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Volume I - Executive Summary

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DEVELOPMENT OF NAVY AIRCRAFT BASELINE RELIABILITY PREDICTION MODELS

VOLUME I - EXECUTIVE SUMMARY

F. D. FERGUSON

J. O. KOLSON

J. T. STRACENER

VOUGHT CORPORATION

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Models were developed for prediction of baseline reliability characteristics of notional (conceptual) Navy fixed wing and rotary wing aircraft. Each model consists of a set of mathematical equations relating two-digit Work Unit Code subsystem Mean Flight Hours Between Failures (MFHBF) to aircraft design/performance parameters. The prediction equations were derived using MFHBF data and aircraft design/performance parameters from each of 43 representative historical Navy aircraft. Candidate predictor variables consisted of 101 design/ →

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20 performance parameters for fixed wing aircraft and 89 design/performance parameters for rotary wing aircraft.

This report contains two volumes:

Volume I - Executive Summary and
Volume II - User's Guide and Model Development.

A summary of development of the baseline reliability prediction models is presented in Volume I. The models and application procedure are contained in Part I of Volume II, User's Guide, while data base development, technical approach, and model validation appear in Part II.

SUMMARY

Vought Corporation has developed, under contract with the Naval Air Systems Command, reliability prediction models for predicting baseline reliability characteristics of notional (conceptual) Navy aircraft based only on values of aircraft design/performance parameters. The models were developed based on the need for prediction models responsive to notional aircraft design/performance parameter values.

The Baseline Reliability Prediction Models consist of two models, one for fixed wing aircraft and another for rotary wing aircraft. The models consist of equations which relate two-digit Work Unit Code (WUC) subsystem Mean Flight Hours Between Failures (MFHBF) to aircraft design/performance parameters. The model for fixed wing aircraft consists of 40 prediction equations while the model for rotary wing aircraft consists of 35 prediction equations.

Development of the Baseline Reliability Prediction Models was accomplished by a three-phase study: (1) Data base development, (2) model derivation, and (3) model validation. The data bases consist of a compilation of MFHBF data at the two-digit WUC subsystem level obtained from the Navy Maintenance and Material Management (3M) System and aircraft design/performance parameters for each of 32 fixed wing and 11 rotary wing historical Navy aircraft. Baseline MFHBF prediction equations were derived through use of statistical methods to select predictor aircraft design/performance parameters and to mathematically relate two-digit WUC subsystem MFHBF to selected aircraft/design parameters.

PREFACE

This final Technical Report on Development of Baseline Reliability Prediction Models study was prepared by the Reliability Engineering Group of the Vought Corporation, Dallas, Texas under Contract No. N00019-79-C-0355 for the Naval Air Systems Command, Washington, D. C. The objective of the study was to develop mathematical models which would permit prediction/evaluation of the reliability characteristics of notional Navy aircraft based only on the aircraft design/performance parameters.

The c ntract was issued on 27 April 1979 by Naval Air Systems Command (NAVAIR), Washington, D. C. Mr. Steve Meek (PMA 2694) was technical contract monitor. The contract period from 27 April through 27 October 1979 covered development of the Baseline Reliability Prediction Model for fixed wing aircraft. An interim report covering this period was submitted to NAVAIR on 27 October 1979. The contract was modified as a result of NAVAIR's exercise of a proposal option. The contract period was extended through 27 February 1980 to provide for development of the Baseline Reliability Prediction Model for rotary wing aircraft. The final report covers the entire period of contract performance from 27 April 1979 to 27 February 1980.

Messrs. Steve Meek (PMA 2694), John Zell (AIR 5185), Dave McGoy (AIR 5185), and Alek Gacic (AIR 5185) provided technical consultation and assistance in acquisition of required data, which contributed significantly to the successful completion of this study. Comments received from NAVAIR's review of the interim report contributed to the final report. Mr. Mike Waltz at the Naval Aviation Logistics Center (NALC) provided valuable suggestions/comments from his review of the interim report and final report draft.

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1. INTRODUCTION

This volume is the first of a two-volume final report presenting the results of a study to develop mathematical models for predicting baseline reliability characteristics of notional (conceptual) Navy aircraft. The term "baseline" is defined as descriptive of reasonable expectations based on historical operational trends. The mathematical models developed provide the capability of predicting baseline reliability characteristics of notional aircraft based only on values of aircraft design/performance parameters.

1.1 Need For This Study. The increased emphasis on reliability by the Navy has resulted in reliability being a major design consideration. This in turn has resulted in a need for increased capability to evaluate weapon system reliability characteristics during the conceptual phase. The need for a mathematical model to evaluate the reliability characteristics of notional aircraft is especially evident when a large number of aircraft are being studied as in the Sea Based Air Master Study effort.

There is also a need for a mathematical model for use in establishing realistic baseline reliability requirements for planned Navy aircraft. The process of establishing baseline reliability requirements should reflect fleet experience of historical aircraft. An additional need is a mathematical model for use in evaluating contractor reliability predictions submitted in response to a Request For Proposal.

1.2 Study Objectives. The objective of this study was to develop mathematical models for prediction of notional Navy aircraft baseline reliability characteristics. To accomplish this objective, models are required which are responsive to variations in aircraft design. In addition, it is required that the models are based on variables whose values are available during conceptual design.

Therefore, the specific objective was to develop mathematical models, relating aircraft reliability characteristics to aircraft design/performance parameters. One model was to be developed for fixed wing aircraft and another for rotary wing aircraft. The mathematical expressions were to be developed by statistical analyses of the relationships between reliability characteristics and aircraft design/performance parameters of 43 historical Navy aircraft.

1.3 Organization of Report. This volume contains three sections. The approach taken in development of the data bases and the Baseline Reliability Prediction Models, including model validation procedures, is presented in Section 2. Section 3 provides a description of the prediction models and presents the reliability prediction technique as well as model usage. Section 4 presents the conclusions derived from the study and recommendations for model refinements.

2. APPROACH

The fixed wing and rotary wing aircraft Baseline Reliability Prediction Models consist of two sets of equations which relate aircraft reliability characteristics at the two-digit WUC subsystem level to design/performance parameters. The following sections cover (1) the data base requirements and development, (2) the development of the model, and (3) the validation of the model.

2.1 General. The Baseline Reliability Prediction Models for fixed wing and rotary wing aircraft were developed by applying statistical methods to derive mathematical expressions relating the Mean Flight Hours Between Failures (MFHBF) of two-digit WUC subsystems and aircraft design/performance parameters from historical Navy aircraft. For each two-digit WUC subsystem included in the fixed wing and rotary wing aircraft models, an equation was derived of the form

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + ... + b_nX_n$$

where $\hat{Y}$ is the predicted value of the MFHBF or natural log of the MFHBF, ln(MFHBF), of a two-digit WUC subsystem, depending on which form provided the best fit,

$X_1, X_2, ... X_n$ are selected aircraft design/performance parameters,

and $b_0, b_1, ... b_n$ are coefficients derived through statistical methods applied to the historical aircraft values for the MFHBF of the two-digit WUC subsystem and the design/performance parameters.

