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# A Method for Forecasting Repair and Replacement Needs for Naval Aircraft

## Phase II

R. C. DeLozier
V. K. Wilkinson

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# A METHOD FOR FORECASTING REPAIR AND REPLACEMENT NEEDS FOR NAVAL AIRCRAFT

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R. C. DeLozier
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# A METHOD FOR FORECASTING REPAIR AND REPLACEMENT NEEDS FOR NAVAL AIRCRAFT

## PHASE II

R. C. DeLozier* V. K. Wilkinson†

## ABSTRACT

This report describes the Phase II work performed on the development of repairs and replacements forecasting algorithms for Naval Aviation Logistics Center support. This new methodology is intended to improve the confidence level between actual and predicted spare parts requirements.

Phase II refined the bivariate regression analysis, developed in the Phase I demonstration effort, and expanded the analyses to the multivariable level. This method assumes that the various steps along the parts' supply line that are required to support the Navy under various operations can be modeled based on historical data, or educated assumptions can be input where data are unavailable or inadequate. To demonstrate the feasibility of the method, the P-3 aircraft was selected, and four recent years of maintenance data were studied. The data covered system and parts replacements and other maintenance actions. Two P-3 component data were examined in search of correlations that might exist between various parameters (e.g., flight-hours and time).

The results of this phase of the study show that a methodology in which a systematic analysis of historical data coupled with input from maintenance experts results in improved predictive ability. The improvement in estimated needs for spare parts vs actual needs can produce significant cost

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savings in logistic costs and greater effectiveness through increased readiness. Also included are estimates of 5 years of replacement needs projected for two selected components. The results of the study, along with recommendations for the next phase of the effort, are presented

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# 1. INTRODUCTION

The Naval Aviation Logistics Center (NALC) presently has a need for an improved predictive methodology capable of modeling multiple variables for projecting the number of failures, repairs, and replacements in naval aircraft and ground support equipment. This report addresses the Phase II effort to develop a forecasting methodology that will improve the confidence level between predicted and observed values for various logistics elements. The development of this methodology attempts also to be compatible with all naval aviation weapons systems at all maintenance sites.

## 1.1 Background and Purpose

In the mid-1970s the Navy adopted Reliability-Centered Maintenance (RCM) techniques for its aircraft.[1] RCM is defined as the logical discipline for developing a preventive maintenance (PM) program that realizes the inherent reliability levels of equipment at minimum cost. However, RCM creates an environment in which future supply support allocations tend to be projected from an extrapolation of previous needs. This method is not flexible enough to predict repair requirements when there are significant changes in operational requirements (e.g., mobilization).

A General Accounting Office (GAO) report[2] issued in November 1984 addressed the Air Force methodology for forecasting aircraft spare parts requirements: "the Air Force forecasts its aircraft spare parts requirements by calculating a ratio of future flying hours to past flying hours for the aircraft using a specific part and then applying this

ratio to the historical demand for the part." The GAO concluded that this technique resulted in erroneous estimates principally because the technique was not administered and executed properly. Specifically, the GAO identified (1) inaccurate data correlating specific parts to specific aircraft types, (2) failure to base projections on the many combinations of aircraft that employ the part, and (3) failure to incorporate the influence of lengthy procurement times into the future flying-hours estimate.

Significantly, the GAO did not take issue with the basic "theory" (or assumption) that any change in flight-hours will cause a correlating increase or decrease in the use of spare parts. It is widely recognized that flight-hours is the most logical measure of an aircraft's lifetime in use. The linear relationship that is presumed to exist between flight-hours and failures is also widely accepted, though with little basis other than the assumption that all parts on the aircraft are characterized by constant failure rates (failures/flight-hour). This assumption is commonly believed to be valid. However, during the periods of early life and later life, parts generally exhibit rapidly changing failure rates, and the assumption does not hold. Furthermore, there may be additional or alternate factors that might compound or overshadow the time-dependent failure behavior.

For predicting expected numbers of equipment repairs and replacements, NALC requested that Oak Ridge National Laboratory (ORNL) develop a methodology that would provide a rational, justifiable, and defensible basis for projected supply support allocations. The ultimate objective is to raise the readiness of fleet weapon systems while promoting efficient planning and budgeting measures within the Naval Air Systems Command (NAVAIR). The importance of this objective is borne out by the fact that 90% of the logistics budget pertains to repairable items.

Currently, the NAVAIR Assistant Program Manager for Logistics/Logistics Manager (APML/LM) for a given aircraft or common item is responsible for obtaining and submitting logistics data for his particular assigned aircraft or common item. To aid NAVAIR and its various field activities with the management of Fleet Repairable Assets, a computerized system known as the Master Index of Repairables (MIR) was designed

and implemented. The system contains data collected from many sources and includes user-calculated (i.e., APML/LM) projections for the number of removed and repaired items per activity. These collected data and projections are combined to form a standardized management report of Repairable Assets.

Thus, there is a mechanism for handling logistical projections, but there is no recognized method for generating them. NALC desires to have a defendable methodology that would exhibit versatility in assisting managers at all work centers with their 5-year planning and budgeting.

## 1.2 Goals

ORNL proposed an approach to the development of a predictive methodology for NALC. The key elements of the proposal included (1) analyzing historic failure data from naval aircraft; (2) gathering expert opinion from all possible sources, such as line maintenance personnel, and making every effort to effectively use experience within the framework of the Naval Aviation Maintenance program; and (3) developing a correlation model. The proposal was designed to provide a demonstration of the approach in a relatively short period of time (6 months) and to submit longer-range plans for further development. Phase I[3] developed and demonstrated the concepts that are refined in Phase II, which has the following goals:

1. refining the bivariate regression analysis by improving the understanding of the data contents and verifying assumptions made during the Phase I analysis,[3]
2. expanding the regression analysis to the multivariable level (three or more) to further reduce the error between predicted and actual time-between-failure (TBF) values,
3. investigating site-specific effects (as independent variables) and other variables identified during the Phase I discussions[3] (time permitting, this information will be incorporated into the regression analyses of Steps 1 and 2), and
4. providing 5-year failure projections for the selected components.

## 1.3 Review of Literature

To gain some insight into the long-term objectives of the NALC project, the appropriate military standards (MIL-STDs) and government reports were reviewed. Two MIL-STDs, a military handbook (MIL-HDBK), and a GAO report, were of particular interest. The "bibles" for logistics work are MIL-STDs 1388-1A, Logistics Support Analysis,"[4] and 1388-2A, "DOD [Department of Defense] Requirements for a Logistics Support Analysis Record."[5]

The MIL-STD 1388-1A indicates that the NALC project would logically fall under Task 501: "to assure the achievement of specified supportability requirements, identify reasons for deviation from projects, and identify methods of correcting deficiencies and enhancing system readiness." Task 501 calls for the analysis of supportability data as they become available from standard supply maintenance and readiness reporting systems and from any special data collection programs implemented on systems or equipment. The results of the analysis should be used as an input to data record B "Item reliability (R) and maintenance (M) characteristics" of 1388-2A. The Navy's standard reference for RCM is MIL-HDBK-266 (Ref. 1).

A GAO report — AD-A147911, The Air Force Can Improve its Forecasting of Aircraft Spare Parts Requirements[2] — to the Secretary of the Air Force is also of particular interest because it outlines the problems of spare parts forecasting. Additional details of the GAO findings may be found in Sect. 1.1 of this document. Note, however, that the GAO findings identify almost identical problems with those experienced with the NALC.

DOD logistics requirements, as outlined in the above three documents, indicate that a literature review should be concentrated into three primary areas: (1) reliability analysis, (2) statistical analysis, and (3) combining (1) and (2) into reliability modeling. This report uses this recommendation; the remaining elements of the literature review follow this format.

### 1.3.1 Reliability analyses

For reliability definitions and basics, the analyses of P-3 component reliabilities used standard techniques, such as those referenced in Henley and Kumamoto's Reliability Engineering and Risk Assessment,[6] Handbook of Industrial Engineering,[7] and Military Standard 721-C.[8] Reliability of military weapons systems may be found in reports such as the IDA/OSD Reliability and Maintainability Study,[9] which gives the results from working groups that examined 16 individual technology areas on 8 weapons systems. These studies resulted in specific reliability and maintainability recommendations in eight areas:

1. technology-based reliability and maintainability program,
2. reliability and maintainability demonstration programs,
3. full-scale engineering development (FSED) planning and analysis,
4. reliability and maintainability standards,
5. FSED management awareness of reliability and maintainability,
6. new systems maturity,
7. collection and use of reliability and maintainability data, and
8. reliability and maintainability training.

Reliability of other types of systems may be found in a number of reports, such as the Part Failure Rate Data Book Outline for Gas Turbine and Combined Cycle Plants.[10]

### 1.3.2 Statistical analysis

Statistical analysis of the NALC data bases was done using standard statistical techniques, such as those presented in Duncan's Quality Control and Industrial Statistics[11] and Hines and Montgomery's Probability and Statistics in Engineering and Management Science.[12] The Statistical Analysis System (SAS)[13] was used for distribution analyses, linear and nonlinear model development, and verification of the personal computer analyses and modeling.

### 1.3.3 Reliability modeling

Modeling of the reliability of the P-3 components was based on reliability and statistical analyses of the NALC P-3 data base. Model

development was based primarily on task 201 (of MIL Standard 785D[14]), which has as its purpose the development of a reliability model for making numerical approximations and estimates to evaluate system, subsystem, and equipment reliability.

Most reliability models use prediction techniques similar to those reported by General Electric's R. B. Spector in his paper "Reliability Prediction Techniques for Second Generation Marine and Industrial Gas Turbines."[15] The prediction techniques are usually based on a failure mode, effect, and criticality analysis technique using generic failure rates derived from operational equipment. These types of analyses generally result in a constant failure rate or, at best, a time-dependent failure rate resulting in a Weibull-type distribution. The literature does not report any multi-regression analyses and modeling as they are used in this project.

Included in the project results are confidence limits, error analysis, and spare parts requirements. These compare favorably with published data, such as that in Beers' Introduction to the Theory of Error,[16] Pascal's paper "Reliability Confidence Levels and OC Curves,"[17] Kacecioglu and Lamarre's paper "Reliability Confidence Levels and OC Curves,"[17] Kacecioglu and Lamarre's paper "Mechanical Reliability Confidence Limits,"[18] the National Aeronautics and Space Administration's Technical Support Package: Computation of Spare Parts Requirements,[19] and Mahmoud's "Accuracy in Forecasting: A Survey".[20]

Based on this phase of the NALC work, future phases should include some availability analysis such as that demonstrated in Parsley's Availability Analysis Program,[21] as well as some risk analysis, such as those in Covello and Mumpower's "Risk Analysis and Risk Management: An Historical Perspective,"[22] and Pate-Cornell and Neu's "Warning Systems and Defense Policy: A Reliability Model for the Command and Control of U.S. Nuclear Forces."[23]

# 2. TASK APPROACH

The approach to performing the task was based on discussions among ORNL engineers with related experience. This chapter describes that approach and the constraints that were observed in this study.

## 2.1 Scope

For the results of the pilot effort to be of more immediate usefulness to NALC, it was proposed that ORNL limit the Phase II scope to a select list of aircraft components. It was suggested that NALC compile a list of aircraft Work Codes (WUCs) according to some measure of importance. Consequently, the two WUCs (five-digit level) chosen to be investigated (Table 1) were selected because of their adverse impact on the level of fleet readiness primarily because of unscheduled maintenance. The investigation was limited to P-3C type/model aircraft. The particular time period for data extended from January 1979 to December 1982.

