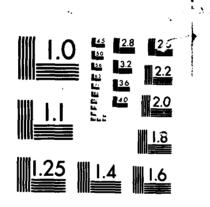
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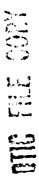
RADC-TR-85-268 Phase | Report February 1986

PREDICTION AND ANALYSIS OF TESTABILITY ATTRIBUTES: ORGANIZATIONAL-LEVEL TESTABILITY PREDICTION

ARINC Research Corporation

Dr. William R. Simpson, John H. Bailey, Katherine B. Barto and Eugene Esker

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ROME AIR DEVELOPMENT CENTER Air Force Systems Command Griffiss Air Force Base, NY 13441-5700

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RADC-TR-85-268 has been reviewed and is approved for publication.

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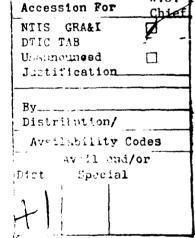
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ADDRESS (City, State, and ZIP Code)			City, State, and Zi		
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Annapolis MD 21401					
NAME OF FUNDING / SPONSORING	86 OFFICE SYMBOL	9 PROCUREME	NT INSTRUMENT	DENTIFICATION	NUMBER
ORGANIZATION Rome Air Development Center	(If applicable) RBET	F30602-84-	-C-0046		
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EXECUTIVE SUMMARY

1. INTRODUCTION

A program was undertaken to develop procedures for analyzing and predicting the testability attributes of systems. This report describes the results of the first phase of that program. The initial phase has concentrated on the three testability attributes most commonly specified for systems:

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

These attributes were defined and scoped and mathematical frameworks have been developed for evaluating each attribute at the organizational level of maintenance. Further, the feasibility of developing prediction procedures for these three attributes was investigated.

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

- 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 upon the combination of actions at the organizational maintenance level necessary to discover the system state (e.g., failed or non-failed).
- 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 insights and visibility into the interpretation, make-up and logical content of an 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. And,
- (2) 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.

This 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. The literature research and survey of organizational level maintenance units that contributed to the development of the definitions of the testability attributes are provided in Chapters 2 and 3 of this report. The sources and types of maintenance data that are available from operational systems that can be used to measure the testability attributes are discussed in Chapter 4. The actual definitions and evaluation algorithms developed from the three models are presented in Chapter 5. The feasibility of developing procedures for predicting the three testability attributes is discussed in Chapter 6. Finally, the results of the first phase of this program are summarized and plans for the development of prediction procedures during the second phase of the program are presented in Chapter 7. Detailed descriptions and mathematical analyses of the three modeling approaches are provided in the appendices.

The work that is presented in this report is the foundation for continuing research. As such, this report is intended to be a working draft, and the reader's comments on the usefulness and possible applications of the work presented in this report are welcomed. Comments may be addressed to Rome Air Development Center, RADC/RBET (H. Dussault), Griffiss AFB NY 13441-5700.

A brief summary of the definitions developed, modeling analyses, and results of the feasibility study follow.

2. PROPOSED DEFINITIONS AND THEIR LOGIC

A key objective of the first phase of the program was to develop accurate, quantitative definitions of the three testability attributes. The definitions to be developed 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. Toward that end, two realistic assumptions were made.

- (1) Any fault indication that does not result in a maintenance action is a nonrelevant event. Under most definitions of system behavior, these events are called false alarms that are recognized but ignored (i.e., not reported). These events are totally unmeasurable and have little impact on the maintenance system.
- (2) Faults that are not literally detected by any means are nonrelevant on the basis that they have no discernable impact on and are not measurable at the organizational level of maintenance.

Before proceeding further with the definitions of the testability attributes for the system and subsystem levels, it is necessary to define normal system maintenance as it is used in the development of definitions for each of the testability attributes.

Normal System Maintenance (NSM) - Techniques that are specified as standard operating procedures for use of BIT, ATE, semiautomatic, or documented manual detection and troubleshooting for a given system under test. They include regular calendar checks and normal "go" checks. NSM is sometimes called "defined means". (1)

(1) <u>RADC Testability Notebook</u>, Hughes Aircraft Company, RADC-TR-82-189, June 1982. The definitions of systems and subsystems must also be addressed before definitions of the testability attributes can be developed. The system/subsystem boundary is an artificial one and is drawn on the basis of analysis needs. A system is taken as a functional or structural entity. Its boundaries are often physical breakpoints between the system and its surrounding environment. For the purposes of this effort the boundaries between systems and subsystems are defined from the analyst's perspective, as may be demonstrated by the following example. The government, concerned with the acquisition of weapon system XYZ, would consider weapon system XYZ to be the system and LRU 5 to be a subsystem of XYZ. However, a contractor who builds LRU 5, and only LRU 5 of weapon system XYZ, would consider LRU 5 to be a system.

The following definitions have been developed for system level fault detection, fault isolation, and false alarms:

- Fault detection 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 where there is no failure in the system. False alarm rate (FAR) is the sum of false alarms over a general time period divided by that time period.

The system definitions must also be consistent with subsystem definitions in the hierarchical sense as subsystems are built into systems. The consistency of the definitions requires that the system/subsystem boundary be defined in advance of any analysis. The following definitions have been developed for subsystem level fault detection, fault isolation, and false alarms.

- Fault detection ~ NSM indicates that a subsystem is not functioning properly, because of a fault within the system. The detection can be proper or improper.
 - -- Proper detection The fault is within the subsystem in which the detection occurs.
 - -- Improper detection The fault is within a subsystem other than the one in which the detection occurs.

- Fault isolation NSM identifies all failed units within a subsystem. The isolation can be proper or improper.
 - -- Proper isolation Only and all failed units are isolated.
 - -- Improper 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 subsystem where there is no failure in the system.

Fraction of faults detected (FFD) and fraction of faults isolated (FFI) are derived by dividing the total system or subsystem detection and isolation values by the total faults in the system or subsystem. Fraction of false alarms (FFA) is derived by dividing the false alarm total by the total number of maintenance actions either at the system or subsystem level. The false alarm rate (FAR) is derived by dividing the false alarm total by the time period over which those false alarms developed.

3. MODELING SUMMARY

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Three representations of the organizational level maintenance process were derived. These three models were based on set theory, modified state, and flow model assumptions, as discussed previously.

All three models agree on functionality. For example, in each of the models, FFA is a function of "cannot duplicate" results and maintenance actions. The form of all key parameters is identical. Further, each model points out that it is important to know what triggers maintenance activity and how fault isolation is achieved. The current Air Force maintenance reporting system, however, does not provide complete information on actions that trigger maintenance (e.g., BIT report, pilot report) or what actions were used to achieve fault isolation 'e.g., tech orders, ad hoc "shotgun" approaches). The models, therefore, point out limitations in measuring the three testability attributes based on field reported data. Each model also points out the difficulty in relating "cannot duplicate" results to false alarms and the importance of measuring false alarms. In every case, the accurate evaluation of FFD and FFI requires an accurate measurement of false alarms.

As mentioned previously, each of the models highlights separate insights into the measurement and analysis of system testability attributes. The set theory model forces an explicit statement of assumptions that are inherent in all three models but not explicitly stated. The set theory model also provides a method for specifying what <u>should</u> be measured. The flow model representation provides a direct link between the maintenance model and readiness and shows the limits that must be placed on data gathering in terms of time sufficiency, periodicity and quantity of data. Because of its inherent simplicity and conformity with current maintenance data gathering, the modified state model represents the best computational fit.

4. FEASIBILITY SUMMARY

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 both of these criteria could be satisfied, the development of prediction procedures would be considered feasible.

As has been discussed previously, 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" events, and a measurement of "cannot duplicate" events and 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 parameters and the testability attributes should be feasible once measures of the attributes can be obtained. These parameters 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 parameters and the testability attributes was conducted 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 appears to be promising.

The continuation of the current work toward developing prediction procedures requires that the difficulties in measuring the three testability attributes be Two different approaches are required to obtain the information overcome. necessary to develop measures of the three testability attributes. First, field data on maintenance actions and "cannot duplicate" events will be gathered for a number of LRUs. Measures of false alarms can be analytically or heuristically determined from this field data. Second, measures of fractions of faults detected and fraction of faults isolated will be derived from engineering and field test data (e.g. maintainability demonstrations and technical and operational evaluations) and the application of testability models and analyses FMEAs). Once measures of FFD, FFI, and FFA have been developed, (e.q. prediction procedures will be developed by relating the testability attributes to system design parameters.



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ACRONYMS AND SYMBOLS

CHAPTER ONE

INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

This report describes research conducted by ARINC Research Corporation in the first phase of a two-phase project. The work was performed under Contract F30602-84-C-0046 with the Systems Reliability and Engineering Branch of the Rome Air Development Center.

The ultimate goal of the research is to build a model that will predict organizational-level testability attributes on the basis of design characteristics. Three basic descriptors of the organizational-level maintenance system were considered:

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

The Phase I technical objectives were to provide the foundation for the development of the predictor model. The approach was developed through the following tasks:

- 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.

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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.^{1,2} Testability design is usually approached from the bottom up, with component and board testability designed in but with little attention given to isolation to 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

aircraft³ and the CH-54 helicopter⁴ 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 avionic repairs for the scheduled air carriers. Those figures suggest the potential for a large return on an investment in improved testability assessment leading to improved testability design.

1.2.1 <u>The Testability Discipline</u>

Testability is coming to be recognized as a valid and useful engineering discipline. The recent issuance of a testability standard. <u>Testa-</u>

bility Program for Electronic Systems and Equipments,⁵ is evidence of the increasing importance of testability in the development of military systems. An equipment 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 <u>Testability as a Design Variable</u>

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.

George Smith II, "Testability Analysis: Predict It More Closely," 1979 Proceedings of the Annual Reliability and Maintainability Symposium, pg 187.

- William L. Kiener and Anthony Coppola, "Joint Services Program in Design for Testability," <u>1981 Proceedings of the Annual Reliability and</u> <u>Maintainability Symposium, pg. 268.</u>
- Special Report on Operational Suitability (OS) Verification Study rocus on Maintainability, ARINC Research Corporation, 1751-01-2-2395, February 1981.
- Thomas N. Cook and John Ariano, "Analysis of Fault Isolation Criteria/ Techniques," <u>1980 Proceedings of the Annual Reliability and Maintainability</u> Symposium, pg. 29.

MIL-STD-2165, 26 January 1985.

In fact, a review of the current literature suggests that even common definitions of testability are hard to find. For example, Malcolm¹ states that built-in-test (BIT) false alarms can be broken into two types: a BIT indication when there are no faults, and a BIT indication when the

fault is in another unit. MIL-STD-1309 2 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 attributes. A testability evaluation should provide not only predictions but also applicable redesign information when testability attributes are predicted to be below desired levels.

1.2.3 Testability and Organizational-Level Maintenance

The problem of testability at the organizational level is separate from but related to the same problem at the intermediate and depot levels. The organizational level is where system faults are first detected. 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 that we will explore, three are directly related to the ability of complex electronic systems to meet mission requirements:

- Fraction of Faults Detected (FFD) Ideally, FFD should be 100 percent. Any fault not detected prior to a mission, either by BIT/BITE or by maintenance operations ready (OPSREADY) test, could result in a failed or aborted mission. Further, if the failure is not detected after 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 (FFI) 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 a system's 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.

¹J. G. Malcolm, "BIT False Alarms: An Important Factor in Operational Readiness," <u>1982 Proceedings of the Annual Reliability and Maintainability</u> Symposium, pg. 206.

Definitions of Terms for Test, Measurement, and Diagnostic Equipment, 30 May 1975.

Fraction of False Alarms (FFA) - The ideal value of FFA is 0 percent; 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 from 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.

A related parameter that will only be dealt with peripherally is false-alarm rate (FAR), the rate of occurrence of false alarms. It is typically computed as the 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 details of the literature search and a compilation of prior efforts in this area. Chapter Three briefly outlines the organizational-level personnel survey and its results. Chapter Four delineates data resources developed for use with this study.

Chapter Five is an explanation of the measurement algorithms developed for use with this study and the hierarchical equation development. Chapter Six reviews the feasibility work.

Our conclusions and recommendations are presented in Chapter Seven. Appendices include the survey forms and mathematical modeling equations. CHAPTER TWO

LITERATURE RESEARCH

2.1 SOURCES

Before constructing precise definitions of the testability measures of fraction of faults detected (FFD), fraction of faults isolated (FFI), and fraction of false alarms (FFA), a literature survey was conducted to gain an understanding of the concepts and definitions currently in circulation. The definitions in this chapter are examples of published definitions and are not recommended for the use of general prediction algorithms. The recommended definitions appear in Chapter Five and Appendix E.

There is a large volume of literature on testability, and yet there is little consensus on the definition of testability terms, because of the variety of intended uses for the literature and the widely varying audience. The literature was collected from numerous sources and entered into a bibliography. Each document was reviewed to find definitions of or statements concerning FFD, FFI, and FFA. The types of data collected and reviewed include the following:

- Military Standards and Handbooks (8)
- Reliability and maintainability symposia papers (9)
- ARINC Research reports (5)
- RADC in-house reports (5)
- Other contractor reports (42), including the following: Hughes Aircraft, Lockheed, IITRI, Grumman, ITT, Sperry-Rand, General Dynamics, Boeing, Westinghouse, Gould, and IDA

In addition, abstracts of more than 500 documents were reviewed. These abstracts were provided through DTIC literature surveys.

2.2 DEFINITIONS

The data sources were used to obtain definitions or concepts of FFD. FFI. and FFA. The definitions were varied. About 20 percent were quantitatively based; the other 80 percent were based only on theory, with no operational links. The following subsections give examples of the types of definitions found. Detailed descriptions of the documents cited are presented in the Bibliography.

2.2.1 Fraction of Faults Detected (FFD)

Fault detection is the capability to detect and indicate one or more failures within the equipment. The detection and indication can be done by BITE, by semiautomatic means, or manually. Fraction of faults detected should be close to 100 percent, since undetected faults can be hazardous to a mission if the faulty equipment is critical to the mission. In the literature surveyed, there were more definitions for "fault detection" than for "fraction of faults detected." The following paragraphs give samples of the definitions found.

The RADC report <u>Analytical Procedures for Testability</u>¹ has several related definitions of FFD:

- Fraction of all faults detected (or detectable) by BIT/TE
- Fraction of all detectable faults detected (or detectable) with BIT/TE
- Fraction of all faults detected through use of defined means ("defined means" implies all means of detection that have been identified)

This set of definitions is mostly theoretical and not quantitative. The definitions restate the same concept three times. The difference between the first two is that the second one clarifies "faults" to "detectable faults," thus assuming that there are undetectable faults. The third definition differs only in its reference to "how detected."

<u>RADC Testability Notebook</u> lists five definitions accumulated through surveys for "fraction of faults detected":

- Percentage of all faults automatically detected by BIT/ETE
- Percentage of all faults detectable by BIT/ETE
- Percentage of all faults detectable on-line by BIT/ETE
- Percentage of all faults and out-of-tolerance conditions detectable by BIT/ETE
- Percentage of all faults detectable by any means

*RADC-TR-83-4, January 1983.

This set of definitions is also more theoretical than quantitative and is very similar in context to the first set of definitions.

