT     1.6232         5.4023E-04   3004.60       0.0000
TWTA         2.6562E-02     5.4023E-04     49.17       0.0000

CASES INCLUDED        16        MISSING CASES    0
DEGREES OF FREEDOM    14
OVERALL F             2.418E+03  P VALUE      0.0000
ADJUSTED R SQUARED    0.9938
R SQUARED             0.9942
RESID. MEAN SQUARE    4.670E-06
```

Table C-22. CCMM Subsystem ANOVA Table for α: One Regressor

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	42.156				
TWTA	1.1289E-02	1	1.1289E-02	1.1289E-02	0.9938
RESIDUAL	6.5375E-05	15	1.1354E-02	7.5696E-04	

Table C-23. Predicted Values and Residuals for α: CCMM subsystem with One Regressor

RUN	α	$\hat{\alpha}$	e	RUN	α	$\hat{\alpha}$	e
1	1.654	1.6497	0.0043	9	1.649	1.6497	-0.0007
2	1.594	1.5966	-0.0026	10	1.598	1.5966	0.0014
3	1.596	1.5966	-0.0006	11	1.598	1.5966	0.0014
4	1.649	1.6497	-0.0007	12	1.645	1.6497	-0.0047
5	1.652	1.6497	0.0023	13	1.651	1.6497	0.0013
6	1.598	1.5966	0.0014	14	1.597	1.5966	0.0004
7	1.596	1.5966	-0.0006	15	1.596	1.5966	-0.0006
8	1.650	1.6497	0.0003	16	1.648	1.6497	-0.0017
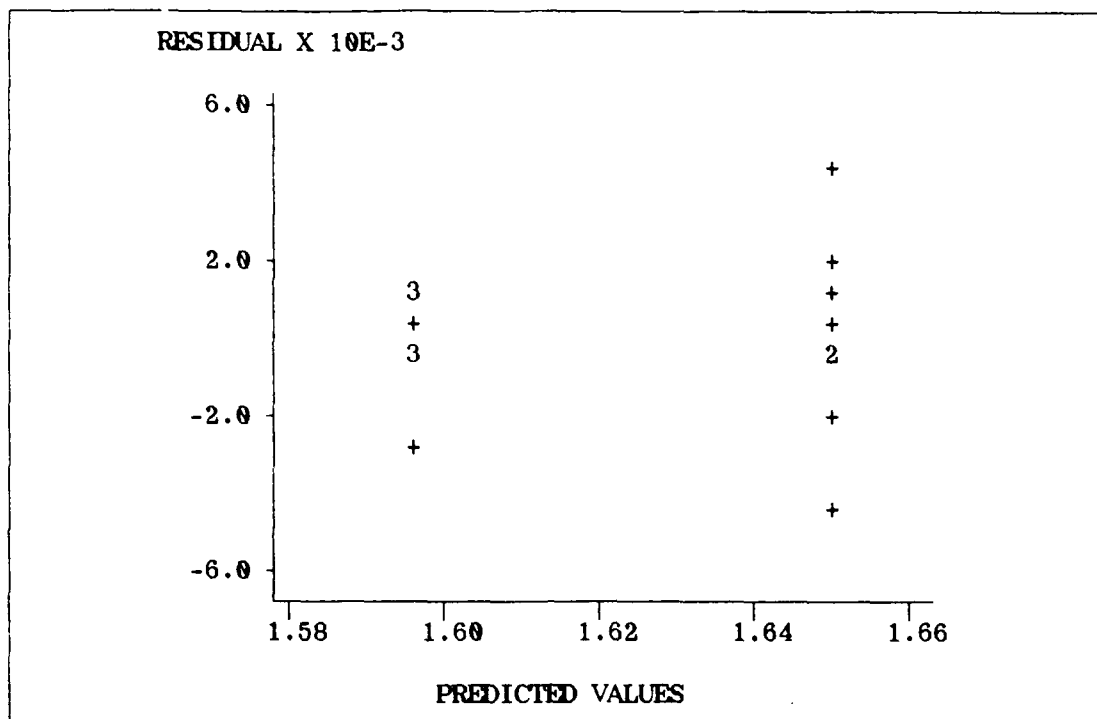
Fig. C-5. COMM Subsystem Residual Plot for α: One Regressor

Table C-24. TTC Subsystem Group Screening Coefficient Table for β: Five Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.52	1.2817E-01	1057.37	0.0000
B	-3.7625E-01	1.2817E-01	-2.94	0.0991
C	-2.6762	1.2817E-01	-20.88	0.0023
D	-2.1625E-01	1.2817E-01	-1.69	0.2336
E	-6.2125E-01	1.2817E-01	-4.85	0.0400
F	-4.5625E-01	1.2817E-01	-3.56	0.0707

CASES INCLUDED   8   MISSING CASES   0
DEGREES OF FREEDOM   2
OVERALL F   96.73   P VALUE   0.0103
ADJUSTED R SQUARED   0.9856
R SQUARED   0.9959
RESID. MEAN SQUARE   1.314E-01

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Table C-25. TTC Subsystem Group Screening ANOVA Table for β: Five
Regressors

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	1.4692E+05				
B	1.1325	1	1.1325	1.1325	-0.1460
C	57.299	2	58.431	29.216	0.8818
D	3.7411E-01	3	58.805	19.602	0.8625
E	3.0876	4	61.893	15.473	0.9295
F	1.6653	5	63.558	12.712	0.9856
RESIDUAL	2.6283E-01	7	63.821	9.1173	
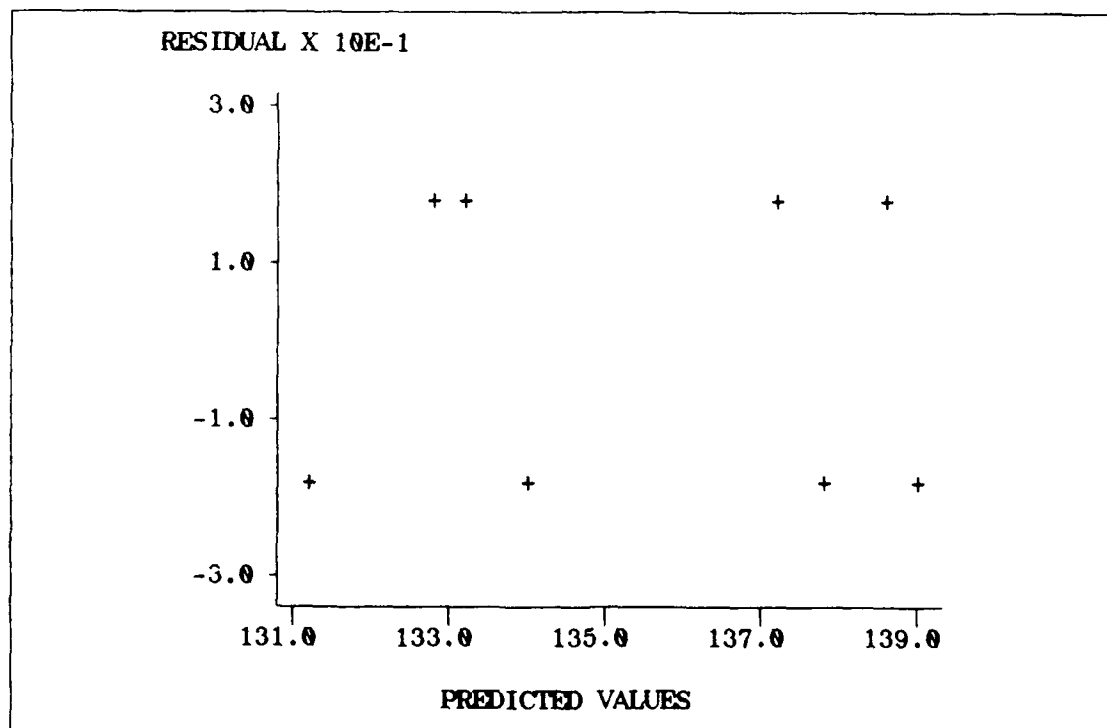
Fig. C-6. TTC Subsystem Group Screening Residual Plot for β: Five
Regressors

Table C-26. TTC Subsystem Group Screening Coefficient Table for α: Three Regressors

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UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

PREDICTOR
VARIABLES     COEFFICIENT     STD ERROR      STUDENT'S T       P

CONSTANT        1.6255        1.2247E-03      1327.22        0.0000
C             -2.5000E-03     1.2247E-03        -2.04        0.1108
E             -5.5000E-03     1.2247E-03        -4.49        0.0109
F             -4.5000E-03     1.2247E-03        -3.67        0.0213

CASES INCLUDED         8          MISSING CASES      0
DEGREES OF FREEDOM     4
OVERALL F          12.61        P VALUE       0.0166
ADJUSTED R SQUARED  0.8327
R SQUARED           0.9044
RESID. MEAN SQUARE   1.200E-05
```

Table C-27. TTC Subsystem Group Screening ANOVA Table for α: Three Regressors

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STEPWISE ANALYSIS OF VARIANCE OF ALPHA