Table 1. P-3 work unit codes identified for investigation

| WUC | Nomenclature |
|---|---|
| 65341 | IFF receiver transmitter |
| 73668 | 319 and 319A tape transport |

## 2.2 General Approach

The primary data sets received from NALC were generated using the Analytical Maintenance Program Analysis Support system (AMPAS). Specifically, the failure data, which were transmitted in a report No. 520* format, were sorted by organization code, bureau number, and job

*For samples of both the 520 and 710 reports see the Phase I report; Ref. 3.

control number date. Records involving the specific WUCs specified for Phase II analyses were culled and tabulated.

These records were then processed (for individual WUCs) to assess the time between verified failures on a given aircraft (i.e., bureau number) in a given squadron (i.e., organizational code). This TBF parameter served as the vehicle for attempted correlation with other independent parameters, including the various operational quantities that are collected on the AMPAS Report No. 710* format (flight activity, inventory, and readiness).

The failure of these WUCs did not appear to correlate with any single parameter or set of parameters. However, flight-hours were singled out for further investigation. Originally, this additional research was intended to be a modified-Delphi information gathering effort. However, time constraints permitted only limited discussions with personnel who were knowledgeable about the WUCs and their failure characteristics. The purpose of the discussions was to uncover information about other (perhaps unknown) parameters to which TBF might be correlated. If quantitative data were indeed available on these variables and could be correlated, then an algorithm could be developed to be used as a projection or forecasting tool.

## 2.3 Data Acquisition

The computer program developed during Phase I[3] was modified during this Phase II effort to include the capability of doing multivariable regression analysis. Additional modifications were made to the programs developed in the Phase I effort to include expanded data base management capabilities and more-varied analysis options, such as rapidly evaluating other statistical parameters. Phase II also included extensive SAS analyses to verify the IBM personal computer analysis of the P-3 components. A remote job entry was established during Phase II to allow direct access to the AMPAS and Naval Aviation Logistic Data Analysis

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*For samples of both the 520 and 710 reports see the Phase I report; Ref. 3.

system at Harry Diamond Laboratory. This connection, when fully implemented, will provide for quick turnaround and improved data analysis capability.

## 2.4 Data Analyses and Failure Projection

After the data for the two WUCs of interest had been obtained from the NALC data base, the procedure for analyses and failure projections (Fig. 1), was used to estimate component failure and replacement requirements. The first step in the process is to analyze, sort, and correct the data. Experience with these particular components indicated that 25 to 30% of the data had to be corrected or updated. The analyses, sorting, and correcting process is an iterative process in which the time between failures is estimated and then analyzed to verify that

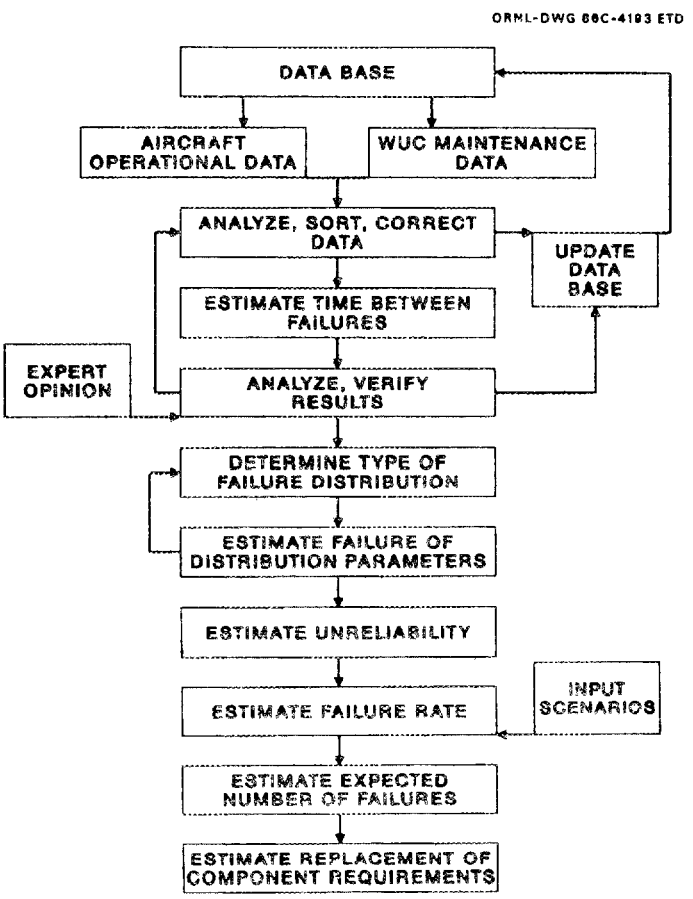


Fig. 1. Replacement component methodology.

the results are reasonable; this task frequently required that the input data had to be screened more carefully and obvious errors deleted or corrected where possible. After the iterative process was completed, TBF was estimated by regression analysis.

As in Phase I, the regression analysis determined TBF as a function of several independent variables (e.g., time, flight-hours, landings, and takeoff). The regression analysis identified possible correlatable independent variables for the entire P-3 fleet. An analysis of failures at each P-3 organization was made to identify those squadrons that showed either very good or very bad maintenance histories. Included in the analysis was the use of expert opinion, primarily from the Patuxent River P-3 maintenance squadron.

After the regression was completed, the type of failure distribution was estimated by examining the frequency distributions of the individual parameters (TBF, flight-hours, and calendar time). This frequency distribution analysis determines the type of distribution (e.g., exponential, Normal, Weibull, or other standard reliability distributions). Given the type of failure distribution, the probability density function parameters (e.g., sigma, mu, beta, or lambda) were estimated. Once the type of failure distribution was established, unreliability was estimated. From that estimate the appropriate failure rate for the component was established. With an estimate of failure rate, the expected number of failures over a given time or number of flight-hours was projected. The last step in this analysis was to estimate the replacement components required for the number of failures projected. However, was not possible to accomplish this last step because of a lack of depot-level data, which were completely missing from the NALC data base for the components of interest. Thus, because the depot level is the level at which the component is ultimately either repaired or replaced, it was not possible to determine how many failures resulted in a component replacement.

# 3. RESULTS

A goal of the Phase II effort was to demonstrate the proposed methodology and approach through examples. The results presented are some indication of the potential improvement in the forecasting of maintenance actions using the method described in Chap. 2. The concept of correlation has been fully covered in the Phase I report.[3] Note that when the results are reviewed, the coefficients of correlation discussed are based on regression analysis using multiple-independent variables. Some of the following discussion is fairly technical, and in an attempt to be as clear as possible, some terms are described from a layman's viewpoint. For a further definition of terms, please see Appendix A and the discussion of correlation in the Phase I report.

## 3.1 Regression Results

NALC requested that two P-3 components (IFF receiver transmitter and 319 tape transport) be analyzed and a projection of replacement parts made for a 5-year period (1983–1987). The results of a multiple-regression analysis are shown in Table 2. Note that no strong correlations exist with any of the independent variables investigated. As a result, the failure information yielded little insight into logistics problems other than the fact that the distribution is highly skewed with a large standard deviation.

Regression analysis was also run on individual squadrons to identify any site-dependent variables. Tables 3 and 4 summarize the results of that analysis. The IFF squadron failure analysis (Table 3), when compared with the overall average, indicates no appreciable differences between squadrons. On the other hand, the P-3 squadron level analysis of the tape transport (Table 4) does indicate some differences among squadrons. For example, squadron AT2 with a mean-time-between-failure (MTBF) of 80 d and squadron PX5 with a MTBF of 127 d both have very low average TBFs when compared with the 224-d MTBF for all squadrons. Also, there are two squadrons, AT3 and P71, that have very high average TBFs of 773 and 490 d, respectively, when compared with the MTBF of all squadrons.

Table 2. Regression correlation coefficients[a]

| Component | Variables (%) ($R^2$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Calendar time | Sorties | Flight-hours | Landings | Best 2-variable | Best 3-variable | Best 4-variable |
| IFF | 4.11 | 0.12 | 0.41 | 0.00 | 4.57 | 4.64 | 4.84 |
| Tape transport | 2.04 | 0.68 | 0.52 | 0.40 | 2.61 | 2.97 | 3.09 |

[a]September 12, 1985, data.

Table 3. P-3 IFF failure analyses at the organizational level[a]

| Squadron | Number of observations | Best single variable correlation | Multivariable correlation (%) | Mean TBF (d) | SD-TBF (d) | Mean sorties | Mean flight-hours |
|---|---|---|---|---|---|---|---|
| All squadrons | 1083 | Time | 4.6 | 258 | 268 | 106 | 518 |
| AT2 | 82 | Landings | 35.2 | 216 | 225 | 100 | 472 |
| AT3 | 61 | Time | 31.5 | 302 | 295 | 116 | 582 |
| AT4 | 54 | Sorties | 22.8 | 254 | 258 | 100 | 524 |
| AT5 | 64 | Time | 38.6 | 271 | 292 | 102 | 522 |
| AT6 | 92 | Landings | 17.4 | 263 | 290 | 153 | 538 |
| AU1 | 71 | Time | 10.7 | 225 | 220 | 104 | 547 |
| AU3 | 76 | Time | 11.8 | 292 | 284 | 100 | 568 |
| AU6 | 51 | Time | 23.0 | 259 | 236 | 104 | 521 |
| A21 | 24 | Sorties | 71.6 | 317 | 385 | 60 | 194 |
| PW2 | 32 | Landings | 61.9 | 276 | 293 | 114 | 577 |
| PW3 | 41 | Time | 33.5 | 278 | 239 | 111 | 611 |
| PW4 | 136 | Time | 30.7 | 280 | 246 | 95 | 367 |
| PW5 | 81 | Landings | 10.0 | 233 | 261 | 89 | 481 |
| PX5 | 40 | Sortie time | 62.1 | 291 | 235 | 101 | 509 |
| P71 | 59 | Time | 39.5 | 292 | 311 | 103 | 503 |
| P72 | 64 | Time | 34.6 | 226 | 261 | 104 | 586 |
| P73 | 55 | Sortie time | 9.9 | 248 | 263 | 101 | 551 |

[a]August 13, 1985, data.

Table 4. P-3 tape transport analyses at the organizational level[a]

| Squadron | Number of observations | Best single variable correlation | Multivariable correlation (%) | Mean TBF (d) | SD-TBF (d) | Mean sorties | Mean flight-hours |
|---|---|---|---|---|---|---|---|
| All squadrons | 2314 | Time | 2.6 | 224 | 350 | 103 | 518 |
| AT2 | 151 | Time | 10.2 | 80 | 156 | 102 | 491 |
| AT3 | 10 | Time | 87.4 | 773 | 493 | 113 | 546 |
| AT4 | 109 | Time | 44.0 | 281 | 395 | 97 | 513 |
| AT5 | 124 | Time | 62.8 | 277 | 401 | 104 | 533 |
| AT6 | 116 | Time | 49.8 | 160 | 265 | 147 | 504 |
| AU1 | 131 | Time | 33.7 | 188 | 319 | 111 | 633 |
| AU3 | 155 | Time | 27.6 | 180 | 282 | 104 | 602 |
| AU6 | 96 | Time | 40.6 | 207 | 340 | 98 | 473 |
| A21 | 30 | Time | 93.8 | 415 | 454 | 49 | 168 |
| PW2 | 16 | Time | 87.8 | 297 | 272 | 123 | 584 |
| PW3 | 10 | Landings | 97.2 | 444 | 426 | 111 | 599 |
| PW4 | 826 | Time | 50.6 | 245 | 333 | 96 | 366 |
| PW5 | 117 | Time | 29.6 | 316 | 432 | 85 | 455 |
| PX5 | 127 | Time | 12.8 | 127 | 215 | 94 | 456 |
| P71 | 14 | Time | 64.3 | 490 | 400 | 105 | 495 |
| P72 | 154 | Time | 41.5 | 265 | 396 | 101 | 543 |
| P73 | 128 | Time | 42.5 | 253 | 410 | 98 | 532 |

[a]August 15, 1985, data.