Figure 2-1 provides an overview of the model development process as well as model usage. Development of the Baseline Reliability Prediction Models required compilation of aircraft design/performance parameters and reliability characteristics of representative historical Navy aircraft, selection of design/performance parameters, derivation of baseline reliability prediction equations, and model validation. The models can then be used to predict the

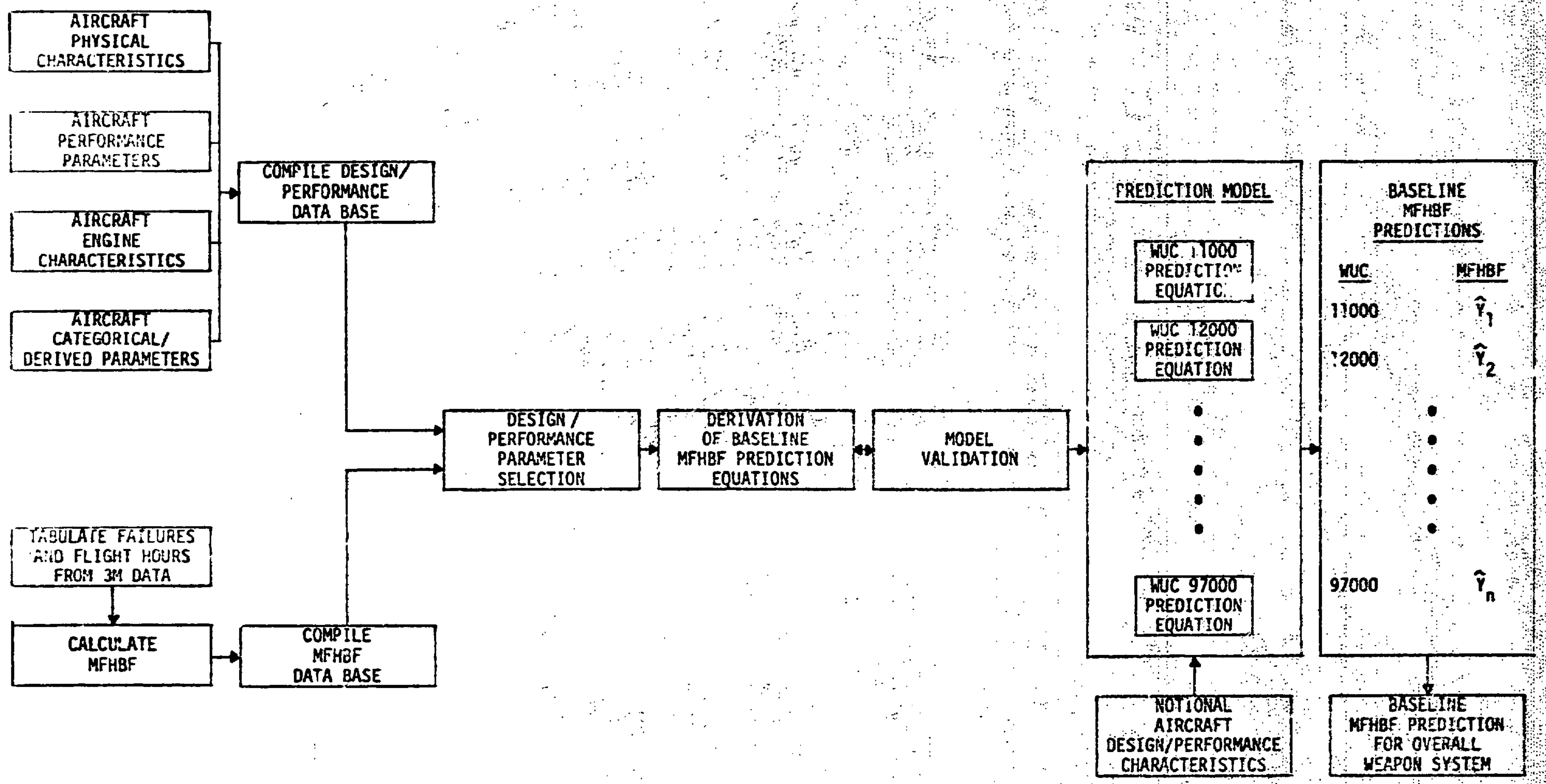

Figure 2-1. Baseline Reliability Prediction Model Development/Implementation Diagram

reliability characteristics of notional Navy aircraft once the aircraft design/performance parameters are definitized.

2.2 <u>Data Base Development.</u> Two types of data were required in the performance of the study: (1) The reliability data base was obtained as Mean Flight Hours Between Failure (MFHBF) values at the two-digit Work Unit Code (WUC) level for historical Navy aircraft from the Navy's fleetwide data system; and (2) the design/performance parameters, which should be available early in aircraft development, were compiled from several sources discussed in Section 2.2.2. These data bases were used to develop two reliability prediction models, one for fixed wing aircraft and the other for rotary wing aircraft.

MFHBF data and design/performance parameters were obtained on each of 43 historical Navy aircraft. Of these aircraft shown in Table 2-1, thirty-two are fixed wing and eleven are rotary wing. The selected aircraft were considered the most representative available for use in deriving the two prediction models which would ultimately be used to predict the reliability of notional aircraft including those in the Sea Based Air Master Study (SBAMS).

2.2.1 Reliability Data Base. The Fleet Weapon System Reliability and Maintainability Statistical Summary Tabulation Report, MSO 4790.A2142.01 is based on the Navy's Maintenance and Material Management (3M) system. This report presents reliability and maintainability summaries by Work Unit Code (WUC) for all Navy aircraft.

Reliability data was compiled over the time period of July 1976 through June 1979 (twelve quarters of data). The MSO Reports prior to July 1976 are semi-annual, instead of quarterly. In order to keep the data reporting periods of equal duration, only MSO Reports from July 1976 forward have been used in this study. The last report that could be included was the quarter ending with June 1979.

Reliability data was collected at the two-digit WUC subsystem level and at the aircraft level for fixed wing and rotary wing aircraft. For each of the twelve quarters, the fleet-wide totals for the number of failures and the corresponding aircraft flight hours were obtained for each aircraft. The

TABLE 2-1. NAVY AIRCRAFT USED IN THE DEVELOPMENT OF THE RELIABILITY PREDICTION MODELS

FIXED WING AIRCRAFT (32)

- Fighter
  - F-4J, N
  - F-14A
- Attack
  - A-4E, F, M
  - A-6A, E
  - A-7A, B, C, E
  - AV-8A
- Reconnaissance
  - RF-4B
  - RF-8G
  - RA-5C
- Electronic Warfare
  - EA-3B
  - EA-6A, B
- Airborne Early Warning
  - E-1B
  - E-2B, C
- Anti-Submarine Warfare
  - S-3A
- Patrol Anti-Submarine Warfare
  - P-3A, B, C
- Carrier on Board Delivery Transport
  - C-1A
  - C-2A
- Flight Refueling Tanker
  - KA-3B
  - KA-6D
  - KC-130F, R

ROTARY WING AIRCRAFT (11)

- Anti-Submarine Warfare
  - SH-2F
  - SH-3A, D, G, H
- Marine Assault
  - CH-46D, F
  - CH-53A, D
- Vertical on Board Delivery/ Search and Rescue
  - HH-3A
  - HH-46A

twelve quarters of data were split into two groups. The first eight quarters from July 1976 through June 1978 became the Reliability Data Base and were used for model development. The four quarters from July 1978 through June 1979 were used to verify the stability of the first eight quarters. The MFHBF was calculated for each of the twelve quarters and for both the eight and four quarter time periods using the formula:

$$\text{MFHBF} = \frac{\text{total flight hours}}{\text{total number of failures}}$$

The WUC subsystems were not standardized for either the fixed or rotary wing aircraft. The effort to standardize the WUC subsystems for five fixed wing aircraft proved to be a larger undertaking in manpower and time than originally anticipated. This led to an agreement with NAVAIR to consider the standardization of the WUC subsystems to be beyond the scope of the funded effort.

The MFHBF data was analyzed for consistent trends, variability, and stability. These analyses were performed among different aircraft for a given two-digit WUC, as well as between different two-digit WUC subsystems of a given aircraft, for both fixed and rotary wing aircraft. When the MFHBF values were plotted against the twelve data quarters for both cases, a wide variety of patterns resulted. While some individual patterns showed definite trends, there was no consistent trend over all aircraft for a given WUC subsystem, or over all WUC subsystems for a given aircraft. The largest variability was shown by those WUC subsystems which had only a few failures reported per quarter for a given aircraft with approximately the same number of flight hours for each quarter. For these WUC subsystems a small change in the reported number of failures for a quarter could have made a significant change in the quarterly MFHBF values. Since the MFHBF values in the data base resulted from averaging over an eight quarter period, the monthly variability did not have a significant effect in most cases. However, a number of cases exist where the calculated MFHBF values represented extreme values or outliers. The term "outlier" was applied to those MFHBF values which were found to lie outside the general pattern formed by the other MFHBF values for a given WUC when plotted against individual design/performance parameters.