There were two literature sources that stated a "fraction of faults detectable" requirement. General Electric Company discusses effectiveness of fault detection as the number of failure events detected correctly divided by the number of actual failures experienced and states that the

optional effectiveness range should be between 85 percent and 90 percent.¹

Sperry Corporation says that "fraction of faults detected is a BIT performance requirement for not less than 98 percent faults detected by the operator using BIT. BIT shall detect failures (and out of tolerance) which represent at least 90 percent of the system (or subsystem) probable failures."²

The Military Standards, including the new MIL-STD-2165, had only definitions of fault detection and no quantitative measures. The standard does include fault detection as an element of system-level test effective-ness in BIT. This is given as:

$$FD = \frac{\sum_{i=1}^{\lambda} FD}{\sum_{i=1}^{\lambda} FD}$$

where λ_1 is the failure rate of the ith item and FD₁ is the fault-

detection prediction for the ith item. All these definitions lack specifics. It is not clear where to draw boundaries. We have developed a consistent, mathematically precise definition (Appendix B) that will be used in this study.

2.2.2 Fraction of Faults Isolated (FFI)

Good fault isolation is the ability to isolate each detected fault quickly and accurately. The "fraction of faults isolated" should be close to 100 percent in order to meet the mission-readiness requirement. Fault isolation can be accomplished through BITE, semiautomatic, or manual fault-isolation procedures. Several of the surveyed sources defined or commented on fraction of faults isolated or related concepts.

<u>Analytical Procedures for Testability</u> defines FFI as "the fraction of those faults detected by BIT/TE which are then isolated with BIT to the replacement level as defined by the maintenance concept." This definition would be measurable when maintenance reporting cited a separate code for BIT/TE-triggered maintenance (often a separate series on the job control

Design Guide, Built-In Test (BIT) and Built-In-Test Equipment (BITE) for Army Missile Systems, Sperry Corporation, TR-RL-CR-81-4, 17 April 1981.

Assessment of Augmented Electronic Fuel Controls for Modular Engine Diagnostics and Condition Monitoring, General Electric Company, USARTL-TR-78-32, December 1978.

number) and the BIT isolation (sometimes in comments, but not always). The algorithm that goes with this definition is

$$FFI = \frac{\sum FI}{\sum D_{BIT/TE}}$$

where $FI_{BIT/TE}$ are only those maintenance actions that are first detected by BIT/TE, and $D_{BIT/TE}$ is the detection of malfunction by BIT/TE. It is not clear whether or not this should include false alarms.

The summation would be over time or a given number of events.

In <u>Assessment of Augmented Electronic Fuel Controls for Modular Engine</u> <u>Diagnostics and Condition Monitoring</u>, GE defines FFI as:

FFI = <u>number of failure events that have occurred</u> number of maintenance actions to correct

This equation is similar to the RADC definition, since "number of failure events that have occurred" is equivalent to number of isolated faults, and "number of maintenance actions to correct" is equivalent to total detected faults. This is also a measurable definition.

These two definitions are both quantitative; yet there are certain unknowns that complicate the measurability of FFI. Not all real faults are detected, or faults are detected that are really false alarms. We may resolve some real faults as "cannot duplicate." Thus these two definitions are not precise enough for our purposes, and a more inclusive equation will be derived that takes into account these factors affecting faults isolated.

Military specifications such as MIL-STD-2165 or MIL-STD-470A provide requirements on fault-isolation times or provide general definitions such as: "The degree to which a test program or procedure can isolate a fault within an item; generally expressed as a percent of the cases for which the isolation procedure results in a given ambiguity group size" (MIL-STD-2165).

2.2.3 Fraction of False Alarms (FFA)

There are many "fraction of false alarms" definitions. Most of the inconsistencies between these definitions are due to inconsistencies in the definition of a false alarm.

A false alarm may be called "an indicated fault where no fault exists" (MIL-STD-1309B), or a "fault indication of a failed item that is operating properly instead of or in addition to designating the real failure," or a "failure detection that cannot be repeated" (our survey; see Chapter Three). These three definitions are not consistent. The definitions and comments concerning fraction of false alarms vary also depending on the

interpretation of a false alarm. The following paragraphs give samples of definitions of "fraction of false alarms."

The RADC report <u>Analytical Procedures for Testability</u> lists the following three definitions of "fraction of false alarms":

- Fraction of all BIT/TE-indicated faults which are false alarms
- Ratio of quantity of BIT/TE false alarms to quantity of faults detected through use of defined means
- Ratio of false alarms to actual faults

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These may seem to be quantitative definitions but, unless there is a clear measure of a false alarm, the quantity of false alarms is not measurable either.

Another FFA definition is from <u>BIT/External Test Figures of Merit and</u> <u>Demonstration Techniques¹</u>: "Fraction of false alarms is the fraction of all <u>BIT/TE-indicated</u> faults which are false alarms. False alarms are those indications of a fault when an actual fault has not occurred." This definition is better in that it defines its interpretation of a false alarm.

MIL-STD-2165 defines a false alarm as a fault indicated by BIT or other monitoring circuitry where no fault exists.

<u>RADC Testability Notebook</u> defines a false alarm as an indicated fault where no fault exists (does not include good items in an ambiguity group). This latter definition is in agreement with MIL-STD-1309B. This publication lists the following measures of effectiveness related to "fraction of false alarms":

- Rate at which false indications occur (per 10⁰ hours)
- Percentage of indicated failures caused by actual failures
- Percentage of BIT/ETE-indicated failures caused by actual failures
- Percentage of BIT/ETE fault isolations to the wrong UUT

These measures are theoretically based and suffer some measurability problems. The first one does not define a false indication. The next two avoid using "false indications" and use only "actual failures" instead as a way around it. The last one fails to indicate how to measure a fault isolation to a wrong unit under test. The last three can be algorithmically developed but lack the precision necessary for this study.

Hughes Aircraft Company, RADC-TR-79-309, December 1979.

2.3 COMMENTS ON DEFINITIONS

The wide variety of definitions available provides a somewhat confusing array of possibilities that are not totally consistent. Many are so tailored to the measurement of specific details that they have limited use; others provide only a theoretically based descriptor for discussion purposes. Those which are quantitative are unmeasurable at the organizational level.

In examining almost 500 related documents (including military standards/handbooks, symposium proceedings, and manufacturer and contractor reports), we encountered an almost endless variety of bookkeeping algorithms. In itself this variety is not bad, because many of these documents are directed toward specific hardware or analysis problems and the definitions are somewhat tailored. It does make it difficult to keep definitions compatible with most of the current literature. Perhaps the single largest shortcoming in the definitions discovered in our literature search was the lack of a consistent set of definitions for FFD, FFI, and FFA. While several of the individual definitions are usable, no matched set exists. Our definitions are based on the relational properties of a good "generic" definition, that is, a definition not intended for use in solving a specific hardware or analysis problem. The relational properties are as follows:

- The definitions should be in accordance with military standards and handbooks.
- The definitions should be consistent with each other.
- The definitions must be:
 - -- Consistent with the intuitive interpretation of the parameter being defined
 - -- Directly or indirectly related to mission readiness factors
 - -- Mathematically precise
 - -- Measurable
 - --- At least experimentally
 - --- Possibly by specialized field reporting
 - --- Possibly through modification of standard field reporting

- -- Capable of being specified
- -- Capable of being demonstrated
- The defined quantities should be predictable.

None of the definitions we examined met all of these requirements. In fact, the preceding requirements probably form an overspecification. The definitions derived for this study and presented in Appendix B are primarily based on the set theory model of the organizational maintenance system and result from compromises and iterations with all of the models. They meet the properties of precision and measurability and are totally consistent, but they may or may not meet the other requirements. Of particular interest is the hierarchical relationship between the system definitions and the subsystem definitions, as discussed in detail in Chapter Five.

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CHAPTER THREE

MAINTENANCE SURVEY

3.1 BASIS OF SURVEY

Chapter Two described the wide variety of research that has been conducted in the testability field. It was found that there is little or no consensus regarding the definition of testability terms. While this appears to offer a wide latitude in the establishment of a set of definitions for developing predictor procedures, it was important to stay within the bounds of intuitive reasoning. At the same time, it was necessary to locate sources of enriched data to supplement the mass of data to be analyzed. Finally, it was desirable to take advantage of the years of hands-on experience within the military system to provide insights into the maintenance and reporting systems. The development of a maintenance survey was thought to be the most prudent approach to satisfying these requirements.

3.2 ORGANIZATIONS SURVEYED

A total of 108 organizational-level maintenance centers were surveyed, including the Strategic Air Command (SAC), the Tactical Air Command (TAC), and the Military Airlift Command (MAC), as well as U.S. Navy Air Wings, Air National Guard (ANG), and commercial aviation groups. The last three categories were surveyed for completeness, with concentration on the Air Force groups for data assistance and model-building efforts. Follow-up visits were made to at least one MAC and SAC operational unit, and several visits were made to TAC units. Most of the commands surveyed and interviewed had both organizational-level and intermediate-level maintenance. The visits clarified survey responses and provided a user-level view of the modeling efforts described in Appendix B. All visited commands provided assistance in structuring the flow model.

3.3 SURVEY CONTENTS

Project team members drew up initial survey questions to be considered. The questions were distributed to RADC and throughout ARINC Research for formal review and comment. In addition, several of our current clients were approached for comments on an informal basis. The resulting survey form is presented in Appendix A.

The survey questions centered on five major areas:

- Number of systems maintained and who maintains them
- Reporting systems that information is received from and sent to
- Local files maintained and access to those files (this information was sought for data enrichment)
- Intuitive definitions of detection, isolation, and false alarms
- Philosophy and insights

To help maximize survey response, (1) the respondents were assured anonymity, and (2) the survey form was limited in length. The first factor helped in obtaining candid answers, and the second served to minimize the effort involved in filling out the form.

3.4 SURVEY RESPONSE

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Although some of the groups contacted failed to respond to official survey inquiries. a substantial return rate was achieved. Response statistics are provided in Table 1.

TABLE 1. SUMMARY OF SURVEY RESPONSES

Item	Quantity	Percent
Organizational-level main- tenance centers surveyed	108	100
Responses received to date	47	44

3.5 SURVEY ANALYSIS

Table 2 provides summary data for the surveys returned. A total of 27 units maintained local data files in addition or as a supplement to the standard reporting systems. Of these, 15 were both available for research and met the requisite data criteria, thus adding to our data resources. Of particular interest were multiple-failure resolution and the "bad actors" files. Almost all of the units surveyed kept track of

TAHLE 2. SUMMARY OF SURVEY RESPONSES

Question	Responses
Maintenance of local data files	Yes: 27 No: 8
files available for tesearch	Yes: 20 No: 7
Information on repair times/fault-isulation times	Repair time: 21 Fault isolation: 13 Weither: 14
files on particularly bad problems	Yes: 27 No: 5 No response: 3
Multiple-failure report types	One report: 11 Multiple reports: 23 No response: 1
Differentiation between operator complaints and foutine maintenance-triggered actions	Yes: 31 No: 3 No response: 1
Reportage of stages of maintenance actions	Yes: 29 No: 2 No response: 4
Differentiation between suspected intermittent and unver- ified problems	Yes: 13 No: 20 No response: 2
Record of how final replaceable units were isolated	Yes: 8 No: 26 No response: 1
Instances when local technician was unable to isolate problem	Yes: 10 Mo: 24 No response: 1
Basis of false alarm ³	A: 14 B: 4 C: 0 Other: 17
Basis of faults detected ³	A: 10 B: 1 C: 12 Other: 12
Basis of faults isolated [*]	A: 8 B: 13 C: 1 D: 1 Other: 12

'See Appendix A for full questionnaire.

²A = Cannot duplicate (CND) or no fault found (NFF).
 B = A, excluding operator-induced CNDs.
 C = B, excluding suspected intermittents.

A = Number of maintenance actions, triffered by normal maintenance, that do not result in CND.
 B = Number of failure modes reported that do not result in CND.
 C = Number of faults detected and isolated by normal maintenance.
 A = Number of faults isolated by using normal system maintenance.

faults isolated by using normal system maintenance. faults isolated by using normal system maintenance plus standard troubleshooting procedures. faults isolated by using normal system maintenance minus operator-triggered maintenance. faults. isolated by using normal system maintenance, that are BIT/ATE. 5 B - Number o C = Number o D = Number o

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"bad actors." but they did not all have local data bases; those that did not relied heavily on personnel experience and expertise. In addition, multiple related failures were generally handled by separate reporting of the individual malfunctions. Sometimes comments on AFTO 349 can confirm some correlation of failures, but these cannot consistently be defined on the basis of the standard reporting.

While most of the information was extremely useful, care should be taken in using Table 2. because some of the responses to the survey can be somewhat misleading. For example, the respondents overwhelmingly affirmed differentiation between operator complaints and normal system maintenance. Closer examination of the responses shows that these complaints are reported by when-discovered codes, job control number prefixes, or comments provided on AFTO 349. There are basic holes in this information flow. Pilot reports of malfunctions indicated by use of preflight check lists are categorized as operator complaints. Often, failures that should result in BIT-generated job control numbers appear only when the pilot did not report these failures on debrief. These factors are discussed in more detail in Chapters Four and Six.

Of primary interest are the responses to the intuitive questions that are the last three entries in Table 2. These questions concern the intuitive definition of false alarm. faults detected, and faults isolated. A general consensus on intuitive definitions would be expected, but more than a third of the responses were other than what had been predicted. In addition, while opinions were strongly expressed (51 written responses), there was no consensus. In fact, no one response to any of the questions approached 50 percent. This result is consistent with the literature search and points out the need for mathematically precise and consistent definitions.

In addition to the survey responses. 15 local data bases located at the organizational level are available for further study.

3.6 SUMMARY AND CONCLUSIONS OF SURVEY

The survey filled three basic needs of the research project:

- We were able to locate and identify data sources for enriching and supplementing the normal Air Force Maintenance Data Collection System.
- We were provided with an introduction to several of the commands and reviewed their maintenance procedures and our models of organizational maintenance. (This worked out very well in that the development of the flow model would have been impossible without

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the participation of the commands. The model ultimately became recognized by organizational maintenance personnel as an accurate representation of organizational maintenance in the Air Force.)

 We found a diversity of "intuitive" concepts of faults detected, faults isolated, and false alarms, which confirmed our literature surveys and reaffirmed the need for precise, quantifiable, and measurable organizational-level measures.

CHAPTER FOUR

DATA SOURCES

A wide variety of data resources were either utilized during the Phase I study or developed for the Phase II study. These resources cover the depth and breadth of maintenance reporting and testing.

We have identified the following three levels of data as being necessary for the development of testability predictors:

- Field Data Data collected through routine reporting channels
- Engineering Test Data Data from validated field tests of limited duration and observed by an engineer
- Design Data Detailed engineering analysis of design-related parameters

During the course of our investigation, we were able to assemble the data summarized in Table 3. To minimize the risk involved in predictor development, all three levels of data should be used. Each of the three levels are discussed in the following subsections. The data appropriate to these studies were derived from a much larger list of candidate data resources.

4.1 FIELD DATA

The primary source of field data to support this study is the AFR 66-1 promulgated Maintenance Data Collection System (MDCS). It is discussed in detail in Air Force Technical Order 00-20-02; we will address those aspects of MDCS which are particularly germane to this study.

4.1.1 AFTO Form 349

The basic source of data for the MDCS is AFTO Form 349, shown in Figure 1. Every reported maintenance action performed on aircraft avionics generates an AFTO 349. There are a number of items on the form that are particularly important to this study.

The first important entry is the job control number (JCN) (block 1). Every maintenance action is assigned a unique JCN, which stays open until the action is complete. Thus, one JCN equals one maintenance action.