Interviews were held in an attempt to determine why these four particular squadrons had such a large variance in MTBFs compared with the total squadrons' average. However, there was no easily explainable reason for these large variances. This question should be pursued to determine if there are site-dependent effects evidenced by these data.

There are some other observations about the regression analysis:

1. Table 2 data contain some refined data correction factors that are not included in Tables 3 and 4 (note the difference in data dates), thus resulting in slightly different correlation coefficients among the three tables. However, these differences do not change the overall results.
2. The mathematics of regression computation always results in a higher regression correlation for smaller numbers of observations. This fact partly explains the higher correlation with individual squadrons.

### 3.2 Frequency Distribution Results

Unless they are condensed or reduced to a more suitable form, statistical data are often so numerous that they are virtually useless. Thus, the first step of a statistical analysis is often the construction of a frequency distribution histogram that divides the data into a small number of classes showing the number of observations in each class. These frequency distribution histograms show the symmetry, number of modes, etc., of the data. They also give a visual indication of the type (normal, Weibull, log-normal, etc.) of distribution the data appear to follow. Identification of the type of distribution is then the basis for further analyses to determine the distribution's parameters.

Figures 2–4 show examples of the component failure frequency distributions for flight-hours, TBFs, and calendar time. Note that most of these frequency distribution tables tend to follow the classic log-normal or Weibull distribution with the mode skewed to the left in all cases.

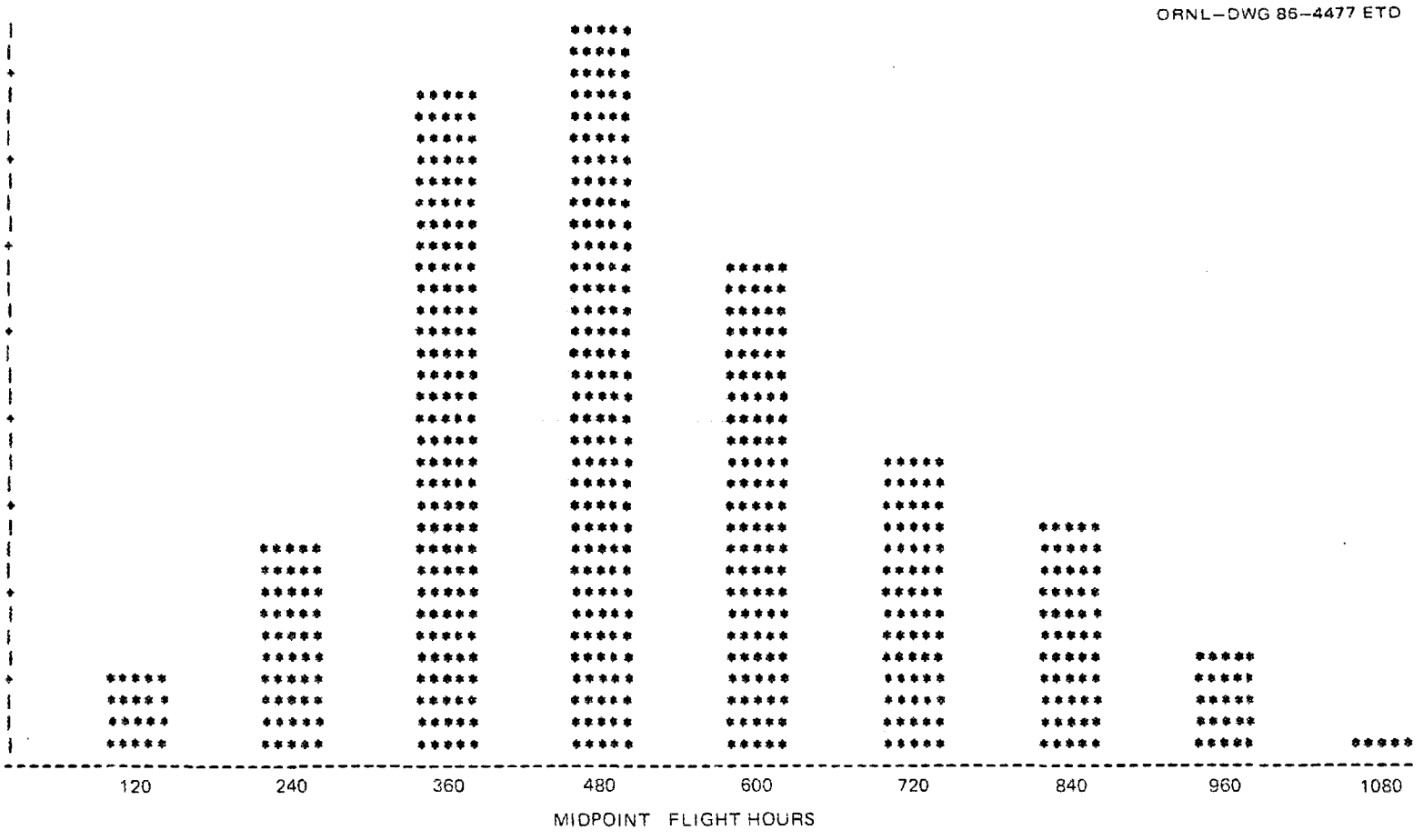


Fig. 2. IFF receiver/transmitter failure frequency distribution for flight-hours.

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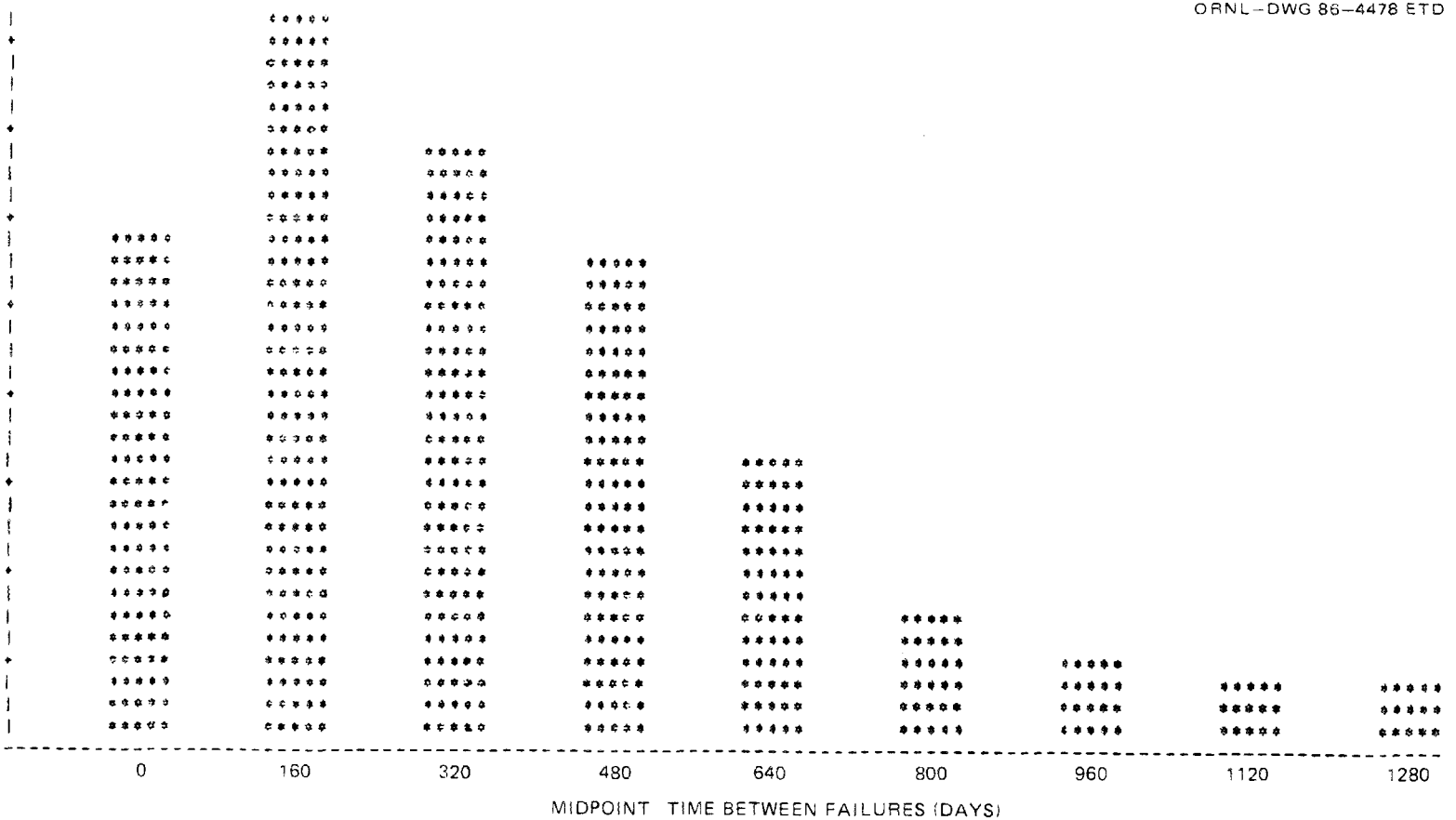


Fig. 3. IFF receiver/transmitter failure frequency distribution for TBFs.