Many of these outliers corresponded to MFHBF values which were computed with only one or two quarters of data reported out of eight quarters. This was considered to be insufficient data to compute a representative long term MFHBF value. A total of 17 MFHBF values for the fixed wing and 12 values for rotary wing aircraft were deleted for this reason.

The long term stability of the MFHBF data was examined by comparing the MFHBF of the candidate data base (the first eight quarters of the twelve quarter period) with the MFHBF of the verification data (the last four quarters). In some cases the MFHBF of the verification data was higher than the candidate data base and lower in other cases. Again, the data showed no consistent trends, and the difference in the MFHBF between the two time periods was not considered significant for any cases. It was concluded that no significant trends or unusual variability existed at the two-digit WUC level over all WUC subsystems or aircraft, and that the MFHBF calculated over the eight quarters from July 1976 through June 1978 were sufficiently stable to be used as the historical Reliability Data Base for the fixed and rotary wing aircraft.

2.2.2 Aircraft Design/Performance Parameters Data Base. The data base consisted of 101 design/performance parameters for each of the 32 fixed wing aircraft and 89 parameters for each of the 11 rotary wing aircraft. These parameters served as the predictor variables for the regression analysis used in developing the reliability prediction equations for the two models. The parameters were compiled from the following sources:

- Standard Aircraft Charcteristics (SAC) Charts (MIL-C-5011A)
- Group Weights Statements (MIL-STD-1374)
- Aircraft and Engine Companies
- Jane's All the World's Aircraft
- NATOPS Flight Manuals
- Aviation Week and Space Technology, Specifications

The Standard Aircraft Characteristics (SAC) Charts and the Group Weight Statements were used as the primary data sources. The remaining sources were used to obtain information not available from these two primary sources. The engine companies, in particular, provided information on several engine parameters.

The aircraft parameters included in the Design/Performance Data Base were divided into four groups as follows:

- o Physical characteristics including dimensions, volumes, and weights.
- o Performance parameters including speed, range, altitude, and rate of climb.
- o Engine characteristics including thrust, size, weight, and fuel consumption.
- o Categorical/derived parameters including squared characteristic values, and ratios of physical characteristics.

Examples of these groups are presented in Tables 2-2 and 2-3 for fixed and rotary wing aircraft, respectively. These parameters were representative of the candidate variables for the thirty-two fixed wing and eleven rotary wing aircraft.

2.3 <u>Prediction Model Development.</u> The Baseline Reliability Prediction Models were developed to predict the MFHBF of notional fixed wing and rotary wing aircraft. Each model consisted of a set of mathematical equations used to predict the baseline MFHBF of notional aircraft at the two-digit WUC subsystem levels. The set of predicted MFHBF values obtained from the equations would then be combined mathematically to obtain a predicted value for the overall reliability of the notional aircraft.

During the model development phase, three tasks were undertaken. First, aircraft design/performance parameters were selected for each two-digit WUC prediction equation. Next, using the parameter values and the MFHBF of historical Navy aircraft for each two-digit WUC subsystem, various analyses were performed to derive the best form of an equation for predicting the MFHBF of each two-digit WUC subsystem. Finally, using the aircraft design/performance parameters which formed the best relationship to the historical MFHBF, the coefficients for the equation were estimated.

2.3.1 Selection of Aircraft Design/Performance Parameters. Selection of

TABLE 2-2. EXAMPLES OF PARAMETERS FOR FIXED WING AIRCRAFT

PHYSICAL CHARACTERISTICS

- Crew Size
- No. of Moveable Flight Control Surfaces
- Wing Sweep at 1/4 Chord
- Max. Aircraft Length
- Wing Area
- Avionics Weight Installed
- Empty Weight
- Max. Take-Off Weight -- Catapult

PERFORMANCE PARAMETERS

- Max. Wing Loading
- Max. Rate of Climb at Sea Level
- Max. Service Ceiling
- Max. Combat Radius
- Max. Speed -- Mach No.

ENGINE CHARACTERISTICS

- Max. Thrust per Engine
- Total Aircraft Thrust -- Military
- Engine Weight Installed per Engine
- Turbine Inlet Temperature
- Specific Fuel Consumption
- Max. Compression Ratio

CATEGORICAL/DERIVED PARAMETERS

- Flight Design Weight to Max. Take-Off Weight
- Military Thrust to Design Weight
- Max. Thrust to Max. Take-Off Weight

TABLE 2-3. EXAMPLES OF PARAMETERS FOR ROTARY WING AIRCRAFT

PHYSICAL CHARACTERISTICS

- No. of Main Rotor Blades
- Main Rotor Radius
- Empty Weight
- Total Fuel Capacity
- Main Rotor Blade Area (Total)
- Max. Disc Loading
- Rotor Weight
- Blade Loading

PERFORMANCE PARAMETERS

- Vertical Rate of Climb at Sea Level -- Military Power
- Max. Speed at Sea Level
- Max. Combat Radius

ENGINE CHARACTERISTICS

- Military or Intermediate SHP per Engine
- Turbine Inlet Temperature
- Total Aircraft SHP -- Military or Intermediate
- Main Rotor Transmission Limits -- SHP

CATEGORICAL/DERIVED PARAMETERS

- Military SHP per Engine to Engine Weight Installed per Engine
- Total Aircraft SHP -- Military or Intermediate Power to Max. Take-Off Weight

the aircraft parameters from the Design/Performance Data Bases for development of prediction equations was based on the following: (1) The parameters had to be applicable to notional aircraft and their values available during the conceptual design phase, (2) the parameters were to have intuitive appeal, from an engineering viewpoint, whenever possible , and (3) historically, the parameters had to be good predictors of the MFHBF of a given two-digit WUC subsystem.

Certain aircraft parameters were either omitted from consideration or their definitions modified due to differences between existing and notional aircraft. Only those parameters which were meaningful for notional aircraft were used in the prediction equations. For example, the Minimum Stall Speed for fixed wing aircraft was not included in the fixed wing aircraft prediction equations, since the parameter has different significance for Vertical/Short Takeoff or Landing (V/STOL) aircraft. Some parameters were defined differently for notional designs to allow the notional aircraft to better conform to existing aircraft features. For example, the Number of Engines is defined to be the number of primary engines for aircraft designs having primary lift/cruise engines and auxiliary lift engines.

As the prediction models were developed for use during conceptual design, the availability of certain notional parametric values required careful consideration. Only those design and performance parameters, normally available at this stage in the design process, were included in the equations. This resulted in the exclusion of parameters associated with detailed design.

Engineering judgment was used in the development of the set of parameters for each two-digit WUC from which the specific aircraft parameters for each equation would be chosen. With the assistance of design and systems engineers, the parameters were assigned one of four levels of priority for each two-digit WUC subsystem. The level of priority assigned reflected the degree of association the aircraft parameter was felt to have with the reliability of the two-digit WUC subsystem. There were two principal reasons for using engineering expertise in the selection process. First, this approach was the fastest means of eliminating parameters which should have no connection with a given two-digit WUC subsystems. Secondly, the use of design/performance parameters with intuitive appeal in the prediction equations was considered desirable.

The selected parameters were then examined for their predictive ability using correlation analysis. Through correlation analysis, the degree of linear association, or correlation, between the MFHBF and the design/performance parameters of interest for each two-digit WUC was determined. If the degree of linear association was strong, as indicated by the correlation coefficient having a value close to +1.0 or -1.0, the parameter was felt to be a potentially good predictor of the MFHBF for the two-digit WUC subsystem. For example, the correlation between the MFHBF for WUC 14000 (Flight Controls) and the Flight Control Surface Area for historical fixed wing aircraft was found to be 0.708. This degree of linear association between the MFHBF and the Flight Control Surface Area is reflected graphically in Figure 2-2. The strong linear trend found in the data implied that the Flight Control Surface Area had historically been a good indicator of the MFHBF for the Flight Controls. Thus, the Flight Control Surface Area was accepted as a potentially good predictor for the reliability of WUC 14000.