	TABLE 3. DATA SOURCES	
Field Data	Engineering Test Data	Design Data
F-15 Maintenance Data Collection System summaries (currently covering six months at one base) for:	Not currently identified	APG-63 intermediate maintenance Technical Orders; detailed engi- neering analysis of F-15 APG-63 Padar is under way: could feed a
 APG-63 Radar Data Processor APG-63 Analog Target Data Processor APG-63 Digital Signal Processor Inertial Navigation Unit Low Band RF Amplifier 		II effort
F-16 enhanced ST/BIT study data (MDCS summaries) for 31 selected LRUs (currently covering three months at four bases)	F-16 Follow-On Operational Test and Evaluation, AFTEC project 76-106, October 1980	Limited access to intermediate maintenance Technical Orders for a subset of the 31 LRUs
C-5 Malfunction Analysis Detection and Recording System (MADARS) sample reports	Not currently identified	Will be gathered under Phase II
Miscellaneous MDCS-based summaries:	Not currently identified	
 Weapon System Management Information System (WSMIS) Maintenance and Operational Data Analysis System (MODAS) 		
15 local data bases covering various systems		Will be acquired as necessary: various STAMP analyses (see Figure 2)

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FIGURE 1. AFTO FORM 349, MAINTENANCE DATA COLLECTION RECORD

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Since the first three digits of the JCN code denote the Julian day, certain <u>rate</u> information is available as well.

Block 3 of AFTO 349 identifies the equipment on which work was performed or from which an item was removed. The block allows sorting of maintenance actions by major equipment type.

The work unit code (block C) further refines the identity of the item being serviced. Each avionic LRU (and SRU) for each aircraft type has a unique work unit code, which allows a sorting of data by LRU type. That is, one could construct a data base of AFTO 349 data and extract all maintenance actions on a given LRU for a given aircraft.

The action-taken code (block B) indicates the action or actions taken to resolve the original discrepancy, such as removal and replacement of an SRU.

The when-discovered code (block E) indicates the point in a mission when the discrepancy being corrected was discovered. Typical entries are pre-flight (no abort), pre-flight (abort), in-flight (no abort), postflight, and special inspection.

The how-malfunctioned code (block F) is a three-digit code that describes the malfunction in general terms. Acceptable codes, which are listed in the maintenance job guides for the major equipment types (the -06 series Technical Orders), may be slightly different for each major equipment. That is, "how mal" codes for the C-5 may be different from those for the F-15. Certain codes are standard, including "cannot duplicate" (CND), i.e., Code 799. This standardization provides a method for estimating one of the testability parameters, as will be seen in Chapters Five and Six.

4.1.2 Assessment of MDCS Data Sources

There is a major shortcoming of the MDCS when it is used for testability analysis. This should not be viewed as an indictment of the MDCS: the system appears to do a good job when it is used for its original purpose. It does provide a measure of maintenance productivity, equipment reliability, and maintenance and support costs. However, the thrust of AFTO 349 is toward maintainability (what failed, how long it took to repair, and so on). The central issue in testability is how effective the maintenance system (built-in-test software, check lists) is in discovering and isolating faults. As can be seen from the discussion in Chapter One, and as will be amplified in Chapters Five and Six, a critical question neither asked on AFTO 349 nor uniformly documented anywhere is whether the fault was detected or isolated by the "normal system" maintenance. "Normal system" here is the set of maintenance aids provided as part of the entire system -- test gear check lists, built-in-test software, and other aids. A number of responses to the maintenance survey (see Chapter Three) indicated that information of this type is retained. However, it is not uniformly coded on AFTO 349; hence, it is very difficult to conduct reasonably accurate statistical surveys dealing with this parameter.

A second flaw in the use of MDCS for testability analysis is that certain responses on AFTO 349s may be politically damaging and thus tend to be avoided. For example, "cannot duplicate" (CND) might be interpreted as resulting from poor training or poor fault-isolation procedures. Thus, pressures might be placed upon maintenance personnel to avoid use of CND for "how mal." We will touch on this issue in Chapter Six.

Nonetheless, the Maintenance Data Collection System is the only source of Air Force-wide automated data analysis available. Any further study must recognize and deal with the above shortcomings.

4.1.3 Specific MDCS Sources

Table 3 lists a number of sources of field maintenance data. Most fruitful for this Phase I study were the F-15 avionics AFTO 349 summaries provided by the 1st TAC Fighter Wing/MA, and the F-16 enhanced ST/BIT reports. The latter included a series of pilot debrief reports that could be correlated to AFTO 349s by matching JCNs. Unfortunately, this proved to be such a time-consuming manual task that we were only able to effectively use data from two of the four bases. In addition, the debrief reports could not be used to reliably partition maintenance actions into "normal" and "other than normal" system maintenance as was hoped. The absence of a set of BIT codes did not mean that BIT did not detect a fault, nor did it mean that the pilot had.

A third source of data, and one that we believe holds the greatest promise for useful analysis, is the C-5 Malfunction Analysis Detection and Recording System (MADARS). Unfortunately, there was a complete mismatch between the field data (MADARS) and engineering/design data (such as Technical Orders) available to us. This will be corrected during Phase II if we utilize the MADARS data. This system is attractive, because it automates the AFTO 349 reporting system in a fairly discrete set. There are three C-5 bases -- Tinker AFB, Oklahoma; Travis AFB, California; and Dover AFB, Delaware -- which raises the possibility of more easily implementing an expanded data-gathering system.

Two larger management information systems are listed in Table 3 -the Weapon System Management Information System (WSMIS) and the Maintenance and Operational Data Analysis System (MODAS). Both obtain their source data from AFTO 349s and thus represent no new information. They may, however, prove fruitful for developing estimations for certain portions of the key testability parameters as a result of their scope. They will be further assessed in Phase II.

Finally, approximately 15 other local data bases were identified as a result of the survey discussed in Chapter Three. These were not investigated.

4.2 ENGINEERING TEST DATA

This level of data was the sparsest of the three levels utilized in Phase I. Development of these data will be necessary in Phase II of this study and will represent the "parameterizing" data necessary to build predictions successfully.

4.3 DESIGN DATA

There was a mismatch between the level of detail available in design data and that available in field data. We had a large amount of field data on F-16 LRUs, but we did not have complete access to F-16 LRU design data. Through the help of the F-16 SPO, however, we were able to identify certain design-related data from intermediate maintenance Technical Orders. If F-16 field data become key to Phase II, we will take action to obtain intermediate-level and depot-level maintenance manuals for the LRUs in question.

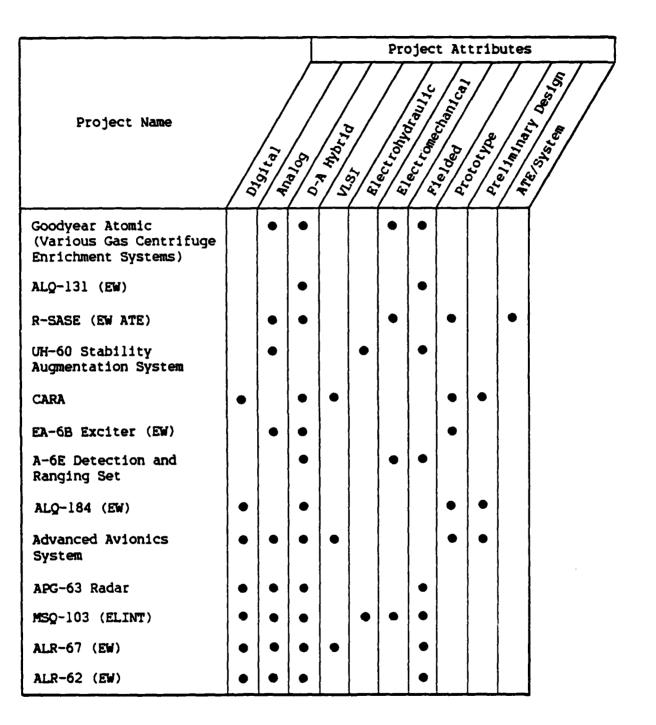
The situation was similar for the F-15: there were two F-15 LRUs (the Inertial Navigation Unit and the Low Band RF Amplifier) for which we were unable to obtain technical design data. Fortunately, we had available the current intermediate-level maintenance manual for the three

APG-63 LRUs shown in Table 3. There is a STAMP^1 testability analysis under way on the F-15 APG-63 Radar; results of the analysis will be available for evaluation with field data during Phase II.

We currently have no technical design data on the C-5 avionics systems; this will be a priority item for Phase II if the C-5 is chosen for predictor development.

If sufficient field data cannot be obtained, we have detailed STAMP analyses of 13 systems, as shown in Figure 2. The majority of these systems are EW mission avionics. If we must employ these analyses in lieu of field data, there may not be enough data points in an equipment spectrum that is broad enough to provide high-confidence estimators. For that reason, the STAMP studies are viewed as a "method of last resort."

STAMP (System Testability and Maintenance Program) is a detailed testability model developed by ARINC Research for design testability analysis and fault-isolation strategy development. It has been, and is being, applied to a number of military systems.



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STREET STREE

FIGURE 2. AVAILABLE STAMP ANALYSES

4.4 SUMMARY OF DATA SOURCES

During this Phase I effort, we learned that the Maintenance Data Collection System may not be adequate in its current form for developing predictors of FFA. FFI, and FAR. A revised or enhanced collection system must be structured to provide the appropriate data. Since the C-5 MADARS is fairly small (compared to the MDCS) and automated, it may be the best candidate for such a restructuring. We will need to gather detailed technical/design data on the C-5 avionics systems if such a restructuring is undertaken.

CHAPTER FIVE

APPLICATION OF ALGORITHMS

5.1 MATHEMATICAL MODELING

Mathematical modeling was undertaken to provide measurement algorithms that were consistent with the derived definitions. We started with the modified state model, which is intended to relate the organizational testability parameters to a search for the system state. This represents the heart of the maintenance problem in that there is an indication of a problem and action must be taken to find out whether a real failure is present and where it is located. As this model was being developed, it became apparent that conflicts in definitions were surfacing. For example. it was not clear whether a "cannot duplicate" (CND) event and a fault-isolation event were mutually exclusive. To resolve these problems, a second model, based on membership in sets, was developed. The primary tool was the Venn diagram, in which both mutual exclusivity and coincident properties are explicit. This set model led to a clear and concise set of definitions that were mathematically precise, as well as an algorithm set that could be used to verify the other models. The state model was then reworked on the basis of definitions generated by the set theory model with most of the conflicts resolved.

A third model, based on the flow of maintenance events, was developed and was pursued concurrently with the other two models. This model was to solve two of the problems being faced. The first problem was relating maintenance actions to readiness. While a preliminary connective had been established with the modified state model, it was less than satisfactory. The flow model would, by tracing events through the mission/maintenance cycle, provide a direct tie-in. The second problem was more basic: There was no direct way to relate what we had done mathematically to the maintenance personnel. The first two models were too "mathematical." The flow model was readily analyzed by maintenance personnel of SAC. TAC, and MAC, and underwent major revisions based on discussions with these personnel. As a clearer picture of the organizational-level maintenance process evolved, modifications were made to both of the other models. Finally, a flow model evolved that was satisfactory to both organizational-level maintenance personnel and the mathematicians.

A detailed review of each of the models is presented in Appendix B. The final form of the definitions is reviewed here and is discussed in both Appendix B and the Executive Summary. It is the purpose of this chapter to relate the measurement models of Appendix B to the problem of computing actual values and to build up system/subsystem algorithms. As will be seen in Chapter Six, the state model most closely approaches the current measurement systems. Algorithmic representations will be drawn by use of this model, although the same systematic procedures can be used (although the specific algorithms will change) for any of the models. This chapter is broken down according to the principal terms FFD, FFI, and FFA, with a breakdown by system, subsystem, and system/subsystem relationship.

The following paragraphs describe some basic items that apply to the mathematics throughout this chapter. The subscript "s" refers to normal system maintenance (NSM). We define NSM as follows:

Techniques that are specified as standard operating procedures for use of BIT. ATE. semiautomatic. or documented manual detection and troubleshooting for a given system under test. They include regular calendar checks and normal "go" checks. NSM is sometime called "defined means."

Thus $\sum MA_s$ refers to maintenance actions triggered by the NSM, and $\sum MA$ is all maintenance actions. Unless otherwise specified, a $\sum symbol$ refers to events over time, so that $\sum MA$ is the sum of all maintenance actions on the system over some measurement period.

The subscript "ss" refers to a subsystem. The system/subsystem boundary is an artificial one, and is drawn on the basis of analysis needs. A system is taken as a functional or structural entity. Its boundaries are often physical break points between the system and surrounding systems. Examples are an entire aircraft, or a weapon system, or even a single LRU within a weapon system. A subsystem, on the other hand, is any portion less than the totality of the universe of concerns. For example, the Government, concerned with the acquisition of Weapon System A, would consider LRU 5 a subsystem of Weapon System A. However, the contractor who builds LRU 5, and only LRU 5. in Weapon System A would consider LRU 5 a system. The subscript "ssc" refers to a subsystem contribution as in the LRU 5 contribution to Weapon System A. Finally, an "i" subscript will be used to refer to the ith subsystem in a system.

5.2 FRACTION OF FAULTS DETECTED (FFD)

Fraction of faults detected should ideally be unity. It is the entry point for maintenance. We will discuss a system-level value of FFD followed by subsystem values of FFD, and, finally, their interrelationships with each other.

5.2.1 FFD - System

The set theory system definition derived for fault detection as taken from Appendix B is:

Fault Detection - Normal system maintenance indicates that the system is not functioning properly, and this indication is the result of a real fault within the system.

To relate this to FFD, we must normalize by the faults within the system. Note that we are dealing only with relevant failures as discussed in Chapter One and Appendix B. The fraction of faults detected at the system level will then be given by: "the ratio of fault detection to faults in the system." From the Appendix B modified state representation, this translates algorithmically to

$FFD = \left(\frac{\sum MA_s - \beta_s \sum CND_s}{\sum MA - \beta \sum CND}\right)$	(Equation 54 of Appendix B)
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The numerator of this term represents the fault detection (that is, the NSM-triggered maintenance actions minus the false alarms generated by NSM). The denominator represents the faults in the system (that is, the total maintenance actions minus all false alarms).

The system-level fault detection can be measured by knowing the NSMgenerated maintenance actions (MA_s), the "cannot duplicate" results of NSM-generated maintenance actions (CND_s), the total maintenance actions (MA), and the total "cannot duplicate" (CND) events, all of which may be measurable at the organizational maintenance level. The term β_{s} CND_s represents the false alarms due to NSM. The term β_{s} CND represents all

false alarms. The factors are derived in Appendix B. β and β_s are

empirical coefficients and represent the percentage of CNDs that are false alarms. These will be empirically determined during the Phase II work and presented in tabular, graphical, or functional forms.

5.2.2 FFD - Subsystem

The subsystem definitions are based on a participating element of a system. If the subsystem is all that is under consideration (that is, a system boundary is drawn around the subsystem) then the system-level definitions apply to that subsystem. For a subsystem, the set theory-derived definition for fault detection is:

Fault Detection - NSM indicates that a subsystem is not functioning properly, because of a real fault within the system. The detection can be proper or improper. **Proper Detection - Fault is within the subsystem in which detection** occurs.

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

To relate this to FFD, we must normalize by the faults within either the system or the subsystem. The fraction of faults detected at the subsystem level will then be given by:

> The ratio of subsystem-level detections to either faults within the system or faults within the subsystem. The subsystem-level contribution will be the ratio of the sum of all detections to the sum of all faults within the system. The subsystem FFD will be the ratio of the sum of the proper subsystem detections to the sum of all faults within the subsystem.