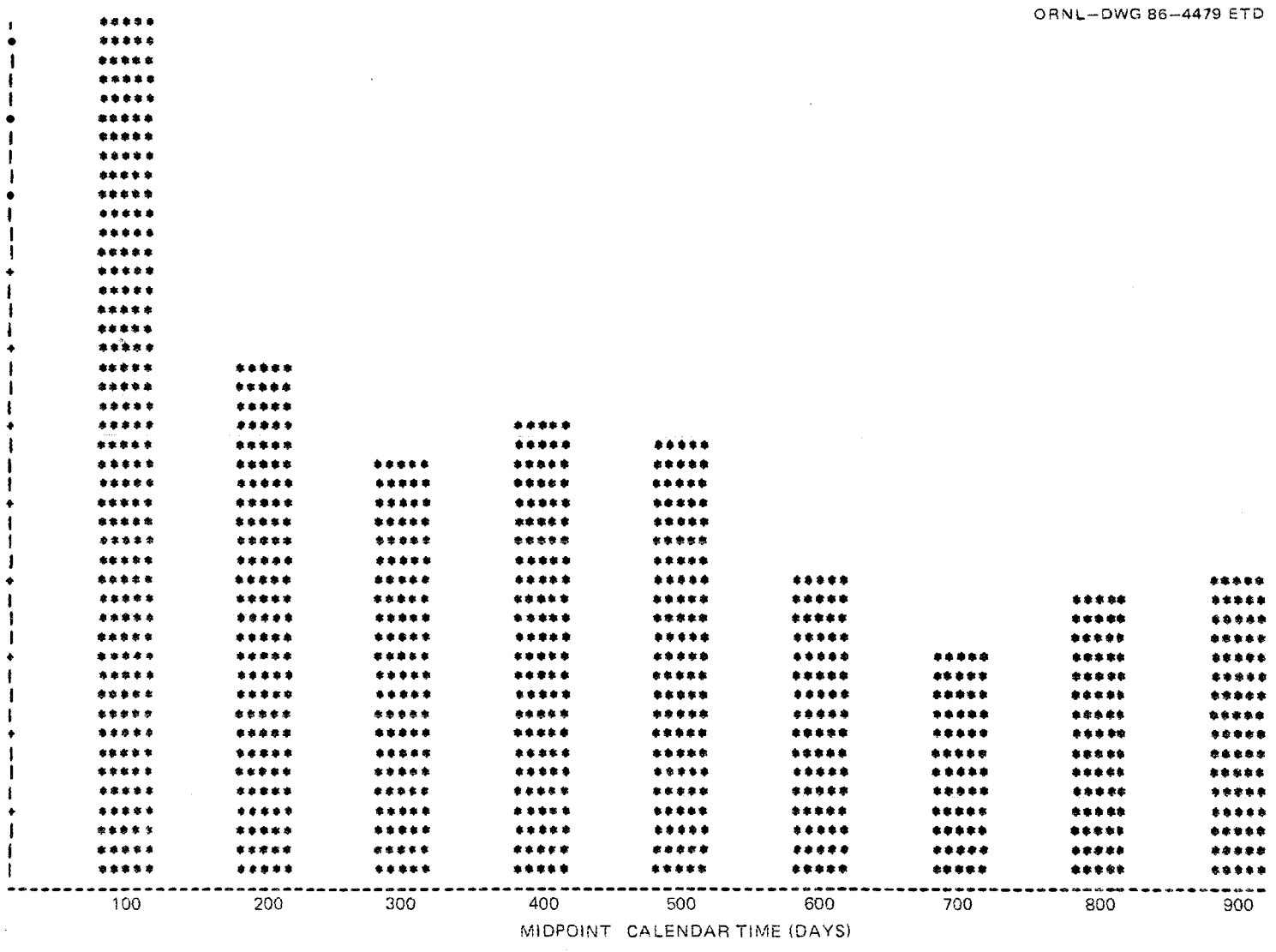


Fig. 4. Tape transport (319) failure frequency distribution for calendar time.

Note that the abscissa values of the frequency distributions represent the range of data values with that midpoint. For example, in Fig. 2 the first bar is the sum of frequency percentage from 60 to 180 h (midpoint 120 h). The second bar is the sum of the percentages in the range of 180 to 300 h. In Fig. 3 the bar with a midpoint shown as zero represents the interval of −80 to 80 days and the 160 days midpoint is the total percentages from 80 to 240 days. (The negative time results from a number of 0 day failures. In Fig. 4 the total percentage from 50 to 150 days is shown as midpoint 100 days with the second bar representing failures which occurred from 150 to 250 days.

### 3.3 Reliability Parameters Results

Tables 5-7 show the calculated (from non-linear regression analyses) failure distribution parameters for the components of interest. Note that flight hours and failure rates are all positively skewed (a measure of the deviation from symmetry about the point of central tendency — a normal distribution has zero skewness) with more than normal kurtosis (a measure of the relative occurrences at the center relative to that along the tails of the distribution — a normal distribution has zero kurtosis). Calendar time, however, shows both negative and positive skewness and a less-than-normal kurtosis, indicating a fairly flat distribution. These failure patterns can cause difficulty in projecting spare-parts needs because the maximum number of failures occurs someplace in the vicinity of 20 d and the average number of failures is ~200 d. A factor of 10 exists between the 20 and 50% probability values. This type of failure rate relationship generally indicates a design problem with the components. If the design solution is a long time in coming, the spare-parts stock-pile must supply a buffer to provide inventory for the times when the high failure rates combine statistically to reduce the stockpile at ten times the average rates.

Figures 5 and 6 show the least-squares fit of the probability density function superimposed on the frequency distribution cells. Note that both figures show the classic Weibull distribution for failure rate or TBFs with a mode at ~20 d.

Table 5. Projected IFF failure distributions[a]

| Variable | Distribution type | Distribution parameters | | Distribution characteristics | |
|---|---|---|---|---|---|
| | | $\sigma$ | $\mu/\beta$[b] | Skewness | Kurtosis |
| Calendar time | Log-normal | 0.95 | 6.10 | -0.09 | -1.16 |
| Average flight-hours | Log-normal | 0.21 | 6.10 | 0.71 | 0.40 |
| Failure rate | Weibull | 19.65 | 0.97 | 5.84 | 38.21 |

[a]Failure rate = 1/TBF.

[b]$\mu$ for a log-normal distribution and $\beta$ for a Weibull.

Table 6. Projected tape transport (319) failure distributions[a]

| Variable | Distribution type | Distribution parameters | | Distribution characteristics | |
|---|---|---|---|---|---|
| | | $\sigma$ | $\mu/\beta$[b] | Skewness | Kurtosis |
| Calendar time | Log-normal | 0.89 | 5.32 | 0.80 | -0.27 |
| Average flight-hours | Log-normal | 0.30 | 6.20 | 0.63 | -0.12 |
| Failure rate | Weibull | 18.16 | 1.05 | 4.06 | 16.64 |

[a]Failure rate = 1/TBF.

[b]$\mu$ for a log-normal distribution and $\beta$ for a Weibull.

Table 7. Projected improved transport (319A) failure distributions[a]

| Variable | Distribution type | Distribution parameters | | Distribution characteristics | |
|---|---|---|---|---|---|
| | | $\sigma$ | $\mu/\beta$[b] | Skewness | Kurtosis |
| Calendar time | Log-normal | 0.74 | 6.44 | 0.04 | -1.11 |
| Average flight-hours | Log-normal | 0.28 | 6.25 | 1.06 | 4.29 |
| Failure rate | Weibull | 41.12 | 1.21 | 4.42 | 21.14 |

[a]Failure rate = 1/TBF.

[b]$\mu$ for a log-normal distribution and $\beta$ for a Weibull.

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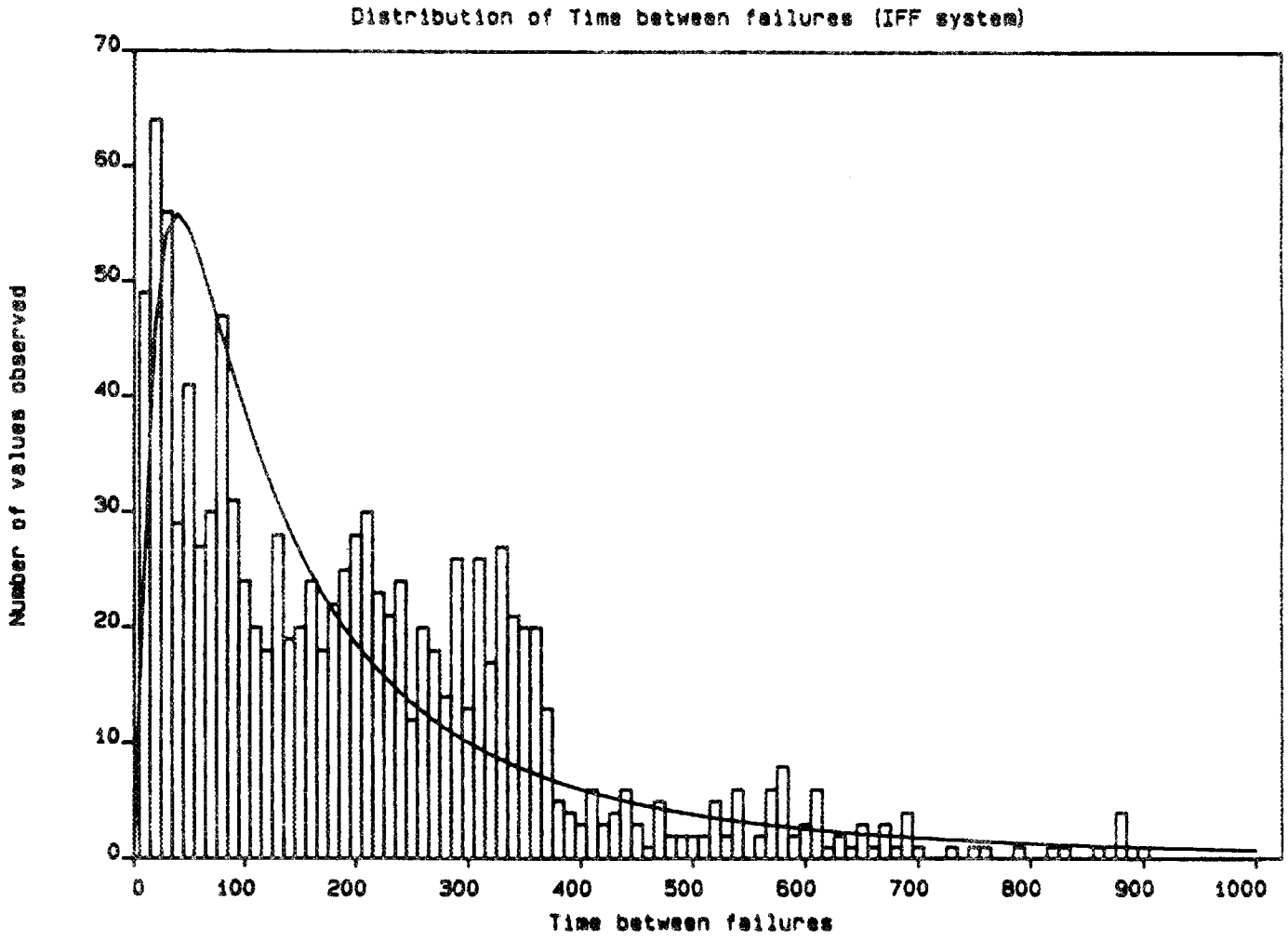


Fig. 5. Distribution of TBFs for IFF receiver/transmitter.