In addition to measuring the linear association between the MFHBF and an aircraft design/performance parameter, correlation analysis was also used to measure the linear association between the aircraft parameters themselves. If the correlation coefficient for two aircraft parameters was close to +1.0 or -1.0, the parameters were considered "statistically equivalent". This meant that, mathematically, they would make approximately the same contribution to the predictive ability to an equation. The strong linear associations between aircraft parameters were important to the development of the prediction equations. These relationships often permitted the substitution of one parameter for another without affecting the predictive quality of the equation. The strong correlation sometimes led to only one of the parameters being used in a prediction equation. As both parameters had the same predictive effect for a given equation, the use of both parameters was mathematically redundant. For example, the Folded Wing Span and Flight Control Surface Area had a correlation coefficient of 0.926. Since the use of both parameters was redundant, only the Flight Control Surface Area was included in the fixed wing aircraft prediction equation for WUC 14000.

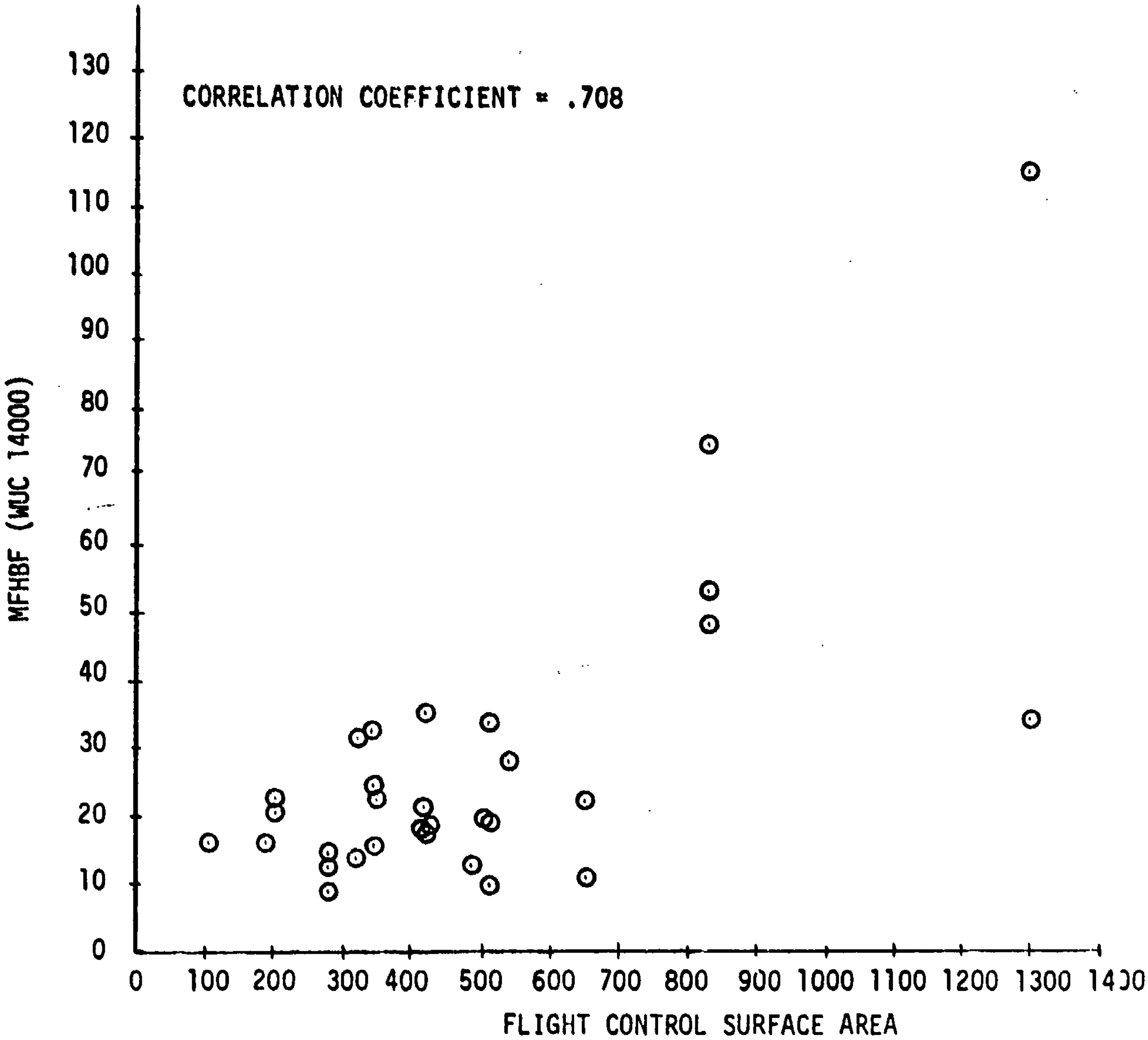

Figure 2-2. MFHBF for Flight Controls vs. Flight Control Surface Area for Fixed Wing Aircraft

Another technique used to examine the predictive ability of the aircraft parameters was a forward selection procedure called stepwise regression. In stepwise regression, parameters were selected, one at a time, from the set of parameters felt to have intuitive appeal, to form an equation for each two-digit WUC subsystem. The criteria for selection required the parameter having the strongest linear association with the MFHBF to be chosen first. In the succeeding steps, the parameters which made the greatest additional contribution to the statistical quality of the equation were added.

The stepwise regression procedure helped to reduce the set of parameters which would receive further consideration. As the number of parameters which could be used to form each prediction equation was mathematically limited by the number of historical aircraft used to develop the equation, some parameters had to be eliminated. Those parameters not chosen in the stepwise procedure were seen as having little predictive ability, and, therefore, omitted from further analysis.

2.3.2 Prediction Equation Derivation. The statistical technique used to derive the prediction equations for the Baseline Reliability Prediction Models was multiple linear regression analysis, or simply regression analysis. Using the regression technique, the MFHBF for historical aircraft were mathematically combined with the corresponding values for the parameters of interest to obtain values for the coefficients of the parameters in each equation.

The functional forms considered for prediction equations involved using a mathematical function of the MFHBF, as well as the MFHBF itself. The "L-shaped" trend found in the graphs of the characteristics versus the MFHBF for historical aircraft indicated the need for a transformed functional form for the prediction equation of most of the two-digit WUC subsystems. Since the "L-shaped" trend, as seen for example in Figure 2-3, was found using different parameters with the same MFHBF data, a transformation was considered for the MFHBF.