From the Appendix B modified state representation these definitions translate algorithmically to:

Subsystem contribution:

$$FFD_{SSC} = \frac{\left(\sum MA_{S} - \beta_{S} \sum CND_{S}\right)_{SS}}{\left(\sum MA - \beta \sum CND\right)_{SS}} = \frac{subsystem \ detections}{subsystem \ faults}$$

This equation requires the same data base as the system-level FFD, except that we must now partition the data on the basis of subsystem properties:

Subsystem FFD:

$$FFD_{SS} = \frac{\left(\sum MA_{S} - \beta_{S} \sum ND_{S}\right) \text{ proper, ss}}{\left(\sum MA_{S} - \beta_{S} \sum ND_{S}\right)} = \frac{\text{proper subsystem detections}}{\text{ subsystem faults}}$$

This equation shows that if the subsystem is considered a system, an improper detection may become a CND.

5.2.3 FFD System/Subsystem Relationships

The definitions of system and subsystem FFD can be related by Equations 40 to 42 of Appendix B as:

$$FFD = \sum_{ss} \frac{\sum FD_{ss_1} - \sum FD_{ss, improper_1}}{\sum \sum F}$$

where $\sum_{SS} FD$ represents subsystem faults detected [also represented by $(\sum_{SS} - \beta \sum_{SS} CND)$] and $\sum_{SS} F$ represents system faults [also represented set of the system faults set o

by ($\sum MA - \beta \sum CND$)] [an improper subsystem fault detection (FD_{SS}, improper)) is as defined in Section 5.2.2],or

 $FFD = \sum_{SS} (\Upsilon_{i} FFD_{SSC})$

where Υ_{i} allocates the portion of the subsystem contribution that applies to the system. For example, Figure 3 shows a system functional makeup.

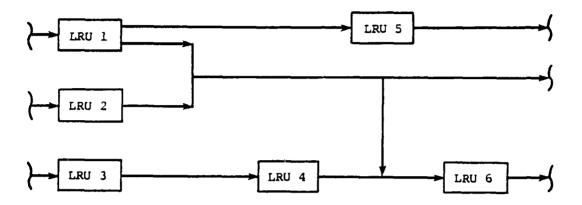


FIGURE 3. PARTIAL SYSTEM FUNCTIONAL MAKEUP

Failures will propagate through the system, and individual detections of a single failure may be observed at the outputs of individual elements. For example, a failure in LRU may be detected at the output of LRU and LRU₅. Y is a measure of the propagation effect and the system functional makeup. If the ith LRU is isolated in testing, then $Y_i = 1$. For the general case, it is a function of feeds and topology. A first-order estimator is given by the complement of the external dependency factor (EDF):

 $\Upsilon_i \simeq (1 - EDF_i) = 1 - \frac{number of inputs to subsystem i}{total subsystem i failure list}$

The total subsystem i failure list would be provided by the FMECA and would include inputs. so that an LRU with 25 possible internal failures and 5 inputs which could also fail would be estimated at:

$$Y_i \simeq (1 - EDF_i) = 1 - \frac{5}{25 + 5} = 0.833$$

A more accurate way to compute Y_1 would be to analyze the system FMECA to tag those faults which actually propagate. The methodology described in this subsection permits the FFD parameters to be built up from subsystems to systems.

Note: A secondary detection such as a backup indication will be counted as a detection by the supporting subsystem. It will be termed "improper" even though it may be correct. Thus, proper/improper is only a partitioning and does not imply correctness of the detection. A prime example, will be in the use of a "centralized" BITE subsystem that may have a subsystem contribution to FFD of 1.0, consisting mostly of improper detections.

5.3 FRACTION OF FAULTS ISOLATED (FFI)

Fraction of faults isolated represents the meat of the maintenance activity. Its ideal value is also unity. We will discuss a system-level FFI, then subsystem values of FFI, and, finally, a system/subsystem relationship.

5.3.1 FFI - System

The set theory system definition derived for fault isolation as taken from Appendix B is:

Fault Isolation - NSM identifies all failed units within the system. An attempted isolation can have any of the following results:

- Proper Fault Isolation Only and all failed units are isolated.
- Improper Fault Isolation All but not only failed units are isolated.
- No Fault Isolation Other combinations that occur, including only but not all failed units.

To relate this to FFI, we will again normalize by the faults within the system. The fraction of faults isolated at the system level will then be given by: "the ratio of NSM isolations to faults within the system." (FFI may also be proper or improper.)

From the Appendix B modified state representation, this definition translates algorithmically to:

$$FFI = \left(\frac{\sum FI_{s}}{\sum MA - \beta \sum CND}\right)$$

(Equation 55 of Appendix B)

The only new term here is the $\sum FI_s$, or system-generated fault isolations that can be measured. β is again empirical, as discussed in Section 5.2.1. A problem unique to FFI is the breakdown between proper and improper. Since FI includes both, a system with high FFI may generate a large number of RTOK events. To create a term less sensitive to this problem, we develop an FFI_p:

$$FFI_{p} = \frac{(\sum FI_{s})_{proper}}{\sum MA - \beta \sum CND} \cong \left(\frac{\sum FI_{s} - \sum RTOK_{s}}{\sum MA - \beta \sum CND}\right)$$

(Equation 56 of Appendix B)

This partially compensates for improper fault isolation, as discussed in detail in Appendix B.

5.3.2 FFI - Subsystem

The set theory-derived definition for fault isolation is identical to the system-level definition. The subsystem algorithms will then be:

$$FFI_{SS} = \frac{\sum_{ss}}{(\sum MA - \beta \sum CND)_{ss}}$$

and

$$FFI_{p,SS} = \frac{\sum FI_{SS} - \sum RTOK_{SS}}{(\sum MA - \beta \sum CND)_{SS}}$$

Both of these values can be converted to subsystem-contribution values. Let K_i be the ratio of faults in the ith subsystem to total faults. Then

$$K_{1} = \frac{\Sigma F_{ss_{1}}}{\Sigma F_{s}} = \frac{\left(\left(\Sigma MA - \beta \Sigma C ND\right)_{ss}\right)_{1}}{\Sigma MA - \beta \Sigma C ND}$$

and

with

5.3.3 FFI System/Subsystem Relationships

The definitions of system and subsystem offer a compatibility, so that the final relationship is given by:

FFI =
$$\sum (K \times FFI) = \sum (FFI)$$

ss i ss, ss ssc i

and

 $FFI = \sum_{i} (K \times FFI) = \sum_{i} (FFI)$ $p \quad ss \quad i \quad p.ss_{i} \quad ss \quad p.ssc \quad i$

where K_i can be directly computed. The methodology described in this subsection allows the buildup of a system FFI from subsystem values.

5.4 FRACTION OF FALSE ALARMS (FFA)

FFA represents the wasted action of maintenance activity. Its ideal value is zero. We will first discuss a system-level FFA, then a subsystem FFA, and, finally, a relationship between the system and subsystem.

5.4.1 FFA - System

The set theory system definition for false alarm as taken from Appendix B is:

False Alarm - There is indication of a failure in the system where none exists.

To relate this to FFA, we must normalize by some factor. If we use system faults as we did with the two previous measures, we will have an ill-defined parameter in that false alarms may exceed actual faults, giving a value of FFA greater than 1. For these reasons the normalizer for FFA is the sum of false alarms and faults. The discussion of relevancy is particularly important to false alarms as pointed out in Chapter One and Appendix B. Of note is the exclusion of the so-called "nuisance" false alarm, which is an indication that is noted and then ignored (not causing a maintenance action).

The fraction of false alarms at the system level will then be given by:

The ratio of the system-level false alarms to the sum of the faults in the system and false alarms.

From the Appendix B state representation, this can be algorithmically represented by:

 $FFA = \left(\frac{\beta \sum CND}{\sum MA}\right)$

(Equation 57 of Appendix B)

Again. B is the only unmeasurable quantity, and it should be familiar by now because it appears in each of the testability parameters to be computed. Of particular note is that false alarms may be specialized to system-generated or operator-generated as desired:

$$FFA_{j} = \frac{(\beta \sum CND)_{j}}{\sum MA}$$

where $(\beta \sum ND)$, measures the jth component of false alarms (e.g.,

system/operator/BIT), and FFA_j is the contribution of the jth component to FFA.

5.4.2 FFA - Subsystem

The subsystem definition for false alarm as taken from the set theory derivation in Appendix B is given by:

False Alarm - There is indication of a failure in the subsystem where there is none in the system.

To relate this to FFA, we must normalize as discussed in Section 5.4.1, so that the subsystem FFA is given by:

The ratio of the subsystem false alarms to the sum of the faults in the system and false alarms.

From the modified state representation, this definition translates algorithmically to:

Subsystem contribution:

$$FFA_{SSC} = \frac{(\beta \sum CND)_{SS}}{\sum MA}$$

This equation, of course, requires us to partition the data on the basis of subsystem properties:

Subsystem FFA:

$$FFA_{SS} = \frac{(\beta \sum CND)_{SS}}{(\sum MA)_{SS}}$$

These measures are easiest to obtain for depot and intermediate maintenance, where the individual unit is the source of the maintenance action.

5.4.3 FFA System/Subsystem Relationships

services established and the working the services.

The definitions of system FFA and subsystem FFA can be related by Equation 53 of Appendix B as:

$$FFA = \sum_{i=1}^{n} \left(FFA_{ss} \right)_{i} - \frac{\sum_{i=1}^{n} \sum_{j=1}^{\tau} ij \left(FA_{ss} \right)_{i}}{\sum MA}$$

where τ_{ij} represents the cross-detection of subsystem j by subsystem i and $\tau_{ii} = 0$. This is precisely the same detection problem discussed in Section 5.2.3, and it reduces false alarms at the system level by a factor applied to each of the submeasures.

This equation can be further expanded as follows:

$$FFA = \frac{n}{1 \leq 1} \left(FFA_{SS} \right)_{1} - \frac{\frac{n}{1 \leq 1} \frac{n}{1 \leq 1} \tau_{1j} \left(FA_{SS} \right)_{1}}{\sum MA} \quad \left(\frac{\frac{n}{k \leq 1} \left(MA_{SS} \right)_{k}}{\frac{n}{k \leq 1} \left(MA_{SS} \right)_{k}} \right)$$
$$= \frac{n}{1 \leq 1} \left(FFA_{SS} \right)_{1} - \frac{n}{1 \leq 1} \frac{\frac{1}{2 \leq 1} \tau_{1j} \left(FA_{SS} \right)_{1}}{\frac{n}{k \leq 1} \left(MA_{SS} \right)_{k}} \quad \left(\frac{\frac{n}{k \leq 1} \left(MA_{SS} \right)_{k}}{\sum MA} \right)$$

$$FFA = \sum_{i=1}^{n} \left(FFA \right)_{i} - \sum_{i=1}^{n} \varepsilon_{i} \left(FFA \right)_{i}$$

where ξ_i is a modified coefficient of the subsystem false alarms for each of the i subsystems and is given by

$$\xi_{1} = \prod_{j=1}^{n} \tau_{1j} \left(\frac{\sum_{k=1}^{n} \left(MA_{ss} \right)_{k}}{\sum MA} \right)$$

The preceding equation can be written as

$$FFA = \sum_{i=1}^{n} \delta_i \left(FFA_{SS} \right)_i$$

where δ_1 is the fraction of the ith subsystem FFA not related to a cross-detection problem applied at the system level. Figure 3 can be

used to illustrate this factor. A detection in the subsystem LRUs may be caused by a failure in LRU_1 , but at the LRU_5 subsystem level it will appear as a false alarm. This is, in fact, related to the factor developed in Section 5.2.3 for FFD, so that:

 $\begin{array}{c} \delta & \cong \Upsilon & \cong (1 - EDF) \\ i & i & i \end{array}$

which may be estimated from the FMECA as discussed in Section 5.2.3.

The methodology discussed in this subsection allows the buildup of a system FFA from subsystem values.

5.5 ALGORITHMIC APPLICATION SUMMARY

An algebra has been developed to permit the definition of organizational-level testability attributes (FFD, FFI, and FFA). This algebra also permits a buildup from subsystems to systems so that lower-level analyses can be combined to give an estimate of system performance. Three parameters are key to the analysis process. At both the system and subsystem levels we must empirically determine the coefficient β that relates the "cannot duplicate" events to false alarms. At the subsystem level we need to determine the coefficient Υ that allocates the portion of the subsystem contribution that applies to the system, and the coefficient δ that represents the false-alarm/detection cross-talk between subsystems. These latter two may in fact be the same parameter. Estimators are provided for Υ and δ , but all three should be empirically derived from field data.

If these algorithms can be used to measure the parameters of interest, then prediction can be developed through a number of cause-and-effect processes, including regression and analytic and theoretical development.

CHAPTER SIX

FEASIBILITY OF PREDICTOR DEVELOPMENT

This chapter discusses the feasibility of developing predictors for the three measures. The basic decision process is defined, and then each major decision made is discussed in detail.

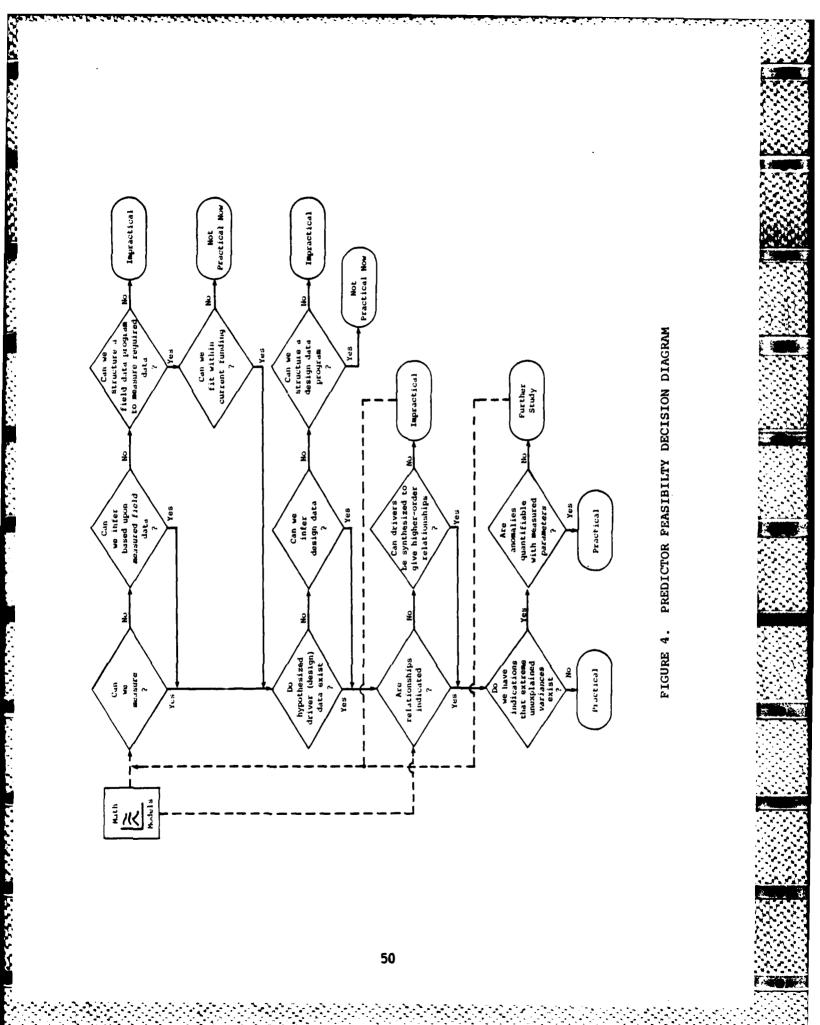
6.1 THE FEASIBILITY DECISION PROCESS

To make the decision concerning feasibility as objective as possible, we have developed a decision process that asks key questions and, on the basis of the response to the questions, indicates whether FFA, FFD, and FFI can be practically predicted, require further study, or are impractical. The generalized decision process is shown in Figure 4.