            INDIVIDUAL   CUM    CUMULATIVE   CUMULATIVE   ADJUSTED
SOURCE          SS       DF        SS           MS        R-SQUARED

CONSTANT    21.138
C           5.0000E-05    1     5.0000E-05   5.0000E-05   -0.0505
E           2.4200E-04    2     2.9200E-04   1.4600E-04    0.4143
F           1.6200E-04    3     4.5400E-04   1.5133E-04    0.8327
RESIDUAL    4.8000E-05    7     5.0200E-04   7.1714E-05
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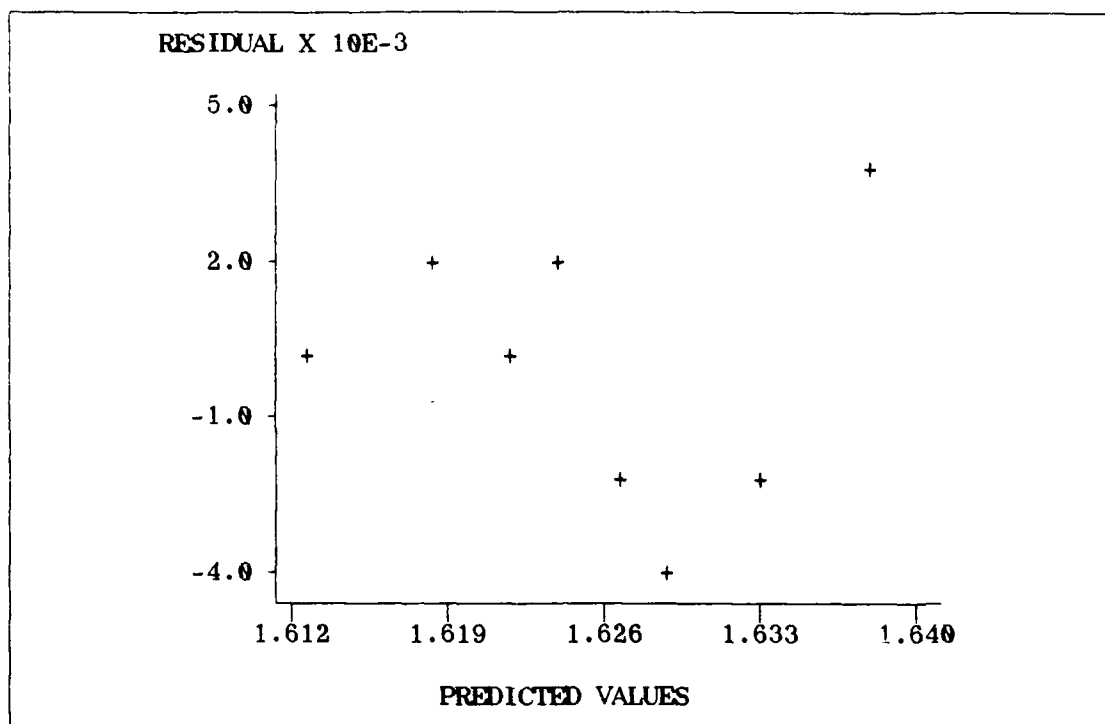
Fig. C-7. TTC Subsystem Group Screening Residual Plot for α: Three Regressors

Table C-28. TTC Subsystem Group Screening Coefficient Table for β: All Main Effects

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.59	7.8765E-02	1721.43	9.0000
A	5.3125E-02	7.8765E-02	0.67	0.5074
B	-3.0625E-01	7.8765E-02	-3.89	0.0008
C	-2.6100	7.8765E-02	-33.14	0.6900
D	5.7500E-02	7.8765E-02	0.73	0.4734
E	-2.9687E-01	7.8765E-02	-3.77	0.0011
F	-3.1250E-03	7.8765E-02	-0.04	0.9687
G	-6.6625E-01	7.8765E-02	-8.46	0.0000
H	-8.5000E-02	7.8765E-02	-1.08	0.2928
I	-1.2875E-01	7.8765E-02	-1.63	0.1170
J	-4.9437E-01	7.8765E-02	-6.28	0.0000

CASES INCLUDED   32   MISSING CASES   0

DEGREES OF FREEDOM   21

OVERALL F   124.3   P VALUE   0.0000

ADJUSTED R SQUARED   0.9755

R SQUARED   0.9834

RESID. MEAN SQUARE   1.985E-01

Table C-29. TTC Subsystem ANOVA Table for β: All Main Effects After Group Screening

STEPWISE ANALYSIS OF VARIANCE OF BETA					
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	5.8830E+05				
A	9.0313E-02	1	9.0313E-02	9.0313E-02	-0.0330
B	3.0012	2	3.0916	1.5458	-0.0558
C	217.99	3	221.08	73.693	0.8682
D	1.0580E-01	4	221.18	55.296	0.8638
E	2.8203	5	224.00	44.801	0.8719
F	3.1250E-04	6	224.01	37.334	0.8668
G	14.204	7	238.21	34.030	0.9344
H	2.3120E-01	8	238.44	29.805	0.9328
I	5.3045E-01	9	238.97	26.552	0.9327
J	7.8210	10	246.79	24.679	0.9755
RESIDUAL	4.1691	31	250.96	8.0955	

Table C-30. TTC Subsystem Coefficient Table for β: Three Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.59	1.1054E-01	1226.58	0.0000
C	-2.6100	1.1054E-01	-23.61	0.0000
G	-6.6625E-01	1.1054E-01	-6.03	0.0000
J	-4.9437E-01	1.1054E-01	-4.47	0.0001

CASES INCLUDED	32	MISSING CASES	0
DEGREES OF FREEDOM	28		
OVERALL F	204.6	P VALUE	0.0000
ADJUSTED R SQUARED	0.9517		
R SQUARED	0.9564		
RESID. MEAN SQUARE	3.910E-01		

Table C-31. TTC Subsystem ANOVA Table for β: Three Regressors

STEPWISE ANALYSIS OF VARIANCE OF BETA					
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	5.8830E+05				
C	217.99	1	217.99	217.99	0.8642
G	14.204	2	232.19	116.10	0.9201
J	7.8210	3	240.01	80.004	0.9517
RESIDUAL	10.949	31	250.96	8.0955	

Table C-32. Predicted Values and Residuals for β: TTC subsystem with Three Regressors

RUN	β	$\hat{\beta}$	e	RUN	β	$\hat{\beta}$	e
1	137.71	137.04	0.6719	17	139.40	139.36	0.0406
2	139.12	138.37	0.7494	18	138.22	138.03	0.1931
3	139.12	139.36	-0.2394	19	136.73	137.04	-0.3081
4	137.80	138.03	-0.2269	20	137.62	138.37	-0.7506
5	134.51	134.14	0.3706	21	132.10	131.82	0.2819
6	133.11	132.81	0.3031	22	133.12	133.15	-0.0306
7	131.72	131.82	-0.0981	23	133.15	134.14	-0.9894
8	132.85	133.15	-0.3006	24	132.22	132.81	-0.5869

Table C-32. (Continued)

RUN	β	$\widehat{\beta}$	e	RUN	β	$\widehat{\beta}$	e
9	138.77	138.03	0.7431	25	138.59	138.37	0.2194
10	139.69	139.36	0.3306	26	137.27	137.04	0.2319
11	138.17	138.37	-0.2006	27	137.28	138.03	-0.7469
12	137.00	137.04	-0.0381	28	138.69	139.36	-0.6694
13	133.45	133.15	0.2994	29	132.79	132.81	-0.0169
14	132.52	131.82	0.7019	30	133.95	134.14	-0.1894
15	132.53	132.8	-0.2769	31	132.55	133.15	-0.6006
16	136.10	134.1.	1.9606	32	130.99	131.82	-0.8281
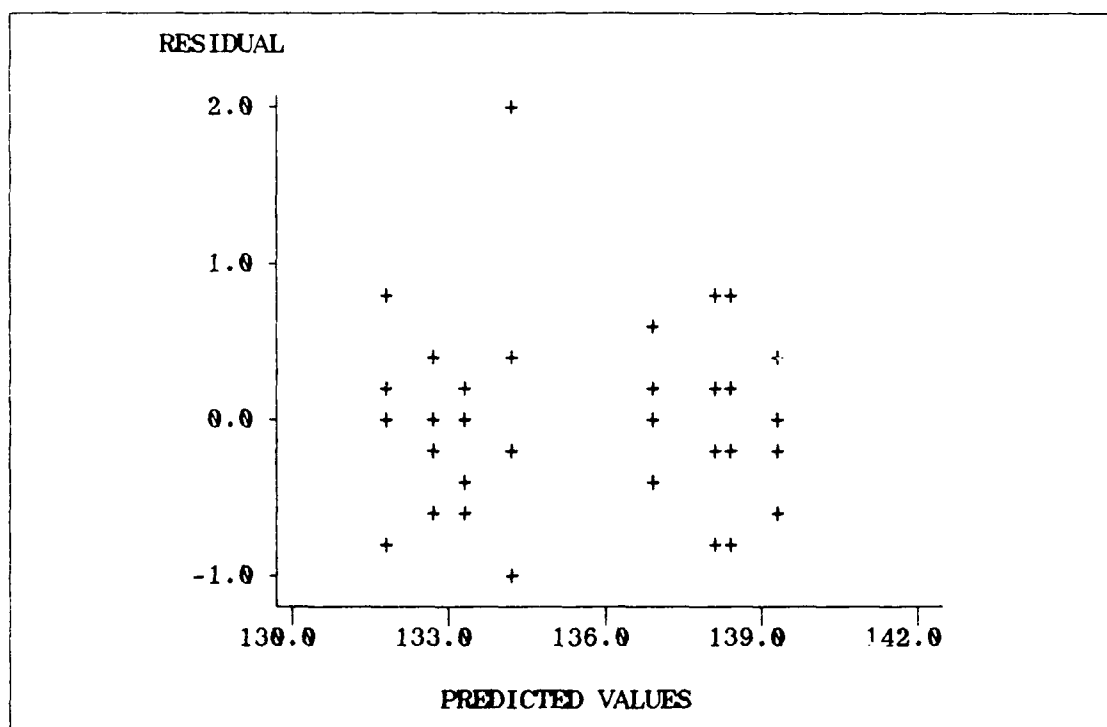
Fig. C-8. TTC Subsystem Residual Plot for β: Three Regressors