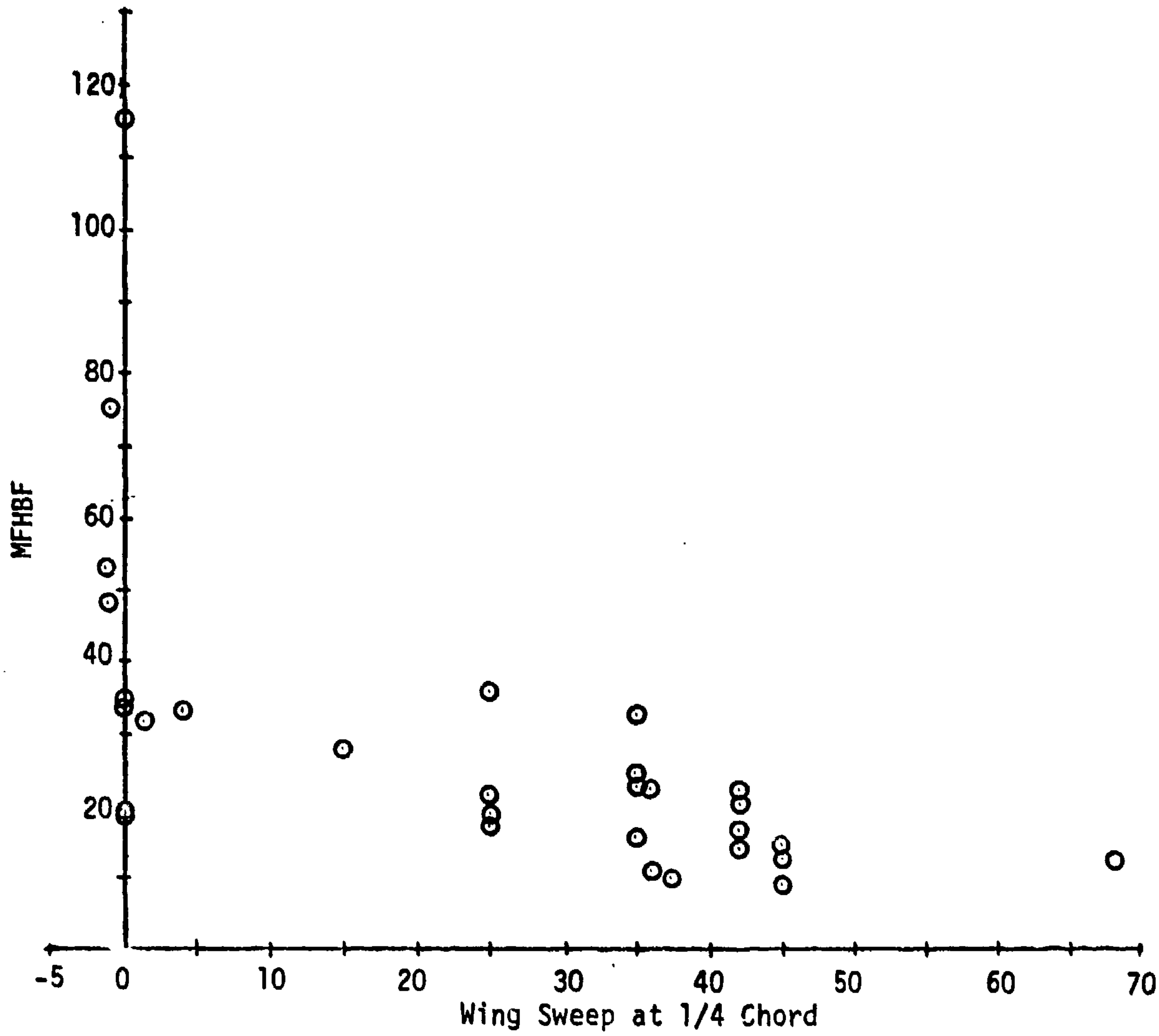

Figure 2-3 . MFHBF for WUC 14000 vs the Wing Sweep for Fixed Wing Aircraft

The natural log of the MFHBF was found to be the best functional form of the MFHBF for most of the prediction equations. A comparison of Figures 2-3 and 2-4, involving the MFHBF of WUC 14000 (Flight Controls) and the Wing Sweep, i.e., the sweepback angle of the wing, for historical fixed wing aircraft, reflects the type of improved linear association obtained with the natural log of the MFHBF. The use of the natural log of the MFHBF, instead of the MFHBF, improved the statistical quality and the predictive ability of most of the prediction equations.

While selected ratios of parameters, such as the Maximum Thrust to Maximum Take-Off Weight and Military Thrust to Flight Design Weight, and cross products, such as the Maximum Landing Weight times the square of the Landing Sink Speed, were used as parameters, other functions of the parameters were not considered for the equations. By using the natural log of the MFHBF, most of the trends indicative of the need for a different functional form for the charcteristics were eliminated. As a sufficient number of meaningful parameters was found to have good predictive ability for developing each equation, no further study of other functional forms was made.

Additional steps, related to the choice of design/performance parameters for the equations, were taken to improve various prediction equations. Certain equations derived through regression analysis, such as those for some avionics and engine related WUC's, were lacking the statistical quality and engineering appeal desired. Parameters not previously considered were added to the Design/Performance Data Base. These parameters were then incorporated into certain equations and analyzed for their predictive ability. In other equations, a "statistically equivalent" parameter, previously identified through the correlation analysis, was substituted for another parameter which had less intuitive appeal.

While the stepwise regression procedure had helped to eliminate those parameters with little predictive ability, further reduction in the number of parameters used in each equation was required. When too many parameters are used in a prediction equation, relative to the number of aircraft used to develop the equation, the equation is said to "overfit" the data. This causes the equation to do well in predicting the historical MFHBF of the aircraft

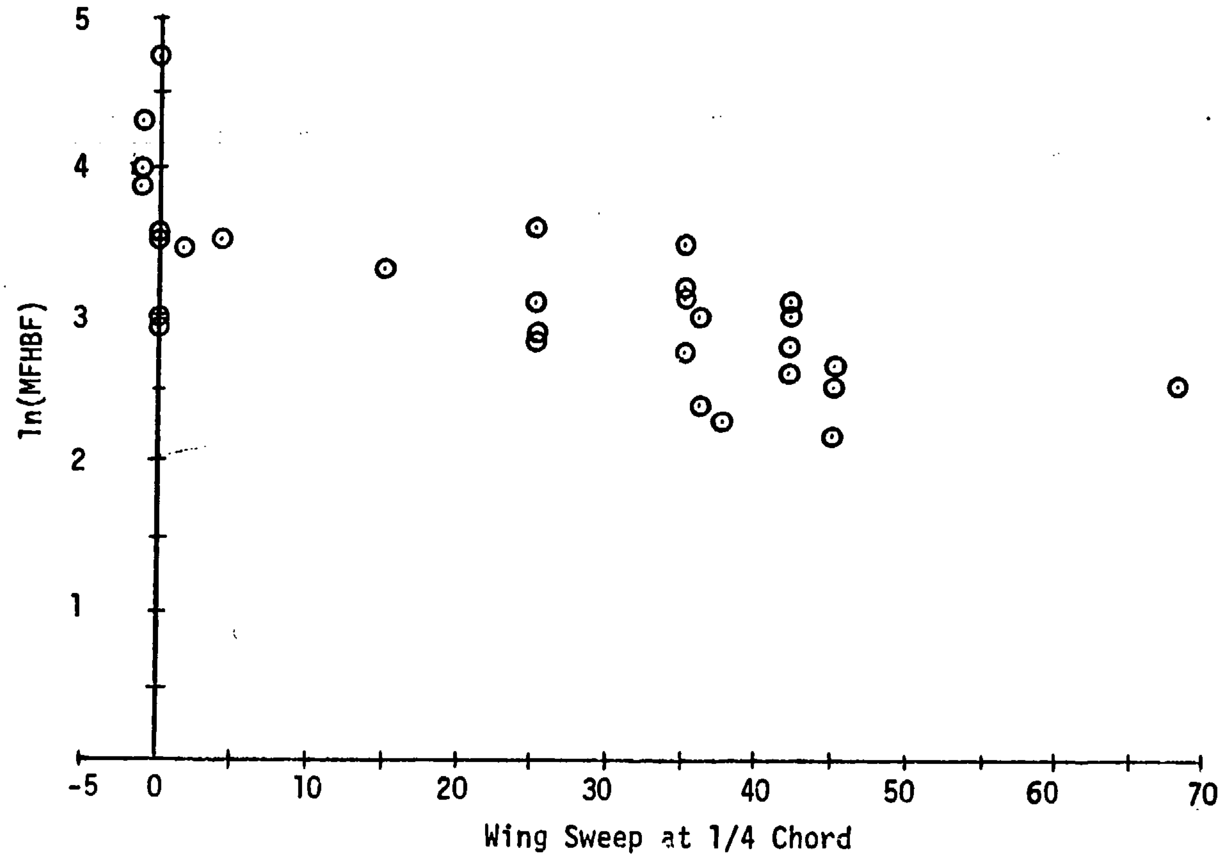

Figure 2-4. Natural Log of the MFHBF (ln(MFHBF)) for WUC 14000 vs the Wing Sweep for Fixed Wing Aircraft

used to derive the equation, but to do poorly in predicting the MFHBF for other aircraft. To reduce the number of aircraft parameters in each equation, statistical measures were used to determine which parameters contributed the least to the statistical quality of the equation. With these parameters eliminated from further consideration, other measures determined which subset of the remaining parameters formed the best equation, statistically.