Starting with each mathematical model (discussed in Appendix B), we ask, "Can we <u>measure</u> the parameters?" This is a function of the elements of the parameter as defined in the mathematical model and of the maintenance data collection and reporting system. If the elements cannot be measured directly, we <u>may</u> be able to <u>infer</u> the elements (or the measure directly) from the data. For example, we may be able to determine (from outside sources) an empirical coefficient that permits inferring one of the elements of a measure. If not, the decision process asks if we can develop a data collection program that <u>can</u> provide the data. If we cannot, there is no need to continue; it is impractical to measure that particular parameter. If a data collection system can be developed, we may continue to the next level only if the system is simple enough to fit within the Phase II effort. If it is not, we will declare that measure "not practical now."

If we successfully traverse the "measurability" portion of the decision process, we next assess the existence of design data that can differentiate various systems; and we ask the same types of questions asked in the measurability loop: If data do not exist, can they be inferred? If not, can we set up a design data program that could produce these data?

Note that we must reach the conclusion of "impractical" if we have answered no to all these questions; to have done so implies that there are no distinctions between electronic equipment -- i.e., no peculiarities



about the design of box A that permit it to be identified as separate and distinct from box B. Intuitively, this is not the case; there should always be some design factor that makes boxes different, if only in function. However, it should be recognized that the key issue is quantifiability, i.e., some way to measure design difference. This is necessary since we cannot develop useful predictors when the variables are totally subjective or unquantified.

If the decision process has shown that the parameter is measurable, and that there are quantifiable design differences between equipments, the next step is to determine if relationships exist between the parameter and the design data. If none exists, we must again conclude that it is impractical to build a predictor of that parameter.

The last level of decision checks to determine if there are unexplained variances in the predictor of FFI. FFD. or FFA: if there are not, we declare it practical to develop a predictor for that testability measure. If unexplained variances exist, we may be able to quantify them with some other measure: if we can, we will declare the development of that predictor practical: if we cannot, we say that the measure requires further study, either to quantify the unexplained variance or to determine if the variances are critical.

This decision process was conducted for each of the three measures of interest -- FFI, FFD, FFA (or FAR). Note that we have used the term "practical" as opposed to "feasible" up to this point. The reason is that we should differentiate between the practicality of a predictor of one measure of testability and the "feasibility" of continuing the entire process in light of the interrelationship of the parameters as shown in Chapter Five and Appendix B.

We have developed a decision approach, which includes consideration of the importance of the measures and the practicality of predicting each measure.

We believe that FFA (or FAR) is central to the feasibility of the overall predictor model, especially in light of its appearance in both of the other two measures. FFD is a critical parameter because of its impact on readiness and mission success -- ideally, we should detect failures in the preflight period so that missions can proceed at full capability. The isolation problem is, in that regard, slightly less critical. Red Ball or Red Streak teams can always perform a wholesale system swapout and let intermediate maintenance perform the actual fault isolation.

The following sections track the decision process for the three testability measures.

6.2 MEASURABILITY

The first level of the decision process is measurability. The three measures and the mathematical expressions are summarized in Table 4; the details of their derivation are examined in Appendix B.

Parameter	Set	State	Flow
FFD	$\frac{\Sigma MA_{s} - (\Sigma CND - \Sigma CND_{i})_{s}}{\Sigma MA - \Sigma CND - \Sigma CND_{i}}$	$\frac{\sum MA}{S} - \beta_{S} \sum CND_{S}$ $\sum MA - \beta \sum CND$	$\frac{\int \dot{M}A_{s} - \beta_{s}C\dot{N}D_{s}}{\int [\dot{M}A - \beta C\dot{N}D]}$
FFI	$\frac{\Sigma FI_{s}}{\Sigma MA - \Sigma CND - \Sigma CND_{i}}$	$\frac{\sum FI_{s}}{\sum MA - \beta \sum CND}$	jři _s j(ma - β cnd)
FFA	$\frac{\sum CND - \sum CND_{i}}{\sum MA}$	<u>βΣ</u> CND ΣMA	<u>βjcnd</u> jma

TABLE 4. TESTABILITY MEASURES

We have shown FFI as the "total" FFI measure, disregarding any distinction between proper and improper fault isolation. This distinction will be discussed in Section 6.2.3 in more detail, because it poses interesting measurability problems.

Several observations should be made: Employing the set theory equations requires a data collection system that can classify each maintenance action and failure indication <u>exactly</u>; that is, it assumes perfect information. For that reason, the set theory equations are not useful from a "measurability" viewpoint; rather, the set theory model was useful in defining the assumptions that were implicitly made in the other two models but were not readily identifiable. Hence, the set theory equations act as a "consistency check" of the other two formulations, and they will not be further addressed in this chapter.

Note also that β CND appears in every testability parameter in the state and flow models and is thus the major key to the success of any predictor model. If we cannot measure and "predict" the "cannot duplicate" term, the other two measures will be in error. For this reason, we will discuss FFA (FAR) first.

6.2.1 Fraction of False Alarms (FFA)

As can be seen in Table 4, FFA is structurally the simplest of the measures and conceptually the easiest to measure.

The maintenance reporting system has a column in which the technician enters a "how malfunction code," and a list of acceptable codes is given. One of these is 799, or "cannot duplicate, bench check good," or "no fault found." Consequently, by counting the number of occurrences of 799 for a given LRU work unit code over a given period, and counting the total maintenance actions (job control numbers) generated for that LRU over the same period of time, we obtain a measure of the fraction of maintenance actions that result in CND (FCND).

Converting FCND to our fraction of false alarms requires that we be able to determine the parameter β , which is the proportion of CNDs that are actually false alarms. This <u>may</u> be possible where "bad actors" are carefully tracked. In that case, a CND that was a <u>repeat</u> CND on that particular serial number LRU would be interpreted as a failure whose isolation escaped normal troubleshooting. Extraordinary measures, not part of normal system maintenance, would be required to verify and isolate the failure. In any case, determining β requires careful tracking of each CND to weed out the "bad actors."

Several of the operational units that we visited reported that they employ some sort of "bad actors" program. Such programs tend to be ad hoc and are almost universally manual, existing in the form of entries in the repair shop's equipment logs or similar files. Consequently, these data are not amenable to computerized analysis and should be viewed as a lastresort source of data.

The C-5 Malfunction Analysis Detection and Recording System (MADARS), on the other hand. is highly automated and appears to be robust enough to infer a β factor for at least some of the C-5 avionics. There is a "bad actors" analysis program, and the requisite serial number tracking capability. In addition, a quick look indicates that it would be feasible to establish a link into the MADARS data base (without disturbing day-to-day operations) for any special-purpose processing that might be needed.

A second factor tends to complicate the determination of FFA. In many cases, maintenance organizations use a summary analysis of the AFTO 349 data to measure performance of the maintenance activities. A possible result is that activities with numerous CNDs will be judged somehow less capable than those with few CNDs. Maintenance technicians will thus be reluctant to use the 799 "how mal" code -- rather, they will find some adjustment to make and will report that action.

The problem is not a simple one; it is natural that some "measure" of technical performance be developed for maintenance activities, and CND rate would seem to indicate the diligence of technicians in fault verification/isolation. On the other hand, there are "genuine" "cannot duplicates" that can be indicative of systemic problems (e.g., BIT inadequacies, test equipment deficiencies, "true" intermittents), and it should be a goal of the maintenance system to highlight them so that they can be addressed, thereby ultimately improving overall readiness.

There also appear to be some CND biases in the opposite direction. One base seemed to be using CND as the "how mal" whenever there was no "remove and replace"; reseating connectors when a fault was indicated resulted in a good bench check, so "how mal" was recorded as 799. Finally, Gemas¹ reported that CND rates have varied as much as 50 percent between bases for the same LRU. The reasons for this variation may be exemplified by the preceding observations. In any case, obtaining an adequate measure of FFA will be dependent on a good, rich data base with sufficient analysis and tracking capabilities to permit estimating the fractions of CND that are false alarms. There appears to be hope for this in the MADARS.

The preceding comments apply to both the state model and flow model representations of FFA. In one case the measured data are a closest count of events; in the other the measured parameter is a rate -- maintenance actions per month, or whatever time period appears useful. Since maintenance actions are tracked by job control numbers, which in turn contain the operation date, rate data are available (and subject to the biases already discussed). In addition, many bases use long-term rates for management reporting, such as CND rate and repair rate. However, to convert these data to a measure of FFA, either a functional form of the data is needed so that the integrations specified in Table 4 can be performed or the data must be stationary over some period. The former requirement is very restrictive, and probably unachievable. The latter is tantamount to saying that the rate of maintenance actions and rate of CNDs are constant over time (for a given LRU). Although this is unlikely to be true, it can be assumed that when taken over a long enough period, the rate may be represented by some average rate over a period T. The equations in Table 4 then provide the same result as the state model:

$$\frac{\beta \int_{T} \dot{CND} dt}{\int_{T} \dot{MA} dt} = \frac{\beta \times \dot{CND} \times t}{\dot{MA} \times t}$$
$$= \frac{\beta \times Total \ CNDs}{Total \ MAs}$$
$$= \frac{\beta \sum_{T} \dot{CND}}{\sum_{T} MA}$$

Although the flow model formulation for FFA does not provide any clearly superior or advantageous way to measure FFA, it does emphasize the need to set the time span long enough to capture any periodicity in the data.

To summarize, fraction of false alarms appears to be indirectly measurable. The solution of FFA that can be directly measured is the number of CNDs divided by total maintenance actions, or "fraction of CND" (FCND).

¹"Aircraft Avionics System Maintenance Cannot Duplicate and Retest-OK Analytical Source Analysis." Capt. G. L. Gemas, AFIT Master's Thesis, September 1983.

If the parameter β can be determined by careful analysis of "bad actors," then FFA = β x FCND. Further investigation into the factors driving β requires access to an extensive data source and the capability to tie maintenance actions to specific LRUs (by serial number). Even if β cannot be determined, the parameter FCND is a useful one, since it does relate to testability design, and "cannot duplicate" events have impacts on operational readiness similar to those caused by false alarms. Note that at the organizational level, every false alarm should be classified as a CND: however, not every CND is a false alarm. If most CNDs are in fact due to false alarms (i.e., β is close to 1.0), then one might consider an estimate of FCND as an upper-limit estimator for FFA.

6.2.2 Fraction of Faults Detected (FFD)

The state representation for fraction of faults detected is

$$\frac{\sum MA_{s} - \beta_{s} \sum CND_{s}}{\sum MA - \beta \sum CND}$$

A flow-model representation has the analog form

$$\frac{\int (MA_{s} - \beta_{s}CND_{s})}{\int (MA - \beta_{s}CND)}$$

As discussed earlier, the flow representation can be reduced to the state representation by taking the integration over a large enough window that the rates can be approximated by constants, and this implies that we must use a similarly "large enough" window in summing events in the state representation. In both representations, the key factor for measurability is the ability to separate system-generated events from non-system (operator)-generated events. This division between "system-generated" ("normal system maintenance") and "non-system-generated" ("other than normal system maintenance") is a crucial one. As discussed earlier, the ultimate goal of this study is to provide a predictor that equipment developers can use to evaluate how well the NSM (the set of built-in-test software. check lists, and Technical Orders) that they provide with the equipment can detect and isolate failed conditions. To develop such a predictor, we must be able to determine whether or not events like failure detections and fault isolations are due to NSM. We must also be able to separate CND_{S} into CNDs and "bad actors." This ability is provided by factor $\beta_{\text{c}},$

which is analogous to β , discussed in Section 6.2.1.

In the normal AFTO 349 maintenance documentation, there is no data field that can reliably indicate whether a fault was detected by the operator or by the BIT. The "when discovered" code indicates "in-flight" or "ground," but it is difficult to argue that "in-flight" implies "pilotdetected" or even that "pilot-detected" means "other than normal systemdetected," since the pilot may have been using a check list with maintenance-related actions. The only way to resolve this situation is to correlate pilot debriefs with the 349s. In general, this is difficult to do in a large-scale automated fashion.

However, the C-5 MADARS offers one approach, and a special BIT study currently under way in the F-16 offers another.

The C-5 MADARS captures malfunction alarms in a series of aircraft avionics; after the mission is completed, the MADARS data are correlated with pilot debriefs. Clearly, any maintenance action resulting from MADARS-noted malfunctions/faults are system-generated.

The F-16 BIT reports malfunctions to the pilot with a Maintenance Fault Listing Summary (MFLS) code. During debrief, these MFLS indications are passed to the maintenance crew. If a maintenance action is initiated for which there is an MFLS and the "when discovered" code is "in-flight," we can assume that action was system-generated.

Both of these methods for determining MA_s and CND_s have some deficiencies. The C-5 MADARS examines only a limited set of C-5 avionics -principally the INS and the Central Air Data Computer -- that would be routinely found in many aircraft. Consequently, the range of data collected would be limited. However, the entire AFTO 349 reporting system at C-5 maintenance complexes is automated, making general tracking of maintenance actions potentially simpler.

The F-16 data set is richer than the C-5 in that it samples a larger set of avionics types; however, the separation of "system-" and "operator-" discovered faults depends on the reliability of the pilot debrief process; if the MFLS codes are not recorded against the resulting maintenance action, a system-generated action or detection will be erroneously counted. This problem can be overcome through appropriate training and follow-up monitoring of the operators and the maintenance personnel.

To summarize, fraction of faults detected requires measuring the CNDs that are false alarms. These are subject to the biases and measurement problems addressed in Section 6.2.1. In addition, FFD requires a way to separate <u>system</u>-discovered CND and MAs from <u>operator</u>-discovered events. There is no formal way to do this in the current standard maintenance reporting system, but both the C-5 MADARS and the F-16 appear to have potential for a specially constructed data collection effort.

6.2.3 Fraction of Faults Isolated (FFI)

From Table 4, the state and flow model representations for FFI are

$$\frac{\sum FI_{S}}{\sum MA - \beta \sum CND}$$

$$\frac{\int FI_{S}}{\int (MA - \beta CND)}$$

Sec. 1

These represent "total" fault isolations, without regard to whether the isolation was correct and minimally sufficient (the fault was isolated only to units that had failed, and not to an ambiguous group of units). To account for imperfect fault isolation, we also developed an FFI performance:

 $FFI_{p} = \frac{\sum FI_{s} - \sum RTOK_{s}}{\sum MA - \beta \sum CND}$

Note that we have reduced the fault isolations by the RTOKs generated at the next level of maintenance. If all fault isolations are correct. RTOK will be zero.

As with FFD, we must measure the CNDs that are false alarms, with all the attendant difficulties, as discussed in Section 6.2.1. In addition, we must measure fault isolations by the maintenance system.