Table C-33. TTC Subsystem Coefficient Table for α: Three Regressors

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UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

PREDICTOR
VARIABLES      COEFFICIENT      STD ERROR      STUDENT'S T        P

CONSTANT         1.6257        2.5470E-04       6382.65        0.0000
C              -2.5937E-03     2.5470E-04        -10.18        0.0000
G              -5.3437E-03     2.5470E-04        -20.98        0.0000
J              -3.9687E-03     2.5470E-04        -15.58        0.0000

CASES  INCLUDED          32        MISSING CASES      0
DEGREES OF FREEDOM       28
OVERALL  F            262.2        P VALUE       0.0000
ADJUSTED R SQUARED   0.9619
R SQUARED            0.9656
RESID. MEAN SQUARE   2.076E-06
```

Table C-34. TTC Subsystem ANOVA Table for α: Three Regressors

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	84.568				
C	2.1528E-04	1	2.1528E-04	2.1528E-04	0.0982
G	9.1378E-04	2	1.1291E-03	5.6453E-04	0.6447
J	5.0403E-04	3	1.6331E-03	5.4436E-04	0.9619
RESIDUAL	5.8125E-05	31	1.6912E-03	5.4555E-05	

Table C-35. Predicted Values and Residuals for α: TTC subsystem with Three Regressors

RUN	α	$\widehat{\alpha}$	e	RUN	α	$\widehat{\alpha}$	e
1	1.617	1.6189	-0.0019	17	1.637	1.6376	-0.0006
2	1.629	1.6296	-0.0006	18	1.627	1.6269	0.0001
3	1.638	1.6376	0.0004	19	1.621	1.6189	0.0021
4	1.627	1.6269	0.0001	20	1.630	1.6296	0.0004
5	1.631	1.6324	-0.0014	21	1.614	1.6137	0.0003
6	1.619	1.6217	-0.0027	22	1.624	1.6244	-0.0004
7	1.614	1.6137	0.0003	23	1.632	1.6324	-0.0004
8	1.625	1.6244	0.0006	24	1.624	1.6217	0.0023
9	1.627	1.6269	0.0001	25	1.629	1.6296	-0.0006
10	1.635	1.6376	-0.0026	26	1.619	1.6189	0.0001
11	1.630	1.6296	0.0004	27	1.627	1.6269	0.0001
12	1.619	1.6189	0.0001	28	1.640	1.6376	0.0024
13	1.622	1.6244	-0.0024	29	1.621	1.6217	-0.0007
14	1.614	1.6137	0.0003	30	1.632	1.6324	-0.0004
15	1.622	1.6217	0.0003	31	1.627	1.6244	0.0026
16	1.635	1.6324	0.0026	32	1.613	1.6137	-0.0007
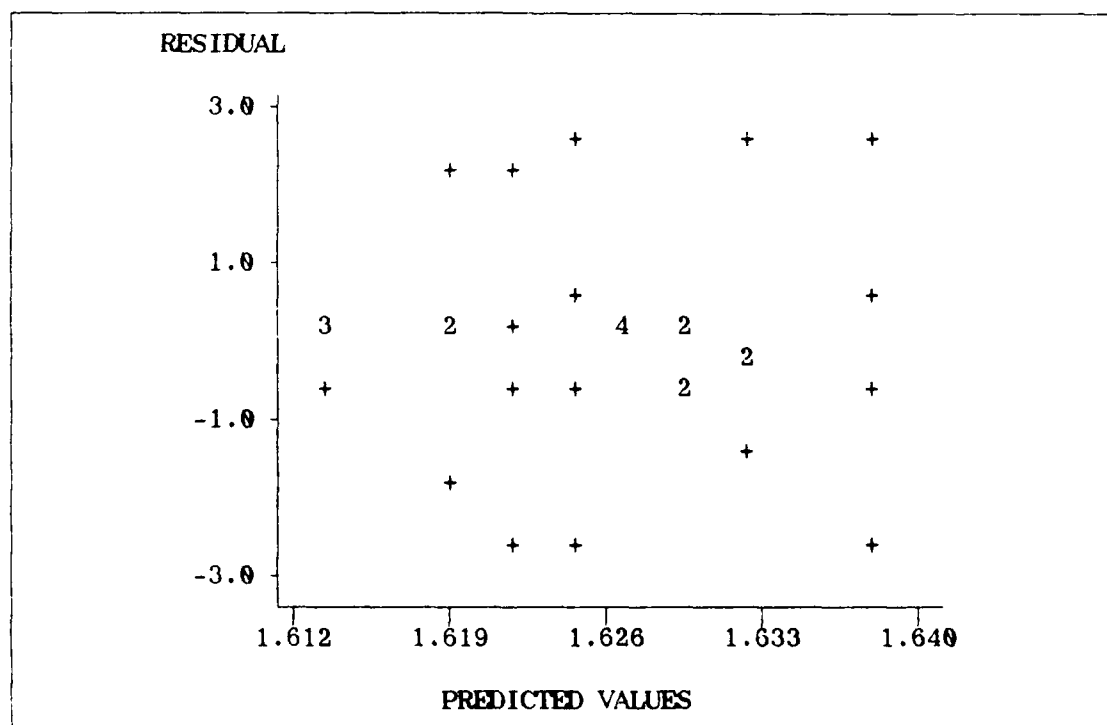
Fig. C-9. TTC Subsystem Residual Plot for α: Three Regressors

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Table C-36. EPS Subsystem Group Screening Coefficient Table for β: Three Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.51	2.0210E-02	6705.03	0.0000
A	-1.0562E-01	2.0210E-02	-5.23	0.0002
G	-2.7437E-01	2.0210E-02	-13.58	0.0000
J	-3.4062E-01	2.0210E-02	-16.85	0.0000

CASES INCLUDED	16	MISSING CASES	0	
DEGREES OF FREEDOM	12			
OVERALL F	165.2	P VALUE	0.0000	
ADJUSTED R SQUARED	0.9705			
R SQUARED	0.9764			
RESID. MEAN SQUARE	6.535E-03			

Table C-37. EPS Subsystem Group Screening ANOVA Table for β: Three Regressors

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9382E+05				
A	1.7851E-01	1	1.7851E-01	1.7851E-01	-0.0138
G	1.2945	2	1.3830	6.9151E-01	0.3271
J	1.8564	3	3.2394	1.0798	0.9705
RESIDUAL	7.8425E-02	15	3.3178	2.2119E-01	

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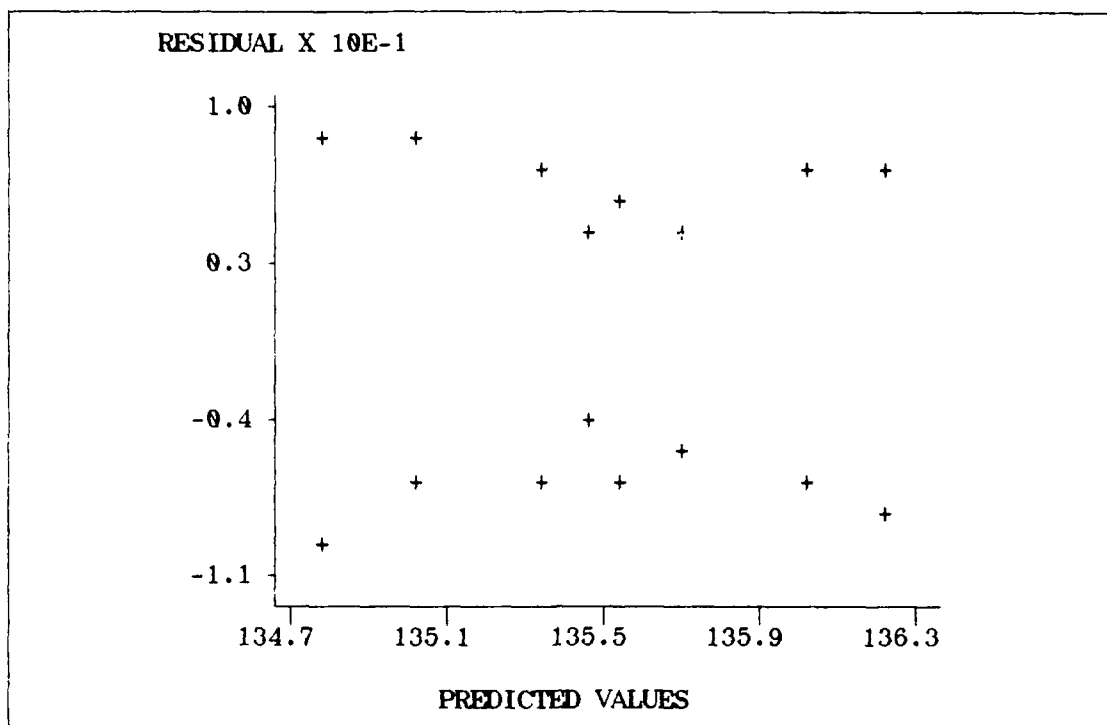
Fig. C-10. EPS Subsystem Group Screening Residual Plot for β: Three Regressors

Table C-38. EPS Subsystem Group Screening Coefficient Table for α: Three Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.6261	1.2500E-04	13009.00	0.0000
A	-1.1250E-03	1.2500E-04	-9.00	0.0000
G	-2.1250E-03	1.2500E-04	-17.00	0.0000
J	2.6250E-03	1.2500E-04	21.00	0.0000

CASES INCLUDED	16	MISSING CASES	0
DEGREES OF FREEDOM	12		
OVERALL F	270.3	P VALUE	0.0000
ADJUSTED R SQUARED	0.9818		
R SQUARED	0.9854		
RESID. MEAN SQUARE	2.500E-07		

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Table C-39. EPS Subsystem Group Screening ANOVA Table for α: Three Regressors

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	42.309				
A	2.0250E-05	1	2.0250E-05	2.0250E-05	0.0340
G	7.2250E-05	2	9.2500E-05	4.6250E-05	0.3649
J	1.1025E-04	3	2.0275E-04	6.7583E-05	0.9818
RESIDUAL	3.0000E-06	15	2.0575E-04	1.3717E-05	
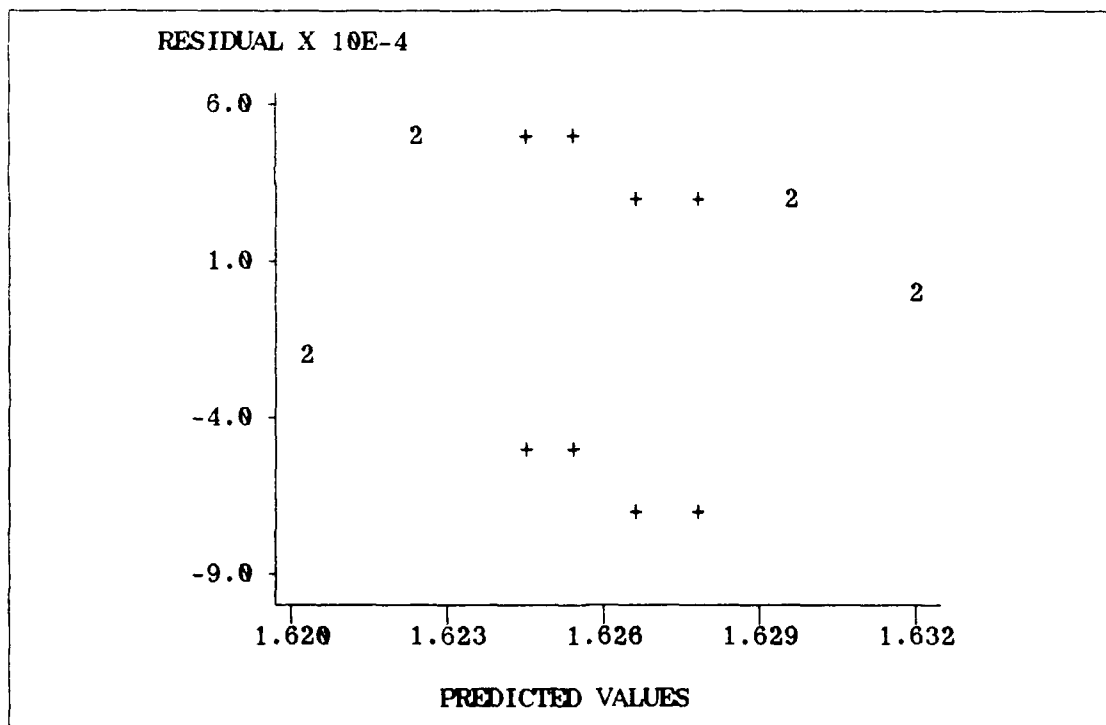
Fig. C-11. EPS Subsystem Group Screening Residual Plot for α: Three Regressors

Table C-40. EPS Subsystem Coefficient Table for β: All Main Effects After Group Screening

