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PREDICTORS OF ORGANIZATIONAL-LEVEL TESTABILITY ATTRIBUTES

ARINC Research Corporation

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A program was undertaken to develop analysis and prediction procedures for evaluation testability attributes at the organizational level of maintenance. The development of testability attribute definitions and analysis procedures was completed as the first phase of this effort and is documented in detail in RADC-TR-85-268, "Prediction and Analysis of Testability Attributes: Organizational-Level Testability Prediction." This report describes the second phase of the effort: the development testability attribute predictors and prediction procedures. A total of 22,000 maintenance actions were examined for 38 line replaceable units, and predictors were developed for the following:

- Cannot Duplicate Burden (CND burden): CND as a percentage of all maintenance actions. CND burden can be used as an estimator of the Fraction of False Alarms (FFA).
- Cannot Duplicate Rate (CND rate): The number of CND events per operating hour. CND rate can be used as an estimator of False Alarm Rate (FAR).

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Isolation Level (IL): The available percentage of fault isolation conclusions. IL can be used as an estimator of Fraction of Faults Isolated (FFI).

Detection Percentage (DP): The attainable percentage of detection conclusions. DP can be used as an estimator of Fraction of Faults Detected (FFD).

PREFACE

This report describes the work conducted by ARINC Research Corporation in the second and final phase of research into field testability of U.S. Air Force electronic systems. The work was performed under Contract F30602-84-C-0046 with the System Reliability and Engineering Branch of the Rome Air Development Center. This work results from the contributions of many individuals without whom the final analyses would be less than complete. Major contributions were made by the following:

- Heather Dussault, RADC/RBET, Griffiss AFB
- MSgt. Larry Spencer, 1st TACFITWING, Langley AFB
- TSgt. Morris Phinnesee, 436 AMS, Dover AFB
- TSgt. Ron Humphrey, ASD/YPFF, Wright Patterson AFB
- SSgt. James Jacintho, 1st TACFITWING, Langley AFB
- Mr. Don Nichols, MMIR Branch Office, Kelly AFB

EXECUTIVE SUMMARY

INTRODUCTION

A program was undertaken to develop prediction procedures for organizational-level testability attributes of complex electronic equipment used by the Air Force. The prediction of these attributes during design phases can be used to monitor and improve the design for field maintainability and to provide an early indication of potential maintainability problems. This report describes that effort. The program was conducted in two phases with the following objectives:

- Phase I
  - Establish definitions and mathematical frameworks necessary for developing prediction procedures.
  - Determine the feasibility of accomplishing the overall objectives of developing prediction equations of testability attributes.
  - Identify design and operational characteristics that influence field testability attributes.
- Phase II
  - Develop field testability attribute prediction equations and techniques.
  - Verify these prediction techniques.
  - Develop guidelines for using the prediction techniques.

Both phases concentrated on three basic descriptors of field maintenance:

- Fraction of faults detected (FFD)
- Fraction of faults isolated (FFI)
- Fraction of false alarms (FFA)

A fourth descriptor, false alarm rate (FAR), a time-normalized value of FFA, was also considered. These four attributes are determined to be the most commonly specified attributes for field-level testability.

PHASE I RESULTS

Introduction

Definitions and mathematical frameworks related to organizational-level testability were developed by applying three approaches to modeling the organizational-level maintenance process. The three modeling approaches employed were:

- Set Theory Model - Based on using Venn diagrams and set-membership approaches to derive definitions and algorithms.
- Modified State Model - Based on combining actions at the organizational-maintenance level necessary to discover the system state (e.g., failed or nonfailed).
- Flow Model - Based on the flow of systems and subsystems through the organizational-level maintenance process.

The Phase I report* describes the models and algorithms used to develop the definitions and evaluation procedures for the three testability attributes: fraction of faults detected, fraction of faults isolated, and fraction of false alarms.

*Prediction and Analysis of Testability Attributes: Organizational-Level Testability Prediction, ARINC Research Corporation, RADC-TR-85-268, Feb uary 1986. AD# A167957.

Definitions

A key objective of the first phase of the program was to develop accurate, quantitative definitions of the three testability attributes. The definitions were to be relevant, consistent with military standards, mathematically precise, and measurable. It would be of little use to derive a set of equations that could not be used to measure fielded system attributes. The following definitions were developed for system-level fault detection, fault isolation, and false alarms:

- Fault Detection - Normal system maintenance (NSM) indicates that the system is not functioning properly, and this indication is the result of a fault within the system.
- Fault Isolation - NSM identifies all failed units within the system. Fault isolation may be either proper or improper.
  - Proper Fault Isolation - Only and all failed units are isolated.
  - Improper Fault Isolation - All but not only failed units are isolated.

  NOTE: Any other outcome of an attempted isolation is considered to result in no fault isolation.
- False Alarm - There is an indication of failure in the system, but there is no failure in the system. False-alarm rate is the sum of false alarms over a general time period divided by that time period.

More detailed descriptions of these and other definitions used in this study are given in the Phase I report.

Phase I Feasibility Summary

The feasibility of developing prediction procedures for the three testability attributes was determined based on two major criteria: (1) the ability to measure FFD, FFI, and FFA in currently fielded systems and (2) the ability to relate specific design characteristics to measured values of the testability attributes. If these criteria were satisfied, the development of prediction procedures was considered feasible.

Field measurement of the three testability attributes of interest is difficult. The current Air Force maintenance data collection system does not provide direct measures of FFD, FFI, or FFA; however, it does record "cannot duplicate" events. A measurement of "cannot duplicate" events and number of maintenance actions could be used to derive a measure of false alarms. The field measurement of FFD and FFI, however, requires direct observation of what triggered the maintenance activity and how fault isolation was achieved. Other measures of FFD and FFI could be derived using system design information, maintainability demonstration and operational test and evaluation data, and testability modeling and analysis data.

Establishing relationships between system design characteristics and the testability attributes was feasible once measures of the attributes or surrogate measures were obtained. These design characteristics include number of elements, number of test points, number of feedback loops, degree of parallelism in the design, and connector dependency. An investigation of possible relationships between the design characteristics and the testability attributes was conducted using a limited data set and only one testability attribute, FFA. The preliminary results of the investigation indicated that a relationship exists between the degree of parallelism in a given design and the number of false alarms experienced by the system. In general, the feasibility of developing the relationships appeared to be promising.

Phase I Implications for Phase II

The continuation of the work into Phase II -- developing prediction procedures -- required that the difficulties in measuring the three testability attributes be overcome. Two different approaches were used to obtain the information necessary to develop measures of the three testability attributes. First, field data on maintenance actions and "cannot duplicate" events were gathered for a number of line replacement units (LRUs). From these field data, measures of upper limits on false alarms were then determined using an heuristic approach. The result was that cannot duplicate (CND) events could be used as an estimator (upper bound) of false-alarm events. Second, measures of fractions of faults detected and fraction of faults isolated were derived from the application of the System Testability and Maintenance Program (STAMP●) analysis model.

STAMP● is an artificially intelligent, computer-aided, design-for-testability (DFT) tool. It has been applied to a large number of systems, many of which are fielded. The results of STAMP● have been found to be consistent with field observations. The STAMP● testability model was chosen because of its compatibility with the project objectives and the availability of prior analyses in-house at ARINC Research Corporation.

STAMP● determines the internal information structure of systems being analyzed by examining the dependency topology of the functions within the system. As such, it is able to map the information that is or is not available at certain points within the system. The following two measures were chosen as surrogate measures of field testability parameters:

a. Isolation Level (IL) - Represents the number of isolation conclusions that can be reached by the information flow in the system. Isolation conclusion is the result of a fault isolation,* that is, a single element that has failed, a group of elements that contain the failure, or no fault found (sometimes referred to as RTOK in STAMP● nomenclature). It is normalized by the total number of conclusions possible. As such, it represents an upper bound on FFI. If a perfect implementation were possible, the IL and FFI should approach equality. In practice, actual test design implementation will not use the complete information flow in the system. (Chapter Four describes this parameter.)

b. Nondetection Percentage (NDP) - This represents the percent of isolation conclusions for which there is no supporting information flow and, as such, gives a measure of nondetection. The complement of this measure is detection percentage (DP=1-NDP) and represents the percent of conclusions for which there is sufficient testability.* This measure represents an upper bound on FFD. If a perfect implementation were possible, the two should approach equality. (Chapter Four describes this parameter.)

*For definition of these terms, see Appendix D.

As a result of the Phase I study, the measures to be used for representing the field testability characteristics of interest were to be developed from the following sources:

Testability Attribute	Source
- Cannot duplicate events	Field Data [combined organizational and intermediate (O/I) level]*
- Maintenance actions (MA)	Field Data (combined O/I level)*
- FFI	STAMP® testability analysis parameter isolation level (IL) used as an upper limit to FFI
- FFD	STAMP® testability analysis parameter detection percentage (DP) (complement of nondetection percentage) used as an upper limit to FFD

Those attributes were used either individually or in combination to develop testability characteristics as follows:

CND burden = CND/MA ≈ FFA (represents an upper limit)

CND rate = CND/operating hour ≈ FAR (represents an upper limit)

IL ≈ FFI (represents an upper limit)

1 - NDP ≈ FFD (represents an upper limit)

These estimators were the focus of the Phase II analysis.

*The merging of the AFTO-349 data for the O/I maintenance levels led to combining them for field data analysis.

PHASE II

Approach

Phase II technical objectives were to provide the basic form and substance of the prediction equations. The approach was developed through the following tasks:

- Collect data on a significantly large sample of systems and maintenance events.

- Develop a theoretical basis upon which to build relational equations.

- Analyze the collected data through regression analysis using the developed theoretical basis.

- Validate the prediction procedures by application to one or more data sets not used during development.

- Develop an applications oriented approach to the utilization of these predictor equations.

Results -- Data Base Development

AFTO-349 field data, which included CND information, were collected for 38 LRUs installed on three aircraft over one year of operations (May 1985 through April 1986). A total of 22,520 maintenance actions were tabulated. In addition, extensive compilation of design data on each of the 38 LRUs was based on the theoretical analysis of functionality and the data gathering forms developed during Phase II.

Testability analyses performed by STAMP® were available for 22 systems, including one system (F-15 Radar, AN/APG-63) in common with available field data. Similar extensive design data were gathered for each of these systems. The STAMP® data were supplemented with a number of "synthesized" systems to bring the total to 35 for the analysis of detection data. The table below provides a summary of observational data used in the analyses.

SUMMARY OF OBSERVATIONS

Testability Attribute	Estimator	Number of Systems LRUs	Number of Field Observations
FFA	CND burden	38	22,520
FAR	CND rate	38	22,520
FFI	IL	22	*
FFD	DP	35	*

*Not measurable by current reporting systems.

<u>The Analytical Development of Relationships</u>

A key element in the Phase II work was to avoid "blind" regression of masses of data. The objective of the analytical development task was twofold. First, identify measurable design characteristics to be used in regression analyses where the dependent variables are fraction of false alarms, fraction of faults isolated, and fractions of faults detected. Second, anticipate and explain the results of the regression analyses through coarse-scale analytical modeling.

To accomplish these goals, causally oriented taxonomic models of cannot duplicate events and failures were developed. These, together with literature surveys and interviews of testability and maintenance experts, were used to develop a comprehensive design data list. This comprehensive list was refined through several iterations into the system-level design data gathering forms described.

Further, analytical expressions were developed that related the dependent variables to 12 generic design characteristic classes shown in the list below.

FUNCTIONAL RELATIONSHIPS TO EXAMINE

Class	CND Rate ≈ FAR	CND Burden ≈ FFA	IL ≈ FFI	DP ≈ FFD
Operational Complexity	X	X	X	X
Topological Complexity	X	X	X	X
Functional Complexity			X	X
Environmental Factors	X	X	X	X
Transient Factors	X	X	X	X
Component Characteristics	X	X	X	X
Numbers of Components	X	X	X	X
Accessibility	X	X	X	X
Failure Rate	X		X	X
Documentation Quality	X	X	X	X
Topological Measures			X	X
Test Measures			X	X

Finally, many of the generic design characteristics were developed into analytic forms to aid in the setup of the regression analysis.

Prediction and Validation Results

Predictions were developed for each of the four parameters previously discussed. Their functional breakdown is presented below.

CND burden = f (accessibility, topological complexity, and environmental factors)

CND rate = f (failure rate, transient factors, and topological complexity)

IL ≈ FFI = f (topological measures, test measures, and component characteristics)

DP ≈ FFD = f (topological measures, test measures, component characteristics, and a number of others)

These functions were confirmed by the analytical model. The exact equations are presented in the text together with computation and measurement procedures necessary to make actual predictions.

The development of predictors, as guided by the analytic development of functionality, was moderately successful. The list below provides a summary of prediction correlations and validation results.

PREDICTION CORRELATIONS AND VALIDATION RESULTS

Testability Parameter	R^2 Correlation Before Validation	Validation Result	R^2 Correlation After Validation	Qualitative Evaluation of Predictor
CND Burden	0.63	Adequate	0.60	Fair
CND Rate	0.92	Excellent	0.91	Excellent
IL	0.80	Good	0.80	Good
DP	0.41	Poor	0.26	Unuseable

Validation was achieved by predicting one or more systems that did not participate in the data base. After validation, these systms were folded back in to improve the statistical significance of the data base.

Conclusions and Recommendations

This research yielded a number of useful insights into field-level testability. The data gathered and analyzed during this project represent a reasonable start on the problem of prediction of field-level testability attributes for complex electronic systems. The correlations for CND rate (an estimator for FAR) and IL (an estimator for FFI) are both sufficient to begin predictive work during design phases. The validation of these prediction equations is believed to be sufficient for their use as estimators for design compliance. There is some concern that a CND rate prediction is tied to the accuracy of a failure rate prediction.

Prediction of CND burden is marginal at this time for design compliance, but may be useful in a design review process as a flag pointing to potential problem areas. Detection percentage has not been well enough defined (in a mathematical sense) for use at this time.

The following actions are recommended:

- Develop a specification procedure for field CND rate as opposed to field false-alarm rate. This would provide a specified field testability parameter that is both field-measureable and predictable.
- Develop a specification procedure based upon the isolation level parameter to provide a specified field parameter that is predictable.
- Use CND rate and IL predictions during preliminary and critical design reviews as the basis for verifying or requiring manufacturer improvements in system testability.
- Use CND burden predictions as an early indicator of potential maintenance problems.

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CHAPTER ONE

INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

The goal of the research performed by ARINC Research Corporation was to build models that will, in some measure, predict organizational-level testability attributes of complex electronic equipment on the basis of design characteristics. Three basic attributes of the organizational-level maintenance system were considered:

- Fraction of faults detected (FFD)
- Fraction of faults isolated (FFI)
- Fraction of false alarms (FFA)
  OR
  False-alarm rate (FAR)

These have been determined to be the most commonly specified attributes of field-level testability. The project was performed in two phases, each with its own technical objectives. Phase I technical objectives were to provide the foundation for the development of the predictor model. Phase II technical objectives were to provide the basic form and substance of predictive equations.

1.1.1 Phase I Technical Tasks

Phase I was conducted through the following tasks and separately reported.[1]

- Survey the current literature and the personnel engaged in organizational-level maintenance.
- Compile and define location and types of data resources currently available.
- Develop a consistent mathematical structure that will permit the measurement of the required parameters and the development of consistent definitions.
- Determine the feasibility of developing useful prediction methods and identify the approaches necessary for such development.

1.1.2 Phase II Technical Tasks

Phase II was conducted through the following tasks:

- Collect data on a significantly large sample of systems and maintenance events.
- Develop a theoretical basis upon which to build relational equations.
- Analyze the collected data through regression analysis using the developed theoretical basis.
- Validate the prediction procedures by application to one or more data sets not used in the above-mentioned development.
- Develop an applications approach to the utilization of these prediction equations.

These tasks are described in this report.

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[1] Prediction and Analysis of Testability Attributes: Organizational-Level Testability Prediction. W. R. Simpson, J. H. Bailey, K. B. Barto, and E. Esker, RADC-TR-85-268, Phase I Report, Rome Air Development Center, Griffiss AFB, New York, February 1986.

1.2 BACKGROUND

As a result of increased system complexity and sophistication, the maintenance of electronic systems is becoming more difficult and costly, despite advances in automatic test equipment.[2,3] Testability design is usually approached from the bottom up, with component and board testability designed in, but with little attention given to isolation of the individual unit in the full system. Current design of systems and tests frequently results in long test times and high ambiguity levels for fault isolation. False-alarm and "retest-OK" (RTOK) rates of 40 percent and greater are not uncommon in many avionic systems. Studies of the F-16 aircraft[4] and the CH-54 helicopter[5] have shown that troubleshooting can consume 50 percent or more of the total man-hours expended on repair. Avionics Maintenance Conference reliability reporting statistics indicate similar trends in avionics repairs for the scheduled air carriers.[6]

1.2.1 The Testability Discipline

Testability is coming to be recognized as a valid and useful engineering discipline. The recent publication of a testability

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[2] George W. Neuman, Testing Technology Working Group Report (IDA/OSD R&M Study), Institute for Defense Analysis, IDA D-41, August 1983.

[3] William L. Kiener and Anthony Coppola, "Joint Services Program in Design for Testability," Proceedings, Annual Reliability and Maintainability Symposium, 1981, pg. 268.

[4] Special Report on Operational Suitability (OS) Verification Study Focus on Maintainability, M. L. Labik, G. T. Harrison, and B. L. Retterer, ARINC Research Corporation, Report 1751-01-2-2395, February 1981.

[5] Thomas N. Cook and John Ariano, "Analysis of Fault Isolation Criteria/Techniques," Proceedings, Annual Reliability and Maintainability Symposium, 1980, pg. 29.

[6] Avionics Maintenance Conference Report, AMC Publication 84-083/MOF-28, May 25, 1984.

standard[7] is evidence of the increasing importance of testability in the development of military systems. A system has good testability when existing faults can be confidently and efficiently identified. Confidence is achieved by frequently and unambiguously identifying only the failed components or parts, with no removals of good items and with minimum loss of time due to false indications or false alarms. Efficiency is achieved by minimizing the resources required, such as man-hours, test equipment, and training.

1.2.2 Testability as a Design Variable

The number of tests and the information content of test results, together with the location and accessibility of test points, define the testability potential of an equipment. Testability is, of course, a design-related characteristic. There are few standardized tools for the evaluation of design testability, particularly at the organizational level. In fact, a review of the current literature suggests that even common definitions of testability are hard to find. For example, Malcolm[8] states that built-in-test (BIT) false alarms can be one of two types: a BIT indication when there are no faults and a BIT indication when the fault is in another unit. MIL-STD-1309[9] defines a false alarm as a fault indication where no fault exists. Whether these two definitions are consistent depends on individual interpretation.

For testability to be appropriately and consistently incorporated into the design process, standard definitions, procedures, and tools must be developed to evaluate and predict organizational-level testability

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[7] Testability Program for Electronic Systems and Equipments, MIL-STD-2165, 26 January 1985.

[8] J. G. Malcolm, "BIT False Alarms: An Important Factor in Operational Readiness," Proceedings, Annual Reliability and Maintainability Symposium, 1982, pg. 206.

[9] Definitions of Terms for Test, Measurement, and Diagnostic Equipment, MIL-STD-1309, 30 May 1975.

attributes. A testability evaluation should provide not only predictions but also applicable redesign information when testability attributes are predicted to be below desired levels.

2.3 Testability and Organizational-Level Maintenance

It is at the organizational level that system faults are first detected. In many instances, the organizational-level maintenance is collocated with and co-reported with the intermediate-level maintenance. The interaction of subsystems complicates fault identification and detection. Organizational-level testability is a primary influence on mission readiness, and lack of fault detection at this level can lead to mission failure. Of the many testability attributes explored, three are directly related to the ability of complex electronic systems to meet mission requirements:

- Fraction of Faults Detected - Ideally, FFD should be 100 percent. Any fault not detected prior to a mission, either by BIT, built-in-test equipment (BITE), or by maintenance operations ready (OPSREADY) test, could result in a failed or aborted mission. Further, if the failure is not detected during or after completion of the mission, the following mission could be jeopardized. In reality, some system faults are less critical than others, and an FFD smaller than 100 percent might be tolerable.

- Fraction of Faults Isolated - The ideal value of FFI is 100 percent. If a detected failure is not isolated quickly and efficiently, the system may not be mission-ready for a long time. To meet the mission-ready requirement, maintenance crews may "change out" entire mission-critical systems or spend a great deal of time using "shotgun" maintenance approaches. These practices complicate already difficult sparing and logistics problems and add to system life-cycle costs. Measures associated with FFI are mean time to fault isolate (MTFI) and mean time to repair (MTTR), as well as ambiguity group statistics and RTOK rates.

- Fraction of False Alarms - The ideal value of FFA is zero; FFA is a complementary factor of FFD. When BIT/BITE or OPSREADY checks indicate failures that cannot be duplicated or isolated because they do not exist, the system is held in a pre-mission-ready status while checks are run and rerun. A high FFA, like a low FFI, leads to system change-outs or shotgun maintenance approaches.

- False Alarm Rate - The rate of occurrence of false alarms. The ideal value is zero. It is computed as a time-normalized sum of false alarms, where the time normalization is either calendar or operating hours.

1.3 REPORT ORGANIZATION

Chapter Two of this report provides a brief overview of the Phase I work and its impact on the Phase II program. Chapter Three details the analytical background to be applied to both the data gathering and equation development. Chapter Four presents a detailed summary of the data gathering efforts and the data used during the analysis.

Chapter Five is an explanation of the data analysis and regressions, including the prediction results and their verification. Chapter Six includes the recommended application of these predictors. It also includes the information necessary to compute all of the variables necessary to apply these equations. Our conclusions and summary are presented in Chapter Seven.

Appendixes A through E include comprehensive design data lists, data gathering forms, regression variables, a glossary, references, and bibliography.

CHAPTER TWO

OVERVIEW

2.1 REVIEW OF PHASE I

Complex interactions occurred between work performed in Phases I and II. These interactions affected the ground rules and structure of Phase II. The purpose of Phase I was to structure the problem of field-level testability prediction so that a consistent mathematical basis could be used in the development of prediction techniques. A key element was in the defined breakdown of the primary analysis parameters of FFD, FFI, and FFA.

The definitions and mathematical frameworks were developed through the application of three different approaches to modeling the organizational-level maintenance process:

- Set Theory Model - Model was developed through the use of Venn diagrams and set-membership approaches to derive definitions and algorithms.

- Modified State Model - Model based on the combination of actions at the organizational-maintenance level necessary to discover the system state (e.g., failed or nonfailed).

- Flow Model - Model that traces the flow of systems and subsystems through the organizational level maintenance process.

The use of the different approaches had several advantages; two of these advantages were the following:

- The insights and visibility into the interpretation, make-up, and logical content of a testability attribute afforded through the use of one modeling approach were often superior to those provided by another. Further, the different viewpoints provided by each of the modeling approaches combined to provide insights into the form and content of the attributes that could not have been provided by the application of a single model.

- The use of the three modeling approaches provided a means for crosschecking the results of the models. Because all three approaches model the organizational-level maintenance process, the three models must provide consistent results.

The Phase I report describes the models and algorithms used to develop the definitions and evaluation procedures for the three testability attributes, as well as data sources, definitions, and feasibility of developing predictors.

The feasibility of developing prediction procedures for the three testability attributes was determined based upon two major criteria: (1) the ability to measure FFD, FFI, and FFA in currently fielded systems and (2) the ability to relate specific design parameters to measured values of the testability attributes. If these criteria could be satisfied, the development of prediction procedures would be considered feasible.

Field measurement of the three testability attributes of interest is difficult. The current Air Force maintenance data collection system does not provide direct measures of FFD, FFI, or FFA. The maintenance data collection system does record cannot duplicate (CND) events, and a measurement of CND events and maintenance actions could be used to derive at least an upper limit on false alarms. The field measurement of FFD and FFI, however, requires direct observation of what triggered the maintenance activity and how fault isolation was achieved. Other measures of FFD and FFI can be derived using system design information, maintainability demonstration and operational test and evaluation data, and testability modeling and analysis data.

Establishing relationships between system design characteristics and the testability attributes should be feasible once measures of the attributes can be obtained. These characteristics include number of elements, number of test points, number of feedback loops, degree of parallelism in the design, and connector dependency. An investigation of possible relationships between the design characteristics and the testability attributes was conducted in Phase I using a limited data set and only one testability attribute, FFA. The preliminary results of the investigation indicate that a relationship exists between the degree of parallelism in a given design and the number of false alarms experienced by the system. In general, the feasibility of developing the relationships appeared to be promising.

2.2 PHASE I IMPLICATIONS TO PHASE II

The continuation of the Phase II work toward developing prediction procedures required that the difficulties in measuring the three testability attributes be overcome. Two approaches were used to obtain the information necessary to develop measures of the three testability attributes. First, field data on maintenance actions and CND events were gathered for a number of line replaceable units (LRUs). Measures of upper limits on false alarms were then obtained from this field data. The result was that we used CND events as an estimator (upper bound) of false-alarm events. Second, measures of fractions of faults detected and fraction of faults isolated were derived from the application of the testability analysis model System Testability and Maintenance Program (STAMP®).

STAMP® is an artificially intelligent, computer-aided, design-for-testability tool.[10] It has been applied to a large number of systems, many of which are fielded. The results of STAMP® have been found to be

[10] W. R. Simpson, "Stamp Testability and Fault-Isolation Applications, 1981-1984," Proceedings of IEEE 1985 Autotestcon, Long Island, New York, October 1985.

consistent with field observations.[11] The STAMP® testability model was chosen because of its compatibility with the project objectives and the availability of prior analyses performed at ARINC Research Corporation.

Two measures within STAMP® -- isolation level (IL) and nondetection percentage (NDP) -- were chosen as surrogate measures of field testability parameters. STAMP® determines the internal information structure of systems being analyzed by examining the dependency topology of the functions within the system. As such, it is able to map the information that is or is not available at certain points within the system. The IL and NDP represent the following:

- Isolation Level - IL represents the number of isolation conclusions that can be reached by the information flow in the system. It is normalized by the total number of conclusions possible. As such, it represents an upper bound on FFI. This upper bound assumes a uniform failure probability. If the factor were weighted for failure rate, it would be almost identical to a field-measured FFI potential. Perfect implementation and relative failure rate weighting would be essential for isolation level and fraction of faults isolatable to approach equality. In practice, actual test design implementation will not use the complete information flow in the system (see Chapter Four for additional discussion of this parameter).

- Nondetection Percentage - NDP represents the percent of conclusions for which there is no supporting information flow and, as such, gives a measure of nondetection. The complement of this measure is detection percentage (DP=1-NDP) and represents the percent of conclusions for which there is supporting information flow. This measure represents an upper bound on FFD. If a perfect implementation were possible, the two should approach equality. (See Chapter Four for additional discussion of this parameter.)

As a result of the data base used for developing the predictor equations, the Phase II work involves field estimators that represent upper

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[11] W. R. Simpson, and J. R. Agre, "Experiences Gained in Testability Design Tradeoffs," Proceedings of the 1984 IEEE Autotestcon Conference, Washington, D.C., November 1984.

limits of the desired parameters. These synthesized measures are the following:

Testability Attribute	Source
- CND (Cannot Duplicate) Events	Field Data (combined O/I level)*
- MA (Maintenance Actions)	Field Data (combined O/I level)*
- FFI	STAMP® Testability Analysis Parameter Isolation Level used as an upper limit to FFI
- FFD	STAMP® Testability Analysis Parameter Detection Percentage (Complement of nondetection percentage) used as an upper limit to FFD

The attributes were used either individually or in combination to develop testability characteristics as follows:

CND burden = CND/MA ≈ FFA (represents an upper limit)

CND rate = CND/operating hour ≈ FAR (represents an upper limit)

IL ≈ FFI (represents an upper limit)

1 - NDP ≈ FFD (represents an upper limit)

These estimators were then the focus of the Phase II analysis as described in the balance of this report.

*The merging of the AFTO-349 data for the organizational and intermediate (O/I) maintenance levels led to combining them for field data analysis.

CHAPTER THREE

ANALYTICAL DEVELOPMENT

3.1 INTRODUCTION

The objective of the analytical development task was twofold. First, identify measurable design characteristics to be used in regression analyses where the dependent variables are fraction of false alarms, fraction of faults isolated, and fraction of faults detected. Second, anticipate or explain the results of the regression analyses through coarse scale analytical modeling.

One of the conclusions of Phase I of this program was that the testability attributes FFA, FFI, and FFD were not compatible with current Air Force maintenance reporting systems and are, therefore, not readily obtainable. Consequently, these attributes were replaced by surrogate measures for the purposes of completing Phase II of this program. Cannot duplicate events, isolation levels, and detection percentages were substituted for FFA, FFI, and FFD, respectively. (See Chapter Two for explanations of the choice of these surrogates and their relationships to the original testability attributes.)

As the original testability attributes were replaced by surrogate measures, so was the approach of the analytic development task. Identification of design characteristics was undertaken to provide the necessary data for statistical regressions on the surrogate attributes. The most significant impact of this modification was in the regression on CND. Whereas IL and DP approximate FFI and FFD, respectively, FA is a proper subset of CND.[1] The net result was that CND, FFI, and FFD were used as the basis for design characteristic identification and for the subsequent analytical modeling.

This task was accomplished in three steps: unrestricted design characteristic identification, selection of measurable characteristics, and interactive refinement during regression analyses. In the sections that follow, these steps and their results are described.

3.2 UNRESTRICTED DESIGN CHARACTERISTIC IDENTIFICATION

The process of identifying design characteristics that can affect the testability attributes CND, FFI, and FFD began with a study of the models for organizational maintenance developed during Phase I of this effort. Particular attention was paid to the Set Theory Model.[1] This model served as the basis for the development of a causally oriented taxonomy of CND (Figure 3-1) and a maintenance-oriented classification of failure events (Figure 3-2). These classifications are discussed in detail in Section 3.4.

A review of pertinent literature, including textbooks, published reports, technical journals, and appropriate military documents, was undertaken. A list of the literature reviewed in this task is included in the bibliography in Appendix D. Also, interviews were conducted with maintenance and reliability experts in the Air Force and at ARINC Research. The results of those investigations were first used to refine and verify the taxonomic models described above. Then, using the models as a basis, further investigations produced an unrestricted list of design characteristics ("wish list") that the research indicated might affect the testability attributes. The goal was to ensure that we would have a superset of the characteristics necessary for successful regression analyses. This "wish list" of design characteristics is given in Appendix A.