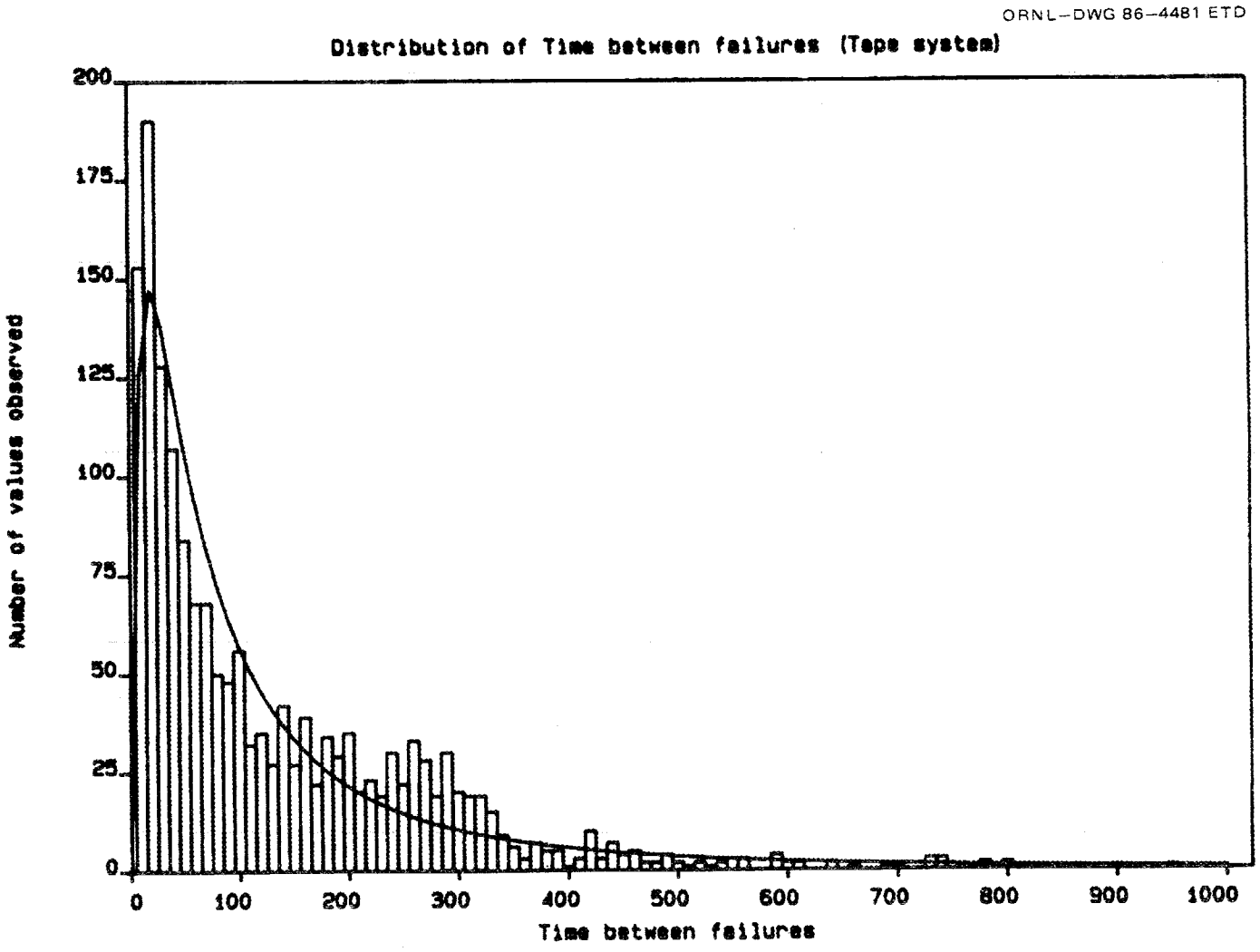


Fig. 6. Distribution of TBFs for tape transport.

## 3.4 Spares Projection

The following algorithm was developed to project spare-part replacement requirements and stockpile needs for aircraft components. This projection is based on a failure rate that can be a function of many variables. For the studies in this report, time was the only variable that had significant correlation; however, in general, this and other replacement equation parameters will be functions of several independent variables. The equation for replacement is given by

$$R_p = [1 - F_r]N_a(t)\eta[s(t) + r(v)] \ ,$$

where

$R_p$ = project replacement rate (numbers per unit time),
$F_r$ = fraction recycled,
$r(v)$ = failure rate (numbers per unit time),
$Na(t)$ = number of aircraft,
$\eta$ = number of components per aircraft,
$s(t)$ = stockpile factor,
$t$ = time dependence,
$v$ = multivariable dependence (i.e., $v = V_1, V_2, V_3$, etc.).

For the two components investigated as examples, the fraction recycled ($F_r$) could not be estimated because of the lack of depot-level data and was assumed to be zero. However, when the model is fully implemented, a value would be estimated for each component for which projections are required.

The failure rates would normally be a function of flight-hours, number of landings, etc. However, this study indicated that the tape transport and IFF demonstrated the best correlation with time. Therefore, standard reliability projection techniques were used. For ease of calculation, the failure rate was assumed to be the Weibull hazard function:

$$r(t) = \frac{\beta \ t^{\beta-1}}{\sigma^{\beta}} \ .$$

The number of aircraft is assumed to be a linear function of time, and, thus,

$$N_a(t) = N_o + \Delta N(t - t_o) ,$$

where

$t_o$ = a base year from which numbers of aircraft are known,
$N_o$ = the number of aircraft at base year,
$\Delta N$ = the number of aircraft added per unit time.

The number of P-3 aircraft reported over the 4 years is shown in Fig. 7. According to the data retrieved from the R710 report, note that the inventory is decreasing. This decrease was checked out with Navy personnel and deemed to be incorrect; data were obtained directly on the P-3 inventory to make the projections.

The term S(t) is a factor that will ensure that the number of parts will be sufficient to maintain some level of confidence that statistical fluctuations will not exhaust the stockpile between the replenishment of components in the inventory. The equation for this factor is

$$s(t) = \frac{gz}{y + 1} ,$$

where

z = one over the mode or failure rate at the mode,
y = the number of times the stockpile is restocked, and
g = a factor that relates to the confidence that the parts supply will not be exhausted.

The value for g is a function of the required confidence and also may be a function of other variables. Figures 8 and 9 show the values resulting from Monte Carlo studies. Note that the solid line in Figs. 8 and 9 is the model projection while the small triangles are a sample of the random number.

Monte Carlo simulations were used because the variables relationships in the model are too complex for analytic solutions. Monte Carlo simulation uses a computer to evaluate the model <u>numerically</u> over the

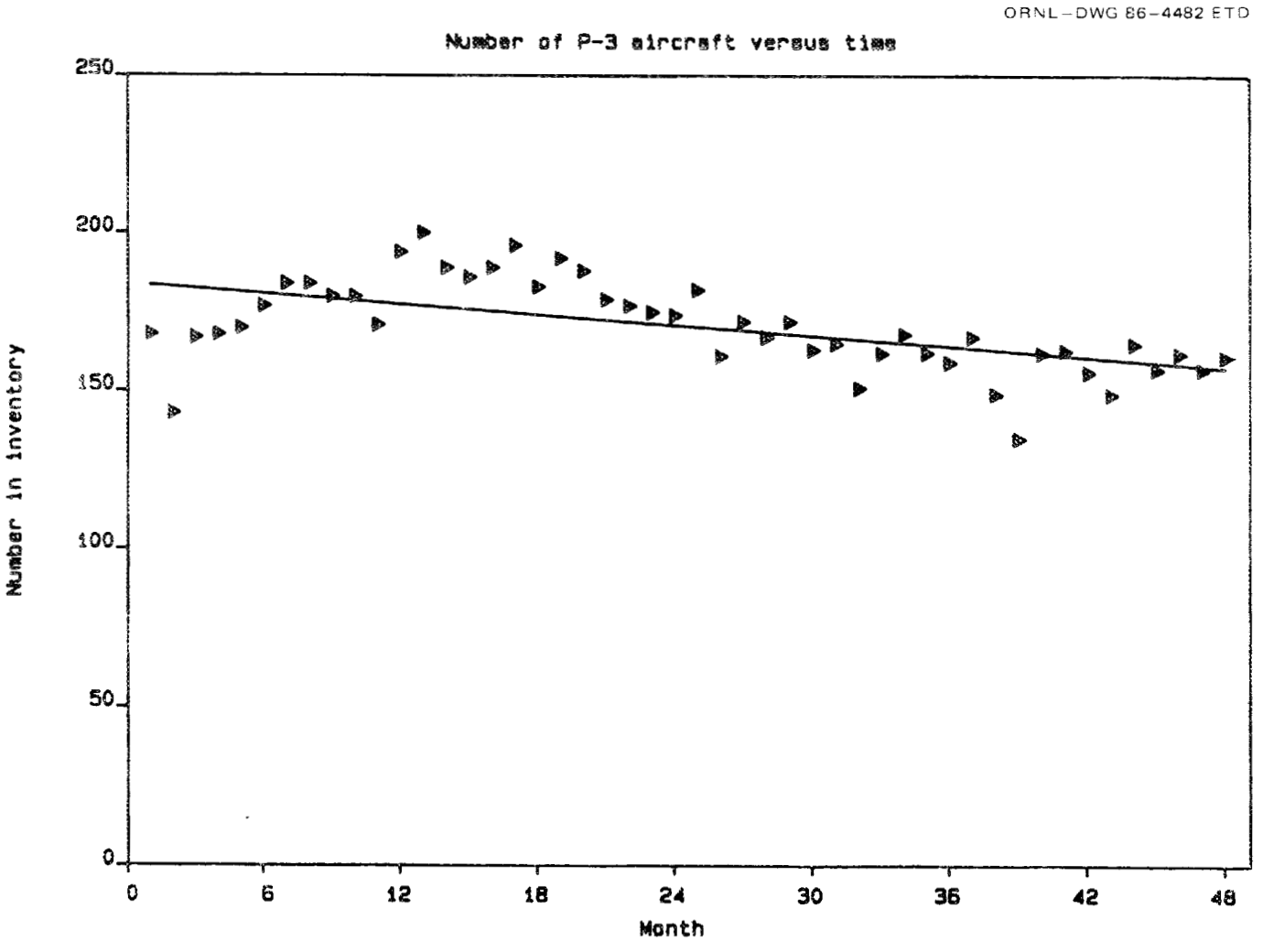


Fig. 7. Number of P-3 aircraft in inventory over 4-year period.

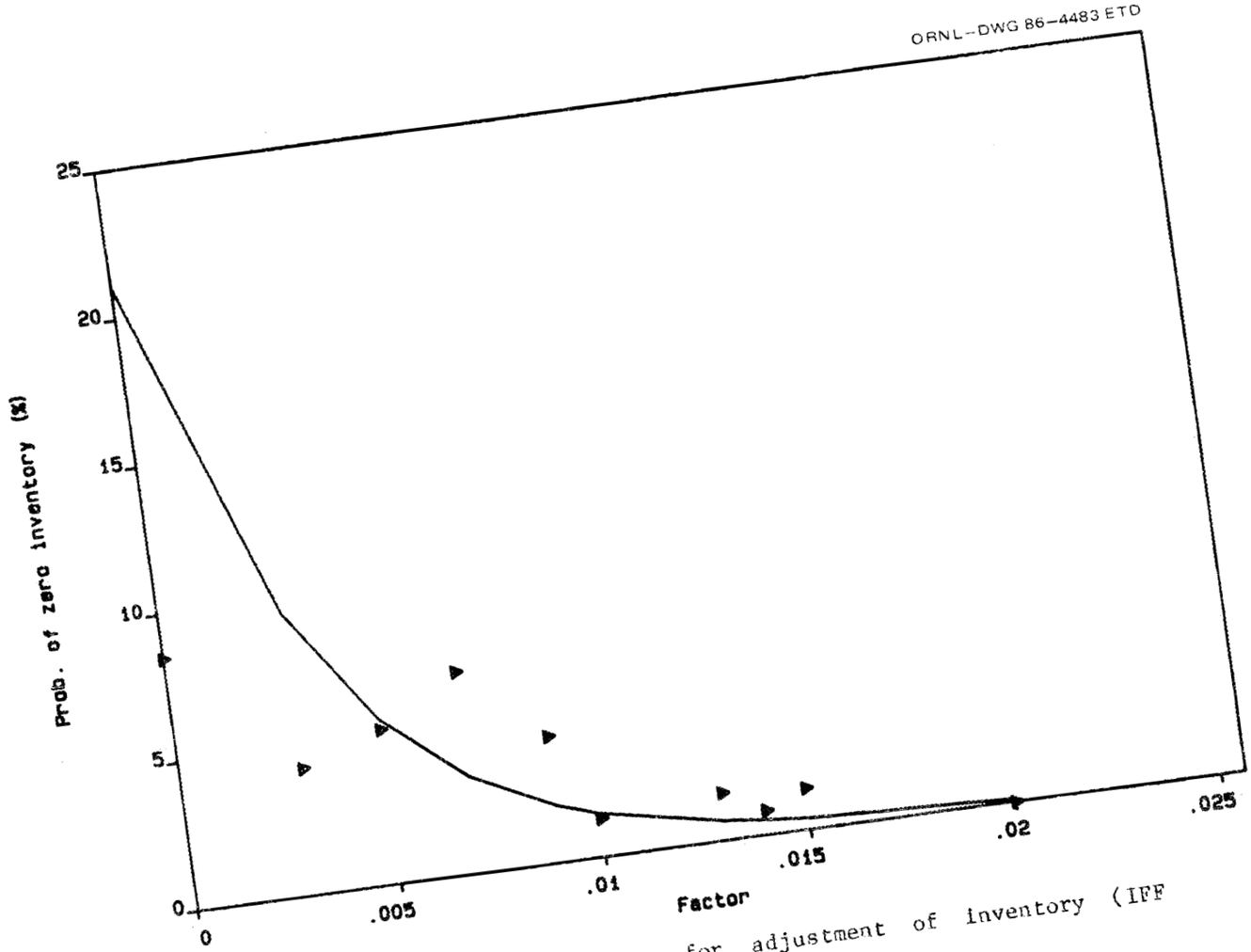


Fig. 8. Values of factor g for adjustment of inventory (IFF receiver/transmitter).