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UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA

PREDICTOR
VARIABLES     COEFFICIENT     STD ERROR     STUDENT'S T        P

CONSTANT        135.51        1.0825E-03    125177.04       0.0000
A             -9.6875E-02     1.0825E-03       -89.49       0.0000
B             -1.8750E-03     1.0825E-03        -1.73       0.1583
C              3.1250E-03     1.0825E-03         2.89       0.0447
D             -1.8750E-03     1.0825E-03        -1.73       0.1583
E              6.2500E-04     1.0825E-03         0.58       0.5946
F             -1.8750E-03     1.0825E-03        -1.73       0.1583
G             -1.8750E-03     1.0825E-03        -1.73       0.1583
H             -1.8938E-01     1.0825E-03      -174.94       0.0000
I             -4.4375E-02     1.0825E-03       -40.99       0.0000
J             -4.4375E-02     1.0825E-03       -40.99       0.0000
K             -3.3937E-01     1.0825E-03      -313.50       0.0000

CASES  INCLUDED          16        MISSING CASES       0
DEGREES OF FREEDOM        4
OVERALL F           1.275E+04    P VALUE       0.0000
ADJUSTED R SQUARED  0.9999
R SQUARED           1.0000
RESID. MEAN SQUARE  1.875E-05
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Table C-41. EPS Subsystem ANOVA Table for β: All Main Effects After Group Screening

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9380E+05				
A	1.5016E-01	1	1.5016E-01	1.5016E-01	-0.0103
B	5.6250E-05	2	1.5021E-01	7.5106E-02	-0.0880
C	1.5625E-04	3	1.5037E-01	5.0123E-02	-0.1785
D	5.6250E-05	4	1.5042E-01	3.7606E-02	-0.2856
E	6.2500E-06	5	1.5043E-01	3.0086E-02	-0.4142
F	5.6250E-05	6	1.5049E-01	2.5081E-02	-0.5713
G	5.6250E-05	7	1.5054E-01	2.1506E-02	-0.7677
H	5.7381E-01	8	7.2435E-01	9.0544E-02	-0.5527
I	3.1506E-02	9	7.5586E-01	8.3984E-02	-0.7816
J	3.1506E-02	10	7.8736E-01	7.8736E-02	-1.1020
K	1.8428	11	2.6302	2.3911E-01	0.9999
RESIDUAL	7.5000E-05	15	2.6302	1.7535E-01	

Table C-42. EPS Subsystem Coefficient Table for β: Three Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.51	1.8182E-02	7452.72	0.0000
A	-9.6875E-02	1.8182E-02	-5.33	0.0002
H	-1.8938E-01	1.8182E-02	-10.42	0.0000
K	-3.3937E-01	1.8182E-02	-18.67	0.0000

CASES INCLUDED   16   MISSING CASES   0
DEGREES OF FREEDOM   12
OVERALL F   161.7   P VALUE   0.0000
ADJUSTED R SQUARED   0.9698
R SQUARED   0.9759
RESID. MEAN SQUARE   5.290E-03

Table C-43. EPS Subsystem ANOVA Table for β: Three Regressors

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9380E+05				
A	1.5016E-01	1	1.5016E-01	1.5016E-01	-0.0103
H	5.7381E-01	2	7.2396E-01	3.6198E-01	0.1637
K	1.8428	3	2.5668	8.5559E-01	0.9698
RESIDUAL	6.3475E-02	15	2.6302	1.7535E-01	

Table C-44. Predicted Values and Residuals for β: EPS subsystem with Three Regressors

| RUN	β	$\hat{\beta}$	e	RUN	β	$\hat{\beta}$	e
1	135.37	135.45	-0.0850	9	135.07	135.08	-0.0062
2	135.65	135.56	0.0888	10	135.94	135.94	0.0000
3	135.16	135.08	0.0838	11	135.45	135.45	-0.0050
4	135.84	135.94	-0.1000	12	135.56	135.56	-0.0012
5	136.14	136.13	0.0063	13	135.67	135.75	-0.0850
6	134.89	134.88	0.0075	14	135.35	135.26	0.0888
7	135.76	135.75	0.0050	15	136.22	136.13	0.0863
8	135.27	135.26	0.0088	16	134.79	134.88	-0.0925

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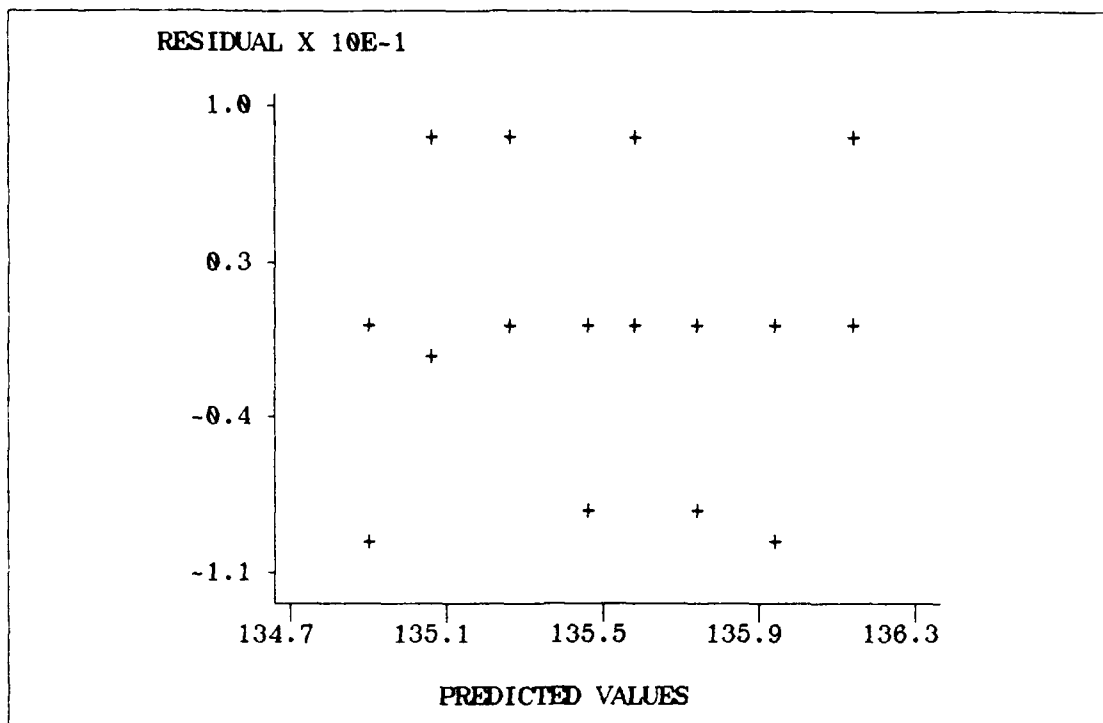
Fig. C-12. EPS Subsystem Residual Plot for β: Three Regressors

Table C-45. EPS Subsystem Coefficient Table for α: All Main Effects After Group Screening

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.6262	1.0825E-04	15022.08	0.0000
A	-1.0625E-03	1.0825E-04	-9.81	0.0006
B	-6.2500E-05	1.0825E-04	-0.58	0.5946
C	6.2500E-05	1.0825E-04	0.58	0.5946
D	-6.2500E-05	1.0825E-04	-0.58	0.5946
E	6.2500E-05	1.0825E-04	0.58	0.5946
F	6.2500E-05	1.0825E-04	0.58	0.5946
G	6.2500E-05	1.0825E-04	0.58	0.5946
H	-2.0625E-03	1.0825E-04	-19.05	0.0000
I	-4.3750E-04	1.0825E-04	-4.04	0.0156
J	1.8750E-04	1.0825E-04	1.73	0.1583
K	2.3125E-03	1.0825E-04	21.36	0.0000

Table C-46. EPS Subsystem ANOVA Table for α: All Main Effects After Group Screening