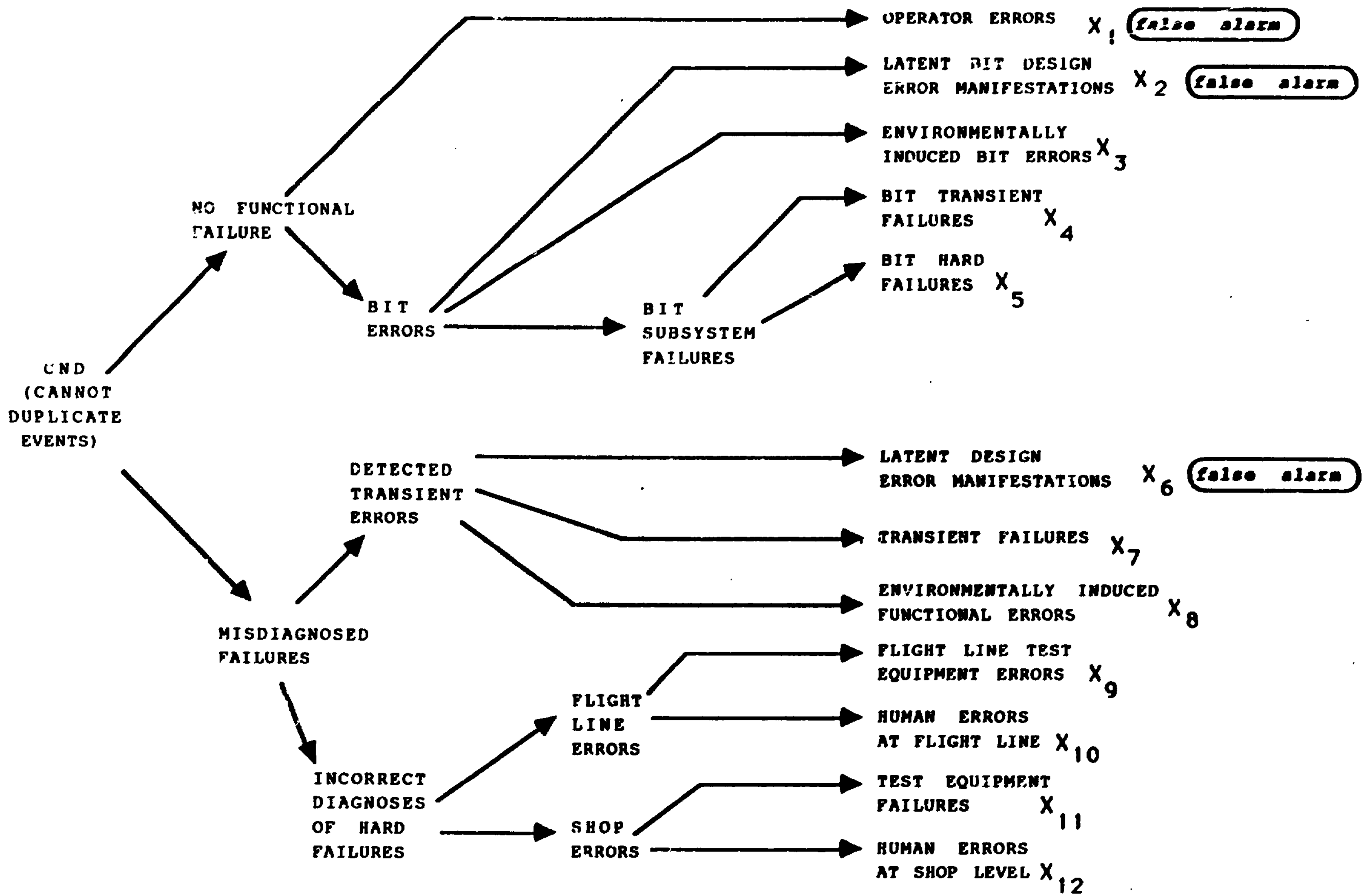

FIGURE 3-1

CAUSALLY ORIENTED TAXONOMY OF CANNOT DUPLICATE EVENTS

(Note: False alarms constitute a proper subset of CND)

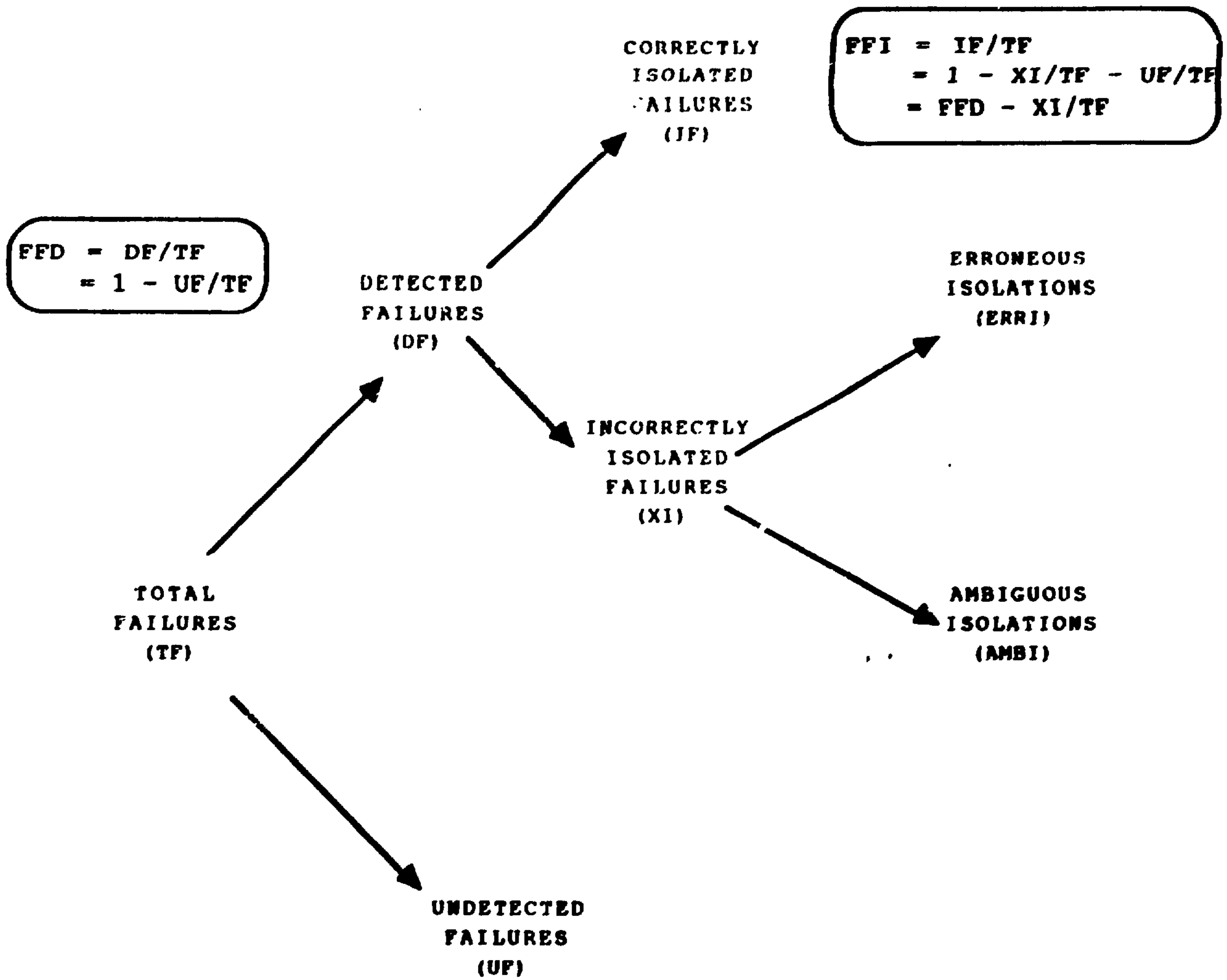

FIGURE 3-2

TAXONOMY OF FAILURES

(The appropriate dichotomies permit the separation of fraction of faults detected and fraction of faults isolated. Note: branch identified "Incorrectly Isolated Failures" represents an area of overlap with cannot duplicate events).

3.3 SELECTION OF MEASURABLE DESIGN CHARACTERISTICS

The list in Appendix A is a set of characteristics meaningful for prediction of testability attributes but not necessarily attainable within the scope of this project. A number of compromises were made to the data set based upon the following criteria:

- Attainable Measures - In places where levels of detail were beyond the engineering labor scope or simply not easily available, meaningful combined measures were sought (see discussion below). Furthermore, each of the measures should be attainable without special structuring of the analysis. For example, the theoretical workup indicated that sneak circuit parameters may indeed be important to the prediction of field CND. None of the systems chosen were analyzed for sneak circuits because such an analysis was well beyond the scope of this project. However, certain internal characteristics of LRUs, such as SRU-LRU interconnects, were available in the documentation, and these were acquired in hopes of developing some sneak circuit-related parameters.

- Universality of Measures - Measures that applied to a specific small subset of the data, but were not applicable to a larger class of systems or were not attainable in a statistically significant number of different electronic systems, were not sought.

- Prediction Applicability - A design measure should be quantifiable by a testability analyst at the time a prediction is normally performed.

Our initial goal was to have a set of design characteristics for each system such that an individual could acquire all of the necessary data within two to three hours by reviewing technical orders and interviewing Air Force maintenance personnel. In practice, the actual data acquisition efforts varied between 1 hour and 16 hours for each LRU examined.

A number of documentation sets (i.e., Technical Orders) were reviewed and analyzed. As a consequence, the level of detail inherent in the design characteristic "wish list" had to be reduced. For example, the unrestricted set of design characteristics required information descriptive of such items as the logic family, level of integration, bandwidth, and packaging for each integrated circuit in a system under analysis. Because Air Force Technical Orders typically only identify a component as being an integrated circuit, only the numbers of integrated circuits in a given design were deemed to be available characteristics for this study. A standard work form was prepared and, subsequently, used to gather design characteristic data during field trips. This work form of measurable design characteristics is shown in Appendix B.

3.4 INTERACTIVE REFINEMENT OF DESIGN CHARACTERISTICS

The goal of this subtask was twofold. First, prior to the regression analysis task, coarsely forecast the dependency of the testability attributes on the various measured and synthesized design characteristics. As such, this required synthesizing appropriate characteristics. A synthesized characteristic is derived from measured characteristics. It is used to describe some behavioral aspect of a design that is not directly measurable due to laws of physics or resource limitations. A second goal of this subtask was (as the regression analysis progressed) to justify any unexpected findings by incorporating the results in the analytical model. Due to a lack of resolution imposed by the coarse scale of the design characteristics measured, the analytical model was restricted to basic, first-order relationships. The subsections that follow explain the resulting model.

3.4.1 Taxonomic Models

3.4.1.1 The Taxonomic Model of CND Events

The Phase I modeling effort showed that all of the testability attributes in question are intimately tied to the field CND problem. For example, in each of the three models developed during Phase I, CND appears in every one of the testability attributes examined (FFD, FFI, FFA, and FAR). To that end, the taxonomic model of CND was developed in the greatest detail. Each of the parameters developed for CND will affect all of the other attributes, and the functionality of any parameter that appears in CND may be expected to appear in each of FFI and FFD. The basic taxonomic model of CND events that will yield parameters for all of the testability attributes is given in Figure 3-1. As shown in the figure, CND can have 12 constituent subclasses, 5 of which represent CND events that are false alarms by the given definitions of Phase I work. The 12 constituent subclasses of CND are the following:

1.* Operator Error - The operator of the system containing the unit under test incorrectly used the unit, incorrectly interpreted unit behavior, or both; the operator erroneously perceived and reported a malfunction, and no malfunction subsequently can be duplicated by maintenance personnel.

2.* Latent Built-In Test Design Error Manifestation - As a product of coincidence, an appropriate sequence of events occurs that causes a latent BIT design error to manifest itself; maintenance personnel subsequently cannot duplicate the sequence of events that precipitates the error manifestation.

3. Environmentally Induced BIT Error - Environmental conditions, such as vibrations, pressure, and temperature, cause transient behavior in the BIT system such that a malfunction is erroneously reported; maintenance personnel subsequently cannot reproduce the conditions that caused the transient behavior.

4. BIT Transient Failure - Component degradation in the BIT subsystem causes a failure of a transient nature, resulting in an erroneous report of a malfunction in the host system, and the transient behavior subsequently is not exhibited during testing by maintenance personnel.

5. BIT Hard Failure - A failure occurs in a BIT subsystem, a malfunction of a system is reported, and the suspect system is not host to the accusing BIT; maintenance personnel subsequently verify the unit to be good.

6.* Latent Design Error Manifestation - As a product of coincidence, an appropriate sequence of events occurs that causes a latent design error in a system to manifest itself; subsequently, maintenance personnel cannot duplicate the sequence of events that precipitates the error manifestation.

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*Subclass is a false alarm as denoted in Prediction and Analysis of Testability Attributes: Organizational-Level Testability Prediction. W. R. Simpson, J. H. Bailey, K. B. Barto, and E. Esker, RADC-TR-85-268, Phase I Report, Rome Air Development Center, Griffiss AFB, New York, February 1986.

7. Transient Failure - Component degradation in the system causes a failure of a transient nature, resulting in a report of a malfunction of the system; the transient behavior subsequently is not exhibited during testing by maintenance personnel.

8. Environmentally Induced Functional Error - Environmental conditions, such as vibrations, pressure, and temperature, cause transient behavior in the system, such that a malfunction is reported; subsequently maintenance personnel cannot reproduce the conditions that caused the transient behavior.

9. Flight Line Test Equipment Error - An error in the test equipment used at the flight line identifies a good unit under test as being faulty; subsequent maintenance levels verify that the suspect unit is not faulty.

10. Human Error at Flight Line - A human error at the flight line results in identifying a good unit under test as faulty; subsequent maintenance levels verify that the suspect unit is not faulty.

11. Shop Test Equipment Failure - An error in the test equipment used at the shop level identifies a faulty unit under test as being good.

12. Human Error at Shop Level - A human error at the shop level results in the identification of a faulty unit under test as being good.

Maintenance personnel are unaware of the subclassifications, and we assume that they follow normal system maintenance (NSM) techniques. Also, the subclasses with operator errors and latent design error manifestations (both in BIT and the host system) -- noted by asterisks -- are false alarms according to the definitions set forth by Simpson et al.[1] A much larger set of subclasses, each of which deals with combinations of the subclasses across different maintenance levels, was considered to be lower order terms and was beyond the scope of this effort.

3.4.1.2 The Taxonomic Model of System Failure Events

In addition to the factors driving CND, one would expect a further influence in the detection and isolation of failures that is tied strictly to the inherent testability of the system. These factors may be explored by use of the taxonomic model for system failures given in Figure 3-2.

The taxonomic model for system failures first dichotomizes the total failures into the subclasses of detected and undetected failures. The ratio of the numbers of detected failures to that of total failures constitutes the testability attribute FFD. The detected failures are further dichotomized into those that are correctly isolated and those that are not. The ratio of the numbers of correct isolations to the total number of failures is the testability attribute FFI.

There are two types of incorrect isolations. The first is the erroneous isolation; the wrong unit or component is determined to be faulty. In Reference 1 this is termed a nonisolation. The second type of incorrect isolation results from ambiguous diagnosis. In Reference 1, this is termed an improper isolation. During the fault isolation process, if the procedure yields a class of potentially bad units, and the test procedures do not allow the resolutions to discriminate the faulty from the good units within the class, that class is called an ambiguity group. By necessity the entire class, both good and bad units, must be sent up to subsequent maintenance levels. The faulty units within the class are considered to be correct isolations. The good units within that class represent incorrect isolations resulting from ambiguous diagnosis. In Figure 3-2 this particular branch of the failure taxonomy corresponds to the "misdiagnosed failure" branch of the CND taxonomic model (Figure 3-1). This serves to verify the pervasive role of the CND testability attribute in the measurement of both FFI and FFD.

3.4.2 CND Causal Relationships that Affect all Testability Attributes

The CND causal relationships are central to all of the testability attributes that we are trying to predict. The functions derived here will be used in the regression analyses for CND burden, CND rate, isolation level, and detection percentage. From Figure 3-1, we recognize that CND events represent a composite of 12 causal subclasses. It is, therefore, possible to write an equation for CND that sums the members of those subclasses as follows:

$$\text{Number of CND events per unit time} = \sum_{i=1}^{12} x_i$$

where x_i is the number of CND occurrences per unit time due to the i^{th} causal subclass as shown in Figure 3-1.

Further, from the taxonomic model of Figure 3-1, we know that the false alarms represent specific subclasses as follows:

$$x_1 + x_2 + x_6.$$

We now examine the functional relationships between the causal subclasses of CND, represented by x_i, and measurable design characteristics. These functional relationships will provide guidance as to design data for use with regressions in the development of predictive equations for the desired testability attributes.

3.4.2.1 Operator Error (x_1)

Operator errors are functions of design characteristics that are somewhat nebulous and not easily measured. Those characteristics relate to the operational complexities of the host system that affect a particular LRU and to the level and quality of support provided to the system operators. The latter of these is a function of such characteristics as operator experience, operator training background, average operator intelligence, and level and quality of support documentation. This class of design characteristics was well outside the scope of this project. Thus, the effect of operator support was eliminated from consideration.

Operational complexity has been well studied. Work in the area of sneak circuit analysis suggested that design characteristics relating to operational complexity were measurable. Our investigations indicated that operational complexity would be a function of the following:

- The number of controllable functions performed by LRU
- The number and kind of LRU-related operator controls
- The number and kind of LRU-related indicators
- Control labels related to LRU operation
- The surface area of LRU-related control panels

Of these, the only measurable characteristics (or surrogate measures) were the number of LRU functions, number of external switches on LRU, and number of indicators on the LRU. We believe that these characteristics have a compounding nature and vary with operational complexity. The compounding nature would be represented by a product. Thus, the operator errors term reduces to the following:

$x_1 = f_1$ [(numbers of LRU functions) * (numbers of external switches) * (numbers of indicators)]

3.4.2.2 Latent BIT Design Error Manifestations (x_2) and Latent Design Error Manifestations in LRU Functions (x_6)

Latent design error manifestations, both in BIT and LRU functions, are predominately functions of sneak circuits. Unfortunately, sneak circuit analysis was outside the scope of this effort, and neither the sneak circuit analysis nor the design characteristics required for such an analysis was acquired. However, a surrogate measure of topological complexity was derived based on the concepts inherent in sneak circuit analysis. As such, this synthesized characteristic, topological complexity (TC), served as an independent variable in the functional relationships for x_2 and x_6.

$$x_2 = f_2 \quad \text{(Topological Complexity, BIT)}$$
$$x_6 = f_6 \quad \text{(Topological Complexity)}$$

Note that the topological complexity of the BIT subsystem is approximated by that of the LRU. This is because such a measure for the BIT subsystem was not attainable. Also, note the variable BIT is a 1 if there is a BIT subsystem, otherwise it is 0. Both x_2 and x_6 should correlate positively with topological complexity. This term, in one form or another, is expected to influence each of the testability attributes.

Topological Complexity: The objective of a measure of topological complexity is to quantify the likelihood that a latent design error exists within a system. Research in the area of sneak circuit analysis has produced an analytic technique for relating latent design errors to system topologies and component make-up. Consequently, sneak circuit analysis served as the starting point for synthesizing a topological complexity characteristic. Two approaches were pursued:

- Measures based on analyses of high-level functional descriptors available in Air Force Technical Orders

- Measures based on more in-depth design analyses

Sneak circuit analysis involves the decomposition of a system into five constituent topological patterns (see Figure 3-3). These topological patterns increase in complexity from a "single-line pattern" to an "H-pattern." Each pattern has associated with it a number of sneak circuit analysis "clues" for application during the evaluation of a system. The number of clues for the topological patterns increases with the complexity of the pattern. That is to say, the single-line pattern has several associated clues, whereas the H-pattern has well over 100 associated

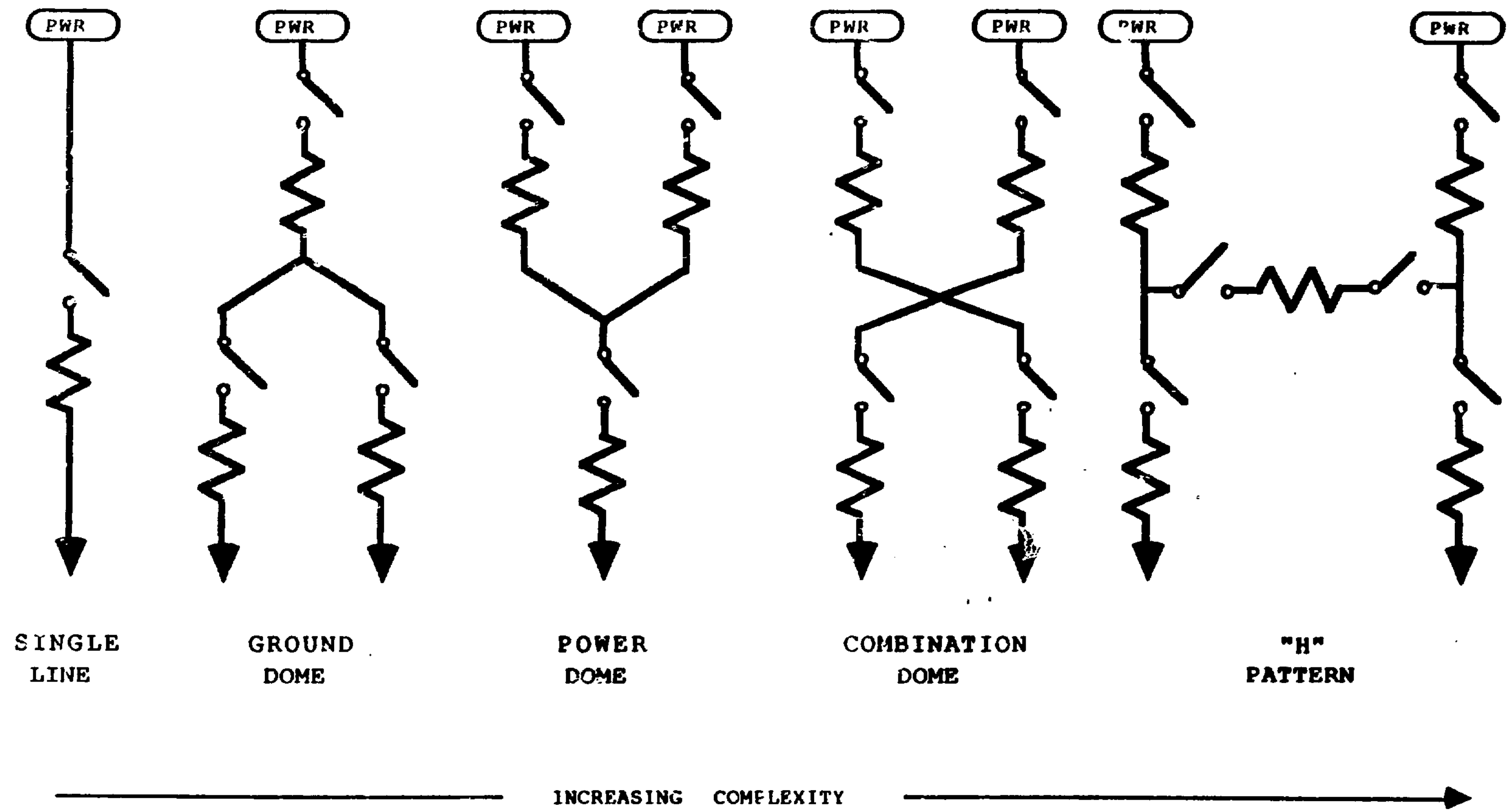

FIGURE 3-3

TOPOLOGICAL PATTERNS FOR SNEAK CIRCUIT ANALYSIS

(Characteristics of the topological patterns are the number of input and output elements (power feeds and grounds), the number of switches, and the number of loads. The characteristics increase as the complexity of the patterns increase. Further, the number of clues for identifying sneak circuits also increases.)

clues. Based on the numbers of associated clues, we reason that the likelihood of finding a sneak circuit increases with the complexity of the topological pattern. It is reasonable to conclude that a linear combination of the numbers of each type of topological pattern found in a system could be used to characterize the likelihood of sneak circuits being present in that system.

If we were to endeavor to analyze a system by counting the various topological patterns, we would be well advised to complete the sneak circuit analysis and correct any latent design errors found. The cost of performing such an analysis is high (prohibitively so for this effort).

Initially, we explored several surrogate measures based on high-level functional block diagrams. One of these was a measure of parallelism that was shown to have a high correlation with CND burden in Phase I.[1] Similar measures were obtained by characterizing the number of nodes and branches in the functional block diagrams and normalizing by both the number of functional blocks and by the number of shop replaceable units (SRUs). In general, these measures are subject to great variation due to differences in documentation. Therefore, we endeavored to develop more stable measures.

To this end, we observed that the essential elements in the sneak circuit topological patterns are switches and input and output (IO) signals (i.e., power feeds and grounds). Further, as shown in Table 3-1, the topological patterns can be characterized by the products of their input and output signals and switches. This product varies strongly with the complexity of each pattern, as do the numbers of associated clues. It stands to reason that we might expect a summation of these products to characterize the likelihood of sneak circuits in a system.

Given the design characteristics that were deemed to be measurable for the purposes of this study, the most we were able to accomplish was to approximate a summation of the topological pattern products. Our surrogate measure characteristic is a product of the number of connections to each

TABLE 3-1

SNEAK CIRCUIT TOPOLOGICAL PATTERN COMPLEXITY

Topological Pattern	IO Signals	Switches	IO x Switches
Single Line	2	1	2
Ground Dome	3	3	9
Power Dome	3	3	9
Combination Dome	4	4	16
H-Pattern	4	6	24

SRU within a given LRU and a linear combination of the components on each SRU that could serve as switches. This linear combination is necessary to allow for the different types of components that may possess different inherent switching capabilities (e.g., integrated circuits versus transistors).

3.4.2.3 Environmentally Induced BIT Errors (x_3) and Environmentally Induced Functional Errors (x_8)

Environmentally induced errors in both the BIT subsystem and in the functional LRU are, by definition, functions of environmental factors. Because the scope of the study did not allow detailed analysis of the BIT subsystems, the assumption was made that BIT is subject to the same environment as the LRU under analysis. Thus, we obtain the following expressions:

$x_3 = f_3$ (environmental factors, BIT)
$x_8 = f_8$ (environmental factors)

The environmental factors deemed measurable in the study were thermal, contamination, mechanical, and electrical. It is expected that f_3 and f_8 are linear combinations of these factors. Although harsh environments are known to have an impact on failure rates of electronic equipment, the degree to which the environment contributes to transient behavior and, consequently, CND events, is not well understood. For instance, at first glance, we would expect a complex electronic system under high environmental stresses to exhibit high transient failure rates and high CND rates. However, especially in military systems, designers are extremely cautious when designing equipment for such environments. This design philosophy should lead to reduced overall CND rates simply because of the high reliability of the systems. Therefore, CND rates may actually vary inversely with environmental factors and still vary with CND as a percentage of overall maintenance actions.

3.4.2.4 BIT Transient Failures (x_4) and LRU Functional Transient Failures (x_7)

Transient failures, in general, can result from degrading and marginal components. It is possible that environmental factors have some type of compounding effect; however, for every stable component that environmental stress forces into a marginal region of operation, there are likely present other marginal components that may be stressed to hard failure. Thus, we expect marginal behavior to depend largely on the types of components used and their failure mode characteristics and on the application characteristics of the parts.

For BIT transient failures, we can apply the following:

$$x_4 = f_4 \text{ (BIT component characteristics)}$$

Because the data gathering resolution did not permit an evaluation of the BIT subsystem level, the component characteristics of the host LRU were assumed to include the BIT subsystem. Therefore,

$$x_4 = f_4 \text{ (component characteristics, BIT = 1)}.$$

For LRU transient failures,

$$x_7 = f_7 \text{ (component characteristics)}.$$

The component characteristics deemed measurable are simply counts of different types of parts (e.g., number of integrated circuits and number of resistors). It is expected that their effects on their own transient behavior are, for the most part, independent. The equations may be rewritten as follows:

$$x_4 = f_4 \left[\sum_{i=1}^{n} A_i \text{ *(number of components of type i), BIT} \right],$$

and

$$x_7 = \sum_{i=1}^{n} B_i \text{ *(number of components of type i)},$$

where n is the number of distinct component types, and A_i and B_i are relative weights.

3.4.2.5 BIT Hard Failures (x_5)

The hard failures that occur in the BIT subsystem are typically predicted based on reliability characteristics of the subsystem constituent components. Therefore, a preliminary equation can be written:

$$x_5 = f_5 \text{ (BIT component characteristics)}.$$

Because data on BIT component characteristics were not available for this study, we made the somewhat tenuous assumption that the BIT component characteristics are similar to those of the LRU it monitors. Thus the equation was rewritten:

$$x_5 = f_5 \text{ (LRU component characteristics, BIT)}.$$

In any BIT subsystem, the hard failures are functions of the failure rates of the BIT's constituent components. Component failure rates are, to a large degree, independent phenomena. Therefore, a linear combination of component-type counts may be used to predict subsystem failure rates, where the coefficients chosen by regression are proportional to the failure rates of the respective component types.

In keeping with our assumption, the BIT hard failures may be expressed as a function of the component-type counts of the LRU under test.

$$x_5 = f_5 \left[\sum_{i=1}^{n} C_i \text{ *(number of components of type i), BIT} \right].$$

3.4.2.6 Test Equipment Errors at Flight Line (x_9)

The performance characteristics of the test equipment used at the flight line can best be estimated by achieving a thorough understanding of the equipment, its design, and its operational environment. None of these data were available to this study. As such, this term was eliminated.

3.4.2.7 Human Errors at Flight Line (x_{10})

Human errors at the flight line are thought to be a function of personnel training and support, test procedure complexity, accessibility, and the failure rates of the specific LRUs. The first of these, personnel training and support, was a characteristic unavailable to this study. The second, test procedure complexity, was measured in a gross fashion -- counting the number of pages in the Technical Orders (TOs). This method has an inherent bias that is not easily overcome, because different vendors use different documentation styles. One possible solution to this dilemma is to draw a ratio of the flight line documentation page counts to the page count of the illustrated parts breakdown (IPBs). This should remove both style and LRU complexity biases. The third characteristic, accessibility, is a function of volume, weight, the number and types of connectors, and other factors that affect removability. In the case of poor accessibility, the unit is less likely to be removed if the evidence of failure is less than overwhelming. The fourth characteristic, LRU failure rate, may be the most important of the three. The more often something fails, the more likely it is to be replaced whether it is good or bad. (An example is the multiple replacement strategies commonly used for such items as spark plugs in automobile maintenance -- replacing all plugs rather than isolating a failed plug.) The equation may now be written:

$$x_{10} = f_{10}\left(\frac{\text{page counts in TO}}{\text{page counts in IPB}},\ \text{accessibility, failure rate}\right).$$

There are reasons to suspect that test complexity factors are compounded by failure rates at extreme values. At moderate values, we expect these two characteristics to exhibit more independent behavior, resulting in a linear combination form. Unlike failure rates and text complexities, accessibility is expected to be independent of the other two and inversely related to CND events.