This parameter can be obtained from the AFTO 349s under the "Action Taken" column. Certain of the AT codes imply a fault isolation, for example, "F" (repaired) or "R" (removed and replaced). Counting system fault isolations then reduces to counting maintenance actions for which the AT code is in the set of "fault-isolated" codes. However, without some indication of the method of fault isolation (normal system means or not), we cannot measure FFI_.

Measuring penalized FFI is even more difficult, because we must determine the RTOKs from the next level of maintenance for a given system. Here the data collection window becomes even more critical, since the RTOKs will be "delayed" by twice the pipeline time from one maintenance level to the next. If the data are stationary, this time shift will not matter, since the rates of RTOK will be constant. We will discuss stationarity of data in Section 6.4.2.

6.2.4 Measurability Summary

On the basis of the preceding discussions, we draw the following conclusions:

- The state model equations are more directly useful for measuring the parameters of interest. The maintenance data collection systems in place are better suited for event counting than for rate measurement.
- The most critical parameter is FFA, since its constituent terms appear in the other two measures (FFD and FFI).
- FFA cannot be directly measured with <u>current</u> data collection systems, since there is no mechanism for determining β , the fraction of CNDs that are actually false alarms.
- FFD cannot be directly measured with current data collection systems, since there is no reliable way to identify system-discovered failures.

 A data collection and analysis program could be structured to provide the necessary data for FFD and FFA measurements, at least for a limited set of avionics. FFI would also be measurable.

In summary, the first level of the decision process suggests that the three testability parameters are not practical now. A special data collection and analysis effort must be established before a predictor model can be developed.

We will continue through the decision tree in the remaining sections of this report as if we <u>could</u> measure the parameters to determine what (if any) other stumbling blocks might exist.

6.3 DESIGN PARAMETERIZATION

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This section addresses the second level of the feasibility decision process, the existence of design-related parameters that differentiate between equipments. In essence, we must answer the question "What attributes does a piece of hardware have that could influence its testability characteristics from all other hardware?" Whether or not these attributes have a quantifiable effect on FFA, FFD, or FFI is an issue that will be resolved in the third level; however, we will attempt in this section to identify parameters that can reasonably be expected to display a relationship.

Intuitively, these equipment design parameters must provide some indication of the interrelationship of the elements of the system in question (e.g., SRU interrelationship for an LRU, component interrelationship for SRUs). Given the success of testability evaluation models such as LOGMOD, STAMP, and others, it is clear that such parameters must exist.

System testing is an attempt to determine the state of the system. System testability is a measure of the ability to correctly determine the system state. Let us examine a system with only two states (failed and good) and one test. Table 5 shows the possible outcome of such testing.

TABLE 5. SIMPLIFIED SYSTEM TEST MATRIX

System State

Test Outcome	Failed	Good
Failed	Detection	False Alarm
Good	Nondection	No Fault

Isolation is an extension of this detection problem to its lowest level. Factors that may influence the detectability of failures or the improper indication of failures may include the following:

- System complexity (number of possible states) In general, the greater the number of elements in a system, the greater the number of possible states. This is further complicated by the types of elements present. For example, a system composed of N two-terminal devices is inherently far simpler than one composed of N VHSIC devices. Some of the states that may be unanticipated may be determined in testing to be false alarms. From a complexity standpoint one would expect digital systems to have a lower detection capability and a higher false-alarm rate.
- Structure The number of paths that lie between a stimulus and its response will be related to the ambiguity in determining the meaning of the output. Parallel structures should then lead to increased false alarms, while serial structures should lead to decreased false alarms. Two possible measures of system structure are parallelism (the number of parallel paths) and feedback.
- Number and sophistication of tests Systems that are pushing the state of the art would tend to have higher failure rates, and tests would be developed to uncover system failures. We would expect a larger number of tests with closer tolerances. Systems that are not pushing the state of the art would tend to have lower failure rates, and tests would be developed to verify proper system operation. We would expect a lower number of more tolerant tests. The former types of systems would then tend to develop a greater false-alarm potential. The latter would have a reduced false-alarm potential but also a reduced detection capability.

Many other factors may be included, such as the following:

- Component technology (e.g., digital, analog, special)
- Design architecture (e.g., function interdependence, interface complexity)
- Maintenance architecture (e.g., test or calibration requirements)
- System maturity

These will be examined for predictor development in Phase II.

The following parameters were developed on the basis of the preceding discussion as a vehicle for determining the feasibility of developing predictors.

6.3.1 Number of Elements

when appropriately normalized, the number of elements indicates something about design complexity. The suggested normalization factor is "functional elements." Hence, we hypothesize a design parameter for LRU testability prediction as

total number of SRUs in ith LRU total subfunctions performed by LRU

where the L subscript indicates an LRU measure.

For SRUs, this parameter would become

number of components in SRU total subfunctions performed by SRU

where the C subscript indicates a component measure.

Hence, in the LRU case, if we had a system that was a communications receiver/transmitter, the following seven system subfunctions might be performed:

-	RF pre-amplification	•	-	Modulator
-	Down-conversion		-	Power amplifier
-	Detection		-	Power supply

Detection

I/O interface

If this system had six LRUs, then the normalized design parameter would be 6 + 7, or 0.857.

For fault isolation, it appears that an ideal value of this parameter would be 1. By determining what subfunction is at fault, the faulty LRU is immediately determined. Numbers less than 1, while still allowing unambiguous LRU identification, imply that serviceable functions are replaced unnecessarily, causing higher-than-necessary cost for replacement parts. Numbers much greater than 1 tend to indicate large ambiguity groups -- for example, if there are three LRUs for each subfunction, identifying the failed subfunction shows only that there is a failure in a set of three LRUs. The maintenance process must expend more time and resources identifying which of the three LRUs is truly faulty. Alternatively, all three LRUs might be replaced, causing a high "retest OK" rate since not all three of the "failed" LRUs truly have failed.

Determining a value for this design parameter may not be a simple matter. It requires detailed understanding of the function of the system. During the design phase, this is not a difficult challenge; LRU functions may not be clearly identified in the field technical manuals.

6.3.2 <u>Number of Test Points</u>

The number of test points provides an indication of the degree of access to the subelements for test purposes. Intuitively, the more subelements (SRUs) or subfunctions an LRU has, the more test points it should have. Consequently, this parameter could be normalized by the number of SRUs (TP_p) or by the number of functions (TP_p) :

 $TP_F = \frac{number of test points}{number of subfunctions}$

OĽ

IPs = <u>number of test points</u> number of SRUs

There is a relationship between TFF and TPg:

 $TP_F = TP_S \times NE_L$, since $NE_L = \frac{number of SRUs}{total subfunctions in LRU}$

Increasing TP_F or TP_S should reflect improved testability. The more test points provided per SRU or function, the better the ability to isolate a failure. Detailed design documentation is necessary to determine this parameter accurately.

6.3.3 Feedback

Feedback in a system's design begins to touch on the "architecture" of the system. A parameter that indicates the degree of feedback present in a system indicates something about the basic "interconnectedness" of the subelements. There are a number of ways in which feedback can be evaluated; two of these are the number of feedback loops (NFL) and the average number of subelements contained (or spanned) in a feedback loop. STAMP refers to this as CFD for component feedback dominance. These parameters are illustrated in the sample system of Figure 5. Here, then. is one feedback loop, formed by CP7 and CP9, so that NFL = 1, CFD = 2.

6.3.4 Parallelism

Parallelism also touches on the "interconnectedness" issue. Systems with <u>no</u> parallelism should be easily fault-isolated (using half-interval search, for example); but techniques for highly parallel systems are less well known, because there seems to be no clearly apparent "optimal strategy" for fault isolation. It should be noted, however, that parallelism in some systems makes it easy to detect the presence of faults. The parameter degree of parallelism (DP) can be expressed as

DP = <u>number of parallel paths</u> number of SRUs

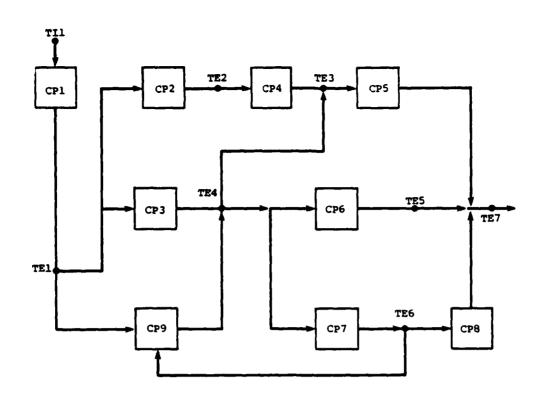


FIGURE 5. SAMPLE SYSTEM

A first-level approximation of this can be obtained by counting the maximum number of paths of a functional or SRU block diagram and dividing that number by the number of SRUs. In the sample system of Figure 5, DP = 5 + 9. A purely serial system would have

 $DP = \frac{1}{number of SRUs}$

which tends to 0 as the number of SRUs increases.¹

6.3.5 External Dependency

The parameters just discussed concentrate on "internal" descriptions of a system. Such measures seem to deny the relationship between a system's performance and its outside interfaces. It is reasonable that, for example, a system's false-alarm rate would be somehow affected by its dependency on external sources of information. A parameter that measures such dependency is external dependency (ED), the ratio of the number of

¹As a working definition for this feasibility work, the number of parallel paths is the largest number of lines on the diagram that will be "cut" by any imaginary vertical line. For the sample system this is five, with the imaginary vertical line between CP4 and CP6. It is recognized that that with a proper redrawing of the figure the number of lines could be four. This will provide some variance in the computation of DP, but this variance should be small in all but those systems containing few SRUS.

input signals to the number of elements. An LRU that gathered large quantities of data from external sources and had a single SRU would have a high degree of external dependency. Thus

ED = <u>number of LRU inputs</u> number of SRUs

6.3.6 Design Parameter Summary

Table 6 summarizes the design-related parameters discussed above; during the actual development of a predictor, other parameters may be developed as well. Section 6.4 addresses the existence of a relationship between these parameters and the measures FFA, FFI, and FFD.

TABLE 6. DESIGN PARAMETERS¹

Name	Symbol	Method of Calculation
Normalized Elements	NE	number of SRUs number of functions in LRU
Normalized Test Points	TPs	number of test points in LRU number of SRUs in LRU
Feedback Loops	FL.	feedback loops in LRU block diagram
Component Feedback Dominance	CFD	number of SRUs in feedback loops total number of SRUs
Degree of Parallelism	DP	number of parallel paths in LRU block diagram number of SRUs in LRU
External Dependency	ED	number of inputs number of SRUs

¹Hierarchial decomposition for LRU → SRU testability. To convert to component testability, replace "SRU" with "component" and "LRU" with "SRU." To convert to system testability, replace "LRU" with "system" and "SRU" with "LRU."

6.4 RELATIONSHIPS

We noted in Section 6.2 that the current maintenance data collection system is not adequate for measurement of the three parameters of interest -- FFI, FFD, and FFA -- largely because there is no current mechanism for identifying those fault detection or isolations due to "defined means." such as pilot check lists, troubleshooting check lists, or builtin test equipment. Without such an indicator, we cannot identify the terms MA_s, CND_s, or FI_s in the equations for FFI or FFD. However, if ß is assumed to be close to 1, we can measure FCND, an estimator of FFA, as discussed in Section 6.2. There is some rationale for doing this, since any CND, whether a false alarm or not, has a detrimental effect on operational readiness. Design effort to reduce CNDs would be ultimately beneficial. In addition, FCND represents an upper limit on FFA.

We will show in this section that there appears to be some relationship between this FCND and at least one design parameter, parallelism.

6.4.1 The Data Set

Chapter Four addressed potential data sources. In anticipation of studying the potential relationships of the three parameters to design data, we obtained a six-month history of a tactical fighter wing maintenance activities (AFTO 349 summaries) on a limited set of avionics. We were able to obtain technical manuals for three of these LRUs. We further obtained pilot debrief reports and AFTO 349 summaries for a set of 31 LRUs, covering three months at four bases from a special test being conducted on a second tactical aircraft. This set was culled to nine LRUs by requiring that at least 30 records (maintenance actions) be present for each LRU in the final set. We then obtained some abbreviated technical data in the form of block diagrams and SRU counts for each of these LRUs.

The LRUs, associated maintenance data, and available technical (design) data are shown in Table 7. We used the number of connectors as a rough estimator of the number of inputs for a given LRU. The resulting parameter is called "connector dependency."

6.4.2 FFA Relationships

The last column of Table 7 summarizes the FCND derived from the maintenance data. We conducted a series of regressions of FCND versus degree of parallelism and versus connector dependency, shown in Figures 6 through 9. Connector dependency displayed very poor correlation with FCND, but an encouraging correlation between FCND and degree of parallelism was discovered, as can be seen in Figures 10 through 13. The exponential form had the highest correlation with the data, and it is probably the most defendable functional form of those attempted (linear, logarithmic, exponential, and power). Clearly, FCND must have an asymptotic upper limit, and that limit should be lower than 1, so that a linear form should be rejected. Furthermore, FCND cannot tend to a negative number, so that the logarithmic form should also be rejected.

If we accept the hypothesis that FCND has a non-zero lower limit, we can imagine that FCND might grow as the degree of parallelism (connective complexity) increases. When this complexity begins to cause FCNDs approaching 50 percent, design emphasis is placed on reducing that growth in FCND. Hence, downward pressure is exerted on the curve, and it tends to flatten. One could argue that this emphasis is placed after the design becomes rather inflexible, and hence "band-aid" fixes must be applied.