```
              STEPWISE ANALYSIS OF VARIANCE OF ALPHA

           INDIVIDUAL    CUM   CUMULATIVE    CUMULATIVE   ADJUSTED
  SOURCE      SS         DF       SS            MS        R-SQUARED

CONSTANT   42.312
A          1.8062E-05     1   1.8062E-05   1.8062E-05     0.0383
B          6.2500E-08     2   1.8125E-05   9.0625E-06    -0.0353
C          6.2500E-08     3   1.8187E-05   6.0625E-06    -0.1211
D          6.2500E-08     4   1.8250E-05   4.5625E-06    -0.2226
E          6.2500E-08     5   1.8312E-05   3.6625E-06    -0.3443
F          6.2500E-08     6   1.8375E-05   3.0625E-06    -0.4931
G          6.2500E-08     7   1.8437E-05   2.6339E-06    -0.6791
H          6.8063E-05     8   8.6500E-05   1.0812E-05    -0.0923
I          3.0625E-06     9   8.9562E-05   9.9514E-06    -0.2310
J          5.6250E-07    10   9.0125E-05   9.0125E-06    -0.4676
K          8.5563E-05    11   1.7569E-04   1.5972E-05     0.9841
RESIDUAL   7.5000E-07    15   1.7644E-04   1.1762E-05

CASES INCLUDED           16         MISSING CASES      0
DEGREES OF FREEDOM        4
OVERALL F             85.18         P VALUE       0.0003
ADJUSTED R SQUARED   0.9841
R SQUARED            0.9957
RESID. MEAN SQUARE   1.875E-07
```

Table C-47. EPS Subsystem Coefficient Table for α: Three Regressors

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     UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

  PREDICTOR
  VARIABLES    COEFFICIENT   STD ERROR    STUDENT'S T      P

  CONSTANT      1.6262      1.5729E-04    10338.90     0.0000
  A            -1.0625E-03  1.5729E-04      -6.76      0.0000
  H            -2.0625F-03  1.5729E-04     -13.11      0.0000
  K             2.3125E-03  1.5729E-04      14.70      0.0000

  CASES INCLUDED          16         MISSING CASES      0
  DEGREES OF FREEDOM      12
  OVERALL F            144.6         P VALUE       0.0000
  ADJUSTED R SQUARED   0.9663
  R SQUARED            0.9731
  RESID. MEAN SQUARE   3.958E-07
```

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Table C-48. EPS Subsystem ANOVA Table for α: Three Regressors

	STEPWISE ANALYSIS OF VARIANCE OF ALPHA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	42.312				
A	1.8062E-05	1	1.8062E-05	1.8062E-05	0.0383
H	6.8063E-05	2	8.6125E-05	4.3062E-05	0.4094
K	8.5563E-05	3	1.7169E-04	5.7229E-05	0.9663
RESIDUAL	4.7500E-06	15	1.7644E-04	1.1762E-05	

Table C-49. Predicted Values and Residuals for α: EPS subsystem with Three Regressors

RUN	α	$\hat{\alpha}$	e	RUN	α	$\hat{\alpha}$	e
1	1.631	1.6316	-0.0006	9	1.628	1.6275	0.0005
2	1.621	1.6207	0.0003	10	1.624	1.6249	-0.0009
3	1.628	1.6275	0.0005	11	1.631	1.6316	-0.0006
4	1.625	1.6249	0.0001	12	1.621	1.6207	0.0003
5	1.628	1.6270	0.0010	13	1.623	1.6229	0.0001
6	1.625	1.6254	-0.0004	14	1.630	1.6295	0.0005
7	1.622	1.6229	-0.0009	15	1.627	1.6270	0.0000
8	1.630	1.6295	0.0005	16	1.625	1.6254	-0.0004
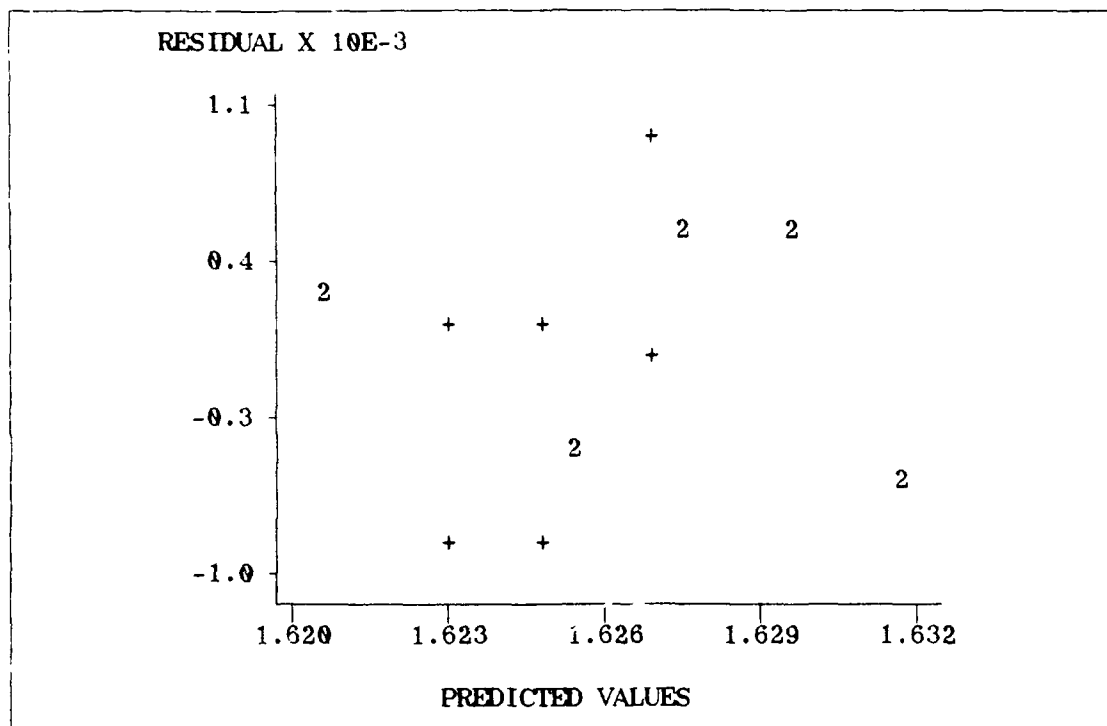
Fig C-13.   EPS Subsystem Residual Plot for α: Three Regressors