3.4.2.8 Shop Test Equipment Failures (x_{11})

The shop test equipment failures are functions of the design and construction of the test equipment used in the repair shops. None of these characteristics were available for the study. Consequently, this subclass was eliminated.

3.4.2.9 Human Errors at Shop Level (x_{12})

Human errors occurring at the shop level are functions of technical training and support, shop level test equipment complexity, and LRU complexity. Although measures of LRU complexity were available to the study, the former two characteristics were not available. Further, it is likely that these characteristics form a compounding relationship. Thus it was believed that data available were inadequate.

3.4.2.10 Summary of CND Causal Relationships to be Applied to Testability Attributes

Of the 12 causally oriented subclasses of CND, three had to be eliminated due to unattainability of appropriate design characteristics. In the nine remaining subclasses, numerous design characteristics were eliminated or replaced by surrogate measures or other synthesized attributes. In addition, numerous characteristics were functionally used for more than one subclass (cross talk). Although beginning with 12 independent subclasses of CND, because of inadequacies in available data the result was a very coarse scale analytical model for CND. It was, nevertheless, adequate to guide the regression analysis.

CND events are a function of the following:

- Operational complexity (3.4.2.1)
- Topological complexity (3.4.2.2)
- Environmental factors (3.4.2.3)
- Transient factors (3.4.2.4)
- Component characteristics (3.4.2.4) and (3.4.2.5)
- Numbers of components by type (3.4.2.4) and (3.4.2.5)
- Accessibility (3.4.2.7)
- Failure rates (3.4.2.7)
- Documentation quality (3.4.2.7)

As noted in Phase I, the testability attributes FFA, FFI, and FFD are mathematically related to CND events. Thus the factors listed above will influence all three testability attributes. Although specific guidance as to anticipated forms of these parameters is given in the cited paragraphs, the actual forms and significance were developed in the regression analyses task as discussed in Chapter Five.

3.4.3 Additional Causal Relationships Associated with FFI

Figure 3-2 is the taxonomic model used in considering fault isolation functions. The fraction of faults isolated in a system is a function of that percentage of the total of failure modes that a given test system is configured to resolve. Thus, all of the failure modes and their associated rates of the replaceable units must be known. We must also know how failure information propagates throughout a system once failures occur. Finally, we must understand what failure information our test system can capture, along with the reliability of that capture. Therefore,

FFI = f (functional topology, component failure rates, component failure modes, test placements, test functions, test reliabilities).

For this study, all of these design characteristics had to be eliminated or replaced by coarse surrogate measures. The resulting functional relationship will include all of the functions listed in 3.4.2.10 as well as:

FFI = f (topological measure(s), functional complexity, test measure(s), number of components)

The topological measures used here are different from the topological complexity measures described in previous subsections. These topological measures must characterize the relationships between the functional topologies of the units-under-test and the corresponding test points. Because of the coarseness of these measurable characteristics, the form of this equation cannot be further refined. However, we expect FFI to vary with tests and inversely with components. Its behavior as a function of topological measure(s) and functional complexity is not certain.

3.4.4 Additional Causal Relationships Associated with FFD

As is the case with FFI, the percentage of faults detected will be related to such design characteristics as functional topology, failure rates, component failure modes, test functions and placements, and test reliabilities. The resulting equation using available characteristics is of a form similar to that of FFI and will include all of the functions listed in 3.4.2.10, as well as:

FFD ≈ g (topological measure(s), functional complexity, test measure(s), number of components)

This correspondence of FFD to FFI is logical given the relative natures of fault detection and fault isolation. For example, at the flight line under ideal conditions, identification and removal of a faulty LRU constitutes a correct isolation. From the perspective of the shop, a fault was detected in the LRU pulled. Similarly, under ideal conditions, when the shop technicians identify and remove a faulty SRU, they have performed a correct isolation. However, from the perspective of the depot, a fault has been detected in that SRU. Thus, we may say that a detection at one maintenance level is equivalent to an isolation at a lower level, and an isolation at one maintenance level is a detection at a higher level. Although it is recognized that the parameters FFI and FFD have the same functions, it is the regression models that should provide the significance of these functions to FFI and FFD.

3.5 CONCLUSION

The analysis in this chapter of the form and rationale of parameter make-up of a testability prediction model for each of CND burden, CND rate, FFI, and FFD is summarized in Table 3-2. Although certain forms and tendencies were hypothesized, the crosstalk between numerous variables (such as total components and total components by type) may cause compensating relationships in the final prediction equations. It is recommended that trends be determined in single variable correlations. All this aside, the model provides a "common sense" quality control mechanism for the regressions of data acquired during this program.

TABLE 3-2

FUNCTIONAL RELATIONSHIPS TO EXAMINE

Parameter	CND Rate ≈ FAR	CND Burden ≈ FFA	IL ≈ FFI	DP ≈ FFD
Operational Complexity	X	X	X	X
Topological Complexity	X	X	X	X
Functional Complexity			X	X
Environmental Factors	X	X	X	X
Transient Factors	X	X	X	X
Component Characteristics	X	X	X	X
Numbers of Components	X	X	X	X
Accessibility	X	X	X	X
Failure Rate	X	*	X	X
Documentation Quality	X	X	X	X
Topological Measures			X	X
Test Measures			X	X

*CND burden is not expected to depend on failure rate because the term appears in both the numerator and denominator.

CHAPTER FOUR

DATA SOURCES AND CHARACTERIZATIONS

4.1 INTRODUCTION

Three categories of data sources were identified in the Phase I report: field data, engineering test data, and design data. Although field data proved to be sufficient for estimating FFA, the form of the Maintenance Data Collection System (MDCS) does not provide the appropriate information for estimating FFD and FFI. (As noted in Phase I, this is not a judgment of MDCS, only the recognition that MDCS cannot be used to estimate a quantity that it was not designed to measure.) Because restructuring of a data reporting system was not feasible, detailed STAMP● analyses (see Chapter Two) for 24 systems were used in lieu of field data for estimating FFD and FFI.

Engineering test data (such as maintenance demonstration data and operational evaluation data) were investigated and found not to be applicable to the needs of this project. The primary difficulty with these data is that the normal evolution of system design takes place concurrently with the gathering of data, which leads to nonstationary effects in the data. Thus, the categories of data sources to be discussed in Phase II are field data, STAMP● analysis data, and design data.

4.2 FIELD DATA

The estimator for FFA is fraction of cannot duplicate (FCND). A false alarm is defined as an "indication of failure in the system where none exists." Considering this definition, FFA is the ratio of false alarms to the sum of false alarms and faults in the system. The how-malfunctioned (how-mal) code for CND, 799, as reported in the AFTO 349 data system, represents the event that a failure is reported (by BIT, normal system maintenance, pilot, etc.), and no fault is found. A related quantity is how-mal code 812, which is the event that a failure is reported in an LRU system and fault is found in a different LRU system. Thus, the estimator for FFA is:

$$FFA \approx \frac{\text{number of 799 how-mal codes} + \text{number of 812 how-mal codes}}{\sum MA} = \frac{\sum CND}{\sum MA}$$

where

MA = total number of maintenance actions.

A second testability measure similar to FFA is the false-alarm rate. FAR is the number of false alarms over a specified time period divided by that time period. The estimator for FAR by LRU type is:

$$FAR \approx \frac{\text{CND for 1 year}}{\text{Operating hours for 1 year}} .$$

Three aircraft were designated as sources for field data in Phase I: the C-5, F-15, and F-16. For each aircraft, LRUs were selected for study on the basis of a reasonable cross section of aircraft electronics, volume of maintenance activity, and availability of design data. The LRUs selected for study are listed in Table 4-1.

For each LRU, totals of maintenance actions and CND were tabulated using the existing MDCS. For the C-5, maintenance action and CND totals were obtained, using the Malfunction Analysis Detection and Recording System (MADARS) as well as using weekly summaries of maintenance activity. For the F-16, maintenance actions and CNDs were totaled by LRU with a tailored computer routine that uses two tapes generated under the Maintenance Fault Listing Summary (MFLS) reporting system. For the F-15, total

TABLE 4-1

LRUs INCLUDED IN STUDY BY AIRCRAFT TYPE

C-5	F-15	F-16
Pitch Augmentation Computer	RFO 001	Central Interface Unit
Central Air Data Computer	Radar Transmitter 022	Fire Control Computer
Stallimiter Computer	Analog Target Data Processor 039	Radar Antenna
MADAR Multiplexer	Digital Radar TDP 042	Fire Control/Navigation Panel
Active Lift Distribution System Computer	Data Processor 081	Radar Transmitter
Go Around Attitude System Computer	Radar Set Control 541	REO/IU
Pitch & PACS Computer	Converter/Programmer	Head-Up Display Unit
Roll, Yaw, & PACS Computer	Digital Computer	Low Power Radio Frequency Unit
Central Multiplexer Adapter	Electronic Control Amplifier	Inertial Navigation Unit
MADAR Data Recorder	Air Inlet Control	
MADAR Computer	IRE	
SAR Auto 107	ICCP	
SAR Auto 117	UHF/RT	
SAR Auto 121		

maintenance action and CND counts were obtained manually from AFTO-349 records. For each aircraft type, the data collected span one year of maintenance activity. A summary of the data is listed in Table 4-2.

TABLE 4-2

SUMMARY OF FIELD DATA

	Aircraft			Total
	Type 1	Type 2	Type 3	
No. of CND Actions	801	3,472	2,274	6,545
No. of MAs	2,688	10,847	8,985	22,520

4.3 STAMP® DATA

4.3.1 FFI

A fault isolation, defined as identification by normal system maintenance (NSM) of all failed units within the system, includes "proper" fault isolation (only and all of the failed items are isolated) and "improper" fault isolation (all but not only the failed items are isolated). Given this definition of fault isolation, FFI can be defined as the ratio of isolations using NSM to faults within the system. The Phase I effort showed that we are not currently measuring (in the AFM-66 data system) parameters that can be used to calculate this number.

STAMP® calculates the similar measure, isolation level. Under ideal circumstances, every system or unit failure can be isolated to a single element. Thus, the total possible number of fault isolations equals the number of elements. However, in actuality, some faulty elements may be isolated only in ambiguity groups. Then the number of fault isolation conclusions will be less than the total possible fault isolation conclusions. A fault isolation conclusion is the result of a fault isolation, that is, a single element that has failed, a group of elements that contain the failure, or no fault found (sometimes referred to as RTOK in STAMP® nomenclature). IL measures this difference and can be expressed as:

$$IL = \frac{\text{Number of fault isolation conclusions}}{\text{Number of elements}}.$$

(In STAMP®, elements may be functional or actual, as well as system level or parts level.)

With this similarity between definitions, IL was considered an appropriate estimator for FFI. Thus, IL measures were collected from 22 of the available STAMP® analyses as estimates of FFI. These systems are listed in Table 4-3.

4.3.2 FFD

Fault detection is defined (as given by the Phase I report) as an indication by NSM that "the system is not functioning properly, and this indication is the result of a real fault within the system." Building upon this definition, FFD is the ratio of fault detection to faults within the system. (In the AFM-66-1 data system, we are not currently measuring parameters that could be used to calculate this number.)

The testability report generated by STAMP® includes the nondetection percentage measure that approximates the complement of this quantity. STAMP® considers each element a potential fault or failure mode and then determines if that element would be detected under the current test situation. If a fault occurs and cannot be detected, then the system, when retested, will appear "OK." Thus, nondetection of a fault is ambiguous with "no fault found." From this reasoning:

$$NDP = \frac{\text{Number of elements not distinguishable from "no fault found"}}{\text{total number of elements}}$$

TABLE 4-3

STAMP® SYSTEMS INCLUDED IN STUDY

AN/ALR-67	Harpoon
IP-1276*	CARA
R-2148*	
C-10250*	RFA
AS-3190*	BIT
Special Receiver*	OFA
Computer*	IFA
	TLI
AN/ALQ-184	SLP
	RT
Digital Section	CPA
RF Section	RA1
	IQD
	AOC
	APG-63
	TEAMPAC**

*Additional derivative systems were derived by deletion of 10 percent and 20 percent of tests for additional data points.
**Additional derivative systems were derived by deletion of 10 percent of tests for additional data points.

To relate this variable to FFD, the variable 1 - NDP = DP, or detection percentage, was considered. DP may be represented as:

$$DP = \frac{\text{number of elements distinguishable from "no fault found"}}{\text{total number of elements}}$$

or

$$DP = \frac{\text{number of elements that are detectable}}{\text{total number of elements}}$$

Considering the similarities between the definitions for DP and FFD, DP was deemed an adequate estimator for FFD. Thus, NDP was collected from the testability report for the same 22 analyses composing the data base for FFI. DP = 1 - NDP was then calculated.

In compiling the data base for FFD, we discovered that 20 out of 22 systems have a value of 1 for DP. This is not surprising because DP is an upper bound for FFD as discussed in Chapter Two. Several alternatives were discussed to counter this difficulty, including presenting the equation FFD = 1 as the best predictor of FFD. Leaving this alternative as a last resort, another procedure was tried -- modifying seven of the 20 STAMP® analyses systems by randomly deleting 10 percent of the systems tests. In addition, six of those seven systems were modified by deleting 20 percent of their tests at random. With fewer tests, more elements were undetectable and the range of values for DP was greater. IL values were also tabulated for the 13 modified systems for comparison to the IL values of the unmodified systems. It was believed that if the IL values from the modified systems were within predictive norms of the IL equation, then the DP values from the modified systems could be included in the data base for estimating FFD.

4.4 DESIGN DATA

After the "wish list" of design information had been compiled, intermediate-level and depot-level maintenance manuals for several F-16 LRUs were examined to determine what design information was available and quantifiable. From this effort, an LRU worksheet (Appendix B) was developed to aid in consistent and efficient data collection (see Chapter Three.)

This LRU worksheet was completed for every LRU from the field data group and every LRU system from the STAMP® analysis systems. Worksheets for field data LRUs were completed from information in intermediate-level and depot-level maintenance manuals and the illustrated parts breakdown and from consulting shop-level and flightline maintenance personnel. Despite the simplicity of the worksheet, some information was difficult to obtain due to variations in manuals written by different vendors. A summary of trips taken to collect design data for the field data LRUs is presented in Table 4-4.

TABLE 4-4

SUMMARY OF DATA COLLECTION TRIPS

Destination	Purpose
Wright Patterson AFB	Design data for F-16 LRUs
Dover AFB	Design and environmental data for C-5 LRUs
Wright Patterson AFB	Completion of design data for F-16 LRUs
Langley AFB	Design and environmental data for F-15 LRUs
MacDill AFB	Environmental data for F-16 LRUs
Kelly AFB	Completion of design data for C-5 LRUs

Worksheets for STAMP● analyses were completed using parts breakdown, blueprints, and wiring diagrams and using information provided by ARINC Research Corporation project engineers who coordinated the respective STAMP● analyses. In addition to the worksheet data, numbers of tests, input items, and components used by STAMP● were included as design variables.

4.5 CND AND FA RELATIONSHIP

A collection of "bad actor" data was used in estimating the parameter β, as described in the modeling efforts of Phase I.[1] β is an empirical coefficient that represents the percentage of CNDs that are false alarms. A CND that is a repeat CND on a particular serial number LRU would be interpreted as a bad actor -- a failure whose isolation escaped normal troubleshooting. If the bad actors could be deleted from the total CND count, remaining would be the false alarms. It was suggested in Phase I that data from a bad actor program be used to empirically estimate ß using the equation:

$$FA = CND - \text{bad actors} = \beta\ CND$$

However, this approach was suggested under the assumption that a bad actor was a repeat CND unit. The actual bad actor data included not only repeat CND items but also items with multiple occurrences of any how-mal code. This made the bad actor data impractical for use in predicting ß. As a result, CND was used as an estimator for FA ($\beta \approx 1$).

Despite this difficulty, the data for the remaining testability attributes appears to be sufficient for deriving a prediction equation, with the possible exception of FFD.

4.6 SUMMARY

Table 4-5 summarizes the number of observations (LRUs or systems) for analysis for each testability attribute. For each observation, the appropriate estimator for the attribute and the design data from that system have been compiled. These data bases served as the basis for the regression analysis.

TABLE 4-5

SUMMARY OF SYSTEMS ANALYZED

Testability Attribute	Estimator	Number of Systems
FFA	CND/MA = CND burden	38
FAR	CND/Op hours = CND rate	38
FFI	IL	22
FFD	DP	35

CHAPTER FIVE

DATA ANALYSIS

5.1 INTRODUCTION

The analyses of the estimators for the testability attributes FFA, FAR, FFI, and FFD were directed to the development of prediction equations for CND burden, CND rate, IL, and DP. For these analyses, computer software was selected and regression analysis was performed. The discussion of the following sections provides the theoretical and mathematical justification for the final form of the prediction equations. The actual computation and use of these equations are discussed in Chapter Six.

5.2 SELECTION OF SOFTWARE

Software was selected from a wide variety of computer packages based upon the following features:

- Basic statistical measures
- Plotting capability (histograms, scatter plots)
- Multiple linear regression
- Nonlinear regression
- Adequate storage capacity

These features and the capability criteria led to the choice of two packages for use in this work: a linear regression package, "The

Statistician" by Quant Systems,[12] and a nonlinear regression package, "Marqfit" by Schreiner, et al.,[13] which uses the Marquardt algorithm. Results from a simple regression with The Statistician were compared with two other linear regression packages to verify the accuracy of the routine. ARINC Research developed microcomputer packages were occasionally used for trending analysis and small computation routines.

5.3 GENERAL NOTES ON THE ANALYSIS

5.3.1 Use of Stepwise Regression

The regression package used to analyze the data included a stepwise regression routine. This routine selects the variable (from a user-selected list of independent variables) that yields the highest contribution to the explanation of the variance of the dependent variable. The routine then computes partial correlations and selects the variable from the remaining list that has the highest contribution given the presence of the first variable. Continuing in this manner, the routine systematically adds one variable at a time to the regression until the list is depleted. This routine proved useful in determining the interaction of different variables.

5.3.2 Selection of an Equation

There are a few considerations in selecting the "best" equation for each of the estimates for the testability attributes: what constitutes "best" and how to deal with illogical variables. Illogical variables include variables that do not behave as expected.

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[12] The Statistician. Quant Systems. Charleston, SC, 1983.

[13] W. Schreiner, et al. "Nonlinear Least Squares Fitting," PC Tech Journal, Vol. 3, No. 5, May 1985, pp. 170-190.

5.3.2.1 What Constitutes "Best"

To be certain that the best possible equation has been chosen, every possible combination of variables should be tested. This is a combinatorial problem. The number of regressions necessary to do every combination is given by:

$$\sum_{i=0}^{N} \binom{N}{i} = 2^N$$

where N is the number of independent variables.

If there were 10 independent variables, this would indicate 1,024 regressions to compute and compare. However, the number of variables for CND burden alone is closer to 80. An exhaustive search of every possible combination of variables was beyond the scope of this effort. Thus, our recommended equations represent the best equation that we have computed, guided by the results of the analytical modeling (the analytical model is discussed in detail in Chapter Three.) The stepwise linear regression routine discussed in 5.3.1 also provided some order to the significance of the data and reduced the necessary combinations to be explored.

5.3.2.2 Illogical Variables

The areas in which a variable exhibited unexpected behavior varied. These areas and the procedures used to deal with the problems are outlined below.

- On occasion, a variable that was not expected to be a major factor would appear to be significant in an equation. Often these variables were included for control to help our own understanding of the problem and to verify our analytical work. In such cases, the analytical models were reviewed to suggest a possible reason for the significance. One such variable was WEIGHT, which initially held substantial significance in determining CND burden. The analytical model suggested that weight might factor into the accessibility of an LRU, along with volume and the number of external connectors. When weight, volume, and external connectors were included simultaneously in a regression, weight became insignificant, confirming the analytic model.

- As part of the analytical modeling, the expected sign of the individual correlation between each variable and the appropriate dependent variable was postulated. At times, the postulated sign and the actual sign differed. These instances raised a flag to investigate the analytical model for either an explanation or a revision of the independent variables. For instance, several of the early topological variables had a negative correlation with CND burden and CND rate, indicating that the more functionally complex systems had fewer CND actions and vice versa. Review of the analytical model revealed better measures of topological complexity which correlated positively with CND burden and CND rate.

  Note that the concern over an unanticipated sign is for the individual correlation as well as the coefficient of the variable in an equation. The latter could reflect correlation between independent variables, and the unexpected sign on one variable may indicate compensation for the over contribution of another variable.

- A few variables were used as control variables. These represented some difference or expected difference that held little value as a design characteristic. If the control variable was significant, it was compared against other variables until the information represented by the control variable was covered by a combination of appropriate design characteristics. One such variable was PLANE, a categorical variable that indicates the aircraft type (C-5, F-15, F-16) that the LRU resided on. Although initially significant, the information represented by PLANE was eventually better represented by other variables (in particular, the environmental variables) that did not indicate aircraft type.

5.3.3 Predictor Development Methodology

In the development of prediction equations, a broad spectrum stepwise linear regression was performed to find the most significant measures in accounting for variation in the dependent variable (CND burden, CND rate, IL, and DP.) These high-value measures were then compared to the analytical workup in Chapter Three and variables that best represented the derived functionalities were developed through subregressions of the dependent variable. These subregressions were done both by stepwise and nonlinear combinations, and output was again compared to derived functionalities. Finally, the synthesized variables were then used in a stepwise linear regression. As can be seen, these last few steps required several iterations and will account for the differing forms of a term like "topological complexity" as it is fine tuned to the appropriate dependent variable. In all, we performed more than 300 regression runs to obtain the equation sets presented in this chapter.

5.3.4 Procedure for Validation

The prediction equations were validated by application to one or more data sets not used in the development of the equations. Thus, two systems were deleted from the total data set for CND burden and CND rate, and one system was deleted for IL and DP. After being used to verify the equations, these LRUs were then folded back into the data bases to enhance the final form of the equation.

5.3.5 An Explanation of Some Regression Statistics and Tests

Various statistics were used to compare regression equations and determine the significance of the equation and variables. These statistics are as follows:

- R^2 - A normalized complement of the square difference between the observed values and the equational values, ranging from 0 to 1 inclusive. As such, it indicates the percentage of the variance in the dependent variable that is explained by the equation (0 represents no explanation and 1 represents perfect explanation). R^2 is used to compare regression equations and, thus, can be used as a measure of "goodness of fit." This sometimes is called the correlation factor.

- F - Measures the global utility of the predictive equation. The F statistic tests that one or more of the coefficients are nonzero by comparison with a tabulated F value. The tabulated F value is based on the number of variables and the number of observations for a given significance level. The observed F value should be greater than the tabulated value for the utility of the equation.[14]

- t statistics - Indicate the degree to which each variable is significant in the equation. The t statistic for each variable tests that its coefficient is nonzero by comparison to a tabulated value. The tabulated value is based on the number of observations and a given significance level. The absolute value of the observed t statistic should be greater than the tabulated value for the inclusion of that variable in the equation.

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[14] J. T. McClave and P. G. Benson, Statistics for Business and Economics, Dellen Publishing Company, San Francisco, California, 1982, pp. 472-478.

5.4 ANALYSIS OF CND BURDEN AND CND RATE

5.4.1 Variables

For each analysis, variables fell into three classifications: initial design variables, combinations of initial variables, and variables synthesized by regression. Initial design variables consist primarily of counts and measures obtained from the worksheets (see Appendix B). In addition, other design variables include parts counts normalized by number of SRUs, a yes or no BIT variable, and a percent digital variable. The environmental variables -- thermal, contaminants, mechanical, and electrical -- were calculated by summing the number of sensitivities ("yes" responses) within each category. A more complete list of the initial design variables is contained in Appendix C.

The second category of design variables includes those variables created from combinations of initial variables. Most combinations suggested themselves, such as volume and the densities. Other combinations were developed when considering the physical situations that might cause CNDs, such as the interactions of power and the environment with other variables. Also in this category is the number of failures and failure rate. Appendix C contains a listing of combinations of initial variables.

Finally, a number of variables were synthesized by regression. These are variables that were believed to combine additively rather than multiplicatively. Multiple regression with the variables to be combined as the independent variables and CND burden or CND rate as the dependent variable yielded the relative proportion of each variable in predicting the dependent variable. Using these proportions as weights, a new variable was created by the sum of these weighted variables. Included in that category are the various parts complexity measures. Appendix C presents variables synthesized by regression.

5.4.2 CND Burden, Estimator for FFA

5.4.2.1 The Prediction Equation

The equation developed to predict CND as a percentage of maintenance actions is as follows:

$$CND/MA = \begin{cases} 0 & \text{IF } Fctn<0 \\ Fctn & \text{IF } 0 \le Fctn \le 100 \\ 100 & \text{IF } 100<Fctn \end{cases}$$

where:

$$Fctn = 25.8 + 4*TOP4 + 0.003*THRMCON - 0.076*THRMCMPLX - 0.002*ACCESS.$$

The variables included in this equation cover a wide range of possible causes of CNDs. The following descriptions of each variable suggests its impact on CND burden.

- TOP4 - The variable TOP4 is a measure of the topological complexity of the LRU. Computed from the functional block diagram, it measures the number of parallel functional paths relative to the number of [illegible]s. This variable is identical to the parallelism variable from Phase I.[1] This variable encompasses characteristics that affect CND causal subclasses described in subsections 3.4.2.1 and 3.4.2.2.

- THRMCON - Intended to measure the interaction between the number of interconnects and a thermally sensitive environment, this variable indicates an internal connection that, when heated, may or may not conduct as expected, either conducting a signal incorrectly or failing to conduct the signal at all. This encompasses factors discussed in subsections 3.4.2.3 and 3.4.2.4.

- THRMCMPLX - This variable reflects the interaction between the thermal environment and thermally sensitive components. As the LRU is exposed to external thermal influences, these components may "chatter," adding noise to the signal. This distorted signal may cause a failure indication that, when the LRU is removed from the thermal stress, cannot be duplicated. (Although this variable has a negative coefficient, the single variable correlation with CND burden is positive, as expected.) This variable also reflects subsections 3.4.2.3 and 3.4.2.4.

- ACCESS: - The variable ACCESS indicates the influence of an LRU's accessibility on the reported number of CND events. A technician will be more certain that an LRU is in need of troubleshooting before removing it from the aircraft if the LRU is heavy and has many connectors. Subsections 3.4.2.7 and 3.4.2.4 relate to the significance of this variable.

Note that THRMCON, THRMCMPLX, and ACCESS also exhibit crosstalk with the concepts of subsection 3.4.2.5. A summary of the regression analysis for CND burden is presented in Table 5-1.

5.4.2.2 Validation of Equation for CND Burden

Two systems were withheld from the regression analysis for CND burden to be used as verifiers of the predictive ability of the equation. For system 1, the equation predicted a CND per maintenance action value of 21.7 percent, compared to the field value of 34.8 percent. The equation predicted a value of 19.6 percent for system 2, which had an observed CND burden of 23.4 percent. These results and the corresponding prediction intervals are presented in Table 5-2. Figure 5-1 presents the observed versus predicted values together with the two verification LRUs. The verification was considered adequate.

5.4.2.3 Final Equation for CND Burden

After the predictive ability of the equation was verified, the two validation systems were folded back into the data set to compute a final form of the equation using all the data at our disposal. Note that the form of the equation and the choice of independent variables remain fixed. Inclusion of the additional two systems is only to make minor adjustments in the constant and coefficients. The resulting equation is:

$$CND/MA = \begin{cases} 0 & \text{IF } Fctn<0 \\ Fctn & \text{IF } 0 \le Fctn \le 100 \\ 100 & \text{IF } 100<Fctn \end{cases}$$

where:

Fctn = [illegible] + 3.9*TOP4 + 0.003*THRMCON - 0.077*THRMCMPLX
[illegible].002*ACCESS.

TABLE 5-1

EQUATION AND STATISTICS FOR CND BURDEN

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	25.8417	3.516443	7.348818	
TOP4	4.075859	1.058394	3.850984	(cross count)/No. of SRUs
THRMCON	3.429899E-03	5.444746E-04	6.299465	(thermal+1) No. of interconnects
THRMCMPLX	-7.606546E-02	2.185168E-02	-3.48099	(thermal+1)*(ICs+10*ind-2.4*cap)/No. of SRUs
ACCESS	-2.006753E-03	4.82536E-04	-4.158764	volume+500*connectors

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	3064.358	4	766.0894
Error	1773.955	31	57.22436
Total SS	4838.313	35	

F = 13.38747

R Squared 0.6333525

c. F TEST STATISTICS

Regression F = 13.39

α =	0.05	0.025	0.01	0.005
$F_{4,31}$ =	2.68	3.23	4.00	4.59

99.5%<Significance Level

d. t TESTS STATISTICS

Variable	Regression ABS (t Value)
TOP4	3.85
THRMCON	6.30
THRMCMPLX	3.48
ACCESS	4.16

$t_{\alpha/2,30}$ = 2.75; α =0.01

Minimum Significance Level for all Variables - 99%

TABLE 5-2

VALIDATION OF EQUATION FOR CND BURDEN

Variable	System 1	System 2
TOP4	1.46	0.56
THRMCON	1430.0	2274.0
THRMCMPLX	-21.4	-22.64
ACCESS	8268.0	9013.0
PREDICTED VALUE	21.7%	19.6%
ACTUAL VALUE	34.8%	23.4%
95% PREDICTION INTERVAL	(6.48, 37.0)	(4.11, 35.0)

Table 5-3 summarizes the regression analysis for this final equation for CND burden. Included in this analysis is a scatter plot of predicted CND burden values versus the actual field values (Figure 5-2).

For ease in using this equation to obtain a predicted value, a worksheet indicating the necessary measures and calculations is found in Chapter Six.