Even with the reduction in the number of parameters, the equations were felt to be responsive to different notional aircraft configurations. Because of the large number of historical aircraft used in development of the models, the average fixed wing aircraft prediction equation still included nine aircraft parameters and the average rotary wing aircraft prediction equation included five aircraft parameters. With this number of parameters, many of the principal design/performance differences between aircraft which were related to a given two-digit WUC subsystem were accounted for in predicting the MFHBF.

2.3.3 Estimation of Coefficients. To derive the final prediction equations, the appropriate method of regression analysis for calculating the coefficients of the parameters was identified for each equation. Because the degree of linear association between parameters of the equation influenced the values of the coefficients, two regression methods were used. When none of the aircraft parameters were strongly correlated, the least squares regression technique was used. Otherwise, the ridge regression technique was required, to preclude the instability of the least squares coefficient values.

The stability of the coefficients related to how the baseline MFHBF predicted value changed as the values for the parameters change. When slight changes in the parameter values caused radical changes in the predicted values, the coefficients were considered unstable. Since the notional values for certain aircraft parameters were expected to differ from the historical values, stable coefficients were required if the equations were to have good predictive ability.

2.4 Model Validation. During model validation, the adequacy of the functional form of the equations, the sensitivity of the equations to the historical data, and the predictive ability of the equations with historical and notional aircraft characteristic values were studied. As these aspects of the equations could not be fully measured with the information provided through correlation and regression analysis, a validation procedure was required prior to finalizing the Baseline Reliability Prediction Models.

The statistical adequacy of the form of the equations was examined by determining whether certain theoretical assumptions about the data were satisfied. If the assumptions were not satisfied for a given equation, too many parameters had been removed and/or a different functional form of the MFHBF should have been used in the equation. As the assumptions appeared to be satisfied for those equations studied, the form of the equations was considered adequate for prediction.

The sensitivity of the equations to the historical data was measured by deleting the historical aircraft one at a time, from the data, and deriving the coefficients using the remaining aircraft. If the size or sign of the coefficients drastically changed, the equation was considered to be sensitive to the number of specific aircraft used to derive the equation. With such sensitivity, it is difficult to determine if the equation is correctly reflecting the relationship between the MFHBF of the two-digit WUC subsystem and the aircraft parameters. While none of the equations studied were considered to be sensitive, those prediction equations derived using a smaller number of aircraft reflected the greatest change in the coefficients.

Two forms of comparison were made in examining the predictive ability of the models for historical aircraft. For a given prediction equation, the predicted MFHBF values for the two-digit WUC subsystem were compared with the historical MFHBF values of each aircraft used to derive the equation. A graph of the predicted values versus the historical values, like the one shown in Figure 2-5 for WUC 13000 (Landing Gear) for fixed wing aircraft, was used to determine an equation's predictive ability for historical aircraft. For those equations examined, their predictive ability appeared reasonable.

A comparison was also made between the predicted MFHBF obtained from the equations and the historical MFHBF, for all applicable two-digit WUC's of a given aircraft. The predicted MFHBF for the two-digit WUC subsystems were

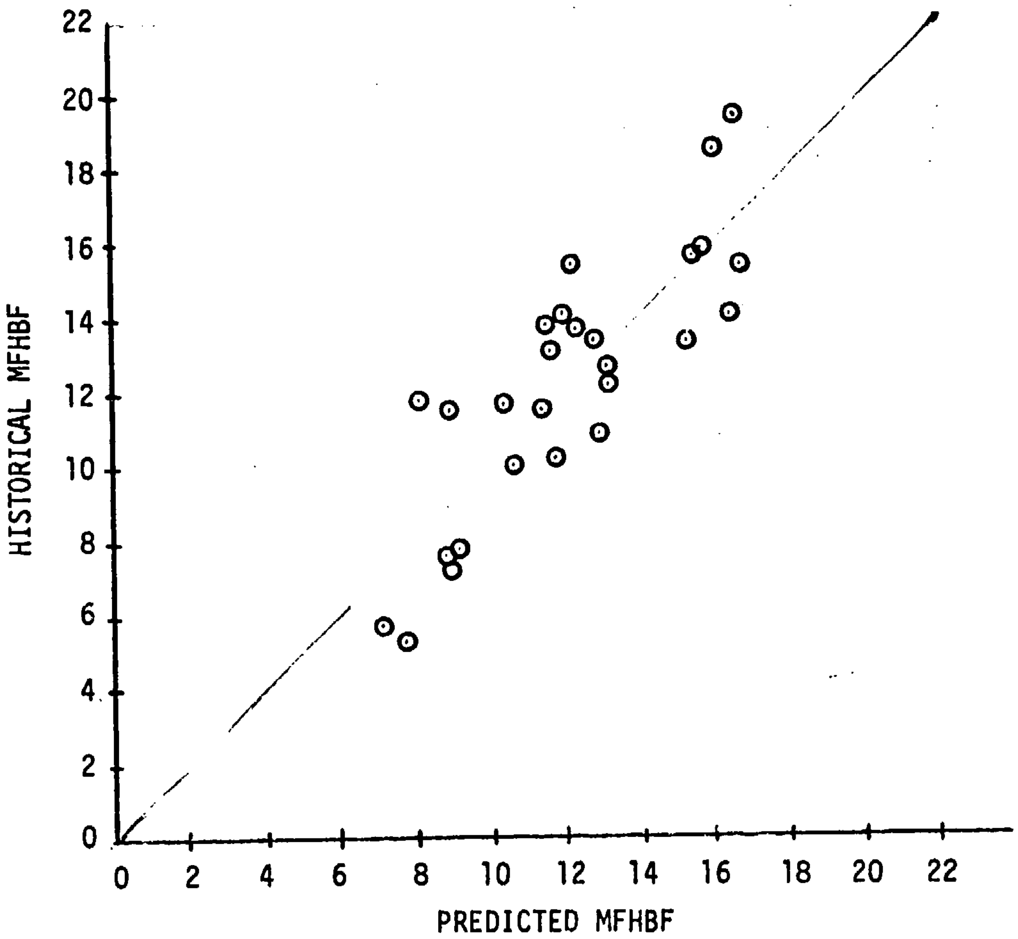

Figure 2-5. Predicted MFHBF vs. Historical MFHBF for Fixed Wing Aircraft -- WUC 13000

then combined to derive the predicted MFHBF for the aircraft, and this value was compared to the historical MFHBF for the aircraft. Unless the model predicts well for historical aircraft, the model is not likely to predict well for notional aircraft.

Results, similar to those presented in Table 2-4 for the A-7E, were found for all historical aircraft. As predicted values for only the two-digit WUC's applicable to the A-7E were derived, the list of two-digit WUC's in Table 2-4 does not include all two-digit WUC subsystems for which prediction equations were developed. For most two-digit WUC's, the predicted values were in reasonable agreement with the historical values. More importantly the predicted MFHBF value obtained by combining the two-digit WUC subsystem predicted values was close to the historical value.

To determine the models' predictive ability for notional aircraft, the baseline MFHBF prediction equations were provided to NAVAIR. NAVAIR used the prediction equations to predict the baseline MFHBF of 40 notional fixed wing aircraft designs and four notional rotary wing aircraft designs of the Sea Based Air Master Study (SBAMS) Aircraft Alternatives Definition Task. These baseline MFHBF values for each two-digit WUC subsystem were compared against the fleet 3M MFHBF values initially used as a NAVAIR Baseline for the SBAMS aircraft estimates. Except for aircraft parameters whose values required extrapolation, both the fixed wing aircraft predictions and the rotary wing aircraft predictions were in reasonable agreement with the previously used baseline estimates.

Extrapolation, i.e., the prediction of baseline MFHBF with notional values for aircraft parameters which are outside the range of historical values, required that adjustment be made in certain prediction equations. These equations involved aircraft parameters such as the Max. Rate of Climb at Sea Level, Total Aircraft Thrust, and Max. Thrust to Max. Take-Off Weight. The value predicted for the baseline MFHBF was unreasonable when the parametric value for the notional aircraft deviated greatly from historical values. To overcome the problem, the parameters requiring extrapolation were either replaced with a statistically equivalent parameter, or combined with different design/performance parameters to form an equation with reasonable predictive ability for notional aircraft.