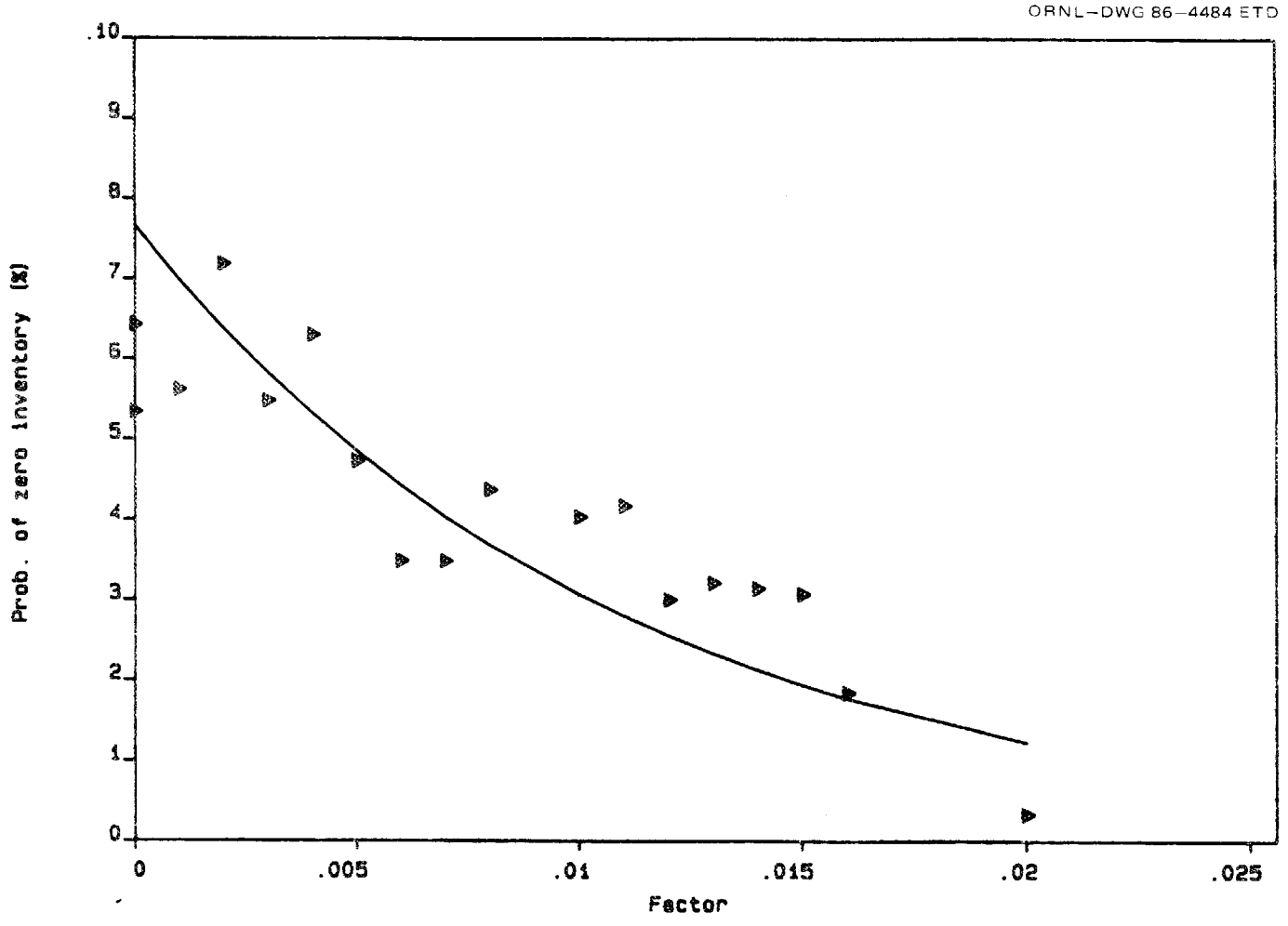


Fig. 9. Values of factor g for adjustment of inventory (tape transport 319).

time period of interest, and data are gathered to estimate the true characteristics of the model.

The Monte Carlo model was used to determine confidence intervals for the stockpile model and to project numbers of repairs at the organization (O), intermediate (I), and depot (D) levels. Figures 10 and 11 show the number of failures each month, and superimposed on this is the Weibull projection used to estimate the number of required actions at each level by multiplying the factor g times the projection line. Note that this contingency is constant with time and, therefore, contingency parts are acquired, spare parts do not continue to build up. The division of failure projection into the various maintenance levels was accomplished by studying the ratio of activities at each level over 4 years preceding the projection years. These ratios were approximately constant and were assumed to be invariant during the projection. This constant assumption should be examined further because for other aircraft and other parts it may well be a function of other variables (e.g., number of catapult launches and hours at sea).

### 3.5 Static Failure Model

To understand the effect of a wide and highly skewed failure distribution on a part inventory and purchase schedule, a model was developed to simulate the failure patterns that could occur after several years. The failures were modeled using the observed failure distribution curve for the tape transport. Each simulation was run over a 4-year period using different values for g in the inventory equation. The number of parts purchases per year was assumed to be one in the absence of any information (the number of purchases per year is an economic consideration). Each simulation results in a time history of a part usage and resultant inventory levels (Figs. 12 and 13). Note that the results go below zero during the simulation and that the ratio of the number of negative days to total days is used as an indicator of probability of zero inventory using a particular g. Figure 12 is an example inventory profile using g = 0 (i.e., no extra units are bought to ensure against zero inventory probabilities). In this example, the

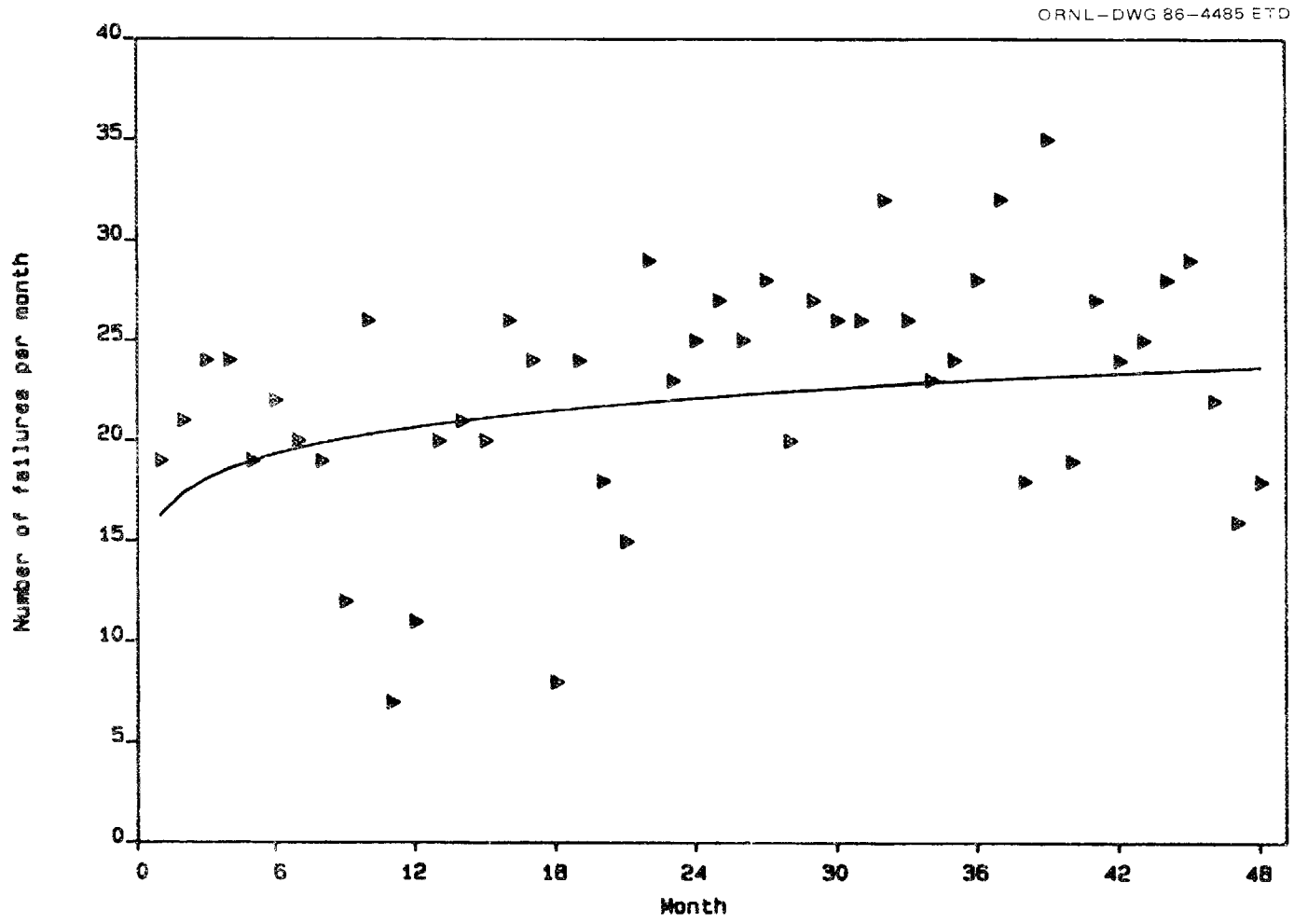


Fig. 10. Number of failures each month over 4-year period (IFF receiver/transmitter).