5.4.3 CND Rate, Estimator for FAR

5.4.3.1 The Prediction Equation

The equation developed to predict CND per operating hours of the LRU is as follows:

$$\text{CND RATE} = \begin{cases} 0 & \text{IF Fctn} < 0 \\ \text{Fctn} & \text{IF } 0 \le \text{Fctn} \end{cases}$$

where:

$$\text{Fctn} = -0.0029 + 0.381*\text{FLRRATE} + 2.7*10^{-5}*\text{TRANSIENT} + 5.7*10^{-11}*\text{TC7}.$$

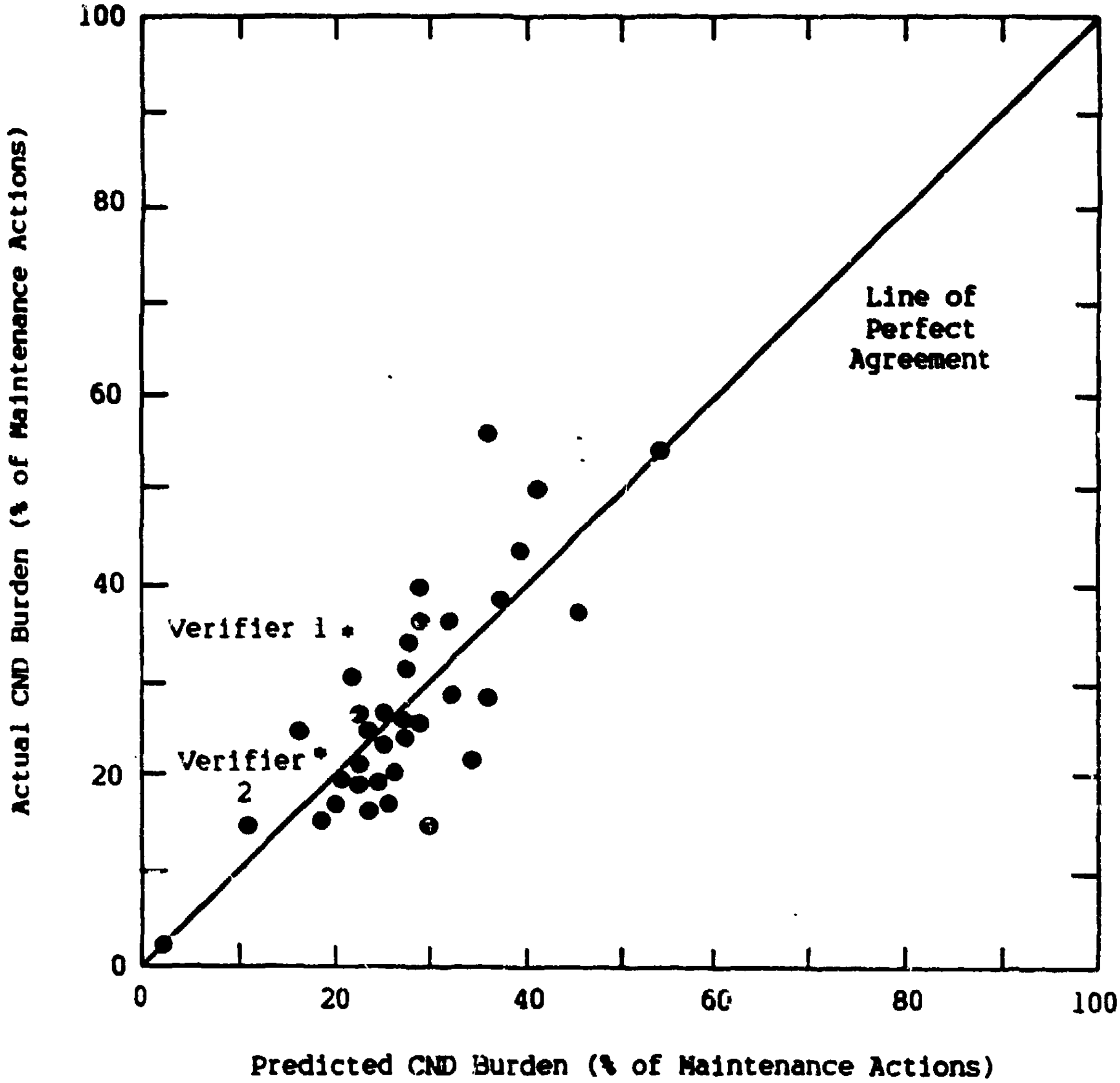


FIGURE 5-1

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR CND BURDEN - INITIAL EQUATION

TABLE 5-3

FINAL EQUATION FOR CND BURDEN

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	25.93132	3.563411	7.277107	
TOP4	3.918272	1.059272	3.699024	(ctors count)/No. of SRUs
THRMCON	3.295488E-03	5.448805E-04	6.048092	(thermal+1)*No. of inter-connects
THRMCMPLX	-7.705728E-02	2.216259E-02	-3.476908	(thermal+1)*ICs+10*ind-2.4*cap)/No. of SRUs
ACCESS	-1.861481E-03	4.788547E-04	-3.88736	volume+500*connectors

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	2963.313	4	740.8281
Error	1943.873	33	58.90525
Total SS	4907.186	37	

F = 12.57661
R Squared 0.6038721

c. F TEST STATISTICS

Regression F = 12.58

α =	0.05	0.025	0.01	0.005
$F_{4,33}$ =	2.66	3.20	3.96	4.52

99.5%<Significance Level

d. t TESTS STATISTICS

Variable	Regression ABS (t value)
TOP4	3.70
THRMCON	6.05
THRMCMPLX	3.48
ACCESS	3.89

$t_{\alpha/2,30} = 2.75$: $\alpha = 0.01$

Minimum Significance Level for all Variables - 99%

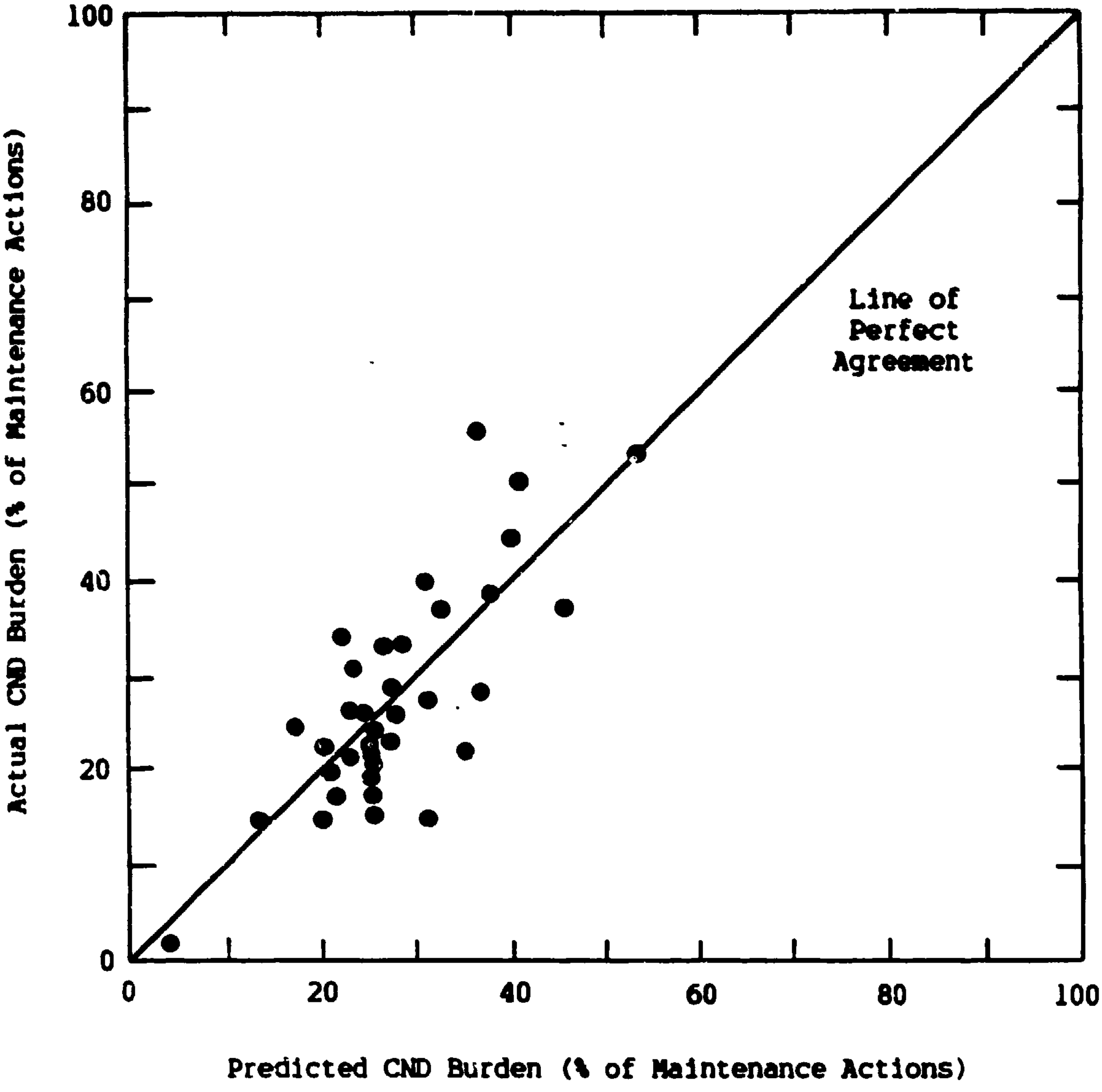


FIGURE 5-2

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR CND BURDEN - FINAL EQUATION

The units are CND events per operating hour. The variables reflect different aspects of the causes of CNDs. The following description of each variable suggests its impact on CND rate.

- FLRRATE - FLRRATE represents the actual failure rate of the LRU. As an item is known to fail more often, that item is removed from the aircraft more often for any failure indication. The more often the LRU is removed, the more chance it has of not being the failed item for that maintenance action. Thus, the CND rate will rise with the failure rate. This variable relates to the analysis in subsection 3.4.2.7.

- TRANSIENT - The variable TRANSIENT indicates those components that were significant in contributing to transient or intermittent behavior. For the data set we collected, these significant components include relays, capacitors, integrated circuits (ICs), resistors, and transistors. This variable represents crosstalk between terms in subsections 3.4.2.4 and 3.4.2.5.

- TC7 - Designed to reflect the topological complexity concept of sneak circuit analysis. TC7 is a product combination of interconnects (which are the input and output of the topological patterns) and the various components that may act as switching devices. For the data set we collected, the switching components which were significant include ICs, transistors, relays, and internal switches. Subsections 3.4.2.2, 3.4.2.4, and 3.4.2.5 indicate the impact of this variable.

A summary of the regression analysis for CND rate is presented in Table 5-4.

5.4.3.2 Validation of Equation for CND Rate

As done for CND burden, two systems were withheld from the regression analysis to be used as verifiers of the predictive ability of the equation. For system 1, the equation predicted a CND rate of 0 per 1,000 operating hours, compared to the field value of 0.99 CND maintenance actions per 1,000 operating hours. For system 2, which had an observed CND rate of 4.9 CND actions per 1,000 operating hours, the equation predicted a CND rate of 5.3 CND actions per 1,000 operating hours. These results and the corresponding prediction intervals are summarized graphically in Figure 5-3, and data are listed in Table 5-5. The verification was considered excellent.

TABLE 5-4

EQUATION AND STATISTICS FOR CND RATE

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	-2.953223E-03	4.994529E-04	-5.912917	
FLRRATE	0.3807576	2.042714E-02	18.63979	(MA-CND)/LRU operating hr/yr
TRANSIENT	2.668999E-05	4.166393E-06	6.40602	(ICs+41*relays+2*cap +2*res-9*xstrs)/No. SRUs
TC7	5.691348E-11	2.589893E-11	2.197523	intcon*(ICs+30*xstrs -160*relays-960*sw)

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	2.402053E-04	3	8.006845E-05
Error	2.134589E-05	32	6.670589E-07
Total SS	2.615512E-04	35	

F = 120.032

R Squared 0.9183874

c. F TEST STATISTICS

Regression F = 120.03

α =	0.05	0.025	0.01	0.005
$F_{3,32}$ =	2.91	3.56	4.46	5.19

99.5%<Significance Level

d. t TESTS STATISTICS

Variable	Regression ABS (t value)
FLRRATE	18.6
TRANSIENT	6.41
TC7	2.20

$t_{\alpha/2,30}$ = 2.04; α = 0.05

Minimum Significance Level for all Variables - 95%

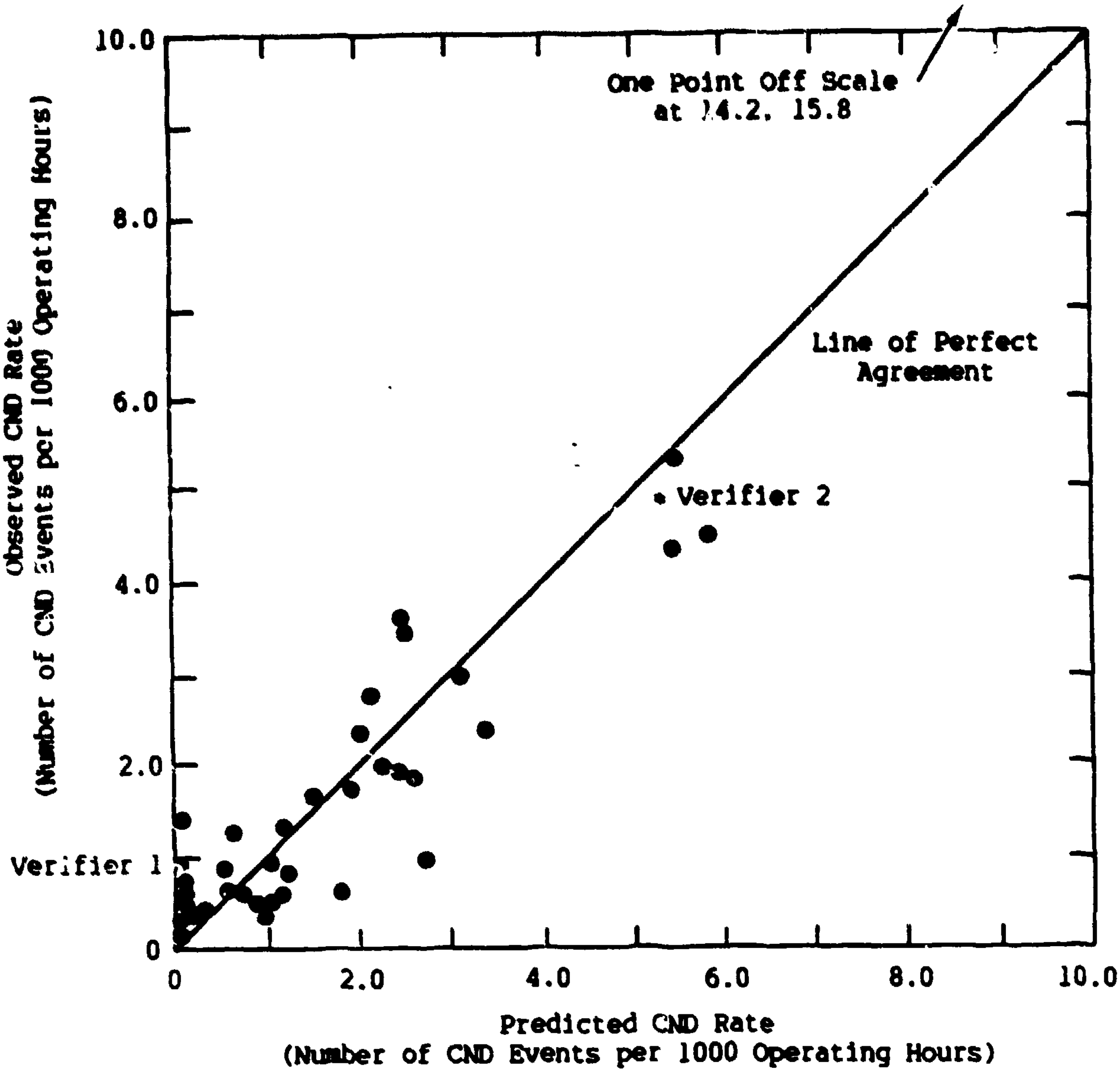


FIGURE 5-3

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR CND RATE - INITIAL EQUATION

TABLE 5-5

VALIDATION OF EQUATION FOR CND RATE
(values for failure rate and CND rate are per operating hour)

Variable	System 1	System 2
FLRRATE	0.00186	0.01606
TRANSIENT	70.4	113.8
TC7	147,862	-15,370,875
PREDICTED VALUE	0	0.0053
ACTUAL VALUE	0.00099	0.0049
95% PREDICTION INTERVAL	(0, 0.0013)	(0.0035, 0.0072)

5.4.3.3 Final Equation for CND Rate

After the predictive ability of the equation was verified, the two validation systems were folded back into the data set to compute a final form of the equation using all the data at our disposal. Note that the form of the equation and the choice of independent variables remain fixed. Inclusion of the additional two systems is only to make minor adjustments in the constant and coefficients. The resulting equation is:

$$\text{CND RATE} = \begin{cases} 0 & \text{IF Fctn}<0 \\ \text{Fctn} & \text{IF } 0\leq\text{Fctn} \end{cases}$$

where:

$$\text{Fctn} = -0.0028 + 0.375*\text{FLRRATE} + 2.6*10^{-5}*\text{TRANSIENT} + 5.9*10^{-11}*\text{TC7}$$

Table 5-6 summarizes the regression analysis for this final equation for CND rate. Included in this analysis is a scatter plot of predicted CND rate values versus the actual field values in Figure 5-4.

TABLE 5-6

FINAL EQUATION FOR CND RATE

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	-2.780678E-03	4.869777E-04	-5.710073	
FLRRATE	0.3749341	2.004064E-02	18.70869	(MA-CND)/LRU operating hr/yr
TRANSIENT	2.563411E-05	4.097731E-06	6.255683	(ICs+41*relays+2*cap+2*res -9*xstrs)/No. SRU
TC7	5.87789E-11	2.402032E-11	2.447049	intcon*(ICs+30*xstrs -160*relays-960*sw)

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	2.477943E-04	3	8.259811E-05
Error	2.319124E-05	34	6.820954E-07
Total SS	2.709856E-04	37	
F 121.0947			
R Squared 0.9144189			

c. F TEST STATISTICS

Regression F = 121.09

α =	0.05	0.025	0.01	0.005
$F_{3,34}$ =	2.88	3.53	4.41	5.1

99.5%<Significance Level

d. t TESTS STATISTICS

Variable	Regression ABS (t value)
FLRRATE	18.7
TRANSIENT	6.26
TC7	2.45

$t_{\alpha/2,30}$ = 2.04; α = 0.05

Minimum Significance Level for all Variables - 95%

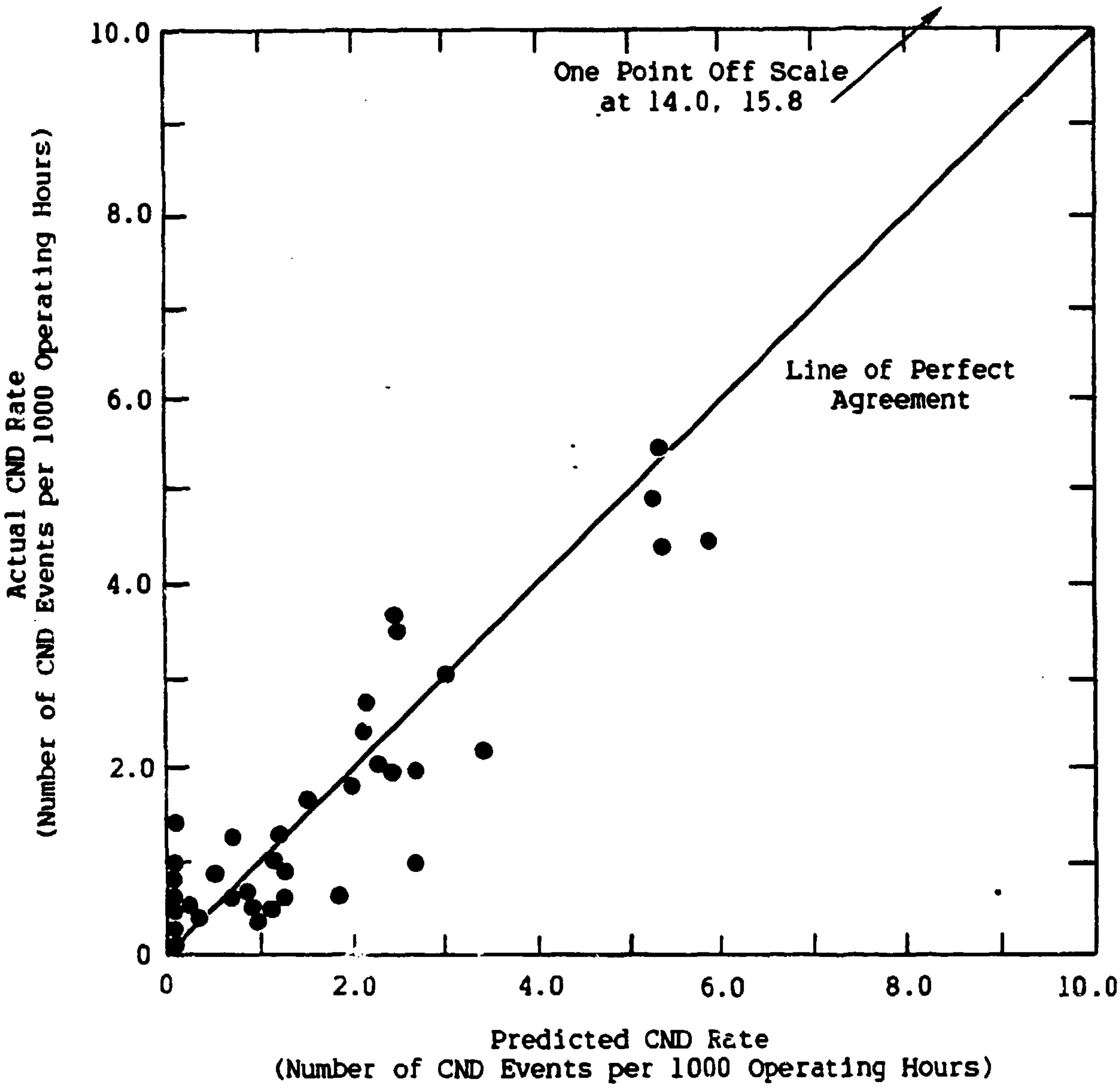


FIGURE 5-4

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES OF
CND RATE - FINAL EQUATION

For ease in using this equation to obtain a predicted value, a worksheet indicating the necessary measures and calculations is found in Chapter Six.

5.4.3.4 Remarks on the Differences in the CND Equations

Before beginning any regression analysis, it was decided to allow statistical significance to guide the form of the prediction equations. Rather than forcing certain independent variables in the equations, variable selection was determined through the regressions themselves. This policy resulted in CND burden and CND rate equations with dissimilar terms. The position of the failure rate term is the primary contributor to this difference. In the case of CND burden, the failure rate term is in the denominator of the dependent variable, as shown by the following equation:

$$\text{CND burden} = \frac{\text{CND rate}}{\text{failure rate} + \text{CND rate}}$$

For CND rate, failure rate is the most significant independent variable in the prediction equation. Because of this difference, dissimilar terms might be expected. For example, THERMAL and interactions of THERMAL with other variables correlated highly with CND burden and CND rate. Yet in the presence of the failure rate term, THERMAL variables became insignificant in the CND rate equation and therefore were not included in predicting CND rate.

5.5 ANALYSIS OF IL, ESTIMATOR FOR FFI

5.5.1 Variables

Variables considered for use in predicting IL fell into the same three classifications as those for CND burden and CND rate: initial design variables, combinations of initial variables, and variables synthesized by regression. Initial design variables include, in addition to the counts and measures found on the worksheet in Appendix B, several STAMP® measures. These include number of tests, number of failure mode components, number of input signals, and test leverage. Although "parts" generally refers to hardware, STAMP® failure mode components are regarded as designated functional units of a system indicating a desired level of fault isolation. Failure mode components may be parts, LRUs, or failure modes of parts depending on the desired analysis. Tests, components, and input signals will be described further in Chapter Six. Appendix C lists the initial design variables for IL.

The majority of the combined variables and synthesized variables consists of multiplicative and additive combinations of the STAMP® measures. Combined variables include tests divided by components, tests divided by parts, input divided by components, and a few others. Synthesized variables include a topological complexity variable and its combinations with other variables. (For a short discussion on the synthesis of a variable using regression, refer to subsection 5.4.1.) Appendix C contains lists of both combined variables and synthesized variables for IL.

5.5.2 The Prediction Equation

The equation developed to predict IL is as follows:

$$IL = \begin{cases} 0 & \text{IF } Fctn<0 \\ Fctn & \text{IF } 0<Fctn<1 \\ 1 & \text{IF } 1<Fctn \end{cases}$$

where:

$$Fctn = 0.615 - 2.48*10^{-8}*TC + 0.218*TEST.CMP + 0.278*INPUT.CMP.$$

The variables included in this equation cover a number of influences on effective fault isolation. The following descriptions of each variable suggest the impact on isolation level.

- TC - The variable TC is a measure of the topological complexity of the LRU. Similar to the topological complexity measure for CND rate, TC approximates the effect of a sneak circuit analysis by compounding the number of interconnects with the type of components that act as switching devices. For this data set, the switching devices that were significant include ICs, relays, and transistors. Background for this variable can be found in subsection 3.4.3.

- TEST.CMP - TEST.CMP is the ratio of number of tests to number of components. As this ratio increases (assuming that the tests are reasonably placed and not all testing the same component), the likelihood of a component having a test that identifies it when it fails also increases. Subsection 3.4.3 discusses the impact of tests and components on IL.

- INPUT.CMP - In STAMP®, many of the components and the input signals are functional. Thus, INPUT.CMP can be viewed as the ratio of functions to components. As the average number of components assigned to a function increases, INPUT.CMP decreases and ability to fault isolate decreases. Subsection 3.4.3 suggests the influence of functional complexity on IL.

A summary of the regression analysis for IL is presented in Table 5-7.

5.5.3 Validation of Equation for IL

One system was withheld from the regression analysis for IL to be used as a verifier of the predictive ability of the equation. This system has a STAMP®-generated IL value of 0.6107 and a predicted value of 0.6966. This result and the corresponding prediction interval is presented graphically in Figure 5-5, and the data are provided in Table 5-8. This verification was considered good.

5.5.4 Final Equation for IL

After the predictive ability of the equation was verified, the validation system was folded back into the data set to compute a final form of the equation using all the STAMP® system data compiled. Note that the form of the equation and the choice of independent variables remain fixed. Inclusion of the additional system is only to make minor adjustments in the constant and coefficients. The resulting equation is:

$$IL = \begin{cases} 0 & \text{IF } Fctn<0 \\ Fctn & \text{IF } 0\leq Fctn\leq 1 \\ 1 & \text{IF } 1<Fctn \end{cases}$$

where:

$$Fctn = 0.590 - 2.41*10^{-8}*TC + 0.237*TEST.CMP + 0.291*INPUT.CMP.$$

TABLE 5-7

EQUATION AND STATISTICS FOR IL

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	0.6151277	9.240679E-02	6.656737	
TC	-2.480748E-08	5.99033E-09	-4.141254	intcon*(ICs+150*relays-17* xstrs)
TEST.CMP	0.2180233	0.1105966	1.971338	tests/components
INPUT.CMP	0.2780414	0.1196387	2.324009	inputs/components

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	0.740594	3	0.2468646
Error	0.190176	17	1.118682E-02
Total SS	0.9307699	20	

F = 22.06745

R Squared 0.7956788

c. F TEST STATISTICS

Regression F = 22.07

α =	0.05	0.025	0.01	0.005
$F_{3,17}$ =	3.20	4.01	5.18	6.16

99.5%<Significance Level

d. t TESTS STATISTICS

	Regression ABS (t Value)	Significance Level
TC	4.14	SL>99%
TEST.CMP	1.97	90%<SL<95%
INPUT.CMP	2.32	95%<SL<98%

α =	0.10	0.05	0.02	0.01
$t_{\alpha/2,20}$ =	1.73	2.09	2.53	2.85

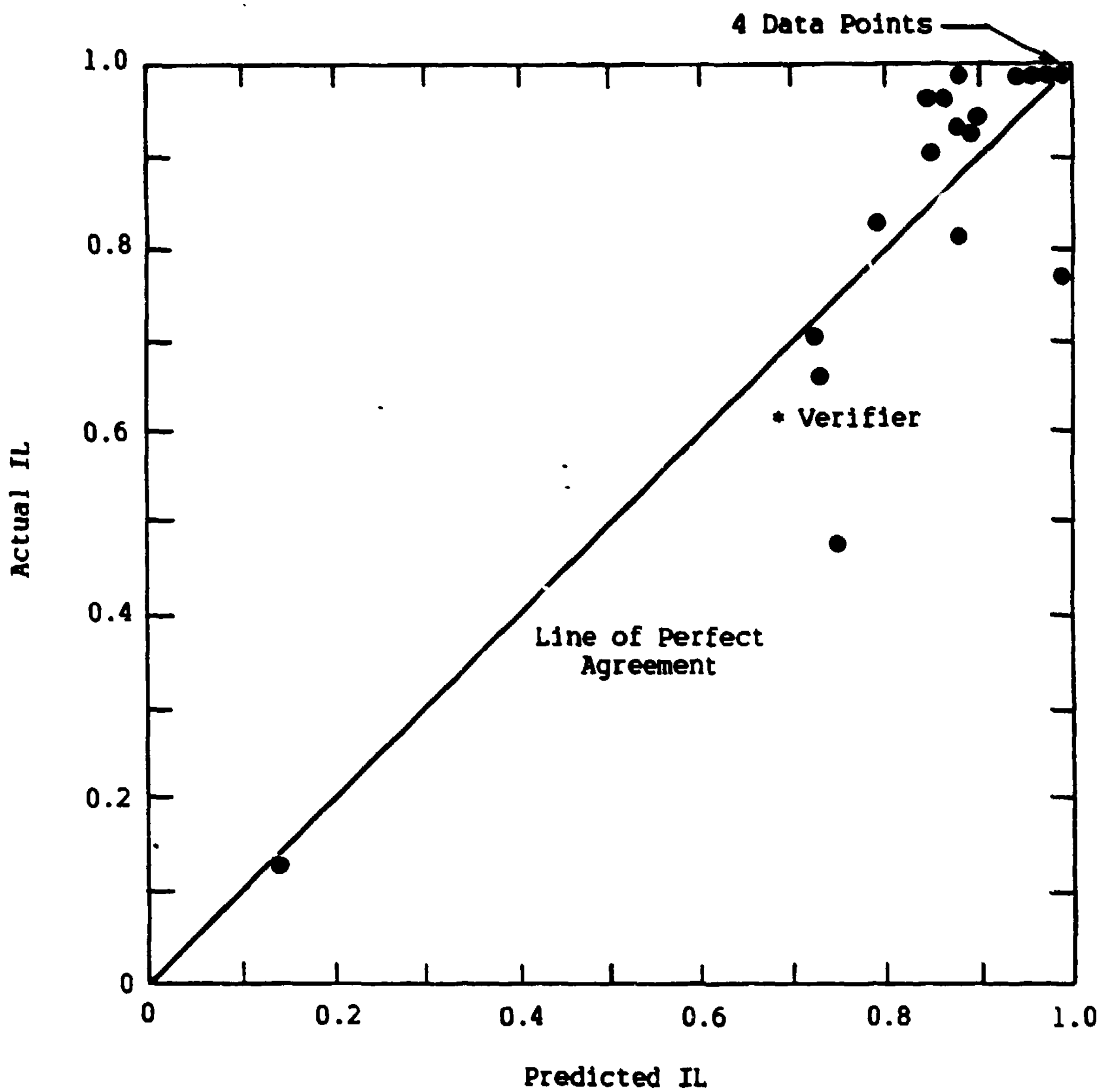


FIGURE 5-5

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR IL - INITIAL EQUATION

TABLE 5-8

VALIDATION OF EQUATION FOR IL

Variable	System
TC	1.509×10^6
TEST.CMP	0.4706
INPUT.CMP	0.0588
PREDICTED VALUE	0.6966
ACTUAL VALUE	0.6107
95% PREDICTION INTERVAL	(0.4528, 0.9405)

Table 5-9 summarizes the regression analysis for this final equation for IL. Included in this analysis is a scatter plot of predicted IL values versus the STAMP®-generated values in Figure 5-6.