TABLE 2-4. PREDICTION OF THE MFHBF FOR THE A-7E

NO.	WUC	PREDICTED MFHBF	HISTORICAL MFHBF
1	11000	10.054	12.090
2	12000	39.365	35.920
3	13000	12.955	10.900
4	14000	20.422	24.570
5	27000	37.840	35.910
6	29000	50.645	42.090
7	41000	65.569	50.790
8	42000	16.275	24.380
9	44000	20.193	21.170
10	45000	34.616	33.640
11	46000	32.622	42.790
12	47000	80.797	116.570
13	49000	106.567	145.630
14	51000	18.948	15.220
15	56000	67.069	363.870
16	57000	52.956	22.760
17	63000	38.278	19.320
18	64000	154.050	564.570
19	65000	89.667	83.490
20	66000	1533.576	3033.700
21	67000	97.200	381.510
22	71000	61.538	25.960
23	72000	26.658	46.610
24	73000	16.305	6.230
25	74000	46.743	53.080
26	75000	35.848	23.600
27	76000	60.636	50.220
28	91000	255.093	235.100
29	96000	3017.173	4127.820
30	97000	2969.561	2962.320
	Aircraft	1.203	1.043

3. RESULTS

The Baseline Reliability Prediction Models have been designed to allow reliability predictions of notional aircraft MFHBF early in the aircraft's design evolution. A description of the prediction models, the procedure used to predict with the models, and considerations in using the model are discussed in the following sections.

3.1 Description of Prediction Models. The Baseline Reliability Prediction Models consist of 75 statistically derived equations using aircraft design/performance parameters; 40 equations for fixed wing aircraft and 35 equations for rotary wing aircraft. With the exception of the fixed wing equation and rotary wing equation denoted by WUC 00000, the equations in each model predict the baseline MFHBF at the two-digit WUC subsystem level. The fixed wing equation and rotary wing equation for WUC 00000 represents those equations developed to predict an overall weapon system baseline MFHBF. These equations are designed to be used as a check or validation of the MFHBF obtained by combining the two-digit WUC subsystem MFHBF predicted values for prediction of the overall notional aircraft.

Tables 3-1 and 3-2 present a description of the prediction equations which comprise the fixed wing and rotary wing aircraft prediction models. The two-digit WUC subsystems for which prediction equations were developed along with the number and type of aircraft parameters used in each equation are presented for both fixed wing aircraft and rotary wing aircraft. Similar information is provided for the overall weapon system baseline MFHBF prediction equation (WUC 00000). One additional equation, denoted by WUC 20000, is presented in Table 3-1 for fixed wing aircraft. This equation which predicts the baseline MFHBF of both turbojet and turbofan engines was created to supplement the baseline equations for WUC 23000 (Turbojet Engines) and WUC 27000 (Turbofan Engines).

Many of the same design/performance parameters were chosen for more than one prediction equation. Other parameters were not included in any final prediction equation of the two-digit WUC subsystems. Thus, only 61 of the 101 parameters of the Design/Performance Data Base for fixed wing aircraft were

TABLE 3-1. COMPOSITION OF PREDICTION EQUATIONS FOR FIXED WING AIRCRAFT

WUC	Number of Aircraft Parameters Used in Prediction Equation: Physical Char.	Performance Parameters	Engine Char.	Categorical/ Derived Parameters	Total
00000	6	0	0	1	7
11000	6	0	0	3	7
12000	4	2	0	3	9
13000	5	1	0	3	9
14000	8	0	1	1	10
20000	2	2	4	1	9
22000	1	1	1	1	4
23000	1	2	3	1	7
24000	2	1	0	1	4
27000	1	1	1	1	4
29000	0	2	5	2	9
41000	6	2	1	0	9
42000	7	1	1	0	9
44000	7	0	1	1	9
45000	6	2	2	0	10
46000	6	1	3	0	10
47000	4	1	0	2	7
49000	6	1	1	2	10
51000	6	2	1	1	10
56000	6	3	0	1	10
57000	5	2	1	1	9
61000	2	2	0	3	7
62000	3	1	0	0	4
63000	5	5	0	1	11
64000	5	2	0	1	8
65000	5	4	0	1	10
66000	2	5	0	2	9
67000	3	2	0	2	7
69000	2	2	0	1	5
71000	6	4	0	1	11
72000	4	2	0	3	9
73000	6	3	0	1	10
74000	6	3	0	0	9
75000	7	2	0	0	9
76000	5	2	0	1	8
77000	1	0	0	0	1
91000	3	6	0	0	9
93000	2	0	0	1	3
96000	4	2	0	1	7
97000	4	2	1	1	8

TABLE 3-2. COMPOSITION OF PREDICTION EQUATIONS FOR ROTARY WING AIRCRAFT

WUC	Number of Aircraft Parameters Used in Prediction Equation				Total
	Physical Char.	Performance Parameters	Engine Char.	Categorical/ Derived Parameters	
00000	4	0	0	1	5
11000	4	1	0	1	6
12000	3	2	0	1	6
13000	5	0	0	0	5
14000	3	0	0	1	4
15000	2	0	3	0	5
22000	1	1	2	0	4
24000	3	0	0	0	3
26000	0	0	4	0	4
29000	1	1	2	1	5
41000	3	1	0	0	4
42000	5	1	0	0	6
44000	5	0	0	0	5
45000	3	1	1	0	5
46000	4	1	1	0	6
49000	4	1	0	0	5
51000	2	2	0	0	4
54000	0	2	0	0	2
56000	3	1	1	0	5
57000	3	2	0	0	5
61000	2	1	0	1	4
62000	2	1	0	0	3
63000	3	1	0	0	4
64000	3	2	0	0	5
65000	2	3	0	0	5
67000	3	2	0	0	5
71000	4	1	0	0	5
72000	3	2	0	0	5
73000	3	0	0	0	3
74000	3	0	0	0	3
75000	4	0	0	0	4
76000	2	0	0	0	2
91000	2	3	0	0	5
96000	1	1	0	0	2
97000	2	2	0	0	4

used in the equations of the fixed wing aircraft model, and only 46 of the 89 parameters of the Design/Performance Data Base for rotary wing aircraft were used in the equations of the rotary wing aircraft model.

3.2 Reliability Prediction Technique. The two Baseline Reliability Prediction Models provide an expedient means of obtaining reliability predictions for candidate aircraft during the aircraft's conceptual design phase. The prediction equations, using design/performance parameters normally available during conceptual design, permit aircraft reliability considerations to become an integral part of the initial performance studies.

To predict the baseline MFHBF of a notional aircraft, the values of the aircraft parameters used in the equations of the appropriate model must be obtained. These parametric values are then substituted into the prediction equations associated with the two-digit WUC subsystems applicable to the notional aircraft and the predicted values of the baseline MFHBF of the two-digit WUC subsystems are calculated. Figure 3-1 outlines the steps followed in predicting the baseline MFHBF of WUC 74000 (Weapons Control) for a hypothetical notional fixed wing aircraft. This example of predicting for a given two-digit WUC subsystem outlines in further detail the final stages of the prediction model development/implementation process shown in Figure 2-1. As the baseline MFHBF prediction equation for WUC 74000 is expressed in terms of the natural log of the MFHBF, ln(MFHBF), the value derived in combining the terms of the equation must be exponentiated to obtain a value for the baseline MFHBF.

Having similarly derived the predicted baseline MFHBF values for the remaining two-digit WUC subsystems applicable to the aircraft, the baseline MFHBF for the overall weapon system may be derived. By summing the reciprocals of the predicted baseline MFHBF for the two-digit WUC subsystems and reciprocating the sum, the predicted baseline MFHBF for the overall weapon system is obtained. This value may then be validated by deriving the overall weapon system baseline MFHBF from the prediction equation for WUC 00000.

3.3 Model Usage/Considerations. Effective use of the fixed wing and rotary wing aircraft prediction models requires consideration of models' capabilities and limitations. These factors are likely to affect the manner in which the models are used and the results are interpreted.