TABLE 7. LRU MAINTENANCE AND DESIGN DATA

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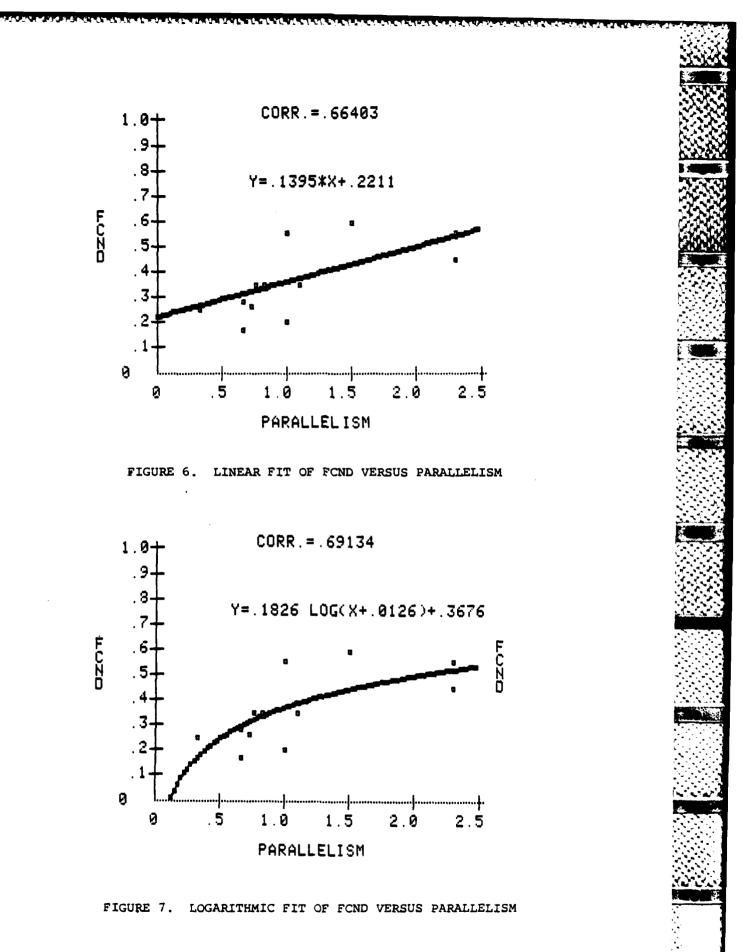
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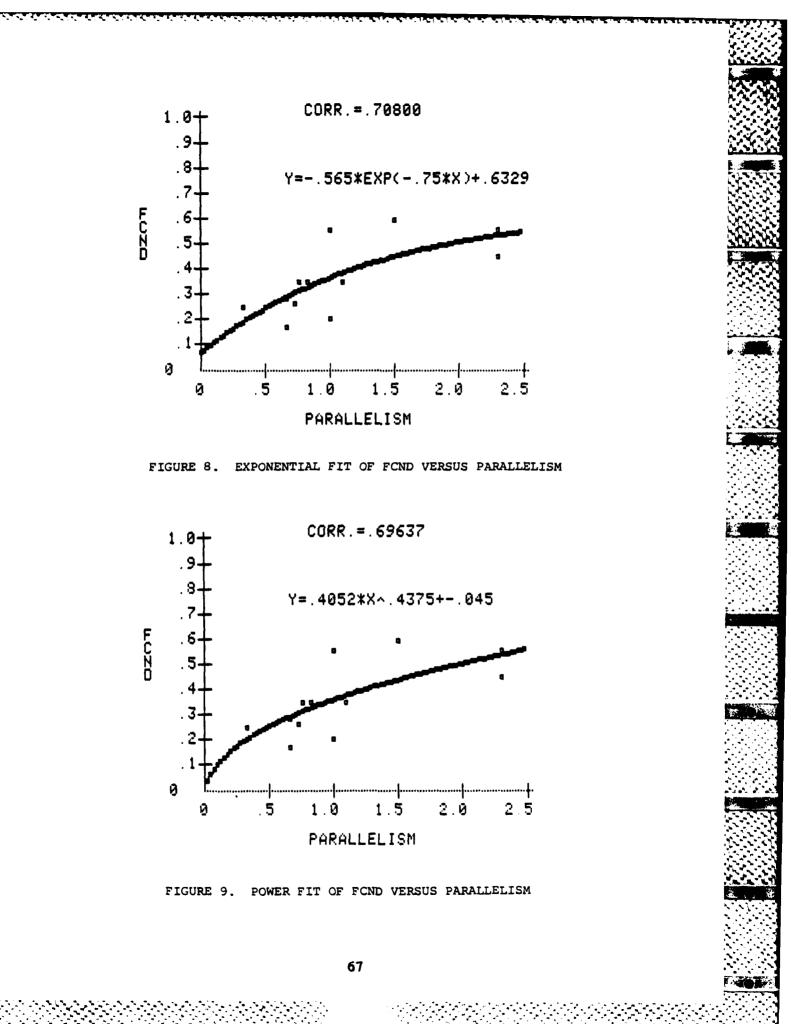
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LRU Title	Number of SRUS	Connectors	Parallel Paths	Connector Dependence	Parallelism	Total Maintenance Actions	Total CND	FCND
Airplane A LRU l	15	4	11	.27	.73	209	56	.26
Airplane A LRU 2	12	5	10	.42	.83	94	33	.35
Airplane A LRU 3	6	4	10	.44	1.1	80	28	.35
Airplane A LRU 4	L	I	16	.14	2.3	56	31	.55
Airplane A LRU 5	Q	æ	6	.5	1.5	69	53	.59
Airplane A LRU 6	12	2	12	.167	l	48	10	.20
Airplane A LRU 7	17	2	13	.11	.76	48	17	.35
Airplane A LRU 8	13	4	13	.31	l	40	22	.55
Airplane A LRU 9	13	2	30	.38	2.3	31	14	.45
Airplane B LRU 10	33	4	22	.12	.67	208	59	.28
Airplane B LRU ll	24	11	8	.46	.33	220	54	.25
Airplane B LRU 12	Q	5	4	.83	.67	328	59	11.

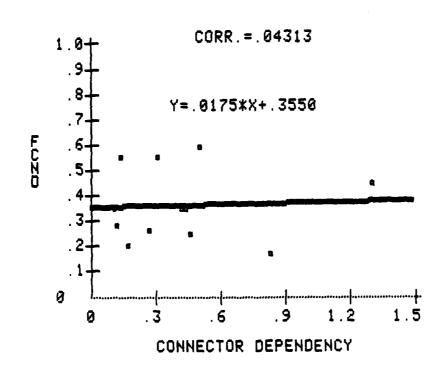
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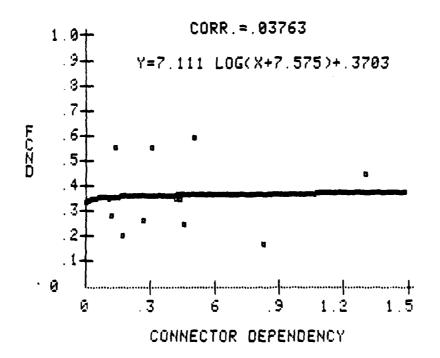
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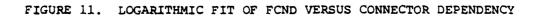


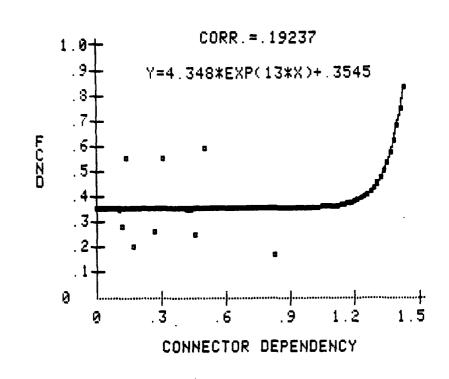
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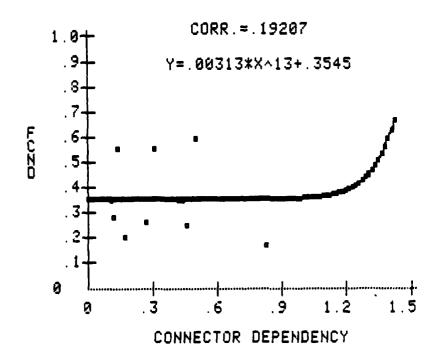














Such fixes tend not to address the false-alarm problem, so the ultimate design may still have higher FCND than would be possible with good design-for-testability.

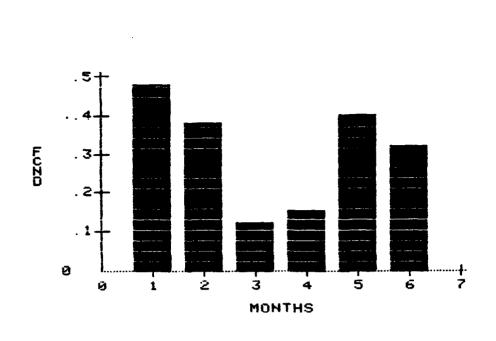
Consequently, a functional form that is asymptotic at both small and large degrees of parallelism (i.e., S-shaped) is a more defendable functional form than a pure exponential or power expression. However, because the data set on which these regressions are made is meager, it is not particularly beneficial to carry this analysis much further. Clearly there appears to be some physically justifiable functional form, and the available data display a fair degree of agreement with that form. We caution the reader that these regressions only indicate some hope of identifying a functional form for FFA when measured with a small data set, and in no way represent relationships that could be used as FFA predictors during the design process.

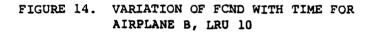
In addition to the usual statistical scatter in the dependent variable (FCND), there is the same uncertainty in the accuracy of the independent variable, because not all of the technical data employed to determine this measure were of the same level of detail. For example, some equipment Technical Orders to which we had access show "functional flow" diagrams, while others were more closely related to wiring diagrams, which might yield a different degree of parallelism.

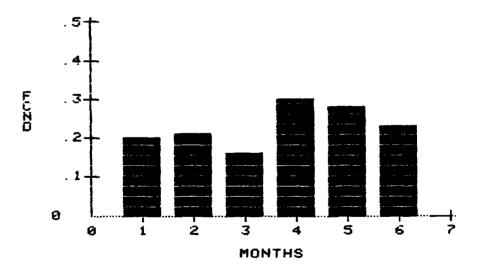
Other important factors associated with the potential relationship between FCND and design parameters are measurability and stationarity. The flow model showed that data must be taken over a long enough period so that any natural periodicity can be averaged out. Figures 14 through 16 show the time variations in FCND for three LRUs over a six-month period. The variations shown in these figures are caused by a combination of timecyclic variations in FCND and sampling variations. Both are handled by using a large number of data points. In the cyclic variation case the period covered by the data samples must be long enough to cover a complete cycle. Sampling variation can be reduced by collecting a large number of data points representing each period in the cycle. For example, if a complete cycle is seven months, the "average" FCND should be taken over an integral number of seven-month cycles. Each month of that cycle should consist of a large number of data points in order to reduce sampling variation. The quantity of data necessary to meet these criteria will be investigated in the second phase of this study.

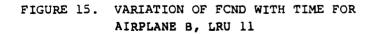
6.4.3 Summary of the Examined Relationship

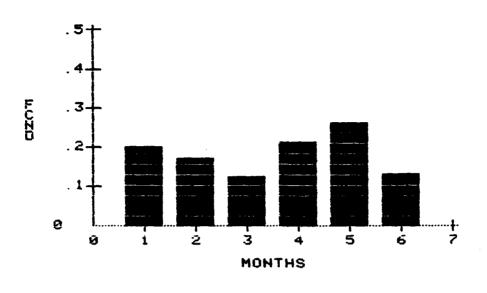
We have shown that there is some justifiable relationship between FCND (FFA with $\beta = 1.0$) and a design parameter for the limited set of avionics shown in Table 6. The standard maintenance data collection system currently employed by the Air Force is not structured to collect the information needed to obtain estimators for FFD or FFI. or to determine false-alarm rate or fraction of false alarms. Without these, it is challenging to investigate the existence of functional forms relating design parameters to field maintenance and testability.

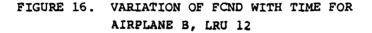












The missing connection is some method for identifying instances in which "defined means" triggered or closed a maintenance action, and for estimating the empirical coefficients β and β_{c} .

6.5 ANOMALY CHECK

It is not possible to evaluate this last element of the predictor feasibility decision process at this time, since measures of FFA, FFD, and FFI are not available to evaluate. We can observe that at least one researcher has noted large variations in CND from base to base on the same equipment, and we have noted a potential for CNDs to be polluted by management emphasis. Given the critical role of CND in the definition of FFA, FFD, and FFI, there is certainly a potential for "unexplained anomalies." It is, however, too early to draw conclusions as to the impact of anomalies on any prediction technique that may be developed.

6.6 SUMMARY OF PREDICTOR FEASIBILITY

We employed the feasibility decision model shown in Figure 4 on each of the three testability parameters under analysis -- FFA. FFD. FFI. All three parameters were found to be potentially practical but not practical

now, because they cannot be measured with the current maintenance reporting system. The resulting decision, based upon alternative approaches to measurement, translates to a feasible decision.

To identify other potential roadblocks to developing predictors for these testability parameters, we continued through the next two tiers of the decision model. We concluded that there are existing design parameters that should have a bearing on FFI, FFD, and FFA. We showed that a modified FFA (FCND), which is really a CND fraction, can be measured and that approximately 50 percent of the variance in CND rate for a small set of LRUs can be attributed to one design parameter, the ratio of the number of parallel paths in a system to the number of subelements in that system.

The results of the Phase I study are guardedly encouraging. The development of the ß parameter, through any one of a number of techniques, will allow a first-order approximation to field FFA. Alternative approaches must be sought for the development of FFI and FFD. These approaches would include exploitation operational tests, M-demo results, and the use of available testability models.

CHAPTER SEVEN

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 SUMMARY AND CONCLUSIONS

The Phase I efforts led to the following conclusions:

- Definitions of key organizational-level testability parameters (FFD, FFI, and FFA) that are consistent with existing documentation and measurable at the organization level have been developed.
- Sufficient mathematical frameworks have been derived to permit the consistent measurement of these parameters for the development of prediction based on design attributes.
- The Air Force Technical Order (AFTO) Maintenance Data Collection System does not currently report all of those items necessary to measure the aforementioned parameters.
 - The proper measurement of FFD will require a report containing the genesis of the maintenance activity, with particular emphasis on whether or not the normal system maintenance procedures were responsible for the maintenance action.
 - The proper measurement of FFI will require a report containing the basis of the resolution of a maintenance activity -- Specifically. whether or not the normal system maintenance procedures were sufficient for resolution of the maintenance activity.
 - The proper measurement of FFA will require some means of separating "cannot duplicate" events of real failures from "cannot duplicate" events of nonfailures, with emphasis on the tracking of maintenance history for some "bad actors."
- The insufficient measurability of the parameters listed above has restricted the feasibility work and limited it primarily to investigation of the FFA parameter.
- Sufficient evidence exists to support the conjecture that the building of a prediction technique is feasible given measurable field parameters.



- Algorithmic techniques for combining subsystem data into system estimators have been developed but remain unverified.
- Techniques for the development of several of the empirical coefficients (β , δ , Υ) need further development.
- There are other bases for the computation of parameters related to FFD, FFI, and FFA that are independent of field data.
- The lack of measurability of field FFD, FFI, and FFA precludes field verification of any predictor model at this time.
- There are fully automated maintenance data collection systems that could be modified to make the analysis of large data samples practical.
- All of the elements necessary to achieve prediction techniques either exist or are obtainable.

7.2 RECOMMENDATIONS

The following actions are recommended:

- Proceed with the development of a first-order prediction technique for the fraction of false alarms (FFA) at the organizational level based on empirically derived coefficients.
- Proceed with the development of prediction estimates of fraction of faults detected (FFD) based on detail design analysis, operational evaluation data, and maintenance demonstration data.
- Proceed with the development of prediction estimates of fraction of faults isolated (FFI) based on detail design analysis, operational evaluation data, maintenance demonstration data, and testability modeling.



MAINTENANCE PROCEDURE QUESTIONNAIRE

The maintenance procedure questionnaire used in this study is reproduced on the following pages.