For ease in using this equation to obtain a predicted value, a worksheet indicating the necessary measures and calculations is found in Chapter Six.

5.6 ANALYSIS OF DP, ESTIMATOR FOR FFD

5.6.1 Variables

Because both DP and IL are STAMP® measures, all of the variables for IL were considered in the attempt to predict DP (see Appendix C). Our analytical model suggested a strong interaction between IL and DP (see 3.4.4 for a discussion of this interaction.) As the analysis of DP continued, other variables were computed and added to the list of variables from the analysis of IL. Of these, only two were initial design variables. They were the STAMP® measures false alarm tolerance (FAT) and the theoretical minimum test . verage (TLMIN). The remaining additional

TABLE 5-9

FINAL EQUATION AND STATISTICS FOR IL

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	0.5902138	8.504251E-02	6.940221	
TC	-2.405566E-08	5.830625E-09	-4.125743	intcon*(ICs+150*relays -17*xstrs)
TEST.CMP	0.2372213	0.1061973	02.23378	tests/components
INPUT.CMP	0.2910916	0.116866	02.490815	inputs/components

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	0.7958355	3	0.2652785
Error	0.1963635	18	1.090908E-02
Total SS	0.9921989	21	
F = 24.31722			
R Squared 0.8020927			

c. F TEST STATISTICS

Regression F = 24.32

α =	0.05	0.025	0.01	0.005
$F_{3,18}$ =	3.16	3.95	5.09	6.03

99.5%<Significance Level

d. t TESTS STATISTICS

	Regression ABS (t Value)	Significance Level
TC	4.13	SL>99%
TEST.CMP	2.23	95%<SL<98%
INPUT.CMP	2.49	95%<SL<98%

α =	0.10	0.05	0.02	0.01
$t_{\alpha/2,21}$ =	1.72	2.08	2.52	2.83

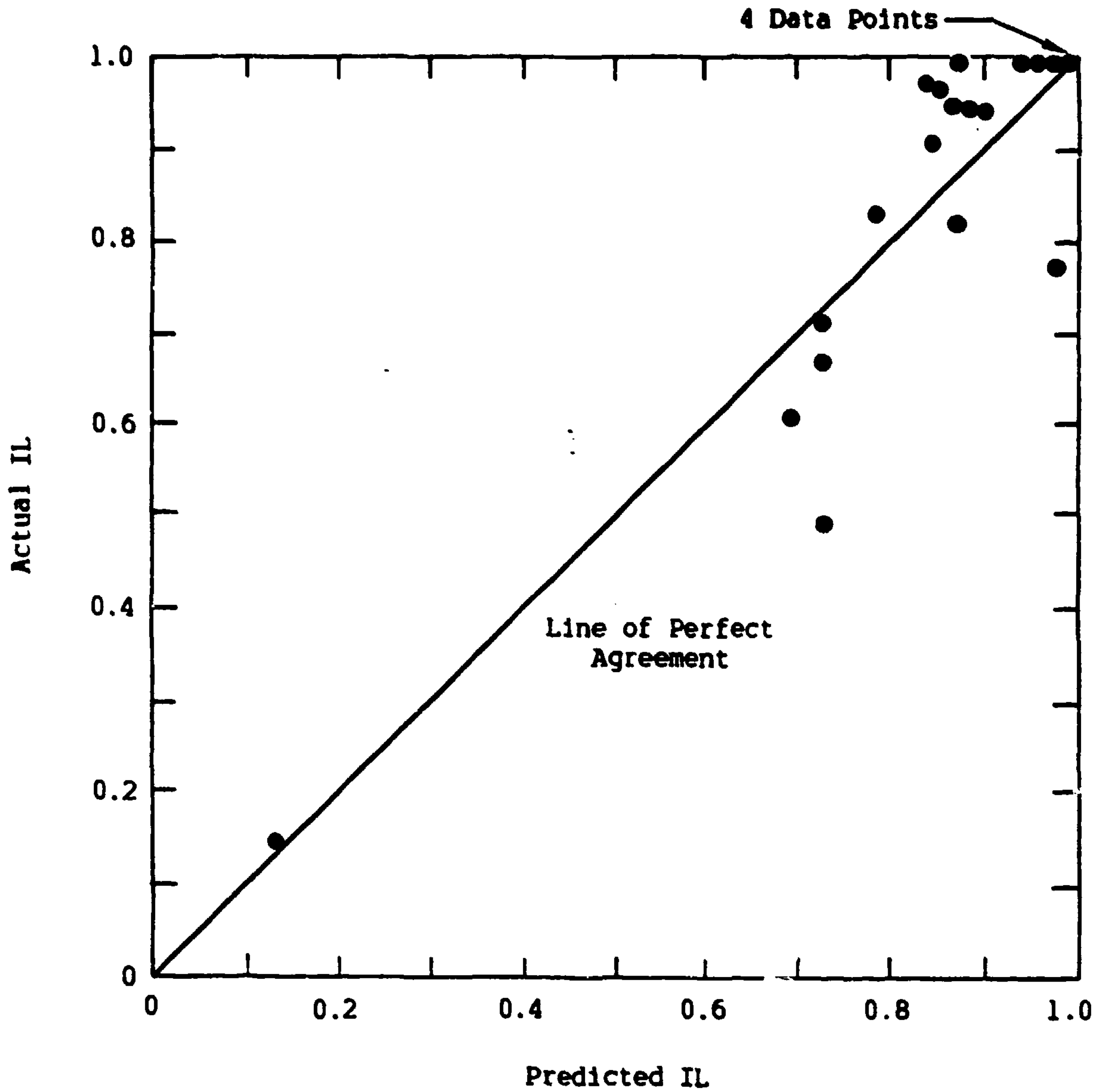


FIGURE 5-6

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR IL - FINAL EQUATION variables were either combinations and functions of the STAMP● measures and initial variables or a synthesis created by regression. These variables are listed in Appendix C.

5.6.2 The Prediction Equation

The equation developed to predict DP is as follows:

$$DP = \begin{cases} 0 & \text{IF } Fctn<0 \\ Fctn & \text{IF } 0 \le Fctn \le 1 \\ 1 & \text{IF } 1<Fctn \end{cases}$$

where:

$$Fctn = 1.04 - 3.39*10^{-5}*OUTMEAS - 4.64*ILFACTOR - 0.036*FATFACTOR.$$

The variables included in this equation cover various aspects of fault detection. The description of each variable suggests its inclusion in the regression equation.

- OUTMEAS - A synthesized variable that approximates the effect of the number of output signals. Detection is maximized if the majority of the tests are located at the system's functional bottlenecks, which commonly occur at output. Thus OUTMEAS can be viewed as a measure of functional topology.

- ILFACTOR - 1-IL represents the percentage of components that cannot be isolated, and ILFACTOR influences nondetection. (The number of components is an inverse complication factor and thus is in the denominator.)

- FATFACTOR - This variable is a measure that describes the test topology. FAT can be expressed as the average number of downstream verifiers for a given test. A verifier is any test that is expected to test "bad" given a bad outcome of the test that it is verifying. Verifiers are determined by extensive functional analysis of the system under test. The procedure is explained further in Chapter Six. FATFACTOR is the sixth root of the inverse of this measure.

All three of these measures relate to the analysis from subsection 3.4.4. A summary of the regression analysis for DP is presented in Table 5-10.

TABLE 5-10

EQUATION AND STATISTICS FOR LP

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	1.042823	2.904382E-02	35.90515	
OUTMEAS	-3.387432E-05	1.313741E-05	-2.578463	IO-3*inputs
ILFACTOR	-4.643569	1.725775	-2.690716	(1-IL)/components
FATFACTOR	-3.628183E-02	2.144648E-02	-1.691738	$(FAT)^{-1/6}$

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	1.128006E-02	3	3.76002E-03
Error	1.644135E-02	30	5.480449E-04
Total SS	2.772141E-02	33	

F = 6.860789
R Squared 0.406908

c. F TEST STATISTICS

Regression F = 6.86

α =	0.05	0.01	0.025	0.005
$F_{3,30}$ =	2.92	3.59	4.51	5.24

• 99.5%<Significance Level

d. t TESTS STATISTICS

	Regression ABS (t Value)	Significance Level
OUTMEAS	2.58	98%<SL<99%
ILFACTOR	2.69	98%<SL<99%
FATFACTOR	1.69	90%<SL<95%

α =	0.10	0.05	0.02	0.01
$t_{\alpha/2,30}$ =	1.69	2.04	2.45	2.74

5.6.3 Validation of Equation for DP

As mentioned before, one system was withheld from the regression analysis for DP to be used as a verifier of the predictive ability of the equation. This system has a STAMP®-generated DP value of 1.0 and a predicted value of 0.8784. This result and the corresponding prediction interval is presented graphically in Figure 5-7, and the data are listed in Table 5-11. The validation for DP is considered poor.

TABLE 5-11

VALIDATION OF EQUATION FOR DP

Variable	System
OUTMEAS	93
1-IL.CMP	0.0229
FAT-.167	1.515
PREDICTED VALUE	0.8784
ACTUAL VALUE	1.0
95% PREDICTION INTERVAL	(0.7935, 0.9632)

5.6.4 Final Equation for DP

At this point, the validation system was folded back into the data set to compute a final form of the equation using all the STAMP® system data compiled. The form of the equation and the choice of independent variables remain fixed. Note that the coefficient for ILFACTOR changed dramatically with the inclusion of this one system. The resulting equation is:

$$DP = \begin{cases} 0 & \text{IF } Fctn<0 \\ Fctn & \text{IF } 0<Fctn<1 \\ 1 & \text{IF } 1<Fctn \end{cases}$$

where:

$$Fctn = 1.03 - 3.12*10^{-5}*OUTMEAS - 0.61*ILFACTOR - 0.035*FATFACTOR.$$

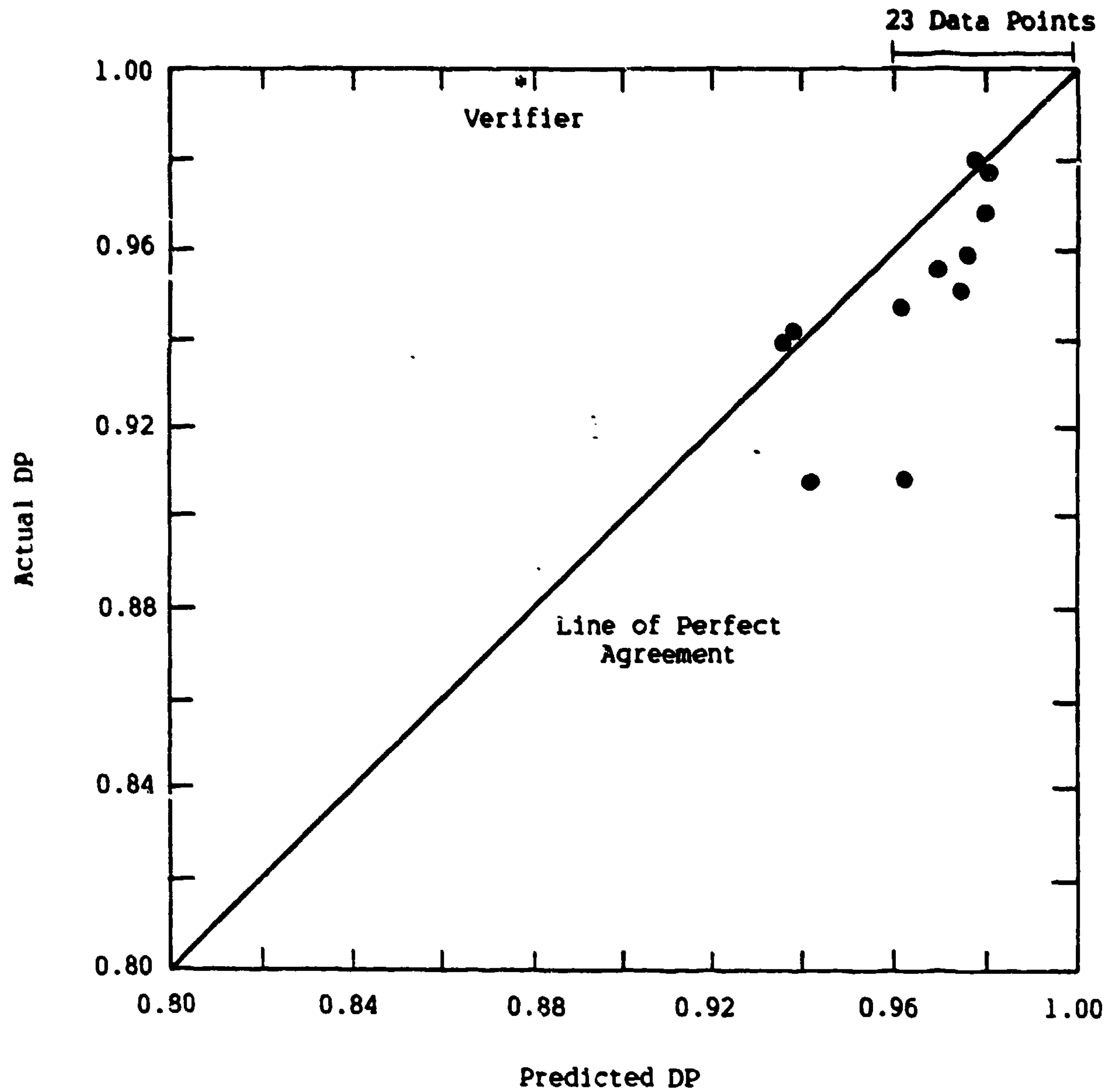


FIGURE 5-7

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR DP - INITIAL EQUATION

Table 5-12 summarizes the regression analysis for this final equation for DP. Included in this analysis is a scatter plot of predicted DP values versus the STAMP® generated values in Figure 5-8. A worksheet indicating the necessary measures and calculations is found in Chapter Six.

5.7 SUMMARY

The development of prediction equations yielded mixed results. Some predictors were excellent, and some were poor. Table 5-13 shows the results obtained for the four predicted testability attributes. The detection percentage estimator for FFD is not predictable enough with the current assignment of parameters to serve any useful purpose other than exploratory research.

TABLE 5-12

FINAL EQUATION AND STATISTICS FOR DP

a. EQUATION SUMMARY

Variable	Coefficient	Std. Error	T-Value	Computation
CONSTANT	1.033635	3.190994E-02	32.39224	
OUTMEAS	-3.116032E-05	1.448685E-05	-2.150939	IO-3*inputs
ILFACTOR	-0.6056138	1.05759	-0.5726359	(1-IL)/components
FATFACTOR	-3.462438E-02	2.370456E-02	-1.460664	$(FAT)^{-1/6}$

b. ANALYSIS OF VARIANCE

Sources of Variation	SS	DF	MSE
Regression	7.25174E-03	3	2.417247E-03
Error	2.077103E-02	31	6.700331E-04
Total SS	2.802277E-02	34	

F = 3.607652
R Squared 0.2587803

c. F TEST STATISTICS

Regression F = 3.61

α =	0.05	0.025	0.01	0.005
$F_{3,31}$ =	2.91	3.58	4.48	5.21

97.5%<Significance Level<99%

d. t TESTS STATISTICS

	Regression ABS (t Value)	Significance Level
OUTMEAS	2.15	95%<SL<96%
ILFACTOR	0.57	INSIGNIFICANT
FATFACTOR	1.46	80%<SL<90%

α =	0.20	0.10	0.05	0.02
$t_{\alpha/2,30}$ =	1.31	1.69	2.04	2.45

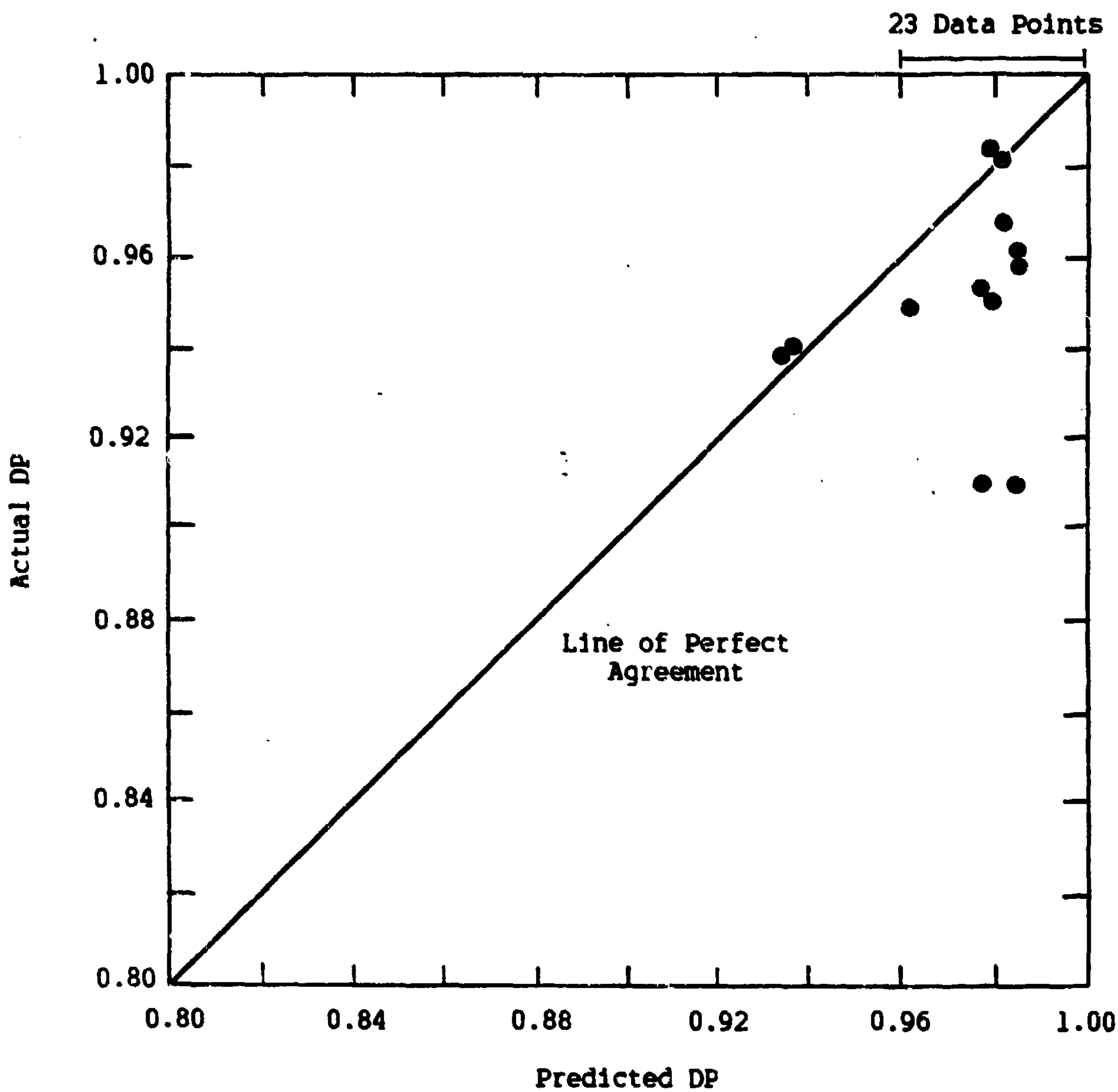


FIGURE 5-8

SCATTER PLOT OF OBSERVED VERSUS PREDICTED VALUES FOR
DP - FINAL EQUATION

TABLE 5-13

RESULTS OF THE ANALYSIS

Testability Attributes	Estimator	R^2	Validation Results	Recommendations
FFA	CND burden	0.6039	adequate	Equation useful for analysis purposes but not recommended for design compliance because of low R^2.
FAR	CND rate	0.9144	excellent	Shows great promise for use in analysis and specification compliance.
FFI	IL	0.8021	good	Shows promise for use in analysis and prediction.
FFD	DP	0.2589	poor	Not recommended for general use.

CHAPTER SIX

APPLICATIONS

6.1 INTRODUCTION

Several theoretical considerations (Chapter Three) led to the final form of the prediction equations, and computer-based statistical regression analyses (Chapter Five) yielded the actual equations. In this chapter, the advantages and shortcomings of the various prediction equations and a step-by-step procedure for applying them are described.

6.1.1 General Notes on Application

The equations of Chapter Five and their respective implementation procedures, described in the following sections, vary widely in their accuracy as predictors. The equations may be ranked in terms of accuracy of prediction as follows:

- CND rate
- IL
- CND burden
- DP

Three points must be considered when evaluating the benefits of using prediction equations:

- The prediction equations are not exact.
- The prediction equations are limited by the quality and domain of the data used as independent variables.

- The prediction equations provide predictions for surrogate measure testability parameters.

Prediction equations are not exact: A prediction interval with an associated confidence level (called a confidence interval estimate) is of more use than the point estimate provided by the equation. The prediction interval provides a measure of the relative precision that can be ascribed to a predicted value. An approximation of this interval can be made by using the standard error of estimates, s, provided in Table 6-1. This table gives the final equations derived in Chapter Five and data necessary to compute the estimated prediction interval,* (L, U) from the point estimate, P.

For IL and DP, the 95 percent prediction interval (L, U) can be computed using the point estimate, P, from the predicted equation and the standard error of estimate, s.

$$L = \text{Max}\ (P - 2s,\ 0)$$

$$U = \text{Min}\ (P + 2s,\ 1),$$

where s is given in Table 6-1. Each of the limits will lie between 0 and 1. For CND burden, the prediction interval (L, U) can be computed by:

$$L = \text{Max}\ (P - 2s,\ 0)$$

$$U = \text{Min}\ (P + 2s,\ 100),$$

*The prediction intervals are approximate, and they are based on the assumption that all the prediction parameters for a given prediction application are at the mean values of the data set used in the regression analysis. Under any other conditions, the confidence interval will be larger. The computation of exact limits requires many additional statistics based on the covariance matrix; these additional statistics are not believed to be necessary for most applications.

TABLE 6-1

REGRESSION EQUATION SUMMARY

Variable	Equation	Standard Error of Estimates (s)	Correlation Factor (R^2)
	CND BURDEN		
VOLUME	LENGTH * HEIGHT * WIDTH		
CNNCT	SMALL EXT.CON +2*MEDIUM EXT.CON +3* LARGE EXT.CON		
ACCESS	VOLUME + 500*CNNCT		
TOP4	FUNCTIONAL CROSS COUNT/NUMBER OF SRUs		
THRMCON	(THERMAL +1)*INTERCONNECTS		
THRMCMPLX	(THERMAL +1)*(ICs +1-*IND -2.4*CAP)/NUMBER OF SRUs		
CND BURDEN	25.9-0.002*ACCESS +3.9*TOP4+0.003*THRMCON-0.077*THRMCMPLX	7.67	0.60
	CND RATE		
FLRRATE	(MA-CND)/LRU OPERATING HOURS: MIL-STD-217 OR EQUIVALENT		
TRANSIENT	(ICs +41*RELAYS +2*CAP +2*RES-9*XSTRS)/NUMBER OF SRUs		
TC7	NUMBER OF INTERCONNECTS*(ICs+30*XSTRS-160*RELAYS-960*SWITCHES)		
CND RATE	-0.0028+0.375*FLRRATE+2.6x10^{-5}*TRANSIENT+5.9x10^{11}*TC7	8.3x10^{-4}	0.91
	IL		
TC	NUMBER OF INTERCONNECTS*(ICs +150*RELAYS -17*XSTRS)		
TEST.CMP	TESTS/COMPONENTS		
INPUT.CMP	INPUTS/COMPONENTS		
IL	0.59 -2.41x10^{-8}*TC +0.237*TEST.CMP +0.291*INPUT.CMP	0.104	0.80
	DP		
OUTMEAS	IO -3*INPUTS		
ILFACTOR	(1-IL)/COMPONENTS		
FATFACTOR	(NUMBER OF TEST VERIFIERS/[TESTS*(TESTS-1)])$^{-1/6}$		
DP	1.03-3.12x10^{-5} *OUTMEAS -0.61* ILFACTOR -0.035*FATFACTOR	0.026	0.26

with CND burden being between 0 and 100 percent. The prediction interval (L, U) for CND rate can be computed by:

$$L = \mathrm{Max}\ (P - 2s,\ 0)$$

$$U = P + 2s,$$

with CND rate being occurrences per operating hour.

Prediction equations are limited by the quality and the domain of the data used as independent variables: Table 6-2 presents the domain (range) of the measured values used as independent variables in the prediction equations. Predictions attempted when measured values are not within the range of data values presented in the table represent an extrapolation that is subject to greater errors than those indicated by the statistical analysis of Chapter Five.

The equations provide predictions for surrogate measure testability parameters: Although they may reasonably predict CND burden, CND rate, IL, and DP, in some instances, there is no guarantee that the results will be reasonable predictions of the testability attributes FFA, FAR, FFI, and FFD.

One or more of the following types of data sources may have to be used to develop the values for the predictor variables:

- Design detail documentation, including specifications, schematics, theory of operation, and parts lists
- Environmental analysis and design expert consultation
- MIL-HDBK-217 or other appropriate failure rate prediction data
- Inspection of hardware prototypes or breadboards

TABLE 6-2

SUMMARY OF VARIABLES AND VALUE DOMAINS

Measured Variable	Applicable Equation	Definition (Report Section)	Range of Data Values
Functional cross count	CND burden	Number of parallel paths (6.2.1.1)	8 - 47
SRUs	CND burden, CND rate, IL	Number of SRUs in the LRU (6.2.1.2)	4 - 42
Length	CND burden	Length of the LRU (6.2.3.1) (inches)	6 - 24.57
Height	CND burden	Height of the LRU (6.2.3.1) (inches)	4.03 - 19.75
Width	CND burden	Width of the LRU (6.2.3.1) (inches)	3.625 - 31.2
Thermal	CND burden	Number of thermal sensitivities (6.2.2.4)	0 - 2
Interconnects	CND burden, CND rate, IL	SRU-LRU interconnects (6.2.2.5)	0 - 5,724
Inputs/outputs	DP	Input/output signal count (6.5.1.1)	17 - 892
Capacitors	CND burden, CND rate	Capacitor count (6.2.2.3)	5 - 2,410
ICs	CND burden, CND rate, IL	Integrated circuit count (6.2.2.1)	0 - 4,712
Inductors/transformers	CND burden	Inductor/transformer count (6.2.2.2)	0 - 247
Relays	CND rate, IL	Relay count (6.3.2)	0 - 87
Resistors	CND rate	Resistor count (6.3.2)	10 - 1543
Switches	CND rate	Internal switch count (6.3.3)	0 - 10
Transistors	CND rate, IL	Discrete transistor count (6.3.2)	0 - 291
Small external connectors	CND burden	0 to 4 pin connectors (6.2.3.2)	0 - 9
Medium external connectors	CND burden	5 to 14 pin connectors (6.2.3.2)	0 - 2
Large external connectors	CND burden	15 and over pin connectors (6.2.3.2)	0 - 11
Failure rate	CND rate	LRU failure rate (6.3.1)	0.43 - 34.3*
Components	IL, DP	Component failure mode count (6.4.2)	10 - 235
Input signals	IL, DP	Input count (6.4.3)	4 - 184
Tests	IL, DP	Test count (6.4.2)	10 - 936
Test verifiers	DP	Downstream test verifiers (6.5.3)	30 - 84 891
IL	DP	Isolation level (6.5.2)	0.1408 - 1

*Per 1,000 operating hours.

6.1.2 Notations Used in This Chapter

In addition to the various conventions and notations already used in this document (see Glossary), a number of graphical notations are employed to illustrate computational algorithms for the prediction equations. These notations are defined in Figure 6-1. The graphical descriptions of the four prediction procedures are designed to serve as templates. Once appropriate data are obtained, one should be able to compute the predicted values by copying the appropriate figures and tables and stepping through the prediction procedures by filling in the blanks on the figures.

6.1.3 Information Sources

Throughout this chapter, suggested documents for fielded systems are listed as sources for the required information. The documents mentioned are for fielded systems for two reasons. First, these were the sources used for this study, and second, documentation for fielded systems is generally more standard in content and format. For systems that are still in the design phase, equivalent documentation may include such sources as circuit diagrams, functional block diagrams, wiring lists, reliability prediction data, failure modes and effects analysis (FMEA), reliability, availability, and maintainability documentation, and the integrated logistics support plan (ILSP). Another source of information would be interviews with technicians or other personnel who have experience with systems fielded in an environment similar to that of the system under design.

6.2 CND BURDEN -- ESTIMATOR FOR FFA

The prediction equation for CND burden is considered adequate. When possible, the alternative predictor, CND rate should be used because of its higher R^2 value. Figure 6-2 shows the equation for predicting CND Burden and the four synthesized variables. These variables are described, along with their synthesis procedures, in the following subsections. Note that CND burden is a percent measure between 0 and 100.