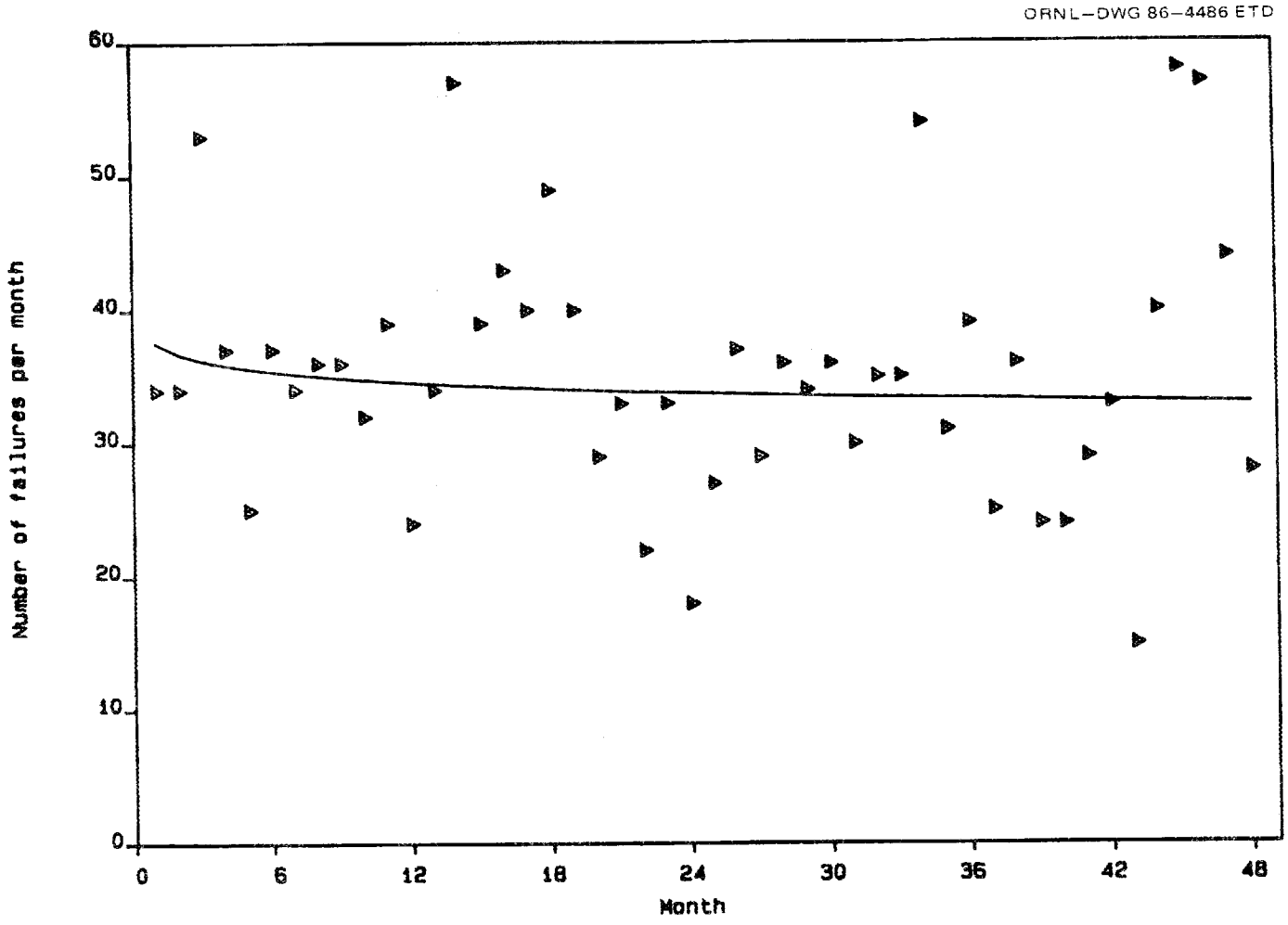


Fig. 11. Number of failures each month over 4-year period (tape transport 319).

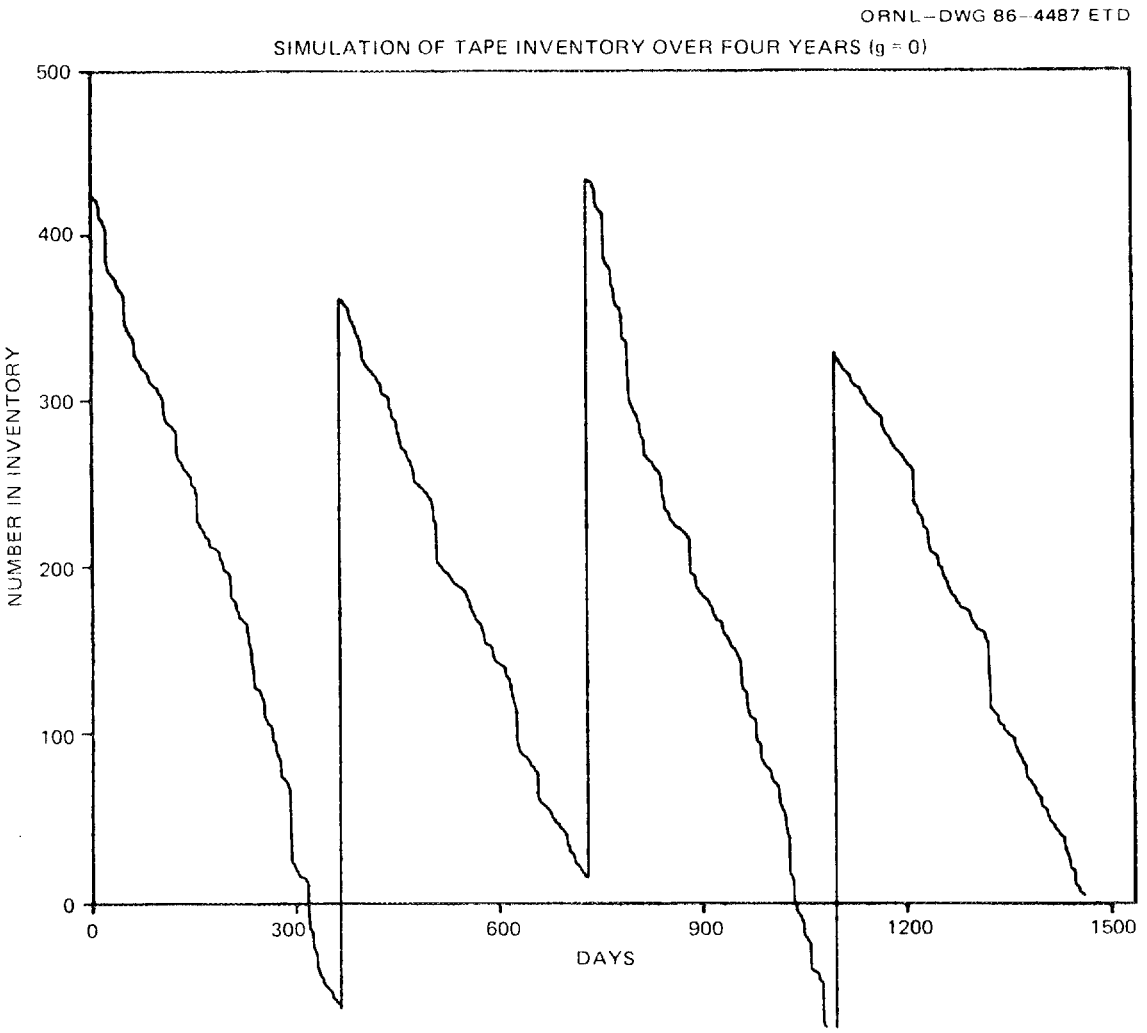


Fig. 12. Simulated 4-year history of inventory level of tape transport for g = 0.0.

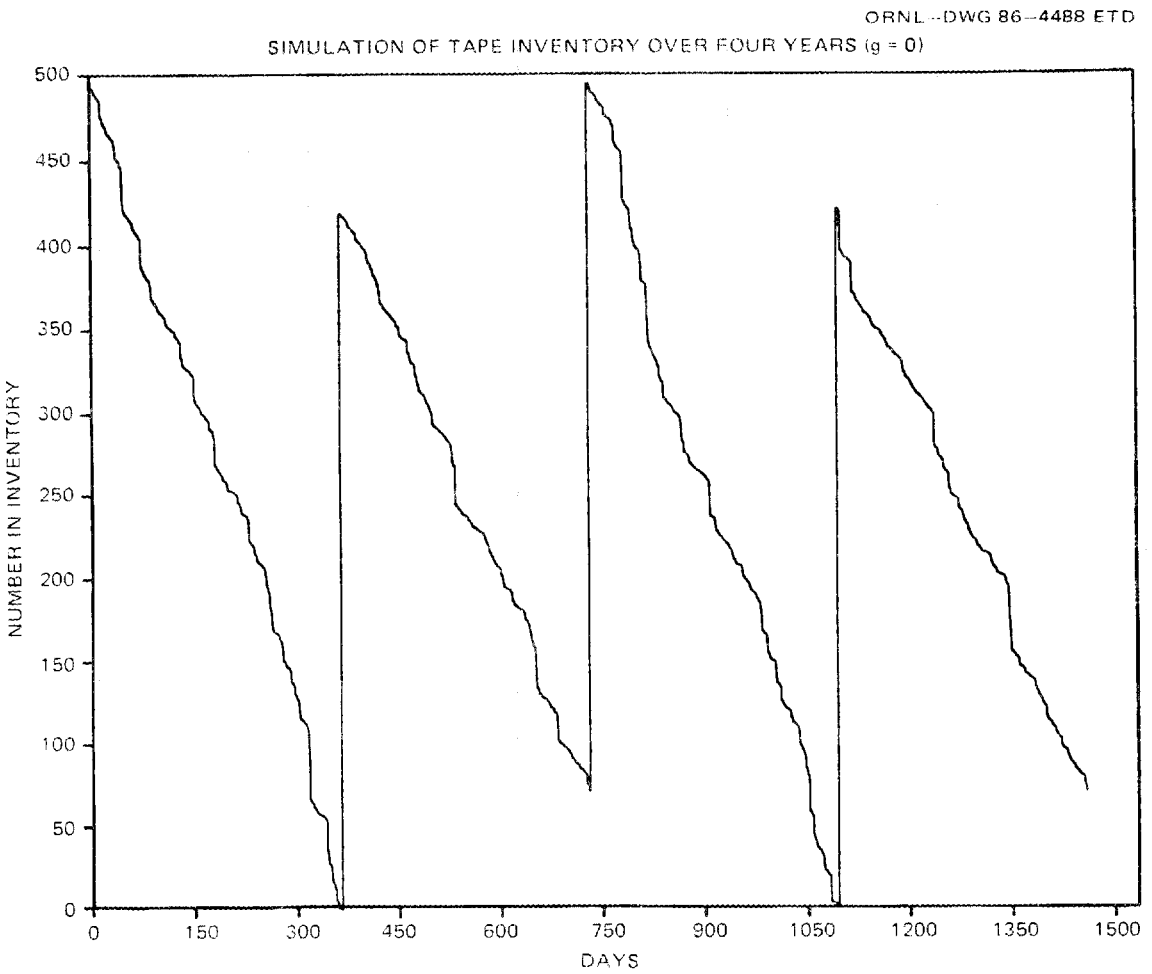


Fig. 13. Simulated 4-year history of inventory level of tape transport for g = 0.02.

inventory went negative two times in the 4-year simulation and was negative ~6% of the total time. The example shown in Fig. 15 illustrates a run using g = 0.02, corresponding to a 99.50% confidence level.

### 3.6 Failure Projections

Figures 14 and 15 show the MIR projections of the expected numbers of IFF and tape transport failure projections for confidence intervals of 95 and 99.5%. The estimates are for years 1983—1987, assuming monthly flight-hours are at the historical mean for years 1979—1982.

These values were generated using the computer programs and models developed during the Phase II effort. First, the failure rate and number of aircraft were estimated over the 4-year period. As can be seen in Figs. 14 and 15, the tape transporter repair requirements were projected to be constant and the IFF to have an increasing number of maintenance actions. The Monte Carlo studies were used to evaluate the "extra" or cushion amount required to ensure a desired confidence in the estimate.

The computer codes scanned the 1979—1982 data of type of maintenance codes and estimated the fraction of components that pass through or require actions at the three maintenance levels 1, 2, and 3. These historical data were used to prorate the actions.