Table C-50. Box-Level Coefficient Table for β: Ten Regressors

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	135.82	4.1075E-02	3306.69	0.0000
TWTA	-7.1875	4.1075E-02	-174.98	0.0000
CMDU	-2.7187	4.1075E-02	-66.19	0.0000
TLMGEN	-5.8875E-01	4.1075E-02	-14.33	0.0000
SXMTR	-4.1625E-01	4.1075E-02	-10.13	0.0002
ARRAY1	-1.0000E-01	4.1075E-02	-2.43	0.0590
ITLM	-1.9375E-01	4.1075E-02	-4.72	0.0053
BAT	-3.5250E-01	4.1075E-02	-8.58	0.0004
TC	4.0750E-01	4.1075E-02	9.92	0.0002
TT	7.5000E-02	4.1075E-02	1.83	0.1274
TS	5.0000E-02	4.1075E-02	1.22	0.2778

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA

CASES INCLUDED   16   MISSING CASES   0
DEGREES OF FREEDOM   5
OVERALL F   3.551E+03   P VALUE   0.0000
ADJUSTED R SQUARED   0.9996
R SQUARED   0.9999
RESID. MEAN SQUARE   2.700E-02

Table C-51. Box-Level ANOVA Table for β: Ten Regressors

STEPWISE ANALYSIS OF VARIANCE OF BETA

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9517E+05				
TWTA	826.56	1	826.56	826.56	0.8522
CMDU	118.27	2	944.83	472.41	0.9832
TLMGEN	5.5460	3	950.37	316.79	0.9890
SXMTR	2.7722	4	953.15	238.29	0.9919
ARRAY1	1.6000E-01	5	953.31	190.66	0.9914
ITLM	6.0063E-01	6	953.91	158.98	0.9915
BAT	1.9881	7	955.90	136.56	0.9943
TC	2.6569	8	958.55	119.82	0.9994
TT	9.0000E-02	9	958.64	106.52	0.9995
TS	4.0000E-02	10	958.68	95.868	0.9996
RESIDUAL	1.3498E-01	15	958.82	63.921	

Table C-52. Box-Level Coefficient Table for β: Six Regressors

```
UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BETA

PREDICTOR
VARIABLES     COEFFICIENT     STD ERROR      STUDENT'S T      P

CONSTANT        135.82        8.4393E-02      1609.41       0.0000
TWTA            -7.1875       8.4393E-02       -85.17       0.0000
CMDU            -2.7187       8.4393E-02       -32.22       0.0000
TLMGEN          -5.8875E-01   8.4393E-02        -6.98       0.0001
SXMTR           -4.1625E-01   8.4393E-02        -4.93       0.0008
BAT             -3.5250E-01   8.4393E-02        -4.18       0.0024
TC               4.0750E-01   8.4393E-02         4.83       0.0009

CASES INCLUDED          16        MISSING CASES      0
DEGREES OF FREEDOM       9
OVERALL F          1.401E+03    P VALUE      0.0000
ADJUSTED R SQUARED   0.9982
R SQUARED            0.9989
RESID. MEAN SQUARE   1.146E-01
```

Table C-53. Box-Level ANOVA Table for β: Six Regressors

	STEPWISE ANALYSIS OF VARIANCE OF BETA				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	2.9517E+05				
TWTA	826.56	1	826.56	826.56	0.8522
CMDU	118.27	2	944.83	472.41	0.9832
TLMGEN	5.5460	3	950.37	316.79	0.9890
SXMTR	2.7722	4	953.15	238.29	0.9919
BAT	1.9881	5	955.13	191.03	0.9942
TC	2.6569	6	957.79	159.63	0.9982
RESIDUAL	1.0256	15	958.82	63.921	

Table C-54. Predicted Values and Residuals for β: Box-Level Model with Six Regressors

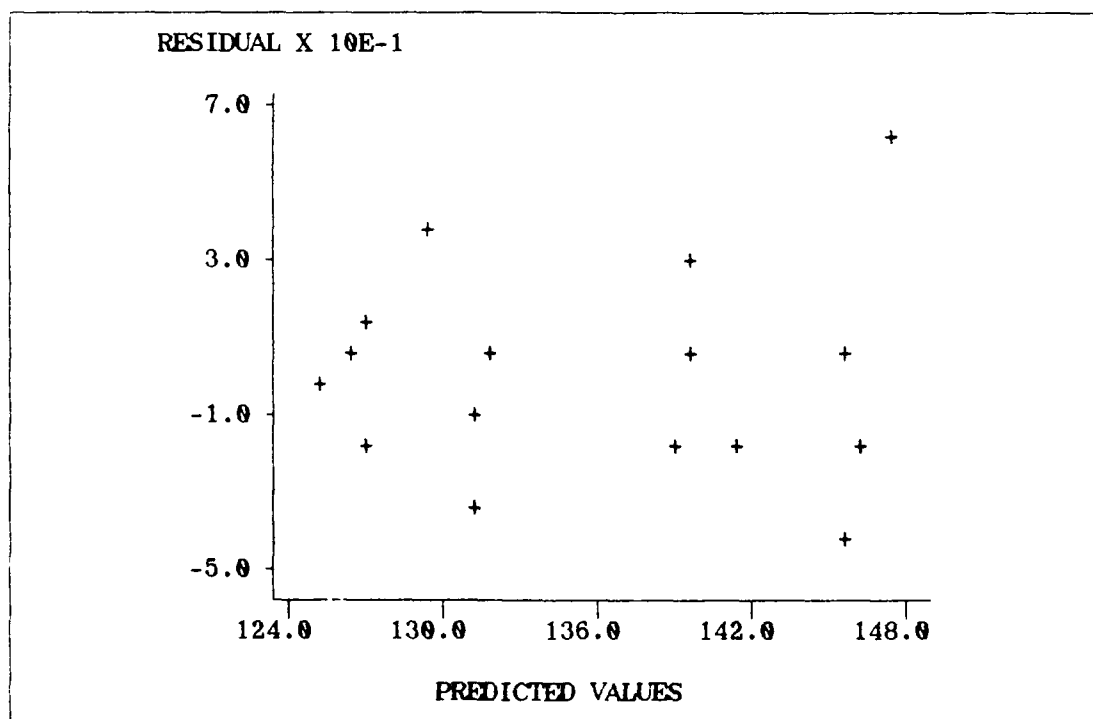| RUN	β	$\hat{\beta}$	e	RUN	β	$\hat{\beta}$	e
1	148.08	147.49	0.5850	9	145.79	145.96	-0.1675
2	131.64	131.60	0.0400	10	131.15	131.47	-0.3225
3	141.05	141.24	-0.1925	11	139.78	139.70	0.0750
4	126.83	126.98	-0.1475	12	126.98	126.85	0.1300
5	145.16	145.61	-0.4525	13	145.52	145.48	0.0350
6	131.01	131.13	-0.1175	14	129.99	129.59	0.4000
7	139.62	139.36	0.2600	15	139.09	139.23	-0.1425
8	126.53	126.50	0.0250	16	124.96	124.97	-0.0075

Fig. C-14. Box-Level Residual Plot for β: Six Regressors.