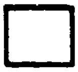
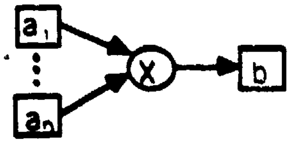
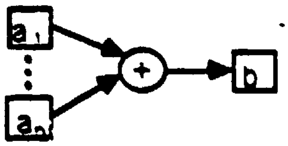
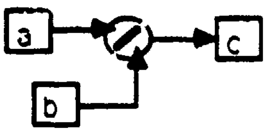
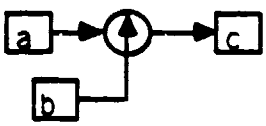
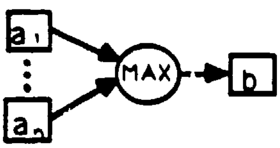
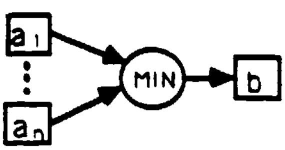
SYMBOL	DEFINITION
	AN ACTIVITY
	A VALUE, VARIABLE OR CONSTANT
	$b = a_1 \times a_2 \times a_3 \times \cdots \times a_n$
	$b = a_1 + a_2 + a_3 + \cdots + a_n$
	$c = a/b$
	$b = -a$
	$c = a^b$
	$b = MAX(a_1, a_2, a_3, \ldots, a_n)$
	$b = MIN(a_1, a_2, a_3, \ldots, a_n)$

FIGURE 6-1

GRAPHICAL NOMENCLATURE APPLIED TO PREDICTION PROCEDURES

6.2.1 Topological Complexity Variable (TOP4)

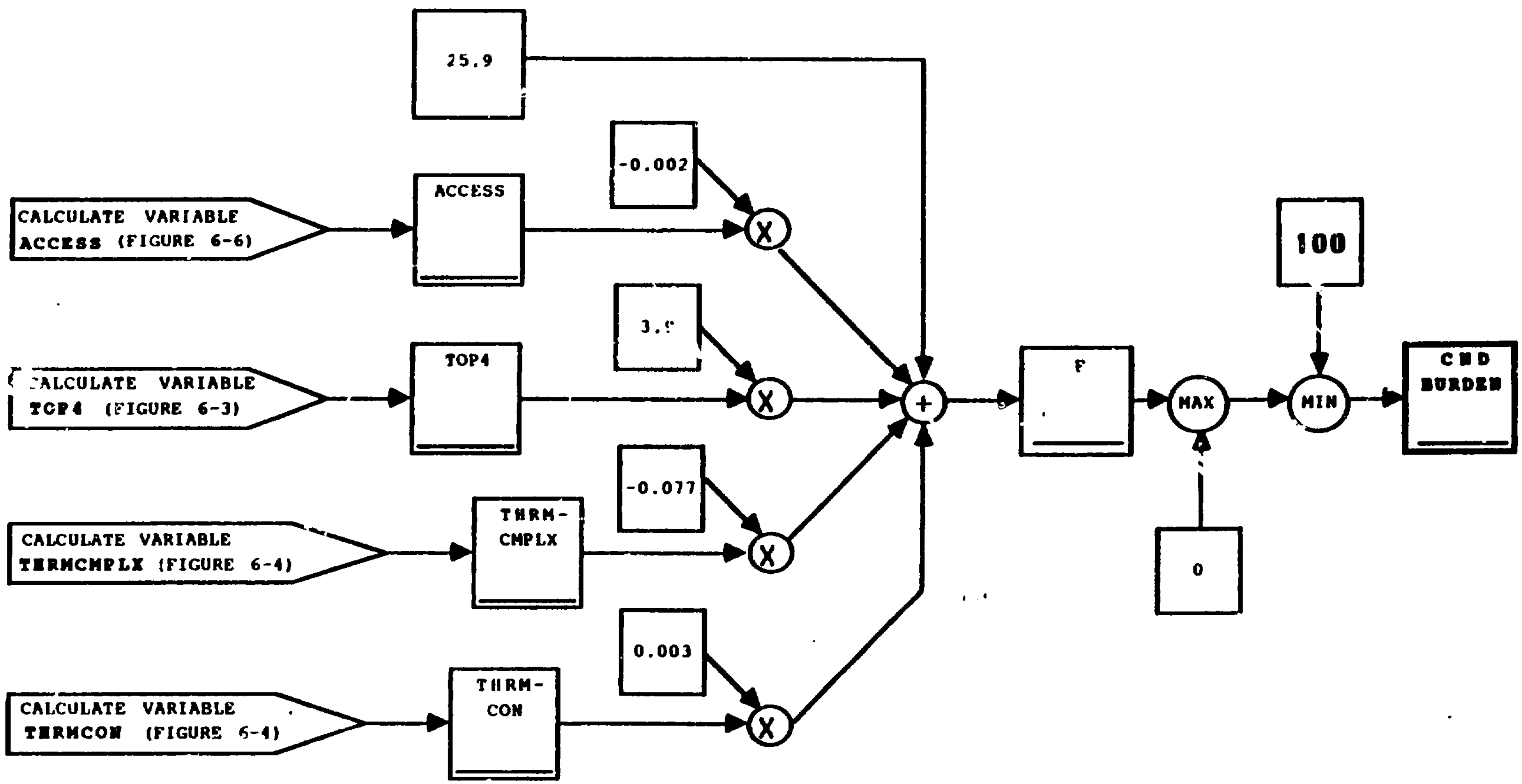
This synthesized variable attempts to numerically characterize the complexity inherent in the topology of an LRU design. (See the discussion on topological complexity in Section 3.4.2.2.) Figure 6-3 summarizes the synthesis of TOP4. Two measurements are required for this variable -- a functional cross-section count and an SRU count. These counts are described in subsections 6.2.1.1 and 6.2.1.2, and are further subdivided in Figure 6-4.

6.2.1.1 Functional Cross-Section Count (CROSS COUNT)

The functional cross-section count of an LRU is measured using a top-level functional block diagram of the LRU (presumed to be oriented from left to right). This type of diagram is typically found in Air Force O-Level Technical Orders. The measurement involves the determination of the maximum number of parallel functional paths in the diagram.

One procedure for performing this measurement is to scan the diagram with a vertically oriented straight edge and to count the number of horizontal paths cut by the edge. The edge is moved from left to right until the count changes. This next count is recorded and the procedure continues. At the conclusion, the maximum number of paths cut by the edge is taken as the functional cross-section count. The diagram used for this measure is the top level functional block diagram illustrating the relationships between SRUs or other functional entities. Each physically drawn line should be counted once, even if it represents a bus or multiple signal line.

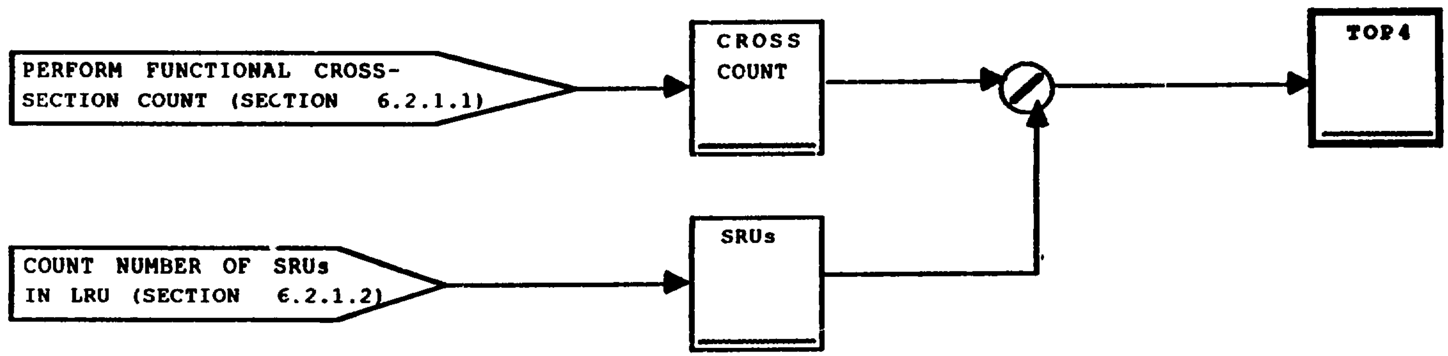
Caution should be used in the interpretation and use of this measure. A functional block diagram might be easily modified to change the outcome of this type of measurement. Although the functional cross-section count indicates some measure of parallelism useful for predicting CND burden, it should not be used beyond this purpose without further analysis.



CND BURDEN = 25.9 -0.002*ACCESS + 3.9*TOP4 -0.077*THRMCMPLH + 0.003*THRMCON

FIGURE 6-2

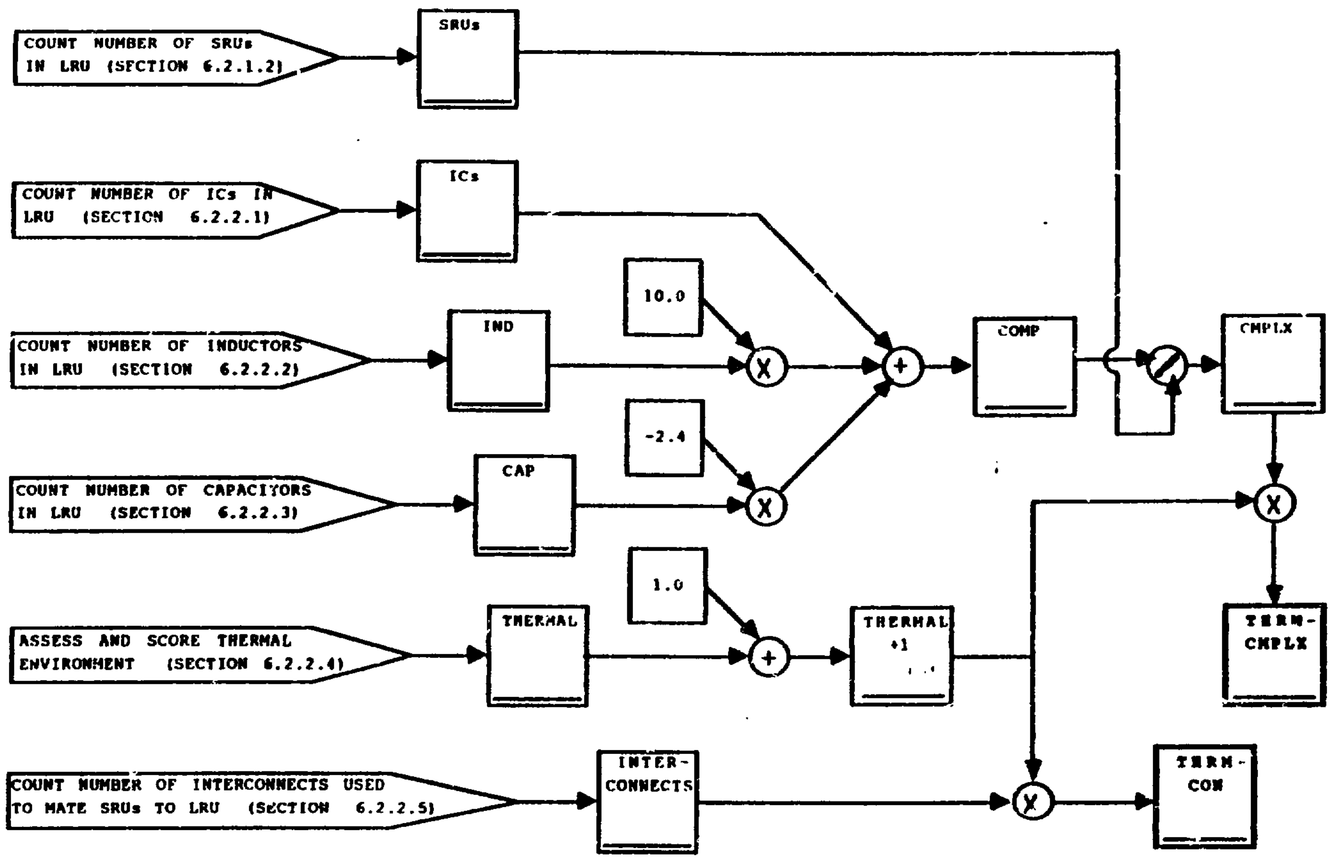
PREDICTION PROCEDURE FOR CND BURDEN



$$TOP4 = \frac{\text{CROSS COUNT}}{\text{NO. OF SRUs}}$$

FIGURE 6-3

SYNTHESIS OF TOP4



$$THRMCMPLX = \frac{(THERMAL+1)*(ICs + 10*IND - 2.4*CAP)}{NO.\ OF\ SRUs}$$

$$THRMCON = (THERMAL+1)*INTERCONNECTS$$

FIGURE 6-4

SYNTHESIS OF THRMCMPLX AND THRMCON

6.2.1.2 SRU Count (SRUs)

This measurement involves the count of the SRUs that compose a given LRU. Not included in this count are SRUs with only mechanical parts (such as gyros) or without any components (such as a mother board). This type of information may be found in Air Force O-Level Technical Orders or equivalent documentation.

6.2.2 Measures of Thermally Compounded Failures (THRMCMPLX and THRMCOM)

The second and third variables affecting CND burden, THRMCMPLX and THRMCON, attempt to characterize the compounded effect of environmentally induced thermal stress on the intermittent behavior of various types of components. The synthesis procedures are given in Figure 6-4. The measurement data required for these procedures are discussed in the following subsections.

6.2.2.1 Integrated Circuit Count (ICs)

This measurement includes both linear and digital integrated circuits and hybrid devices. A count of the total number of these components used in an LRU is made. The sources for this information include Air Force Technical Order illustrated parts breakdown (IPBs), schematic diagrams, or other design documentation.

6.2.2.2 Inductor Count (IND)

The IND measurement represents the total number of inductors in an LRU design. This number includes inductors used in power supply filters, high frequency chokes, and transformers. It does not include the inductances in relay coils. Sources for this information include IPB documentation and schematic diagrams.

6.2.2.3 Capacitor Count (CAP)

This measurement is the total count of capacitors used in the LRU. Information sources are the same as for ICs and inductors.

6.2.2.4 Thermal Environment (THERMAL)

This variable, THERMAL, is an integer in the range 0 to 3 and is derived by completing the information requested in the form shown in Figure 6-5. THERMAL attempts to characterize the level of thermal stress to which a given LRU is subject due to its environment. The source of this information must be an Air Force flight line maintenance specialist, environmental design expert, environment simulation program, or some other equivalent source.

6.2.2.5 SRU-to-LRU Interconnects (INTERCONNECTS)

This variable, INTERCONNECTS, is the total number of electrical interconnects used to mate all of the SRUs to a given host LRU. This number includes all signals, power, and grounds. Only those interconnects that carry electrical functions are used. No spares are included in the count. These data are obtained by analyzing Air Force I-Level Technical Orders, IPBs, or equivalent documentation.

6.2.3 Accessibility Variable (ACCESS)

The ACCESS variable is designed to measure the difficulty with which the LRU is removed from the aircraft for fault investigation. Figure 6-6 depicts the computation of ACCESS. VOLUME and CNNCT, the two variables used to calculate ACCESS, are discussed in subsections 6.2.3.1 and 6.2.3.2.

6.2.3.1 Volume (VOL)

The variable VOL is a product of LRU height, width, and length. The measures must be in inches for the equation. These measures are commonly found in Air Force O-Level Technical Orders or equivalent documentation.

6.2.3.2 External Connectors (CNNCT)

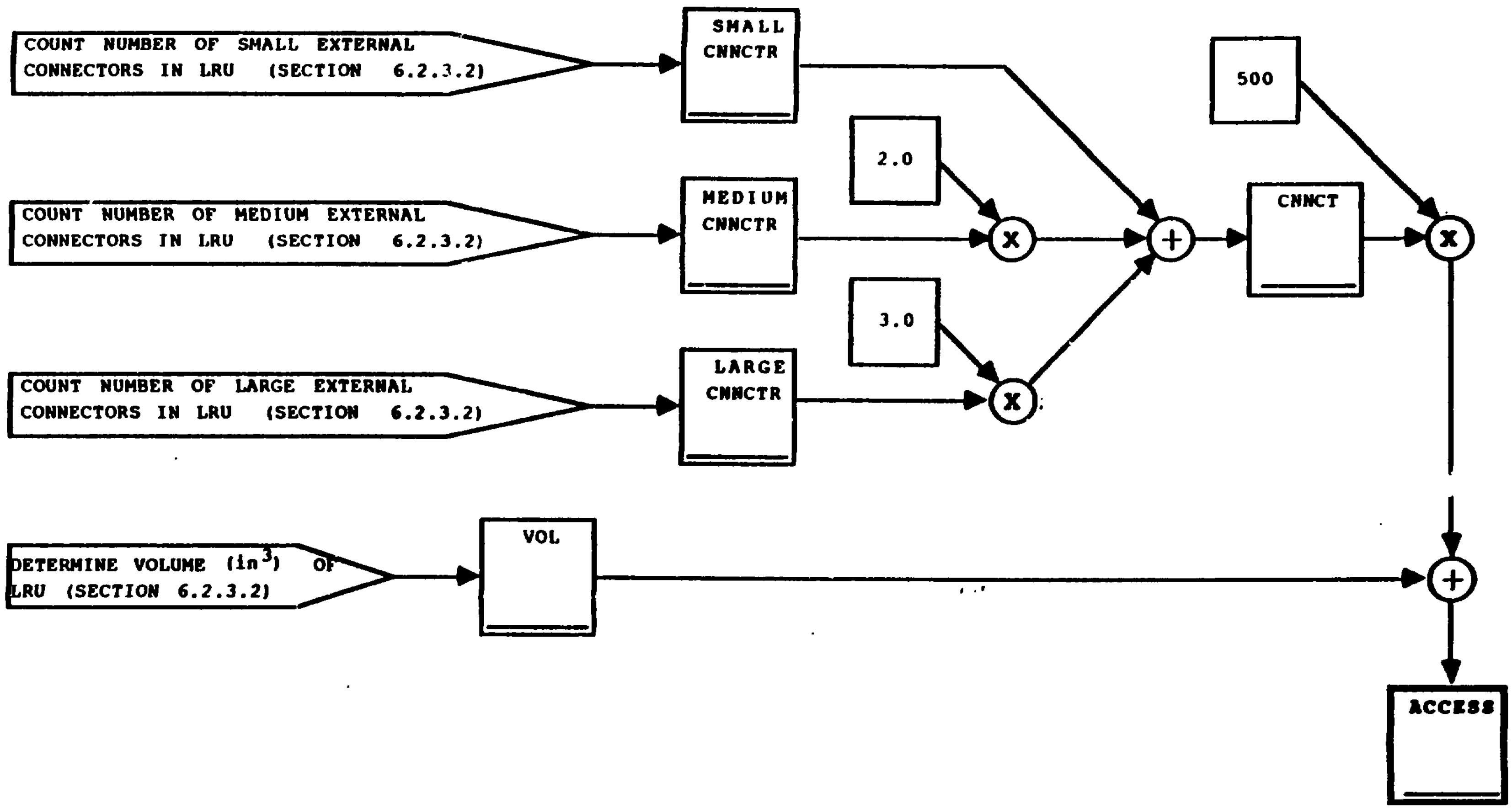
As seen in Figure 6-4, CNNCT is a linear combination of small, medium, and large external connectors. These do not include test or programming connectors. Small, medium, and large are classifications based on the pin count: 0 to 4 pins constitute a small connector, 5 to 14 pins constitute

THERMAL ENVIRONMENT CHARACTERIZATION		
SYSTEM:	**YES**	**NO**
IS THE SYSTEM LIKELY TO BE SUBJECT TO TEMPERATURE EXTREMES, DUE TO CLIMATE, ALTITUDE, ADJACENT SYSTEMS, OR COMBINATIONS THEREOF?		
IS THE SYSTEM LIKELY TO BE SUBJECT TO A HIGH DEGREE * OF THERMAL CYCLING, DUE TO CHANGES IN CLIMATE AND/OR ALTITUDE, OPERATIONAL PROFILES OF ADJACENT SYSTEMS, OR COMBINATIONS THEREOF?		
IS THE SYSTEM LIKELY TO BE SUBJECT TO THERMAL SHOCK * , DUE TO MISSION CHARACTERISTICS, ADJACENT SYSTEM BEHAVIOR, OR COMBINATIONS THEREOF?		
ADD THE NUMBER OF "YES" RESPONSES HERE: **THERMAL ENVIRONMENT**	☐	

* A qualified maintenance technician at the flight line level is the best source for this information.

FIGURE 6-5

THERMAL ENVIRONMENT CHARACTERIZATION



ACCESS = VOL + 500*(SMALL CNNCTR+2*MEDIUM CNNCTR+3*LARGE CNNCTR)

FIGURE 6-6

VARIABLE SYNTHESIS FOR ACCESS

medium connector, and 15 and more pins constitute a large connector. CNNCT is then calculated by adding the number of small external connectors, twice the number of medium connectors, and three times the number of large connectors. The number of pins and connectors may be found in Air Force O-Level Technical Orders, by inspection of the LRU, or by equivalent documentation.

6.3 CND RATE -- ESTIMATE FOR FAR

The prediction equation for CND rate is reasonably accurate. When possible, this attribute should be used instead of CND burden. However, as is the case with all models, the output of this prediction equation is only as good as the measurement data used. One of the measures used to generate CND rate is LRU failure rate. During system design, field failure rates may be unknown and, thus, must be estimated. If the estimate is very coarse, the resulting prediction of CND rate also will be coarse. When this estimate is known to be highly inaccurate, it may be advisable to use CND burden. The CND rate is measured in occurrences per hour.

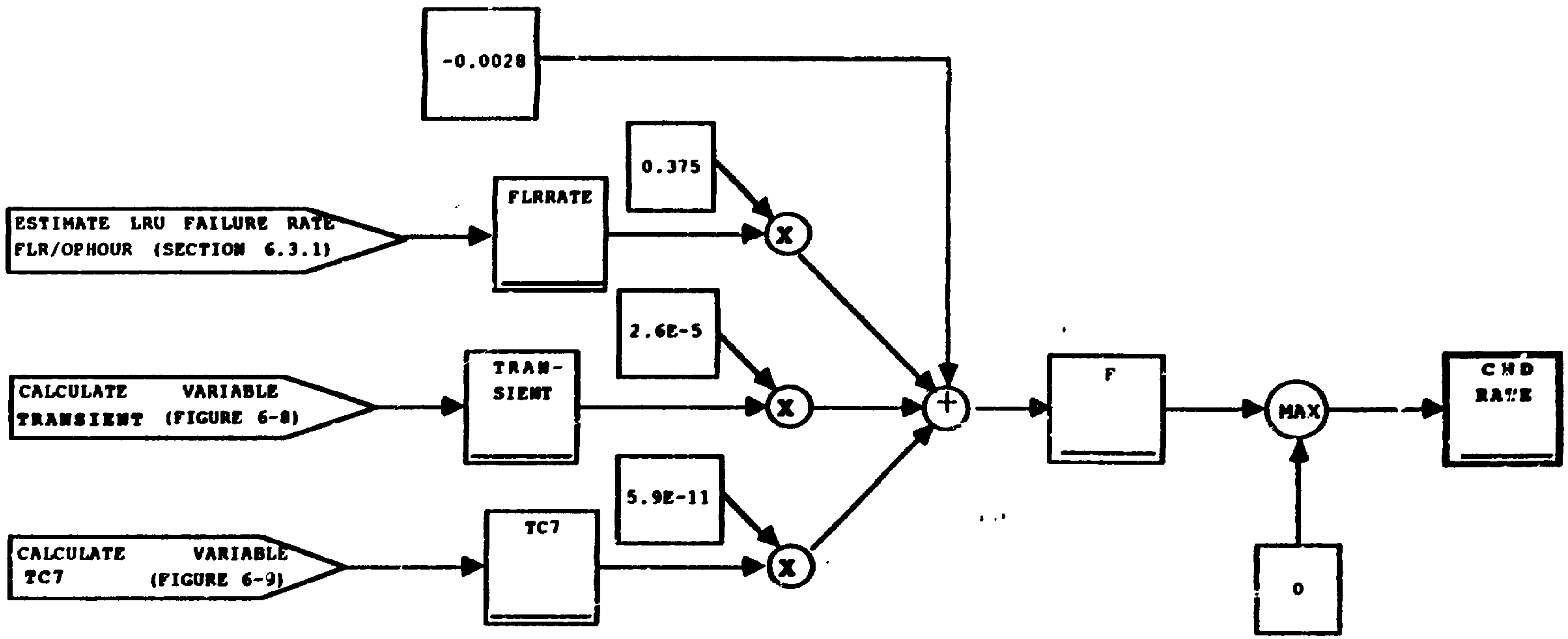
The CND rate predictor requires the LRU failure rate variable and two synthesized variables. These are discussed in the following subsections. The procedure for predicting CND rate is detailed in Figure 6-7 and subdivided further in Figures 6-8 and 6-9.

6.3.1 LRU Failure Rates (FLRRATE)

If CND rate is being predicted for a system in the field, actual failure rate data should be compiled and used as the value for the variable FLRRATE. Failure rate must be the number of LRU failures per operating hour. The failure rates used in this study were calculated as follows:

$$\text{Failure rate} = \frac{\text{No. of maintenance actions - no. of CND events}}{\text{No. of aircraft in survey * no. of operating hours per aircraft}}$$

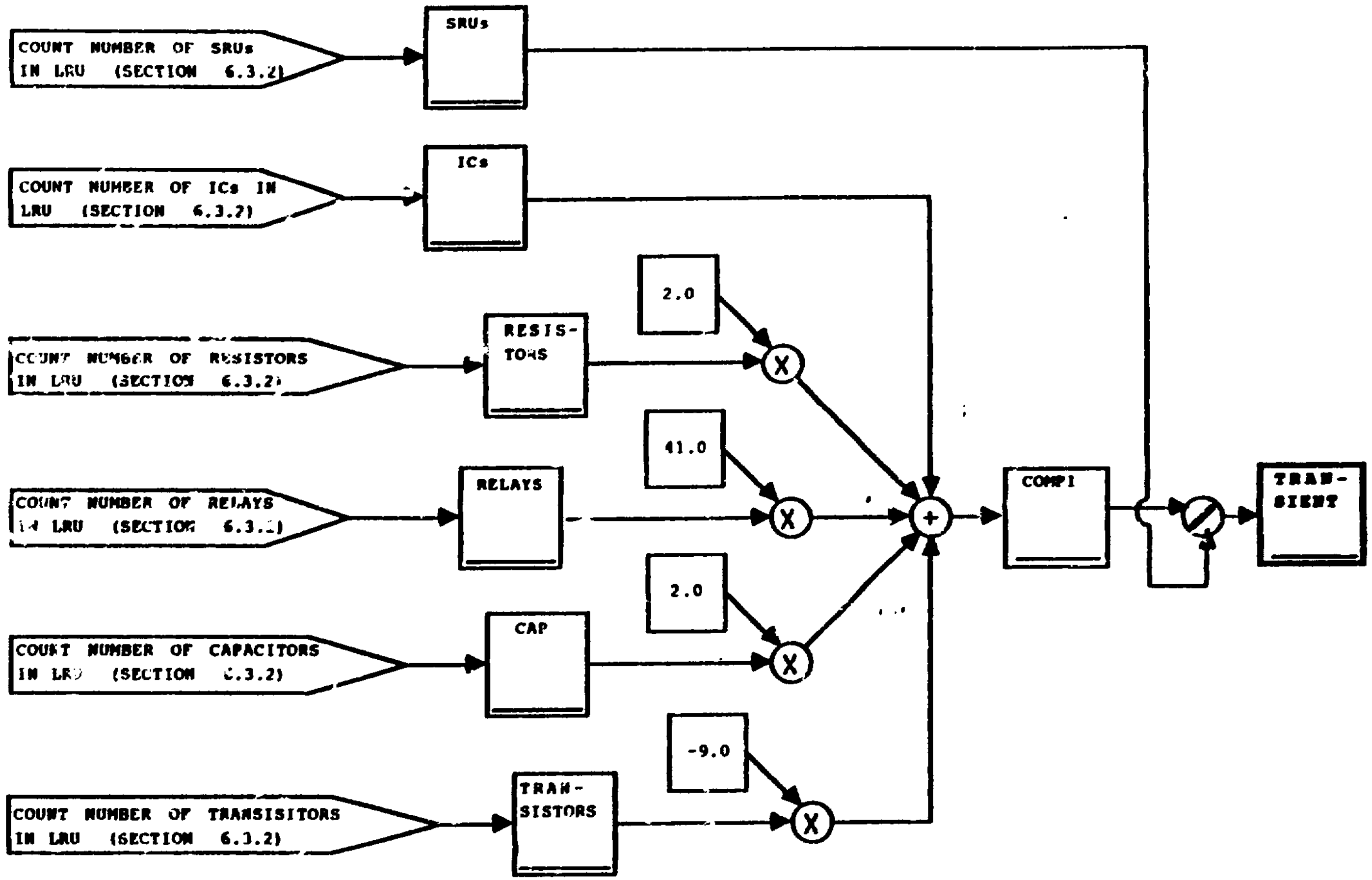
This yields units of failures per operating hour.