FIXED WING AIRCRAFT BASELINE MFHBF PREDICTION EQUATION
WEAPONS CONTROL: WUC 74000

ln(MFHBF) = 12.23948 - (.090434)(MAX. NO. OF EXTERNAL ARMAMENT STORES)
-(1.51854)(NO. OF GUNS) - (.0010195)(AVIONICS WT. INSTALLED)
-(.00072135)(TOTAL GENERATOR ELEC. POWER)
+(.0030741)(TOTAL ECS WT.) - (.0002672)(MAX. PAYLOAD)
+(.00038138)(MAX. COMBAT RADIUS)
+(.11427)(MIN. COMBAT MISSION TIME)
-(3.36561)(MAX. SPEED -- MACH NO.)

NOTIONAL FIXED WING AIRCRAFT

CHARACTERISTIC	VALUE
MAX. NO. OF EXTERNAL ARMAMENT STORES	16
NO. OF GUNS	1
AVIONICS WEIGHT INSTALLED	1322.65 LBS
TOTAL GENERATOR ELECTRICAL POWER	25 KVA
TOTAL ECS WEIGHT	274.81 LBS
MAX. PAYLOAD	9136 LBS
MAX. COMBAT RADIUS	976 N.MI.
MIN. COMBAT MISSION TIME	1.96 HRS
MAX SPEED -- MACH NO.	.91
⋮	

$$\ln(MFHBF) = 12.23948 - (.090434)(16) - (1.51854)(1) - (.0010195)(1322.65) - (.00072135)(25) + (.0030741)(274.81) - (.0002672)(9136) + (.00038138)(976) + (.11427)(1.96) - (3.36561)(.91)$$

$$= 3.84467$$

PREDICTED BASELINE MFHBF

WEAPONS CONTROL: WUC 74000

$$MFHBF = e^{3.84467}$$

$$= 46.743$$

Figure 3-1. Prediction of Baseline MFHBF of Weapons Control Subsystem for Hypothetical Notional Aircraft

Data base period technology and historical reliability practices constrain the resulting prediction equation estimates to baseline values. To determine the final notional aircraft reliability values, the baseline MFHBF must be adjusted to reflect potential improvements achievable through technological advances, the Navy's "New Look" emphasis, duty cycle, and corrective design features to eliminate or reduce historical failure modes. By incorporating estimated improvement factors into the baseline MFHBF predicted values, the "then-year" prediction of the MFHBF for WUC subsystems of fixed wing and rotary wing notional aircraft is obtained.

The objective of the Baseline Reliability Prediction Models is to predict the overall reliability of fixed wing and rotary wing notional aircraft. By predicting the MFHBF at a two-digit WUC level, the prediction for the notional aircraft MFHBF should be more sensitive to the overall configuration; and since these predicted values of MFHBF are combined mathematically to obtain the predicted baseline MFHBF of the aircraft, the aircraft MFHBF prediction should, in general, be more accurate.

The goal of the regression analysis performed in the study was to derive the "best" functional relationship between the MFHBF and the aircraft design/performance parameters for the two-digit WUC subsystems of the model. The goal of the regression analysis was not to determine which aircraft parameters were the cause of the failures at a two-digit WUC level. The appearance of a parameter in a baseline MFHBF prediction equation cannot be interpreted as an indication of a "cause and effect" relationship. Similarly, the addition or subtraction of parameters in the prediction equation cannot be interpreted to mean the MFHBF has a positive or negative association with the design/performance parameters. A prediction equation must be considered in its entirety.

Differences between existing and notional or conceptual aircraft designs have affected the development of the Baseline Reliability Prediction Models and might modify its usage. For example, the current 3M subsystem nomenclature may not be representative of future aircraft equipment and functional partitioning. For some notional design/performance parameters an equivalent parameter is not found in existing aircraft; therefore, the parameters cannot be considered in the model. Other parameters require a modified definition to use the equations for prediction of notional aircraft reliability.

Some design/performance parameters of existing aircraft have values which establish boundaries which may not be consistent with those of notional aircraft. The values for notional aircraft parameters, such as the Maximum Rate of Climb at Sea Level, Turbine Inlet Temperature, Total Aircraft Thrust and Thrust to Weight parameters, may lie outside the range for existing aircraft and thus require extrapolation.

4. CONCLUSIONS AND RECOMMENDATIONS

Baseline Reliability Prediction Models presented in this report accomplish the study objectives. A means is now available for evaluating the baseline reliability characteristics of notional Navy aircraft based only on values of aircraft design/performance parameters. This will ensure that reliability can be given consideration in conceptual design commensurate with the increased emphasis on reliability within the Navy. In addition, the models can be used by NAVAIR in establishing weapon system reliability requirements and evaluating contractor reliability predictions of proposed aircraft.

4.1 Conclusions. The models developed during this study can be applied to prediction of the baseline MFHBF for a wide variety of notional Navy aircraft and mission variants for both fixed and rotary wing aircraft. This flexibility results from the large number of Navy aircraft, 43, used in development of the prediction models.

The development of models for the prediction of baseline MFHBF at the two-digit WUC subsystem entailed a comprehensive effort. Reliability characteristics and aircraft design/performance parameters of historical Navy aircraft were utilized in prediction equation development. Rigorous statistical methodology was used to identify significant aircraft design/performance parameters for predicting subsystem MFHBF. The statistically important parameters were not always those deemed most important by the design and systems engineers.

The engine WUC's received considerable attention. The statistically best equations for prediction of engine MFHBF were contrary to expectations, as engine parameters such as Turbine Inlet Temperature, Compression Ratio, and Bypass Ratio were not found to be important predictor variables. This result could be due to the long span of time associated with progessively improved technology, as reflected by increased Turbine Inlet Temperature, decreased Weight, decreased Specific Fuel Consumption, while reliability has remained essentially constant. Another factor could be that the fuel control within the engine subsystem has resulted in masking the relationship between engine reliability and engine parameters.

The avionics subsystems also received special attention during prediction model development. One difficulty resulted from the fact that avionics related aircraft parameters generally available during conceptual design were Avionics Weight, Installed and Uninstalled, and Environmental Control System Weight. These parameters were not sensitive enough to the two-digit WUC avionics subsystem configurations. Also, rapid technological advances which can provide improved reliability has enabled simultaneous performance increases. This often has resulted in no apparent increase in reliability.

4.2 Recommendations. The Baseline Reliability Prediction Models developed during this study and presented in Tables 2-1 and 2-5 in Volume 2 are complete and are in a usable form. However, ways of increasing usage flexibility and enhancing the models have been identified during the study. These are reflected in the following recommendations:

1. Remove the failures reported against the fuel system from the engine WUC's to more accurately reflect engine associated failures, and then derive new baseline MFHBF prediction equations for the engine by again considering engine related parameters such as Turbine Inlet Temperature, Compression Ratio, and Number of Engine Parts.

2. Identify design/performance parameters available during conceptual design which are more responsive to avionic subsystems configuration and refine the baseline MFHBF prediction equations for two-digit WUC avionic subsystems.

3. Assess trends in reliability due to changing technology of engines, avionics, and structures. Mathematically relate MFHBF to technology sensitive design/performance parameters so that then-year reliability parameters of notional Navy aircraft may be evaluted in addition to baseline reliability parameters.

4. Refine the models to reflect the contribution of each aircraft, used in development of a prediction equation, according to the total number of flight hours for the aircraft. That is, permit those aircraft with more flight hours to carry more weight in the analysis of the data than those aircraft with fewer flight hours.

5. Assess the effects of (1) fleet age in terms of flight hours and calendar time, (2) equipment utilization, (3) carrier vs. noncarrier usage, and (4) failure definition on reliability, and refine the models to incorporate any significant factors.

6. Investigate the feasibility of model simplification, i.e., reduction in the number of terms per equation, with no resultant loss in precision, by use of ratios and other functional forms of aircraft design/performance parameters.

7. Maintain the models by updating the data bases to reflect changes in Navy fleet composition and operation, and refine the prediction equations as necessary to reflect significant changes.