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Table C-55. Box-Level Coefficient Table for α: Ten Regressors

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA				
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.6231	1.6771E-04	9678.45	0.0000
TWTA	2.6625E-02	1.6771E-04	158.76	0.0000
CMDU	-2.2500E-03	1.6771E-04	-13.42	0.0000
TLMGEN	-5.1250E-03	1.6771E-04	-30.56	0.0000
SXMTR	-3.6250E-03	1.6771E-04	-21.62	0.0000
ARRAY1	-1.0000E-03	1.6771E-04	-5.96	0.0019
ITLM	-2.0000E-03	1.6771E-04	-11.93	0.0001
BAT	2.3750E-03	1.6771E-04	14.16	0.0000
TC	-7.5000E-04	1.6771E-04	-4.47	0.0066
TT	1.2500E-04	1.6771E-04	0.75	0.4896
TS	1.2500E-04	1.6771E-04	0.75	0.4896

CASES INCLUDED 16   MISSING CASES 0
DEGREES OF FREEDOM 5
OVERALL F 2.719E+03   P VALUE 0.0000
ADJUSTED R SQUARED 0.9994
R SQUARED 0.9998
RESID. MEAN SQUARE 4.550E-07

Table C-56. Box-Level ANOVA Table for α: Ten Regressors

STEPWISE ANALYSIS OF VARIANCE OF ALPHA					
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	42.153				
TWTA	1.1342E-02	1	1.1342E-02	1.1342E-02	0.9218
CMDU	8.1000E-05	2	1.1423E-02	5.711E-03	0.9234
TLMGEN	4.2025E-04	3	1.1844E-02	3. -03	0.9599
SXMTR	2.1025E-04	4	1.2054E-02	3.0104E-03	0.9797
ARRAY1	1.6000E-05	5	1.2070E-02	2.4139E-03	0.9796
ITLM	6.4000E-05	6	1.2134E-02	2.0223E-03	0.9861
BAT	9.0250E-05	7	1.2224E-02	1.7463E-03	0.9982
TC	9.0000E-06	8	1.2233E-02	1.5291E-03	0.9995
TT	2.5000E-07	9	1.2233E-02	1.3592E-03	0.9995
TS	2.5000E-07	10	1.2233E-02	1.2233E-03	0.9994
RESIDUAL	2.2500E-06	15	1.2236E-02	8.1572E-04	

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Table C-57. Box-Level Coefficient Table for α: Six Regressors

```
UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF ALPHA

PREDICTOR
VARIABLES     COEFFICIENT      STD ERROR      STUDENT'S T      P

CONSTANT       1.6231          7.5726E-04      2143.43       0.0000
TWTA           2.6625E-02      7.5726E-04        35.16       0.0000
CMDU          -2.2500E-03      7.5726E-04        -2.97       0.0140
TLMGEN        -5.1250E-03      7.5726E-04        -6.77       0.0000
SXMTR         -3.6250E-03      7.5726E-04        -4.79       0.0007
BAT            2.3750E-03      7.5726E-04         3.14       0.0106

CASES INCLUDED            16         MISSING CASES       0
DEGREES OF FREEDOM       10
OVERALL F             264.7         P VALUE      0.0000
ADJUSTED R SQUARED    0.9888
R SQUARED             0.9925
RESID. MEAN SQUARE    9.175E-06
```

Table C-58. Box-Level ANOVA Table for α: Six Regressors

```
STEPWISE ANALYSIS OF VARIANCE OF ALPHA

             INDIVIDUAL    CUM    CUMULATIVE    CUMULATIVE    ADJUSTED
SOURCE          SS         DF        SS            MS        R-SQUARED

CONSTANT     42.153
TWTA         1.1342E-02     1     1.1342E-02    1.1342E-02    0.9218
CMDU         8.1000E-05     2     1.1423E-02    5.7116E-03    0.9234
TLMGEN       4.2025E-04     3     1.1844E-02    3.9478E-03    0.9599
SXMTR        2.1025E-04     4     1.2054E-02    3.0134E-03    0.9797
BAT          9.0250E-05     5     1.2144E-02    2.4288E-03    0.9888
RESIDUAL     9.1750E-05    15     1.2236E-02    8.1572E-04
```

Table C-59. Predicted Values and Residuals for α: Box-Level Model with Six Regressors

RUN	α	$\hat{\alpha}$	e	RUN	α	$\hat{\alpha}$	e
1	1.608	1.6051	0.0029	9	1.601	1.6026	-0.0016
2	1.665	1.6631	0.0019	10	1.649	1.6511	-0.0021
3	1.598	1.6006	-0.0026	11	1.600	1.5981	0.0019
4	1.656	1.6586	-0.0026	12	1.649	1.6466	0.0024
5	1.596	1.5996	-0.0036	13	1.587	1.5876	-0.0006
6	1.648	1.6481	-0.0001	14	1.649	1.6456	0.0034
7	1.599	1.5951	0.0039	15	1.583	1.5831	-0.0001
8	1.644	1.6436	0.0004	16	1.638	1.6411	-0.0031
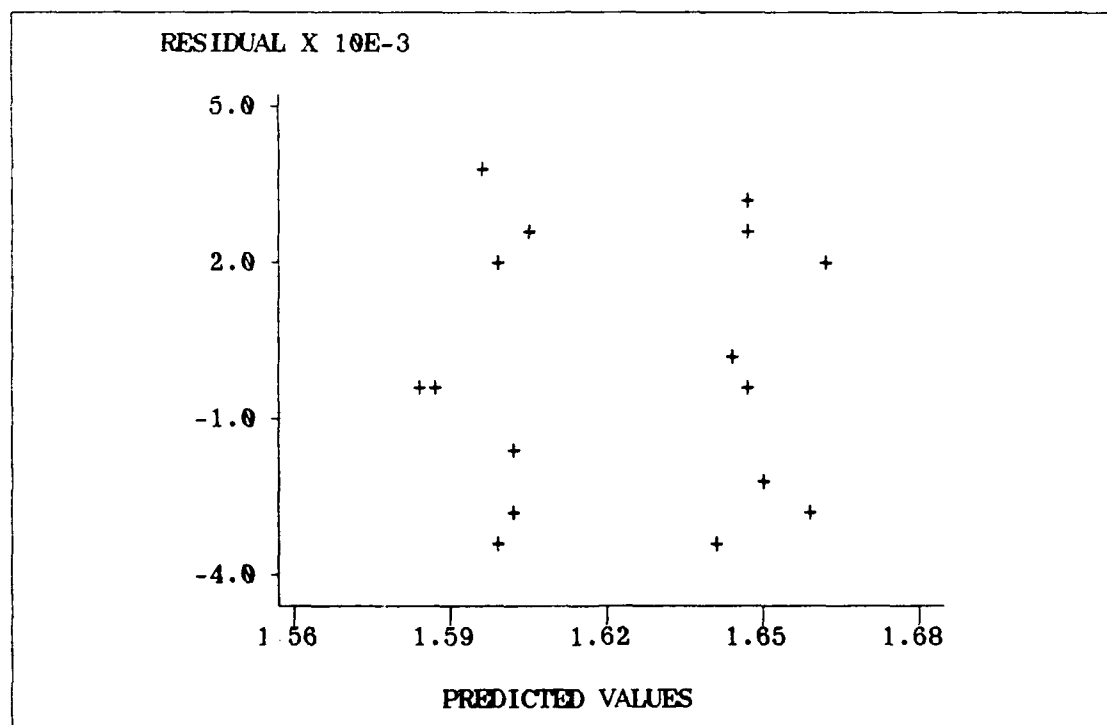
Fig. C-15. Box-Level Residual Plot for α: Six Regressors

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Table C-60. Availability Coefficient Table: Ten Regressors

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	8.5864E-01	1.0078E-05	85201.32	0.0000
TWTA	-1.1769E-02	1.0078E-05	-1167.79	0.0^00
CMDU	-5.4562E-03	1.0078E-05	-541.41	0.0000
TLMGEN	-1.5937E-03	1.0078E-05	-158.14	0.0000
SXMTR	-1.1187E-03	1.0078E-05	-111.01	0.0000
ARRAY1	-2.8125E-04	1.0078E-05	-27.91	0.0000
ITLM	-5.5625E-04	1.0078E-05	-55.20	0.0000
BAT	-4.6875E-04	1.0078E-05	-46.51	0.0000
TC	1.3125E-04	1.0078E-05	13.02	0.0000
TT	1.8750E-05	1.0078E-05	1.86	0.1219
TS	1.8750E-05	1.0078E-05	1.86	0.1219

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF AVAILABILITY

CASES INCLUDED   16   MISSING CASES   0
DEGREES OF FREEDOM   5
OVERALL F   1.700E+05   P VALUE   0.0000
ADJUSTED R SQUARED   1.0000
R SQUARED   1.0000
RESID. MEAN SQUARE   1.625E-09

Table C-61. Availability ANOVA Table: Ten Regressors

STEPWISE ANALYSIS OF VARIANCE OF AVAILABILITY

SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	11.796				
TWTA	2.2161E-03	1	2.2161E-03	2.2161E-03	0.7879
CMDU	4.7633E-04	2	2.6924E-03	1.3462E-03	0.9705
TLMGEN	4.0641E-05	3	2.7330E-03	9.1101E-04	0.9864
SXMTR	2.0026E-05	4	2.7531E-03	6.8826E-04	0.9951
ARRAY1	1.2656E-06	5	2.7543E-03	5.5086E-04	0.9952
ITLM	4.9506E-06	6	2.7593E-03	4.5988E-04	0.9977
BAT	3.5156E-06	7	2.7628E-03	3.9468E-04	0.9998
TC	2.7562E-07	8	2.7631E-03	3.4538E-04	1.0000
TT	5.6250E-09	9	2.7631E-03	3.0701E-04	1.0000
TS	5.6250E-09	10	2.7631E-03	2.7631E-04	1.0000
RESIDUAL	8.1250E-09	15	2.7631E-03	1.8421E-04	