CND RATE = -0.0028 + 0.375*FLRRATE + 2.6E-5*TRANSIENT + 5.9E-11*TC7

FIGURE 6-7

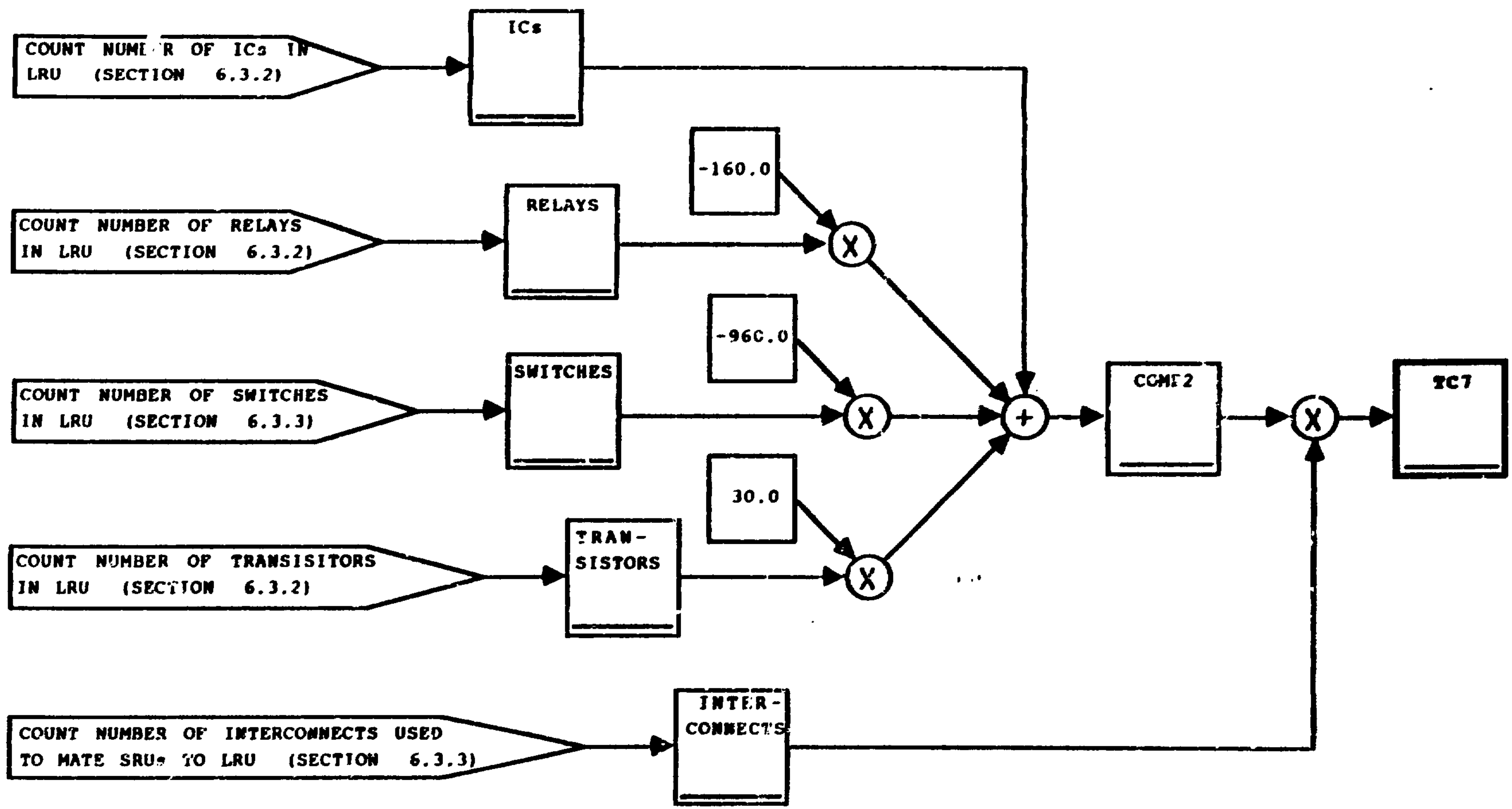
PREDICTION PROCEDURE FOR CND RATE



$$\text{TRANSIENT} = \frac{\text{ICs} + 2*\text{RESISTORS} + 41*\text{RELAYS} + 2*\text{CAP} - 9*\text{TRANSISTORS}}{\text{NO. OF SRUs}}$$

FIGURE 6-8

VARIABLE SYNTHESIS OF TRANSIENT



TC7 = INTERCONNECTS*(ICs - 160*RELAYS - 960*SWITCHES + 30*TRANSISTORS)

FIGURE 6-9

VARIABLE SYNTHESIS FOR TC7

When used for a system in the design stage, the failure rates may have to be estimated. There are a number of viable techniques for this estimation:

- Use of MIL-HDBK-217
- Vendor and manufacturer estimates of failure rates based on testing and screening and simulations
- Other reliability estimation programs

6.3.2 Tendency for Transient Behavior (TRANSIENT)

The second variable used to estimate CND rate, TRANSIENT, attempts to characterize the tendency of an LRU to exhibit intermittent failures resulting from marginal or degrading components. This synthesis procedure is depicted in Figure 6-8. The measurements required are available from Air Force Technical Orders (I-Level and IPBs) or equivalent documentation. The measurements are the following:

- RELAYS: The total number of relays in an LRU
- CAPACITORS: The total number of capacitors used in an LRU
- RESISTORS: The total number of resistors, both fixed and variable, in an LRU
- TRANSISTORS: The total number of discrete transistors, including FETs, BIPOLAR, SCRs, and TRIACs, etc., that are in an LRU design
- INTEGRATED CIRCUITS: The total number of ICs in an LRU (see Section 6.2.2.1)
- SRUs: The total number of SRUs that compose a LRU (see Section 6.2.1.2)

6.3.3 Topological Complexity (TC7)

TC7 numerically characterizes the likelihood of a sneak circuit existing in an LRU. For more details, see the discussion of topological complexity in Section 3.4.) The equation for synthesizing this variable is shown in Figure 6-9. TC7 requires three of the same variables that

TRANSIENT requires -- RELAYS, ICs, and TRANSISTORS. In addition, there are two other variables, SWITCHES and INTERCONNECTS.

SWITCHES is a count of the number of switches in the LRU design. This count may be obtained by reviewing Air Force Technical Orders (I-Level and IPBs) or equivalent documentation.

INTERCONNECTS is the total number of electrical interconnects used to mate SRUs to a host LRU. This measurement is described in Section 6.2.2.5.

6.4 IL -- ESTIMATOR FOR FFI

The predictor equation for IL is reasonably accurate; however, IL is not FFI, only an upper bound. Thus, the resulting value obtained from this procedure will represent an estimate of the upper limit of FFI as discussed in Section 2.2. The procedure for estimating IL is described in Figures 6-10 through 6-12. The IL predictor uses three synthesized variables as discussed in the following subsections. The IL is a normalized value between zero and one with no units.

6.4.1 Topological Complexity (TC)

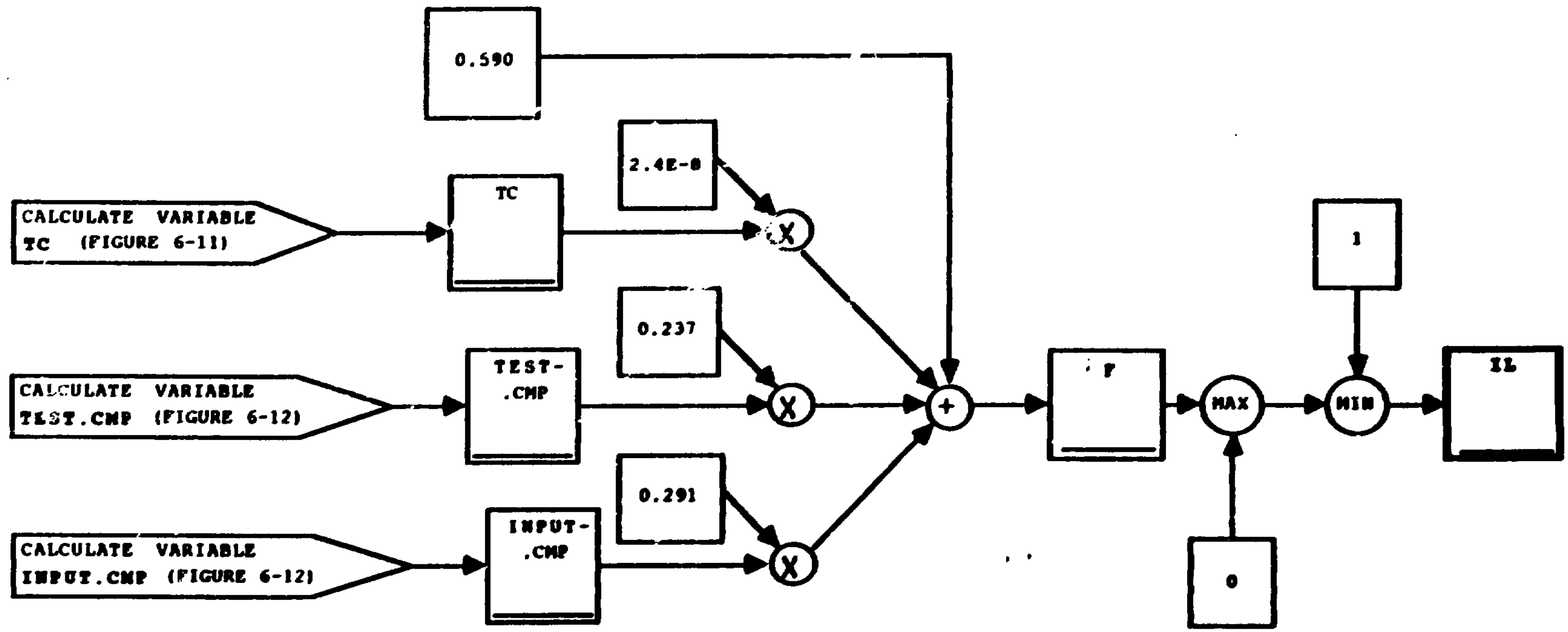
Figure 6-11 depicts the synthesis of TC. This variable is similar to the variable TC7 used in the predictor equation for CND rate. A discussion of the measured data is given in Section 6.3.2.

6.4.2 Test System and Functional Characteristic (TEST.CMP)

Figure 6-12 depicts the synthesis of TEST.CMP. This consists of two design characteristics (tests and failure mode components).

Tests* will include the sum total of signals, indications, or other observable events that may be either an output of the system or caused to happen during a test procedure. Failure mode components are regarded as

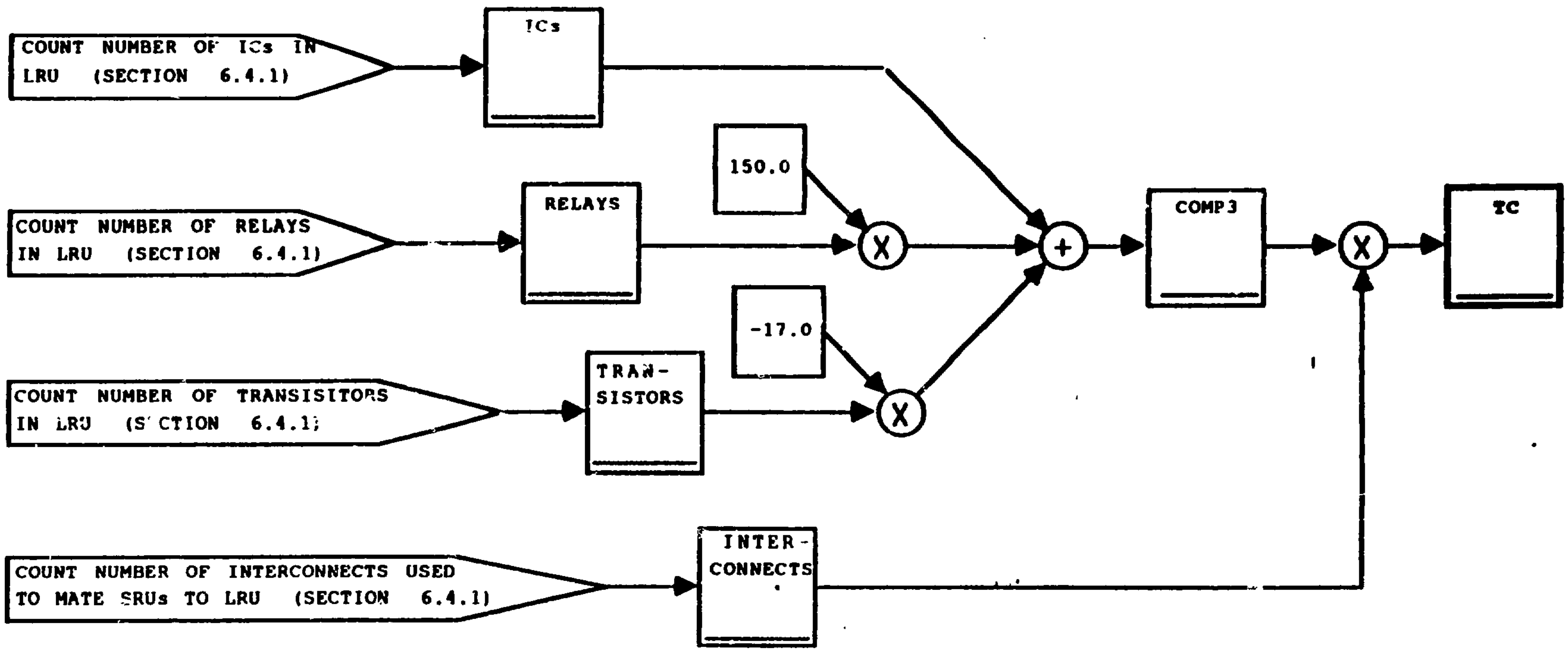
*For definition of this term, see Appendix D.



IL = 0.59 + 2.4E-8*TC + 0.237*TEST.CMP + 0.291*INPUT.CMP

FIGURE 6-10

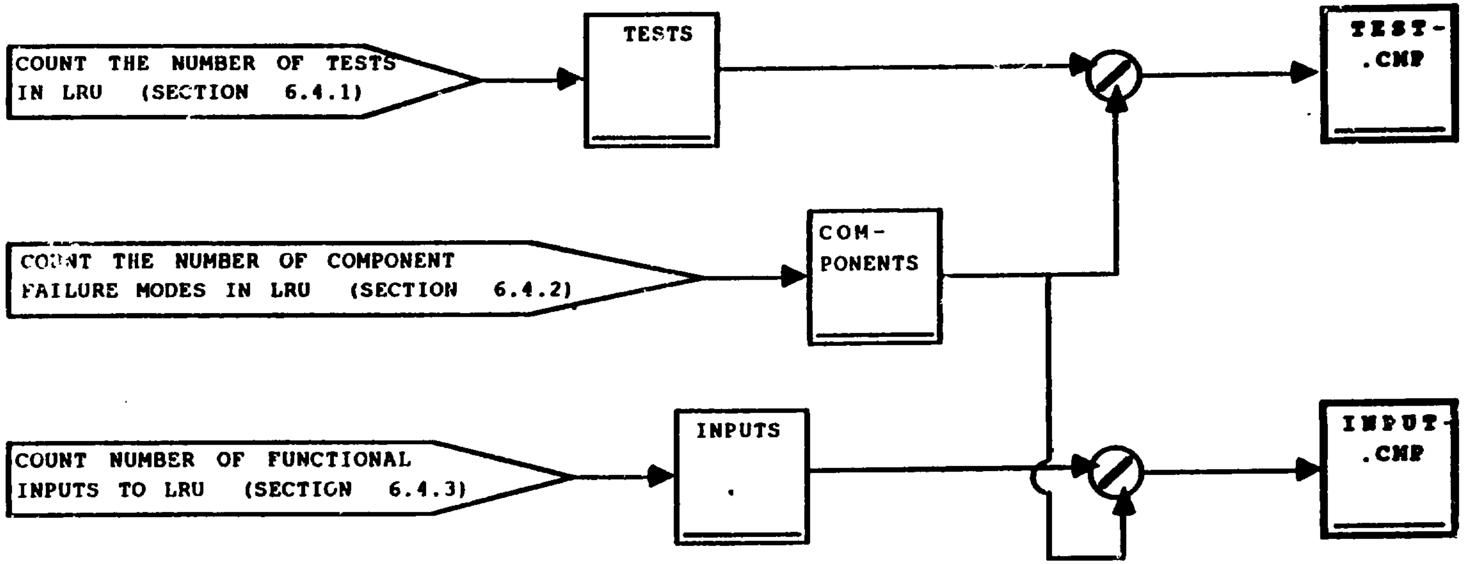
PREDICTION PROCEDURE FOR IL



TC = INTERCONNECTS*(ICs + 150*RELAYS - 17*TRANSISTORS)

FIGURE 6-11

VARIABLE SYNTHESIS FOR TC



$$\text{TEST.CMP} = \frac{\text{NO. OF TESTS}}{\text{NO. OF COMPONENTS}}$$

$$\text{INPUT.CMP} = \frac{\text{NO. OF INPUTS}}{\text{NO. OF COMPONENTS}}$$

FIGURE 6-12

VARIABLE SYNTHESIS FOR TEST.CMP AND INPUT.CMP designated functional units of a system indicating a desired level of fault isolation. They may be parts, LRUs, or failure modes of parts depending on the desired analysis. (The total number of failure conclusions that could be reached based on different failures that could happen to the system is components.)

6.4.3 Test System and Functional Characteristic (INPUT.CMP)

Figure 6-12 depicts the synthesis of INPUT.CMP. This consists of two design characteristics (functional input signals and failure mode components). Functional input signals consist of all input representing a function, where an input is defined as any active electrical signal including power and ground but not including spares. For example, a bus line with several signals but only one function would be considered as one functional input signal.

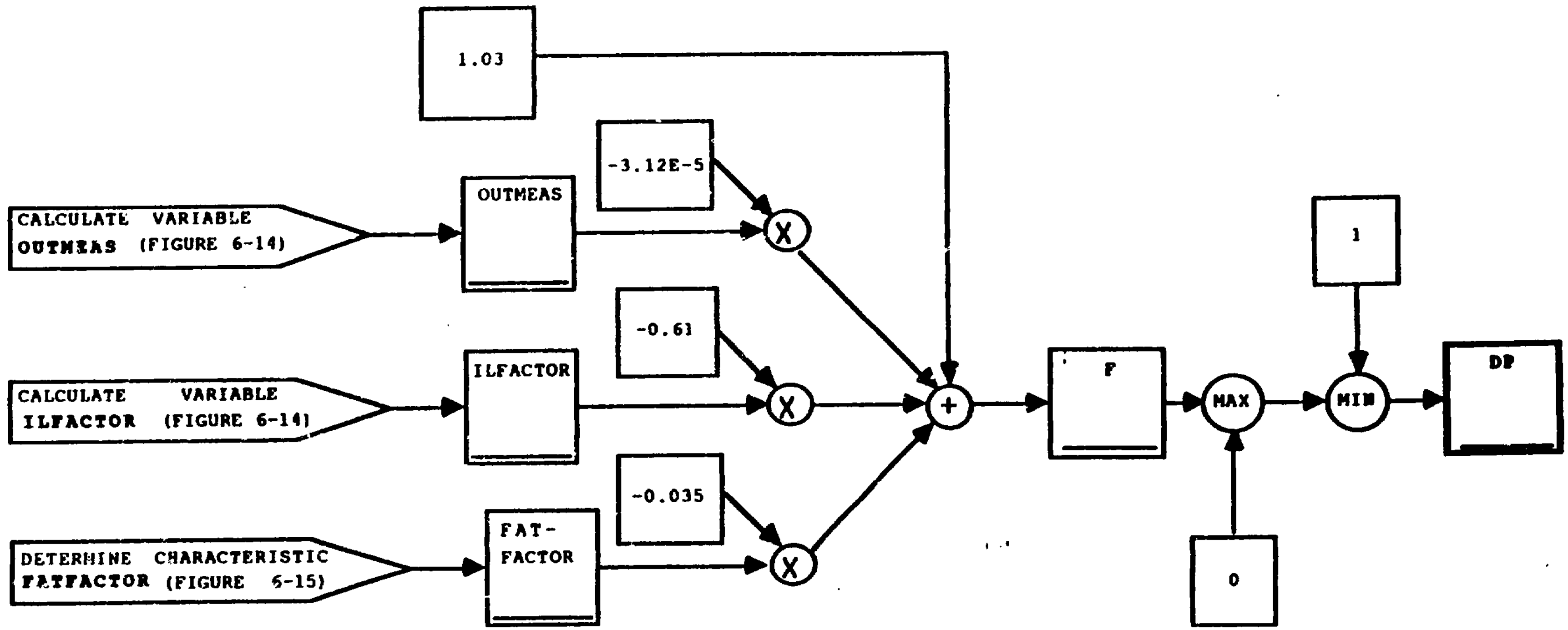
6.5 DP -- ESTIMATOR FOR FFD

The prediction equation for DP is poor in terms of accuracy. Its use is not recommended. The validity of any estimates derived using this equation is further compromised due to use of the independent variable, IL. (IL is an estimate itself.) The dependence of detection on isolation (and vice versa) is a confirmation of the analytical work for these terms as discussed in Chapter Three.

The procedure for prediction of DP is described in Figures 6-13 and 6-14. The variables used in the prediction of DP are discussed in the following sections. DP is a normalized value ranging between zero and one with no units.

6.5.1 Output Measure (OUTMEAS)

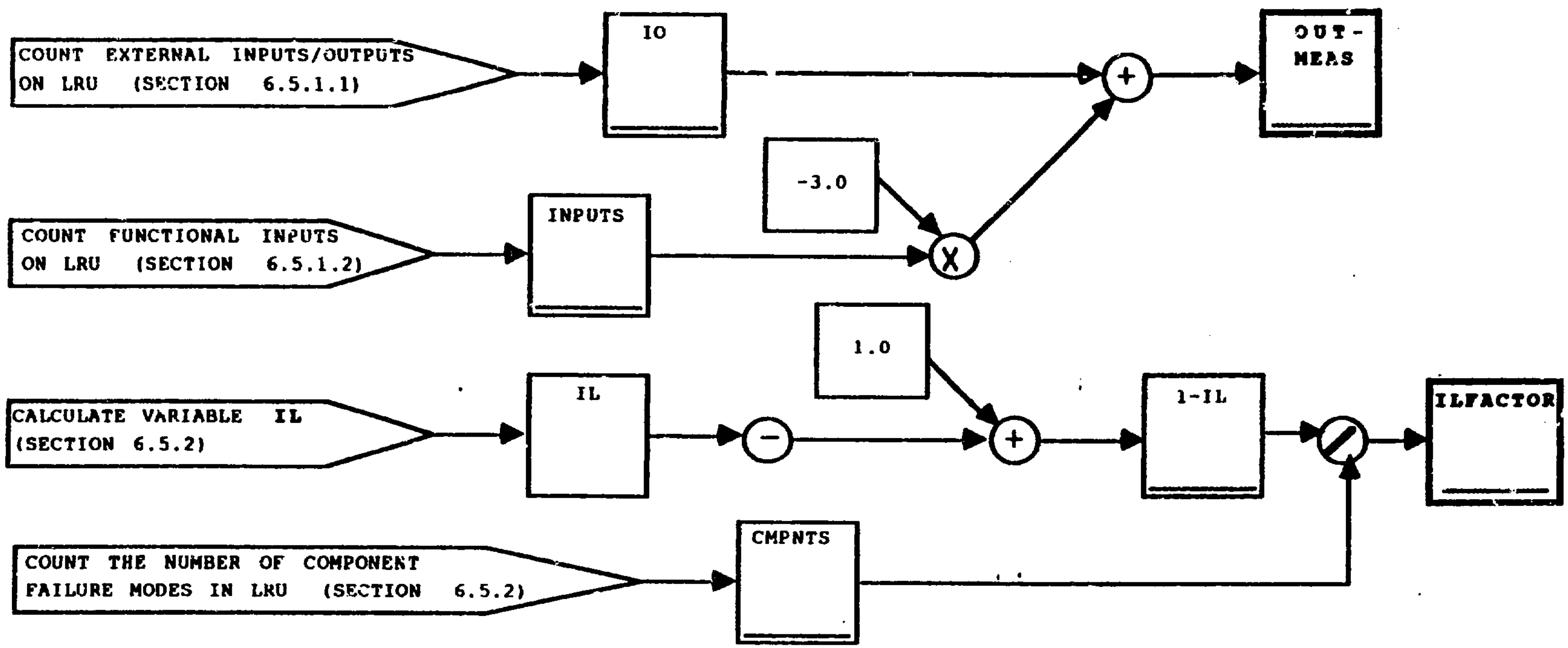
The first variable in the equation for DP, OUTMEAS, approximates the number of functional output signals in a system. Its synthesis is detailed in Figure 6-13. Two variables, IO and INPUTS, are used to calculate OUTMEAS.



DP = 1.03 - 3.12E-5*OUTMEAS - 0.61*ILFACTOR - 0.035*FATFACTOR

FIGURE 6-13

PREDICTION PROCEDURE FOR DP



OUTMEAS = IO - 3*INPUTS

$$\text{ILFACTOR} = \frac{1 - \text{IL}}{\text{NO. OF COMPONENTS}}$$

FIGURE 6-14

VARIABLE SYNTHESIS OF OUTMEAS AND ILFACTOR

6.5.1.1 Input/Output (IO)

This variable measures the actual input and output signals to and from the LRU. IO is the number of active pins in the external connectors. This active pin count can be obtained from Air Force I-Level Technical Orders or equivalent documentation.

6.5.1.2 Input Signals (INPUT.CMP)

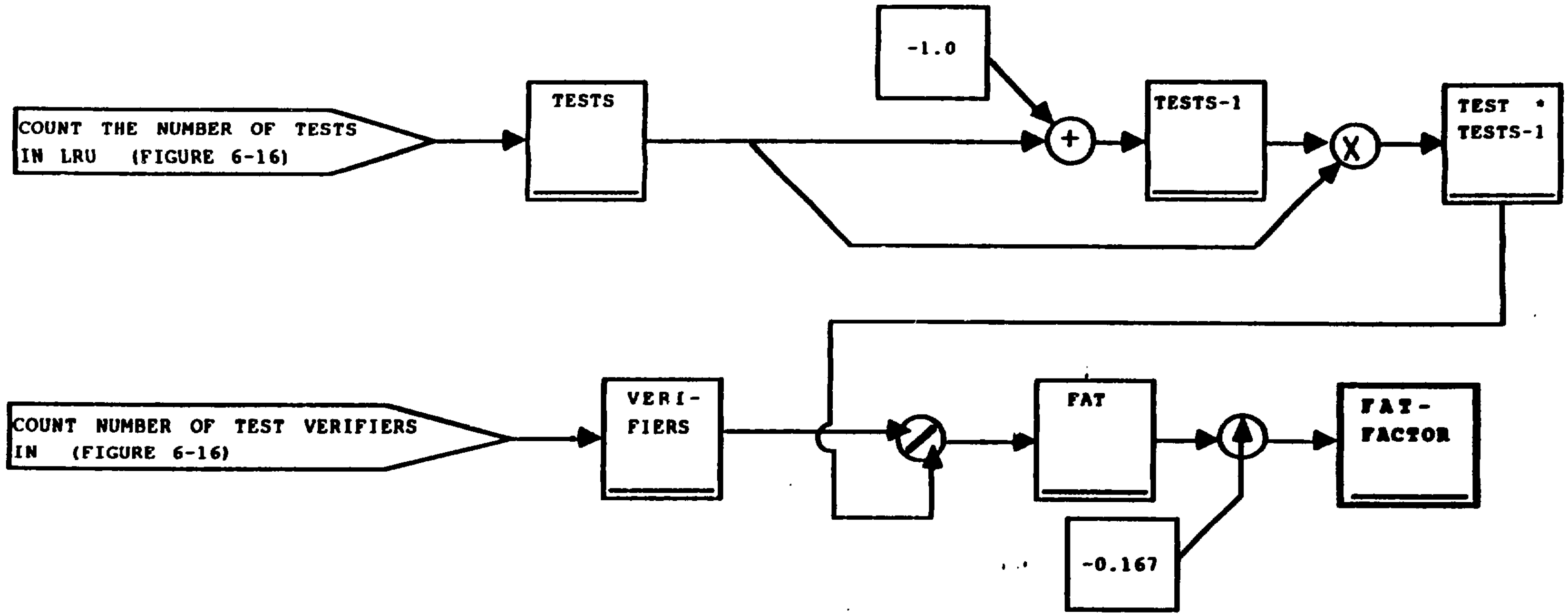
This variable is described in Section 6.4.3.

6.5.2 IL Component (ILFACTOR)

The elements necessary to compute this factor are described in Section 6.4.

6.5.3 Test Redundancy Measure (FATFACTOR)

The synthesized variable FATFACTOR is derived from a count of the number of tests (described in Section 6.4.2) that make up the test system and a count of the total number of test verifiers within that system as in Figure 6-15. For a given test, t_i, and another test, t_j, if we expect t_j to test "bad" when t_i tests "bad," t_j is said to verify t_i. All t_j's that exhibit this behavior are said to be test verifiers of t_i. Verifiers are determined by extensive functional analysis. A table for collecting data for the computation is shown in Figure 6-16.



$$\text{FATFACTOR} = \left(\frac{\text{NO. OF VERIFIERS}}{\text{TESTS*(TESTS-1)}} \right)^{-1/6}$$

FIGURE 6-15

VARIABLE SYNTHESIS FOR FATFACTOR

FAT WORK FORM

SYSTEM: ____________________ Page ______ of ______

TEST NAME	TEST ID NO.	ID NO.s OF OTHER TESTS THAT VERIFY THE CORRECTNESS OF THE TEST SPECIFIED IN THE LEFT COLUMN											NO. OF ENTRIES

NUMBER OF TESTS THIS PAGE		SUMMATION OF ROW ENTRIES	
		TOTAL FROM PREVIOUS PAGE	
		TOTAL ROW ENTRIES. IF THIS IS THE LAST PAGE THIS IS THE **NUMBER OF TEST VERIFIERS.**	
SUMMATION OF TESTS FROM PREVIOUS PAGE			
		SUMMATION OF TESTS. IF THIS IS THE LAST PAGE, THIS NUMBER REPRESENTS THE **NUMBER OF FUNCTIONAL TESTS.** IF NOT, THIS NUMBER CARRIES TO THE NEXT PAGE.	

FIGURE 6-16

FAT WORKSHEET

CHAPTER SEVEN

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 REVIEW OF RESULTS

This research yielded a number of useful insights into field-level testability. The data gathered and analyzed during this project represent a reasonable start on the problem of prediction of field-level testability attributes for complex electronic systems. The correlation for CND rate (an estimator for FAR) and isolation level (an estimator for FFI) are both sufficient to begin some predictive work during design phases. The validation of both of these predictors is believed to be sufficient for use as estimators for design compliance. There is some concern that a CND rate prediction is tied to the accuracy of a failure rate prediction. Failure rate has been difficult to predict in the past. Several options are available for predicting this value. The best generally available source of information is MIL-HDBK-217. The correlation of CND rate is good enough that we can state that the accuracy of prediction of CND rate will be roughly equal to the accuracy of prediction of failure rate. Prediction of CND burden is marginal at this time for design compliance, but may be useful in a design review process as a flag pointing to potential problem areas. If an accurate failure rate prediction is available, it may be better to estimate CND burden using CND rate prediction rather than using the CND burden prediction. This can be accomplished by

$$\text{CND burden} = \frac{\text{CND rate}}{\text{Failure rate} + \text{CND rate}}.$$

Detection percentage has not been well enough defined (in a mathematical sense) for any use at this time, except for exploratory purposes.