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| CT | INDEX WUC | INDEX TEC | CF | ACTIVITY | AL | 1st WKL YR | 1st YR REM QTY | 1st YR REP QTY | 2nd YR REM QTY | 2nd YR REP QTY | 3rd YR REM QTY | 3rd YR REP QTY | 4th YR REM QTY | 4th YR REP QTY | 5th YR REM QTY | 5th YR REP QTY | UPDT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 7366800 | APBD | | | 1 | 83 | 470 | | 470 | | 470 | | 470 | | 470 | | |
| | | | | | 2 | 83 | | 106 | | 106 | | 106 | | 106 | | 106 | |
| | | | | | 3 | 83 | | 364 | | 364 | | 364 | | 364 | | 364 | |
| A | 6534100 | APBD | | | 1 | 183 | 273 | | 280 | | 285 | | 290 | | 295 | | |
| | | | | | 2 | 283 | | 273 | | 280 | | 285 | | 290 | | 295 | |
| | | | | | 3 | 383 | | 0 | | 0 | | 0 | | 0 | | 0 | |

Fig. 14. Five-year (1983—1987) MIR projections for expected numbers of removal and repair actions at 95% confidence level (A7366800APBD is tape transport; A6534100APBD is IFF receiver/transmitter).

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| CT | INDEX WUC | INDEX TEC | CF | ACTIVITY | AL | 1st WKL YR | 1st YR REM QTY | 1st YR REP QTY | 2nd YR REM QTY | 2nd YR REP QTY | 3rd YR REM QTY | 3rd YR REP QTY | 4th YR REM QTY | 4th YR REP QTY | 5th YR REM QTY | 5th YR REP QTY | UPDT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | A7366800 | APBD | | | 1 | 83 | 561 | | 561 | | 561 | | 561 | | 561 | | |
| 4 | | | | | 2 | 83 | | 126 | | 126 | | 126 | | 126 | | 126 | |
| 4 | | | | | 3 | 83 | | 437 | | 437 | | 437 | | 437 | | 437 | |
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| 4 | A6534100 | APBD | | | 1 | 83 | 295 | | 302 | | 307 | | 312 | | 317 | | |
| 4 | | | | | 2 | 83 | | 295 | | 302 | | 307 | | 312 | | 317 | |
| 4 | | | | | 3 | 83 | | 0 | | 0 | | 0 | | 0 | | 0 | |
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Fig. 15. Five-year (1983–1987) MIR projections for expected numbers of removal and repair actions at 99.5% confidence level (A7366800APBD is tape transport; A6534100APBD is IFF receiver/transmitter).

# 4. CONCLUSIONS AND RECOMMENDATIONS

The single, most significant conclusion reached in the course of this study is that (considering both Phase I and Phase II results) a methodology in which systematic analysis of historical data is coupled with input from experts results in an improved predictive ability. An additional conclusion is that many correlation "numbers," established from data analysis alone, raise other questions instead of providing answers. For example, the complete lack of depot-level data severely limited logistics model development. Such peculiarities give rise to doubts about the usefulness of the data base and underline the need for information gathering at the organizational level. This approach was amply illustrated in the discussions during which it was concluded that a modified-Delphi or some other interactive technique is a necessary element in developing a realistic forecasting ability.

Note that the failure records have been shown to require considerable correction. However, the principal information on the records (aircraft bureau number, squadron, failed part, date of failure, cause codes, repair codes, etc.) can meet most of the data needs for failure projections.

The recommendations presented here are principally suggestions for program direction. They pertain primarily to the next immediate phase of work. The recommendations reflect comments from project sponsors at NALC who received preliminary results before publication of this document.

The foremost recommendation is to continue to work toward the ultimate program objectives of (1) developing procedures, guidelines, computer models, and other tools that will assist NALC in its decision-making processes and (2) transferring the system into practical use by NALC managers. The following Phase 3 task is the next logical step toward that objective.

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# Appendix A

## RELIABILITY DEFINITIONS[1]

AVAILABILITY: A measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called or at an unknown time.

FAILURE: The event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified.

FAILURE MECHANISM: The physical, chemical, electrical, thermal or other process which results in failure.

FAILURE MODE: The consequence of the mechanism through which the failure occurs, i.e., short, open, fraction, excessive wear.

FAILURE, RANDOM: Failure whose occurrence is predictable only in a probabilistic or statistical sense. This applies to all distributions.

FAILURE RATE: The total number of failures within an item population, divided by the total number of life units expended by that population, during a particular measurement interval under stated conditions.

MAINTAINABILITY: The measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.

MAINTENANCE: All actions necessary for retaining an item in or restoring it to a specified condition.

MAINTENANCE, CORRECTIVE: All actions performed as a result of failure, to restore an item to a specified condition. Corrective maintenance can include any or all of the following steps: Localization, Isolation, Disassembly, Interchange, reassembly, Alignment, and Checkout.

MEAN-TIME-BETWEEN-FAILURE (MTBF): A basic measure of reliability for repairable items: The mean number of life units during which all parts of the item perform within their specified limits, during a particular measurement interval under stated conditions.

MEAN-TIME-BETWEEN-MAINTENANCE (MTBM): A measure of the reliability taking into account maintenance policy. The total number of life units expended by a given time, divided by the total number of maintenance events (scheduled and unscheduled) due to that item.

MEAN-TIME-TO-REPAIR (MTTR): A basic measure of maintainability: The sum of corrective maintenance times at any specific level of repair, divided by the total number of failures within an item repaired at that level, during a particular interval under stated conditions.

RELIABILITY: (1) The duration or probability of failure-free performance under stated conditions.

(2) The probability that an item can perform its intended function for a specified interval under stated conditions.

SYSTEM: General — A composite of equipment and skills, and techniques capable of performing or supporting an operational role, or both. A complete system includes all equipment, related facilities, material, software, services, and personnel required for its operation and support to the degree that it can be considered self-sufficient in its intended operational environment.

TIME: The universal measure of duration. The general word "time" will be modified by an additional term when used in reference to operating time, mission time, test time, etc. In general expressions such as "Mean-Time-Between-Failure (MTBF)," time stands for "life units" which must be more specifically defined whenever the general term refers to a particular item.

WEAROUT: The process which results in an increase of the failure rate or probability of failure with increasing number of life units.

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# Appendix B

## ANALYSIS METHOD FOR APPROXIMATING THE FIRST OCCURRENCE TIME-BETWEEN-FAILURE

To model the effect of several variables on aircraft part failures, individual failures must be tracked as a function of time-between-failures (TBFs). This is required to relate this time interval to operational variables corresponding to the same time period (e.g., flight-hours and number of landings). However, in most cases data are not available for the entire time an aircraft has been operational, and TBF must be estimated for that portion of the total time. For example, though the data may start in 1979, the aircraft has had repairs and replacements of parts in years before 1979; it is impractical or impossible to obtain these earlier data.

To estimate TBF's, a technique that introduces little or no bias but enhances the regression analysis results is used. The technique uses a stochastic model that by its very nature reduces the probability of introducing bias while including as much inferred information as possible.

Figure B.1 illustrates TBF as a linear function of calendar time. The 45° line on this figure indicates the division between regions designated 1 and 2. In Region 1 each TBF must be estimated because no failure data are available before that time. For example, at calendar time 100 no TBF value above 100 can be evaluated because no data are available before time 1. Consequently, Region 1 values for TBF must be estimated. In Region 2 TBFs can be evaluated by simple subtraction. For example, if a failure is on day 134 and the previous failure was on day 101 for the same part and aircraft, TBF, neglecting the repair time, is 33 d at day number 134. The problem with Region 1 is that we do not know the time at which the previous failure occurred. To estimate that time, the average failure rate will be assumed to be relatively constant within the region (T1 to T2). This assumption implies that the mean-time-between-failure (MTBF) for the data set is

$$MTBF = (T \quad - T \ )\frac{N_s}{N_f} ,$$

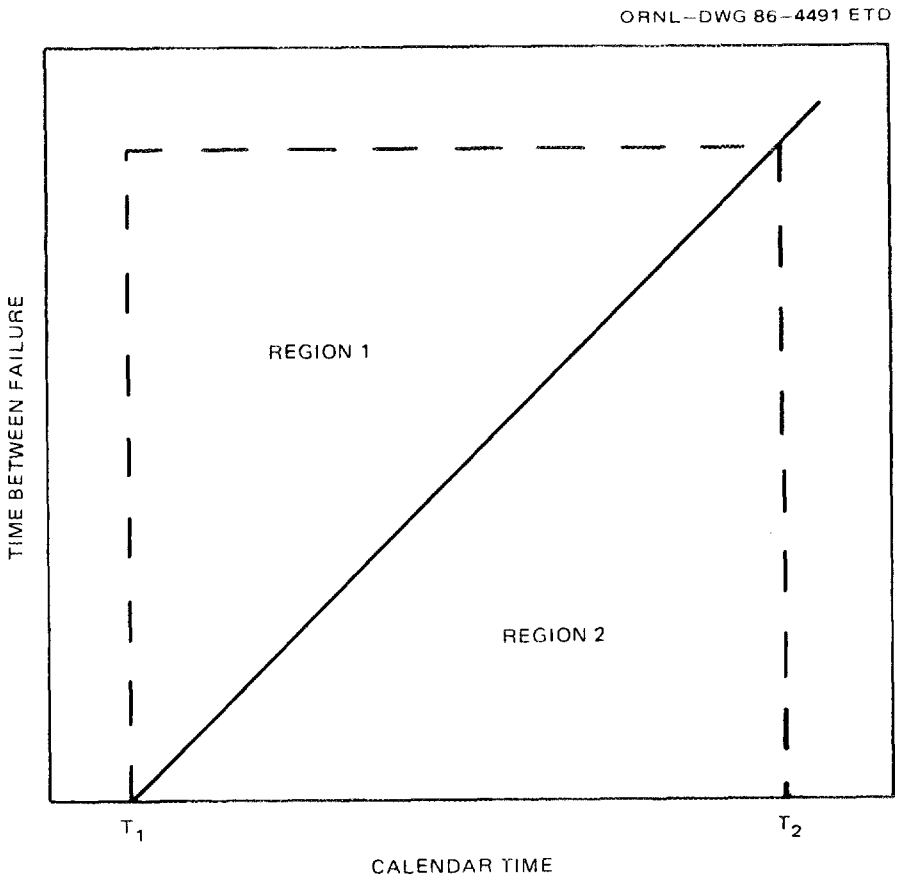


Fig. B.1. TBF vs time.

where

$T_2$ = time of last data entry,
$T_1$ = time of first data entry,
$N_s$ = average number of parts at risk,
$N_f$ = total number of part failures.

To separate the two regions, MTBF will be written as

$$MTBF = (\Sigma TBF1 + \Sigma TBF2)/N_f \ .$$

This equation simply states that the sum of each of the two regional TBFs divided by the number of failures is equal to MTBF. The individual values for each region are given by

$$MTBF1 = \Sigma TBF1/N1$$

and

$$MTBF2 = \Sigma TBF2/N2 \ ,$$

where

MTBF1 = MTBFs in Region 1,
MTBF2 = MTBFs in Region 2,
N1 = number of failures in Region 1,
N2 = number of failures in Region 2.

These equations are used to derive an estimate for the MTBF of Region 1:

$$MTBF1 = (MTBF*N_f - \Sigma TBF2)/N1 \ .$$

To evaluate Region 1 TBF estimated (TBFE) at time (t), the time to the first data entry (T1) and the MTFB1 value must be considered. A final consideration before an estimate can be made is the type of distribution of the data in Region 1. To illustrate the importance of the distribution, consider that an average value of 50 can be obtained with bimodal data of 55 and 45, and 50 is also the average value for uniform data between 1 and 99. In these analyses, the distribution is assumed uniform, and, thus, a random number (RND) is generated between 0 and 1 for the equation

$$TBFE = 4/3*MTBF1*RND*g + T2*(1 - g) \ ,$$

where g is a uniform function between 1 and 0 as t increases from T1 to T2. Thus, $g = (T2 - t)/T2$. Note that 4/3 times an RND that averages 1/2 results in an average 2/3 value that is the geometric center of Region 1.

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