Table C-62.   Availability Coefficient Table: Four Regressors

```
┌──────────────────────────────────────────────────────────────────────┐
│                                                                        │
│   UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF AVAILABILITY           │
│                                                                        │
│   PREDICTOR                                                            │
│   VARIABLES      COEFFICIENT     STD ERROR      STUDENT'S T      P      │
│                                                                        │
│   CONSTANT       8.5864E-01      2.3869E-04      3597.38      0.0000    │
│   TWTA          -1.1769E-02      2.3869E-04       -49.31      0.0000    │
│   CMDU          -5.4562E-03      2.3869E-04       -22.86      0.0000    │
│   TLMGEN        -1.5937E-03      2.3869E-04        -6.68      0.0000    │
│   SXMTR         -1.1187E-03      2.3869E-04        -4.69      0.0007    │
│                                                                        │
│   CASES INCLUDED          16         MISSING CASES     0               │
│   DEGREES OF FREEDOM      11                                           │
│   OVERALL F            755.1         P VALUE      0.0000                │
│   ADJUSTED R SQUARED   0.9951                                          │
│   R SQUARED            0.9964                                          │
│   RESID. MEAN SQUARE   9.115E-07                                       │
│                                                                        │
└──────────────────────────────────────────────────────────────────────┘
```

Table C-63.   Availability ANOVA Table: Four Regressors

	STEPWISE ANALYSIS OF VARIANCE OF AVAILABILITY				
SOURCE	INDIVIDUAL SS	CUM DF	CUMULATIVE SS	CUMULATIVE MS	ADJUSTED R-SQUARED
CONSTANT	11.796				
TWTA	2.2161E-03	1	2.2161E-03	2.2161E-03	0.7879
CMDU	4.7633E-04	2	2.6924E-03	1.3462E-03	0.9705
TLMGEN	4.0641E-05	3	2.7330E-03	9.1101E-04	0.9864
SXMTR	2.0026E-05	4	2.7531E-03	6.8826E-04	0.9951
RESIDUAL	1.0027E-05	15	2.7631E-03	1.8421E-04	

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Table C-64. Predicted Values and Residuals for Availability: Four Regressors

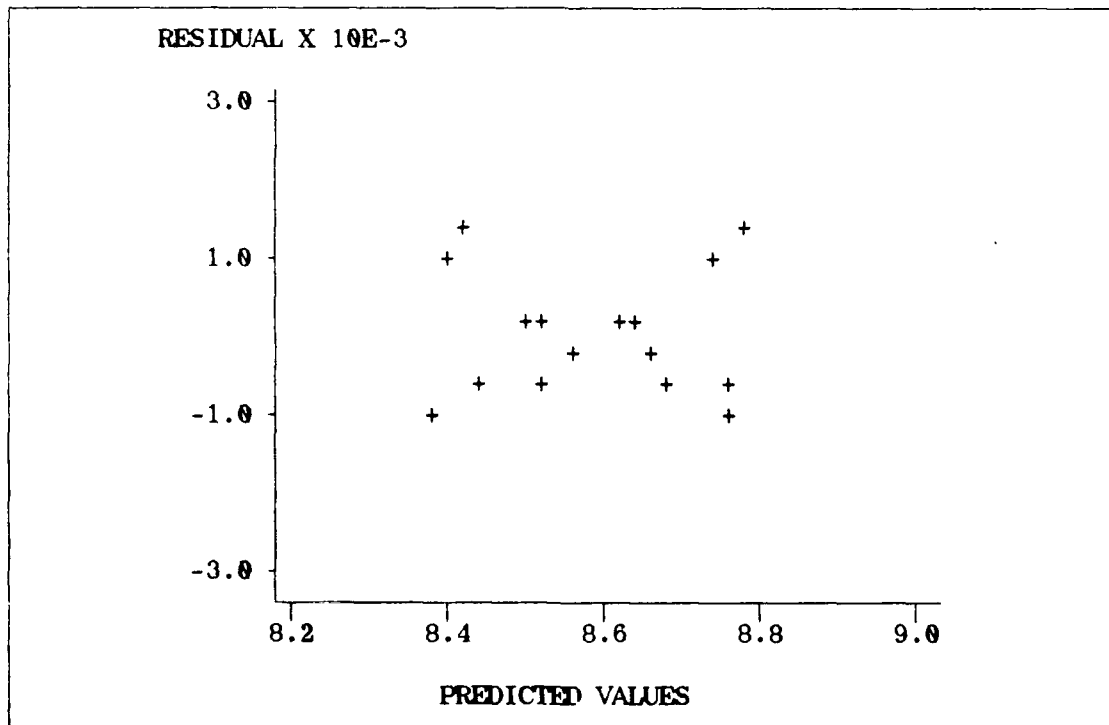| RUN	A	A	e	RUN	A	A	e
1	0.8801	0.8786	0.0015	9	0.8757	0.8763	-0.0006
2	0.8547	0.8550	-0.0003	10	0.8523	0.8528	-0.0005
3	0.8672	0.8677	-0.0005	11	0.8651	0.8654	-0.0003
4	0.8435	0.8441	-0.0006	12	0.8433	0.8419	0.0014
5	0.8742	0.8754	-0.0012	13	0.8740	0.8732	0.0008
6	0.8519	0.8519	0.0000	14	0.8499	0.8496	0.0003
7	0.8647	0.8645	0.0002	15	0.8623	0.8622	0.0001
8	0.8418	0.8409	0.0009	16	0.8376	0.8387	-0.0011

Fig. C-16. Availability Residual Plot: Four Regressors

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Vita

Captain James R. Wolf ████████████████████████████████████ ████████████████████████████████████, in 1977 and attended the University of Washington, from which he received the degree of Bachelor of Science in Aeronautics and Astronautics in June 1984. Upon graduation, he attended USAF Officer Training School and received his commission. He was assigned to USAF Space Division (AFSC), Los Angeles AFB, where he served as orbital operations engineer for the International Satellite Communications System Program Office and, later, as orbital operations manager for the Defense Satellite Communications System Program Office. During his time in Los Angeles, he attended Chapman College and received the degree of Master of Business Administration in May 1988. He entered the School of Engineering, Air Force Institute of Technology, in June 1988.

REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS

2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release; distribution unlimited

4 PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GSO/ENS/89D-17	5 MONITORING ORGANIZATION REPORT NUMBER(S)

6a NAME OF PERFORMING ORGANIZATION School of Engineering	6b OFFICE SYMBOL (If applicable) AFIT/ENS	7a NAME OF MONITORING ORGANIZATION

6c ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433-6583	7b ADDRESS (City, State, and ZIP Code)

8a NAME OF FUNDING/SPONSORING ORGANIZATION	8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11 TITLE (Include Security Classification)
SENSITIVITY OF SPACE SYSTEMS AVAILABILITY PREDICTIONS TO UNDERLYING COMPONENT RELIABILITY ESTIMATES

12 PERSONAL AUTHOR(S)
James R. Wolf, B.S., M.B.A., Capt, USAF

13a TYPE OF REPORT MS Thesis	13b TIME COVERED FROM _____ TO _____	14 DATE OF REPORT (Year, Month, Day) 1989 December	15 PAGE COUNT 190

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Availability Spacecraft Components
22	02		Reliability Spacecraft
13	08		

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Thesis Advisor: Kenneth W. Bauer, Major, USAF
                  Asst Professor
                  Department of Operational Sciences

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☑ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a NAME OF RESPONSIBLE INDIVIDUAL Kenneth W. Bauer, Major, USAF	22b TELEPHONE (Include Area Code) (513) 255-3362	22c OFFICE SYMBOL ENS

Space system availability prediction is the process of estimating
the likelihood that a space system will be available to perform its
assigned mission, as a function of time. The ability to make these
predictions accurately is fundamental to the efficient employment of Air
Force resources.

Availability prediction is based on the estimated reliability of
individual spacecraft and the components of which they are comprised.
This study made use of response surface methodology to determine the
sensitivity of the system availability prediction to the estimated
reliabilities of individual spacecraft components.

The study was conducted in two steps. First a coarse screening was
conducted to identify components which significantly influenced the
parameters of a best-fit Weibull approximation to the spacecraft
reliability function. Then the Weibull parameters and the availability
prediction itself were regressed against the reliabilities of the
critical components and the results were used to quantify the effects of
uncertainty in the reliability estimates.

For the spacecraft and mission models investigated, the screening
technique was extremely successful, identifying 5 of 100 components at
the box level as critical to the spacecraft reliability function.
Availability, however, was found to be relatively insensitive to
component reliability. In particular, the uncertainty failed to account
for the fact that observed space system availability usually far exceeds
the prediction. This may be due to overly-conservative factors in the
reliability analysis such as duty cycle and stand-by redundancy
correction factors, or it may be that uncertainty in the individual
component reliability estimates is signifcantly greater than was assumed
in the study. Further research is required to resolve this issue.

To the extent that the spacecraft reliability function can be
trusted, the response surface methodology employed here provides a very
useful way to quantify the benefits that might be received either by
improving the reliability of critical components or by reducing the
uncertainty in their reliability estimates.