7.2 IMPROVING THE PREDICTIONS

7.2.1 Increasing Data Samples

The data forms in Appendix B provide the basis for achieving a statistically more significant data base for future work. The completion of data forms, such as those found in Appendix B could be made a contract requirement for any new system purchased. Further, one may want to modify such a form to reflect a higher content of the "wish list" given in Appendix A. After a sufficiently large sample of these modified design description data forms and similar data from the AFM 66-1 data gathering system are gathered, the analyses presented in Chapter Five can be redone to reflect the increased robustness of the design data. In addition to a more idealistic design variable data base, a greater number of aircraft types than that (three) used for this study may prove beneficial, especially if state-of-the-art electronic systems are represented.

7.2.2 More Precise Field Data

The field data gathered during these efforts were well within the statistically significant range and only limited additional gains can be made with increased sample size. Using improved field data, as outlined in the Phase I Report,[1] especially in the area of how faults were detected and how they were fault isolated, would improve predictions. By being able to categorize "how" questions, the set theory model shows that a more precise delineation of field data is possible. This would reduce the need for the large number of surrogate measures used for this work. Improved measurability may also be the key to the problem of predicting detectability (FFD), which has thus far eluded us.

7.3 ADDITIONAL AREAS OF RESEARCH

It may be desirable to conduct further research on the impact of this work in testability predictions on other areas. Two such areas identified are:

- Life-Cycle-Cost Analyses
- Maintenance and Readiness Analyses

The major influence of failure rate on CND rate indicates yet another reason to specify high reliability. Field false-alarm rate predictions (estimated by CND rate) should be included in life-cycle cost analysis of reliability goals and standards.

The inherent relationship between maintenance and readiness was demonstrated during the Phase I field maintenance model development. The flow model offers a method by which these relationships may actually be quantified. The data necessary to apply the flow model to an actual maintenance system is both large and labor-intensive, but may well be worth the effort.

7.4 RECOMMENDATIONS

The following actions are recommended:

- Develop a specification procedure for field CND rate as opposed to field false-alarm rate. This would provide a specified field testability parameter that is both field measurable and predictable.

- Develop a specification procedure based upon the isolation-level parameter to provide a specified field parameter that is predictable.

- Use CND rate and IL predictions during preliminary and critical design reviews as the basis for verifying or requiring manufacturer improvements in system testability.

- Use CND burden predictions as early indicators of potential maintenance problems.

If a working prediction procedure for FFD is to be achieved, modifications to the AFTO-349 maintenance data collection system will need to be made or a special study undertaken to measure the necessary information as suggested in Phase I. This includes reporting the origin of the maintenance activity (pilot, BIT, etc.) and the basis of the resolution of the activity (if NSM was sufficient). It is believed that such information would also improve the prediction procedure for FFI and remove the dependency of both FFD and FFI on STAMP®-related measures.

APPENDIX A

UNRESTRICTED VARIABLES FOR DEVELOPMENT OF PREDICTION EQUATIONS

COMPONENT CHARACTERISTICS

Actuators

- Number Used
- Actuation Medium (Rotational Mechanical, Acoustic, etc.)
- Ratings
  - Output Ranges
  - Input Requirements
  - Power Dissipation
- Electrical Impedance
  - Nominal
  - Minimum
  - Maximum
- Utilization
  - Loading
  - Frequency of Use
  - Duty Cycle
- Principle of Operation

Capacitors-Fixed Value

- Number Used
- Rating
  - Capacitance
  - Voltage
  - Discharge Rate
- Usage
  - Voltage
    - Mean
    - Variance
    - Spectra
  - Current
    - Mean
    - Variance
- Construction
  - Materials
  - Packaging

Capacitors-Variable

- Number Used
- Rating
  - Capacitance
  - Voltage
  - Discharge Rate
- Usage
  - Voltage
    - Mean
    - Variance
    - Spectra
  - Current
    - Mean
    - Variance
- Construction
  - Materials
  - Packaging
- Mechanical Action
- Mechanical Usage Profile

Circuit Boards: Wire Wrap and Multiwire

- Number Used
- Construction
  - Materials
  - Bonding Techniques
  - Traces
    - Topological Complexity
    - Densities
  - Solder Technique
- Level of Quality Control
- Component Mounting
  - Number Layers
  - Number Through-hole Connections
  - Board Mounting to Connectors/ Frame

Circuit Boards: Wire Wrap and Multiwire (continued)

- Thermal Conductivity
- Coatings

Circuit Breakers

- Number Used
- Construction
  - Packaging
  - Contact Materials
- Action
  - Toggle
  - Push Button
- Rating
  - Voltage
  - Current
- Utilization
  - Voltage
    - Nominal
    - Peak
  - Current
    - Nominal
    - Peak

Connectors (Including On-Board Connectors)

- Number Used
- Number of Pins
- Construction
  - Type
    - Edge
    - Pin and Socket
  - Materials
    - Contact
    - Package
  - Mating Depth
- Action
  - Zero Insertion Force
    - Isolation of Contact Area from Environment
    - Insertion/Extraction Force
    - Alignment Sensitivity
    - Mating/Demating Technique
      - Manual
      - Semiautomatic
      - Automatic
      - Tool Assisted

Connectors (Including On-Board Connectors) (continued)

  - Pressure
    - Pressure Lock
    - Screw Lock
- Ratings
  - Voltage
  - Current
  - Frequency
- Utilization
  - Electrical
  - Mechanical

Crystals

- Number Used
- Frequency
- Precision
- Environmental Support
- Packaging
- Power
  - Rated
  - Utilization

Diodes

- Number Used
- Type (Zener, Pin, Varactor, etc.)
- Application (Switching, Power, etc.)
- Rating
  - Forward Bias
    - Peak Current
    - Maximum Current - Time
      - Voltage Drop
      - Capacitance
  - Reverse Bias Peak Voltage
- Utilization
  - Forward Bias
    - Peak Current
    - Nominal Current
  - Reverse Bias Peak Voltage
  - Frequency Spectra

Indicators

- Number Used
- Type
  - Incandescent

Indicators (continued)

- Neon
- LED
- LCD

Ratings
- Voltage
- Current
- Frequency

Utilization Duty Cycle

Construction
- Packaging
- Mounting

Inductors

Number Used

Ratings
- Inductance
- Volt-ampere Capability

Construction
- Core
  - Material
  - Structure
  - Shape
  - Dimensions
  - Variability
- Windings
  - Wire Gauge and Type
  - Number of Turns
  - Average Winding Radius
- Mounting

Utilization
- Spectra
- Voltage
  - Peak
  - Nominal

Mechanical

Integrated Circuits

Number Used

Scale of Integration (SSI, MSI, LSI, VLSI, VHSIC)

Application (Digital, Linear, Voltage Regulation)

Logic Family/Solid State Technology (e.g., TTL, ECL, CMOS, etc.)

Bandwidth
- Capability
- Utilization

Integrated Circuits (continued)

Supply Voltage Requirements

Power Consumption

Packaging
- Can
- Leadless Chip Carrier
- Dip

Pin-out
- Input
- Output
  - Number
  - Fan-Out Capability

Usage Duty Cycle

Mounting Technique

Relays

Number Used

Rating
- Activation
  - Voltage/Current
  - Time Delay
- Coil Inductance
- Signal
  - Maximum Voltage
  - Maximum Current
  - Minimum Voltage
  - Minimum Current

Construction
- Packaging
- Mounting

Utilization
- Duty Cycle
- Switching Rate
- Signal
  - Nominal Voltage
  - Peak Voltage
  - Nominal Current
  - Peak Current

Operational Design
- Solid State
- Reed
- Normally Open/Closed
- Movement/Holding Mechanism

Resistors-Fixed

Number Used

Rating
- Resistance
  - Value

Resistors-Fixed (continued)

Precision
Power
Small Signal Capacitance
Composition
Usage
Voltage
Nominal
Peak
Frequency Range
Mounting Method
Thermal Dissipation Method

Resistors-Variable

Number Used
Rating
Resistance Value
Power
Small Signal Capacitance
Construction
Materials
Mechanical
Structure
Rotary
Slide
Resolution
Usage
Voltage
Nominal
Peak
Frequency Range
Mechanical
Adjustment Rate
Duty Cycle

Sensors

Number Used
Sensing Medium (Acoustic, Gas Pressure, etc.)
Ratings
Input Sensitivities
Output Ranges
Power Requirements
Electrical Impedance
Nominal
Maximum
Minimum

Sensors (continued)

Utilization
Environment
Range
Nominal
Loading
Principle of Operation

Software

Implementation Languages
Complexity
Lines of Code
Nesting
Numbers
Levels
Type
Specifications

Switches

Number Used
Type
Manual Automatic
Actuating Mechanism
Mechanical
Electromagnetic
Throws
Poles
Action
Momentary Push Button
Push Button
Toggle
Knife
Rotary
Construction
Materials
Packaging
Ratings
Voltage
Current
Frequency
Utilization
Voltage
Current
Frequency
Mechanical
Frequency
Duty Cycle

Transformers

Number Used
Construction
  Core
    Area Product
    Material
    Composition (Laminated, Power, Tape Wound, etc.)
  Primary Coil
    Turns
    Wire Type
    Taps
  Secondary Coil
    Turns
  Wire Type
    Taps
Utilization
  Primary Voltage
    Nominal
    Peak
      Frequencies
        Nominal
        Maximum
  Secondary Loading
    Nominal
    Peak

Transistors

Number Used
Family (Bipolar NPN, Bipolar NPN, N-Channel, JFETS, etc.)
Application (Linear, Digital, Power)
Ratings
  Bandwidth
  Transconductance
  Capacitances
  Peak Voltages
  Peak Currents
Usage
  Power Dissipated
  Frequency Range
  Peak Voltages
  Peak Currents
  Cooling Technique
Mounting Technique
  Mechanical
  Long Lead - Floating
  Short Head
  Thermal Mount

SYSTEM CHARACTERISTICS

Construction

Packaging
  Materials
  Dimensions
Component Density

Functions

Number of Discrete Functions
Usage
  Frequency
  Duty Cycle
Fault Tolerant Characteristics
Inputs
Outputs

Interfaces

Electrical
  Inputs
  Outputs
Mechanical
  Mounting
  Operational
Operator
  Difficulty of Use
  Operator Qualifications

Requirements

Power
  Minimum
  Maximum
  Nominal
Voltages
Cooling

Topology

Subsystems
  Number
  Types
  Interdependencies
Sneak Circuits
Fault Tolerant Characteristics

Usage

- Frequency
- Duty Cycle

TESTABILITY CHARACTERISTICS

Built In Test

- Exists (Y/N) Unit
- Hosted in Under Test (Y/N)
- Tests
  - Number
  - Information Captured
  - Reliability/Confidence
  - Interdependencies
- Construction
  - Components
  - BIT Topology

External Testing

- Tests
  - Number
  - Information Captured
  - Reliability/Confidence
  - Interdependencies
- Construction
  - Components
  - Test System Topology
- Operational
  - Difficulty of Use
  - Operator Qualifications

ENVIRONMENT

Contamination

- Particulates
  - Types
  - Concentrations
    - Nominal
    - Extremes
- Moisture
  - Nominal
  - Extremes
- Lubricants
  - Types
  - Concentrations

Contamination (continued)

    - Nominal
    - Extremes
- Fuel
  - Types
    - Concentrations
      - Nominal
      - Extremes

Electromagnetic

- Electromagnetic Interference
  - Spectra
    - Nominal Magnitude
    - Maximum Magnitude
- Power Surges
  - Frequency of Occurrence
  - Magnitude (Max)
- Static Discharge
  - Frequency of Occurrence
  - Magnitude (Max)
- Transient Spectra
  - Nominal Magnitude
  - Maximum Magnitude

Mechanical

- Vibration Spectra
  - Nominal Magnitude
  - Maximum Magnitude
- Shock
  - Frequency of Occurrence
  - Magnitude (Max)
- Acoustic Spectra
  - Nominal Magnitude
  - Maximum Magnitude
- Pressure
  - Nominal
  - Extremes
  - Maximum Rate of Change

Thermal

- Ambient Temperature
  - Nominal
  - Extremes
  - Cycling
- Shock
  - Frequency of Occurrence
  - Magnitudes

MISCELLANEOUS

Acquisition Cost
BIT/TE Cost
Degree of Burn-In
Demonstration Results
Design Life
Equipment Type
Acceptance Testing Complexity
FMEA Requirement
Lines of Code
Operating Code
BIT Code
Lot Size
Maintenance Concept
Maintenance Accessibility
Manufacturer
Maturity
Off-the-Shelf Percent
Pages of Maintenance Documentation
Quantity Produced
R&D Cost
Testability Requirement

APPENDIX B

ARINC RESEARCH TESTABILITY PARAMETER WORKSHEET

ARINC RESEARCH TESTABILITY PARAMETER WORKSHEET

LRU (MNEMONIC/NAME) :

USED IN WEAPON SYSTEM:

ANALYST(S): ______________________

____

____

DATE: ______________________

INFORMATION SOURCES: ______________________

____

____

____

____

ATTACH LRU FUNCTIONAL BLOCK DIAGRAM

worksheet page 1

TESTABILITY PARAMETER WORKSHEET	
NAME OF LRU	
PART NUMBER(S)	
MANUFACTURER ADDRESS	
DATE OF INITIAL DEPLOYMENT	
APPPROXIMATE COST FOR PROGRAM DEVELOPMENT	
WAS THERE A	
TEST REQUIREMENT	YES [ ]　　　NO [ ]
M DEMO	YES [ ]　　　NO [ ]
FLY OFF	YES [ ]　　　NO [ ]
LRU FUNCTIONS	

TOPOLOGICAL MEASURES

(THESE MEASURES WERE ADDED TO THE ORIGINAL WORKSHEET DURING THE ANALYSIS)

CROSS COUNT	
INPUTS/OUTPUTS	
NODES	
BRANCHES	
FUNCTIONS	
NUMBER OF SRUs	

worksheet page 2

TESTABILITY PARAMETER WORKSHEET		
NAME	SRU 1	
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	
	11	
	12	
	13	
	14	
	15	
	16	
	17	
	18	
	19	
	20	

ENVIRONMENTAL FACTORS CHECKLIST		
THERMAL CHARACTERISTICS		
EXTREMES	YES [ ]	NO [ ]
CYCLING	YES [ ]	NO [ ]
SHOCK	YES [ ]	NO [ ]
CONTAMINATION FACTORS		
PARTICULATES	YES [ ]	NO [ ]
MOISTURE	YES [ ]	NO [ ]
LUBRICANTS	YES [ ]	NO [ ]
FUEL	YES [ ]	NO [ ]
MECHANICAL CHARACTERISTICS		
VIBRATION	YES [ ]	NO [ ]
SHOCK	YES [ ]	NO [ ]
ACOUSTIC	YES [ ]	NO [ ]
PRESSURE	YES [ ]	NO [ ]
ELECTRICAL FACTORS		
EMI	YES [ ]	NO [ ]
SURGE	YES [ ]	NO [ ]
STATIC	YES [ ]	NO [ ]
TRANSIENTS	YES [ ]	NO [ ]

worksheet page 3

TESTABILITY PARAMETER WORKSHEET

BASIC DESIGN AND MAINTENANCE FACTORS

LRU DUTY CYCLE	
NOMINAL%	
MAXIMUM %	
MINIMUM %	
SIZE	
LENGTH	
HEIGHTH	
WIDTH	
WEIGHT	
PEAK POWER	
NOMINAL POWER	
INPUT VOLTAGE	
EXTERNAL CONNECTORS	
SMALL (1-4)	
MEDIUM (5-14)	
LARGE (OVER 15)	
INTERNAL CONNECTIONS	
OPERATING TEMPERATURE	
COOLING TEMPERATURE	
ALTITUDE LIMITATIONS	
DISCRETE VOLTAGES	
FAULT TOLERANT CHARACTERISTICS	YES [ ] NO [ ]
SIGNAL FREQUENCY RANGE	
PAGES OF DOCUMENTATION	
INTERMEDIATE LEVEL	
DEPOT LEVEL	
IPB	
SOTA LEVEL (measured on a scale of 1-10)	

worksheet page 4

TESTABILITY PARAMETER WORKSHEET

COMPONENT WORK SHEET

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	TOTAL
RESISTORS																					
POTENTIOMETERS																					
CAPACITORS																					
MICROCIRCUITS																					
DIGITAL																					
LINEAR																					
VOLTAGE REG																					
TRANSISTORS																					
GP/POWER																					
SWITCHING																					
FET																					
UNIJUNCTION																					
DIODES																					
REGULAR																					
ZENER																					
VARACTOR																					
INDUCTORS/ TRANSFORMERS																					
RELAYS																					
CIRCUIT BREAKERS																					
SWITCHES																					
LIT PUSHBUTTON																					
ROTARY																					
TOGGLE																					
INDICATORS																					
CRYSTALS																					
TEST POINTS																					
PARTS																					
LRU INPUTS/																					
LRU OUTPUTS																					
INTERCONNECTS																					

worksheet page 5

TESTABILITY PARAMETER WORKSHEET

ADDITIONAL NOTES AND COMMENTS

worksheet page 6

APPENDIX C

VARIABLES USED FOR REGRESSION ANALYSES

TABLE C-1

CND INITIAL DESIGN VARIABLES

Parts* (Normalized by No. of SRUs)	External*	Topological**	Environment*
Total Parts	Input/Output Signals	$\frac{\text{IO + Branches}}{\text{Functions + Nodes}} = \text{TOP1}$	Thermal
Resistors	Length		Contaminants
Potentiometers	Height	$\frac{\text{IO}}{\text{Functions}} = \text{TOP2}$	Mechanical
Capacitors	Width	$\frac{\text{Cross Count}}{\text{Functions}} = \text{TOP3}$	Electrical
ICs	Weight		
Transistors	Power	$\frac{\text{Cross Count}}{\text{No. of SRUs}} = \text{TOP4}$	
Diodes	External Connectors		
Inductors/ Transformers	No. SRU		
Relays	Plane		
Switches	BIT (Y/N)		
Indicators	Pages of Documentation		
Crystals	Percent Digital		
Interconnects			

*Taken from the worksheets as delineated in Chapter Three and given in Appendix B.

**Derived based upon analytical work given in Section 3.4.2.2.

TABLE C-2

CND VARIABLES CREATED FROM INITIAL VARIABLES

Densities*	Power Interactions**
Volume	Pwrden = power*parts density
Density = 1/volume	Thrmpwr = power*(thermal + 1)
Pwrden = power/volume	Pwrvol = power*volume
Prtsden = No. parts/volume	Voverp = volume/power
	Pwrthcon = power*interconnects*(thermal + 1)
	Pwr01 = 0 if pwr < 150 watts; 1 if pwr > 150 watts

Environmental Interactions†	Topological Interactions††
Thrmcom = (thermal + 1)*interconnects	ICtopl = ICs*TOPl
Mechio = (mechanical + 1)*IO	Indtopl = ind*TOPl
Mechcon = (mechanical +1)*interconnects	Captopl = cap*TOPl
Thrmcmplx = (thermal + 1)*cmplx	

Miscellaneous§

Basewt = 1 per no. of bases in data collection

Failure= MA - CND

Flrrate = No. of failures/LRU Operating hours

*Based upon analysis of accessibility parameters in 3.4.2.1 and 3.4.2.7.
**Control variables.
†Based upon analysis of environmental factors in 3.4.2.3.
††Based upon analysis of topological parameters in 3.4.2.2.
§Based upon failure frequency parameters in 3.4.2.7.

TABLE C-3

CND VARIABLES SYNTHESIZED BY REGRESSION

Thermal Density*

```
Thden6   = thermal + 6*prtsden
Thden5   = thermal + 5*prtsden
Thdenm   = prtsden*(thermal + 1)
Thden1.5 = thermal + 1.5*prtsden
```

Accessibility**

```
Access = vol + 500*cnnct
where:
  Cnnct = small ext cnnctrs
   + 2*med ext cnnctrs
   + 3*large ext cnnctrs
```

Parts Complexity†

```
Sum2      = [diodes + 1/inductors]/No. SRUs
Sum3      = [resistors + transistors]/No. SRUs
Sum4      = [diodes - 2*inductors]/No. SRUs
Capind    = [capacitors - 2.2*inductors]/No. SRUs
Cmplx     = [ICs + 10*inductors - 2.4*capacitors]/No. SRUs
Transient = [41*relays + 2*capacitors + ICs +2*resistors
            -9*transistors]/No. SRUs
```

Topological Complexity††

```
Tpcmplx   = f(IO,interconnects,SRU,parts)
tc1 - tc6 = intermediates (topological)
tc7       = interconnects* (ICs + 30*transistors - 160*relays
            - 960*switches)
tc8       = interconnects* (ICs + 120*relays + 460*switches
            - 40*transistors)
```

*Based upon initial stepwise linear regressions and environmental functions in 3.4.2.3.

**Based upon initial stepwise linear regressions and accessibility functions in 3.4.2.1 and 3.4.2.7.

†Based upon initial stepwise linear regressions and parts functions in 3.4.2.4, 3.4.2.5, and 3.4.3.6.

††Based upon initial stepwise linear regressions and topological functions in 3.4.2.2.

TABLE C-4

IL INITIAL DESIGN VARIABLES

Parts*	External*	STAMP● Measures**
Number of SRUs	Input/output	Number of tests
Total parts	Length	Number of components
Number of resistors	Height	Number of input signals
Number of potentiometers	Width	Test leverage
Number of capacitors	Weight	
Number of ICs	Power	
Number of transistors	External connectors (Small, Medium, Large,	
Number of diodes		
Number of inductors/ transformers		
Number of switches		
Number of indicators		
Number of crystals		
Number of filters		
Number of interconnects		

*Based upon worksheets in Appendix B.
**Based upon functionalities developed in 3.4.3.

TABLE C-5

IL COMBINED AND SYNTHESIZED VARIABLES

Combination of Initial Variables

Densities*	Miscellaneous**
Volume	test.cmp = tests/components
Parts density	input.cmp = inputs/components
	test.prt = tests/parts
	comp.tst = components/tests
	io.cmp = io/components

Variables Synthesized by Regression

Topological Measures**

TC=interconnects*(ICs + 150*relays - 17*transistors)
TC.prt = TC/parts
TC.tst = TC/tests
test.tc = tests/TC
testtc.cmp = tests*TC/components

*Based upon accessibility in 3.4.2.1 and 3.4.2.7.
**Based upon IL functionalities in 3.4.3 and topological parameters in 3.4.2.2.1 together with initial stepwise linear regressions.

TABLE C-6

DP COMBINED AND SYNTHESIZED VARIABLES*

tc2 = interconnects*(30*transistors-ICs - 300relays)

tsttc = tests*TC

testtc2 = tests*tc2

tc2sqd = $(tc2)^2$

exptst.ctc = exp(test.ct2)

tst - 1.ct2 = 1/tst.ct2

abstc2.tst = abs(tc2)/tests

tlmin.tst = tlmin/tests

exp - tlm.tst = exp(- tlmin.tst)

exptst.att = exp(test.att)

lnIO = ln(IO)

ILFACTOR = (1 - IL)/components

IO.tst = IO/tests

OUTMEAS = IO - 3*inputs

lninvFAT = ln(FAT^{-1})

FATFACTOR = $FAT^{-1/6}$

test.tc = tests/TC

test.ctc = tests/components*tc2

test.ct2 = test.ctc/tc2

tsttc.cmp = (tests*$tc2^2$/components

lntst.ct2 = ln(tst.ct2)

comp.tIO = components/(tests*IO)

exptlm.tst = exp(tlmin.tst)

tst.att = tests/(abs(tc2)*tlmin)

abstc2.tst = abs(tc2)/tests

exp - IO = exp(- IO)

IO.cmp = IO/components

IOcmp = IO*components

exp ILFACTOR = exp(ILFACTOR)

FAT-n = FAT^{-n} where n is a constant

*These were synthesized based on the initial stepwise linear regressions and all of the functions reported in Chapter Three. The large number of synthesized variables points to the weak correlations that were present with no apparent dominance by any combination of terms.

APPENDIX D

GLOSSARY OF ACRONYMS AND TERMS

1.0 ACRONYMS

AFTO	Air Force Technical Order
ATE	Automatic Test Equipment
BIT	Built-In Test
BITE	Built-In Test Equipment
CND	Cannot Duplicate
DFT	Design for Testability
FAR	False-Alarm Rate
FAT	False-Alarm Tolerance
FCND	Fraction of Cannot Duplicate
FFA	Fraction of False Alarms
FFD	Fraction of Faults Detected
FFI	Fraction of Faults Isolated
how-mal	How-Malfunctioned
IC	Integrated Circuits
IL	Isolation Level
IO	Input and Output (Signals)
LRU	Line Replaceable Unit
MA	Maintenance Action
MADARS	Malfunction Analysis Detection and Recording System
MDCS	Maintenance Data Collection System
MFLS	Maintenance Fault Listing Summary
MTFI	Mean Time to Fault Isolate
MTTR	Mean Time to Repair

NDP	Nondetection Percentage
NFF	No Fault Found
NITS	Not Isolatable This Station
NSM	Normal System Maintenance
O/I	Organizational and Intermediate
OPSREADY	Operations Ready
RTOK	Retest-OK
SRU	Shop Replaceable Unit
STAMP®	Systems Testability and Maintenance Program
SUT	Subsystem Under Test
TC	Topological Complexity
TLMIN	Theoretical Minimum Test Leverage
TO	Technical Order

2.0 TERMS

Abnormal Fault Isolation - Techniques used to identify the cause of subsystem under test (SUT) failure by means other than normal system maintenance procedures: for example, (1) removal of multiple replaceable units and (2) shotgun removal of replaceable units until the SUT is operational.

AFTO-349 - Air Force Maintenance Data Collection Record.

Attribute - A hypothesized inherent aspect of a system that may or may not be observable or computable, but is inferred to describe some aspect of the system.

Bad Actor - Any SUT with repeat failure indications that cannot be duplicated or verified during normal system maintenance. Bad actors may be "recognized" over a period of time or may be "indicated" by outside sources. Bad actors may be generic -- line replaceable unit (LRU) type -- or specific -- a given serial number.

Built In Test (BIT) - A test subsystem that is a physical part of a host system whose purpose is fault detection. For a given LRU within the system, BIT may be fully contained within the LRU or the LRU may be tested by systemwide BIT. For purposes of this report, either case may exist.

Cannot Duplicate (CND) or No Fault Found (NFF) - There is a prior indication of failure, and the failure cannot be duplicated by maintenance.

Characteristic - attribute.

Failure Mode Component - A failure mode, piece of hardware, or other functional entity that could be concluded as the cause of a system anomaly.

Depot-Level Maintenance - Performs piece part repair within an SRU.

False-Alarm Rate (FAR) - The rate of occurrence of false alarms, typically computed as the time-normalized sum of false alarms, where the time normalized is either calendar or operating hours.

Fault Isolation - The method by which failures are located as a first step in the repair process.

Functional Input Signal - All input representing a function. For example, a bus line with several signals but only one function would be considered as one functional input signal.

Inherent Testability - A testability measure that is dependent only on hardware design and is independent of test stimulus and response data (MIL-STD-2165 definition).

Input Signal - Any active electrical signal including power and ground but not including spares.

Intermediate-Level Maintenance (I-Level) - Performs shop-replaceable unit (SRU) replacement repair at shop level.

Intermittent Failure - Transient failure mode of the SUT that is not reproducible by using normal system maintenance. The failure may or may not be present during maintenance checks. Repeat transient failures may label an SUT as a "bad actor" and result in replacement without maintenance verification of the fault.

Line-Replaceable Unit (LRU) - Organizational-level repair unit consisting of a collection of parts packaged for replacement at the flight line.

Maintenance System Fault Detection - An indication is provided by normal system maintenance that the SUT is not functioning properly because of a real failure within the SUT.

Maintenance System Fault Isolation - Ability to identify all failed replaceable units within the SUT using normal system maintenance. Fault isolation may be subdivided into the following categories: BIT fault isolation, automatic fault isolation, and manual or semiautomatic fault isolation.

Measure - An individual quantity that can be obtained by observation, calculation, or other direct means.

Nonrelevant Event - Any fault indication that does not result in a maintenance action.

Normal System Maintenance (NSM) - Techniques that are specified as standard operating procedures for use of BIT, automatic test equipment (ATE) semi-automatic, or documented manual detection and troubleshooting for a given system under test. This includes regular calendar checks and normal go-checks. It is sometimes called "defined means."

Not Isolatable This Station (NITS) - Normal or abnormal fault-isolation procedures cannot determine the cause of fault in the SUT. Maintenance concept at O-level may be to ship the SUT to another level.

Operational Maintenance Level (O-Level). - The level of maintenance concerned with the operational readiness of the weapon system and generally consists of repair action by LRU replacement.

Organizational-Level Maintenance - Performs LRU replacement and provides point of readiness for operation.

Parameter - A variable that is fixed in value.

Redball - A last-ditch effort to save a mission when the scheduled aircraft is faulty. TAC and SAC call this "Redball," and MAC calls it "Red Streak." It also has been referred to as "Blue Streak" by SAC.

Retest-OK (RTOK) - A replaceable unit is removed, but no failure is discovered at subsequent levels of maintenance. A RTOK does not automatically imply that no failure exists.

Shotgun Maintenance - Random removal and replacement of LRUs in order to find and repair faults.

Shop-Replaceable Unit (SRU) - Intermediate-level repair unit consisting of a collection of parts packaged for replacement at the shop level.

Subsystem False Alarm - A failure indication in a subsystem when there is no failure in the system.

Subsystem Improper Fault Detection - Fault is within the subsystem other than the one in which detection occurs.

Subsystem Improper Fault Isolation - All but not only failed units are isolated.

Subsystem Proper Fault Detection - Fault is within the subsystem in which detection occurs.

Subsystem Proper Fault Isolation - Only and all failed units are isolated.

Subsystem Under Test (SUT) - All of the equipment associated with a subsystem, including BITE but excluding test equipment that is not physically attached during normal operation.

Surrogate - A measure, variable, attribute, or parameter that is used as a substitute for another measure, variable, attribute, or parameter because it is either easily available, a good estimate, inexpensive to obtain, or all of the above.

System False Alarm - Normal system maintenance indicates a failure in the SUT when there is no failure present.

System Go-Check - Normal maintenance procedures used to verify that SUT is functioning properly.

System Improper Fault Isolation - All but not only failed units are isolated.

System Proper Fault Isolation - Only and all failed units are isolated.

Test - An individual stimulus response where the stimulus may or may not be present in the system. A fault isolation (test procedure) will consist of many such tests.

Testability - A design characteristic that allows the status (operable, inoperable, or degraded) of an item to be determined and the isolation of faults within the item to be performed in a timely manner (MIL-STD-2165 definition).

Variable - A numeric quantity which is synthesized by combinations of measures, attributes, or other properties.

APPENDIX E

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