3	MAINTENANCE PROCEDURE QUESTIONNAIRE		العربة المر الحرية عليه الحرية على
	ng of our goals will be achieved if eeding with answers. The following		
<pre>and hardware-spec ing procedures ou any nonprescribed - Cannot Duplicate system is fault-f tion of failure, - Fault Isolation. all failed replac - Complex System.</pre>	A system consisting of multiple repl	r manual troubleshoot- . It does not include mance procedures. es indicate that the ere has been an indica- is obtained to identify aceable units that are	
	such a way as to make fault isolati		
-	ike a copy of the survey results and the analysis of organizational maint		
tronic systems. App facility? (e.g., AN/YYY-XXX, R	adar System, Plight Control System, not individual replaceable assembli	e maintained by your Inertial Navigation	
A. Estimated percen	tages of:		
Contra	ctor-maintained	Other (explain)	
	ctor-maintained	Other (explain)	
		Other (explain)	
Milita		Other (explain)	
Milita		Other (explain)	
Milita B. Comments What reporting syste Maintenance Data Col		nformation to? (e.g., L Aviation Logistics	
Milita B. Comments B. Comments What reporting syste Maintenance Data Col Data Analysis System	erry personnel-maintained erns do you receive from and supply in llection System (MDC), AFM-66-1, Naval	nformation to? (e.g., L Aviation Logistics	
Milita B. Comments What reporting system Maintenance Data Col Data Analysis System apply.	ems do you receive from and supply in llection System (MDC), AFM-66-1, Naval a (NALOA), Maintenance Material Manag	nformation to? (e.g., L Aviation Logistics gement) Check all that	
Milita B. Comments What reporting system Maintenance Data Col Data Analysis System apply.	ems do you receive from and supply in llection System (MDC), AFM-66-1, Naval a (NALOA), Maintenance Material Manag	nformation to? (e.g., L Aviation Logistics gement) Check all that	
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Milita B. Comments What reporting system Maintenance Data Col Data Analysis System apply. Data System	ems do you receive from and supply in llection System (MDC), AFM-66-1, Naval a (NALOA), Maintenance Material Manag	nformation to? (e.g., L Aviation Logistics gement) Check all that	
Milita B. Comments What reporting system Maintenance Data Col Data Analysis System apply. Data System	ems do you receive from and supply in llection System (MDC), AFM-66-1, Naval a (NALOA), Maintenance Material Manag	nformation to? (e.g., L Aviation Logistics gement) Check all that	

12.5

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	Do	you maintain local maintenance action files for complex electronic systems?	
		YesNo	
	۸.	If yes, how long a calendar period is represented by your files?	11. 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
	в.	If yes, are you willing to have these files examined for research purposes?	
	c.	Do your records contain information on:	
		Repair times? Fault isolation times?	
	D.	Do you keep maintenance history files on particularly bad problems (subse- quent repairs from repeated gripes)?	
		Yes No	ц. ,
	E.	Are multiple failure replacements handled by one report or by multiple reports?	
		One Multiple	F
	F.	How?	5. 19
			ことも
Q4 .		you differentiate in reporting between maintenance action triggered by oper- or complaints and maintenance action triggered by routine maintenance?	;
		Yes No	() (2)
	λ.	If yes, how do they differ in reporting?	1 1 1 1 1
	в.	Do you report which stage of routine maintenance triggered a maintenance action (e.g., pre-flight, in-flight BIT, post-flight, calendar checks)?	
		YesNo	
	с.	When routine maintenance gives a No-Fault-Found (NPF) or Cannot Duplicate (CND), do you differentiate between suspected intermittent and simply un- verified problems?	
		Yes No	
	D.	How?	X
		2	

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	E. Do you record the manner in which final replaceable units are isolated
	(e.g., BIT, ATE, semiautomatic, manual by the book, nonprescribed procedures).
	Yes No
	F. Now/Comments
Q5.	Do you record instances in which the local technician is unable to isolate a problem uncovered during normal maintenance?
	YesNo
	λ. Bow/Comments
	B. How are these instances (of Q5) handled in general (e.g., multiple replace- ments, bring in more talent, send unit under test out)?
	Comments
	The following variables are used in trial definitions. Please consider each
	fully; choose the most appropriate or the most in line with your view. You may ide an alternative definition or a critique of the listed definitions.
Q6.	Number of false alarms, based on:
	A The total number of Cannot Duplicates (CNDs) or No-Fault-Found (NFF).
	B The total number of CNDs, excluding operator-reported faults that re- sult in a CND.
	C The total number of CNDs as in B, also excluding those tagged as sus- pected intermittents by maintenance.
	Alternative Definition or Comments
	3

27.	Number of faults detected, based on:	
	A The total number of maintenance actions triggered by normal mainte- nance that do not result in a CND.	
	B The total number of failure modes triggered by normal maintenance that do not result in a CND.	
	C The number of faults detected and isolated by normal maintenance.	
	Alternative Definition or Comments	
Q8.	Number of faults isolated, based on:	
	λ The total number of faults isolated to a replaceable unit using only defined maintenance procedures.	
	B (λ) plus standard troubleshooting techniques.	
	C (λ) minus the operator triggered maintenance actions.	
	D all of (A) that are by BIT/ATE only	
	Alternative Definition or Comments:	
Q9.	Philosophy. Please provide us with insights you might have into keys to im- provement and important factors that determine the following: false alarms, fault detections, fault isolation, or others.	
Q10.	Can you recommend other sources of information?	
	A	

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APPENDIX B

MATHEMATICAL REPRESENTATIONS OF ORGANIZATIONAL MAINTENANCE

1. MATHEMATICAL MODELING APPROACH

Mathematical modeling was undertaken to provide measurement algorithms that were consistent with the derived definitions. We started with the modified state model, which is intended to relate the organizational testability parameters to a search for the system state. This represents the heart of the maintenance problem in that there is an indication of a problem and action must be taken to find out whether a real failure is present and where it is located. As this model was being developed, it became apparent that conflicts in definitions were surfacing. For example, it was not clear whether a "cannot duplicate" (CND) event and a faultisolation event were mutually exclusive. To resolve these problems, a second model, based on membership in sets, was developed. The primary tool was the Venn diagram, in which both mutual exclusivity and coincident properties are explicit. This set model led to a clear and concise set of definitions that were mathematically precise, as well as an algorithm set that could be used to verify the other models. The state model was then reworked on the basis of definitions generated by the set theory model with most of the conflicts resolved.

A third model, based on the flow of maintenance events, was developed and was pursued concurrently with the other two models. This model was to solve two of the problems being faced. The first problem was relating maintenance actions to readiness. While a preliminary connective had been established with the modified state model, it was less than satisfactory. The flow model would, by tracing events through the mission/maintenance cycle, provide a direct tie-in. The second problem was more basic: There was no direct way to relate our mathematical approach to the maintenance personnel. The first two models were too "mathematical." The flow model was readily analyzed by maintenance personnel of SAC, TAC, and MAC, and underwent major revisions based on discussions with those personnel. As a clearer picture of the organizational-level maintenance process evolved. modifications were made to both of the other models. Finally, a flow model evolved that was satisfactory to both organizational level maintenance personnel and the mathematicians. Symbols used in this section are defined in the Acronyms and Symbols section of this report.

A detailed review of each of the models is presented in this appendix, and the final form of the definitions is reviewed.

2. THE SET THEORY REPRESENTATION

In order to develop a consistent set of definitions by which to proceed, a set theory representation of failure and maintenance events as shown in Figure B-1 was developed. It is through set membership that a consistent set of definitions will emerge. Each of the set designations will be examined separately. Two basic assumptions are made:

- 1. Any fault indication that does not result in a maintenance action is a nonrelevant event. Under most definitions of system behavior these would be called false alarms that are recognized but ignored; they are totally unmeasurable and have little impact on the maintenance system and are therefore considered nonrelevant.
- 2. Failures that are not detected by any means are nonrelevant. This last point will be discussed in detail later in this appendix.

These assumptions imply that latent failures (i.e., failures that are present in the system but were not discovered because the requisite subsystem was not exercised) will not be dealt with until such time as they are discovered and trigger a maintenance action.

Section 2.1 through 2.7 are discussions of the primary sets shown in Figure B-1. Each of these sections includes a Venn diagram, algebraic terms, and related maintenance terms, followed by a brief discussion of the set.

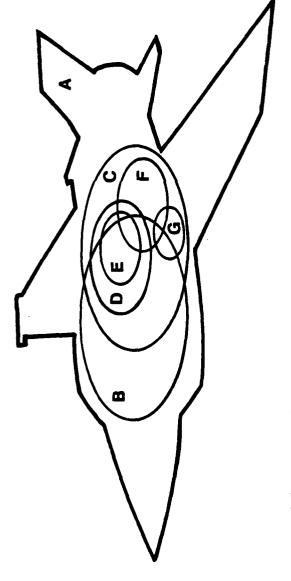
2.1 Universe of System Configurations¹



(Maintenance Term: None)

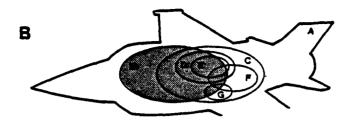
This set represents the mapping of all systems for which the organizational maintenance unit has responsibility. It includes failed and nonfailed units, those undergoing maintenance or performing a mission, and those simply available for a mission. The universe is the departure point for further calculations and will include the definition and breakdown of systems and subsystems.

¹In this appendix, a configuration represents a system state consisting of combinations of equipment states, failure indications, and maintenance events (e.g., available, in repair, undergoing checks).



- A = Universe of System Configurations
- **B** = Set of System Configurations with Failures
- C = Set of Failure Indications
- D = Set of Isolation and Repair Events
- E = Set of Isolation and Repair Events Not by Normal System Maintenance
- F = Set of Failure Indications Not by Normal System Maintenance
- **G** = **Cannot Duplicate Events**

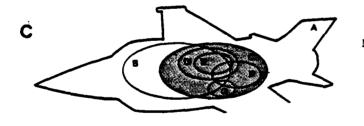
FIGURE B-1. SET THEORY REPRESENTATION OF MAINTENANCE OF COMPLEX ELECTRONIC SYSTEMS 2.2 Set of System Configuration with Failures



(Maintenance Term: F - Failures or Faults)

This set represents the subset of the universe that contains failures. Its members are not directly measurable but may be estimable by FMECA and RAM analysis. This set points out the real problem of detection. Obviously, only failures that are detected, by some means, can be measured. In fact, it can be conjectured that a failure that is not detected by some means in the long run does not matter, because it must have an imperceptible impact on the mission. An example was pointed out in our discussions with MAC personnel: a wiring problem on one of the C-5 intercom systems was present in an aircraft for many missions because the failure manifested itself only when two of the crew were on different intercom channels. It turned out to be an undetected failure for an unknown number of missions, because it did not affect those missions. Tt finally became a crew- or operator-reported maintenance discrepancy when an attempt to use the intercom in this mode was made on one mission. The only measurable event was the operator report and subsequent maintenance action.

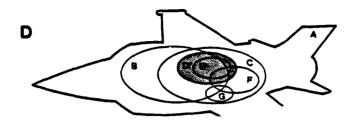
2.3 <u>Set of Failure Indications</u>



(Maintenance Term: MA - Maintenance Actions)

This set represents the subset of the universe that results in a failure indication and subsequent maintenance action. It is the universe of, and is measurable by, maintenance actions. It will include some failures and some nonfailures. This set is called the universe of maintenance actions because anything that can be measured at the organizational level is included in this space. Outside this set we can only estimate data on the basis of known or conjectured system characteristics. Inside this set we may be able to develop hard evidence, based on maintenance reporting, for some of the set attributes.

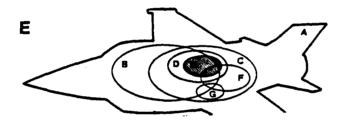
2.4 Set of Isolation and Repair Events



(Maintenance Term: FI - Fault Isolation)

This set represents the collection of maintenance actions that result in isolation and repair. Members of the set are inherently measurable, although care must be taken to remove biases in the maintenance reporting system. It has been observed that the use of CND rate for a "grading" criterion in the shops can lead to reporting a CND as a recalibration to avoid the high CND rate. This practice could misrepresent a CND as an isolation and repair event. This set is a subset of C.

2.5 Set of Isolation and Repair Events Not by Normal System Maintenance



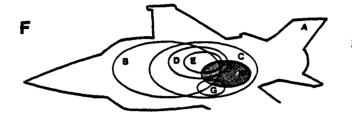
(Maintenance Term: FI - Nonsystem Fault Isolation)

This set represents isolation and repair events that are accomplished outside the provided maintenance structure for the specific equipment. The provided structure in these cases fails to give the information necessary for isolation and repair; and the experience, training, and intuition of maintenance personnel are called upon to make the final determination. The more fully automated the system is today, the less likely a distinction will be measurable between sets D and E. The older, manually driven reporting systems such as SAC B-52 maintenance will

Normal system maintenance - Techniques that are specified as standard operating procedures for use of BIT, ATE, semiautomatic, or documented manual detection and troubleshooting for a given system under test. They include regular calendar checks and normal "go" checks. This is sometimes called "defined means" (RADC Testability Notebook).

include comments that might provide the information necessary to define this set. Such older system reports of AFTO 349 data are not amenable to computer processing, because the comment fields require manual sorting. In general, however, the set membership is measurable and could be reported. This set is a subset of C and D.

2.6 Set of Failure Indications Not by Normal System Maintenance

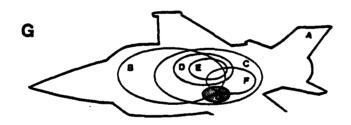


(Maintenance Term: MA - Non-NSM Maintenance Action)

This set represents the failure indications that occur outside normal system maintenance. These are typical pilot- or crew-reported malfunctions that BIT or other normal system maintenance does not also report. The failure indication may also be the result of a maintenance analysis. This set is a subset of C. Current systems measure this set only in the AFTO 349 comments, but this set membership could be reported separately.

2.7 <u>Cannot Duplicate Events</u>

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(Maintenance Term: CND - Cannot Duplicate)

This set represents the failure indication events that result in a maintenance determination of "cannot duplicate" (CND). There are many reasons for the CND, only some of which are related to false alarms. G is a subset of C and is exclusive of D and E. It is not only measurable but reported under AFTO 349 maintenance reporting schemes. Care must be taken to avoid biases such as those recounted under Section 2.4.

The set theory representation can now lead to a more precise definition of design goals. Ultimately, it is desirable for a design to yield the congruency of B, C, and D, and to force sets E, F, and G to the null set. More generally, we would like the normal system maintenance to detect and isolate all faults without false alarms, CNDs, or maintenance technician intervention.

2.8 Key Parameter Definitions

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The definitions that follow are keyed to the consistency of the set theory model but are left in generic terms for use with the other models that are to be applied to these definitions. Note that the terms "proper" and "improper" are for the purpose of partitioning and do not imply "correct" or "incorrect"; "optimal" or "suboptimal"; or any other connotation. For example, while a centralized BITE subsystem will correctly detect faults in other subsystems, these detections will still be improper by these definitions. We will first break these down for a system as a whole.

System-level definitions are as follows:

- Fault detection Normal system maintenance indicates that the system is not functioning properly, and this indication is the result of a real fault within the system.
- Fault isolation NSM identifies all failed units within the system. An attempted isolation can have any of the following results:
 - -- Proper fault isolation Only and all failed units are isolated.
- Improper fault isolation All but not only failed units are isolated.
 - -- No fault isolation -- Other combinations that occur, including only but not all failed units.
- False alarm There is indication of a failure in the system where none exists. False-alarm rate (FAR) is the sum of false alarms over a general time period divided by that time period.

Related definitions are provided in the Glossary.

The system definitions must be consistent also in a hierarchical sense as subsystems are built up into systems. The boundary between system and subsystem must be defined in advance. Subsystem-level definitions are as follows:

- Fault detection NSM indicates that a subsystem is not functioning properly, because of a real fault within the system. The detection can be proper or improper:
 - -- Proper detection Fault is within the subsystem in which detection occurs.
 - Improper detection Fault is within the subsystem other than the one in which detection occurs.
- Fault isolation NSM identifies all failed units within a subsystem. The isolation can be proper or improper:
 - -- Proper fault isolation Only and all failed units are isolated.
 - -- Improper fault isolation All but not only failed units are isolated.
 - -- No fault isolation Other combinations that occur, including only but not all failed units.
- False alarm There is indication of a failure in the subsystem where there is none in the system.

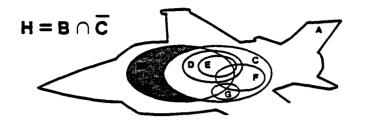
Careful application of these definitions can lead to parameter representation of the organizational-level characteristics. However, care should be taken in bookkeeping algorithms to account for multiple or misplaced indications between the system and subsystem. For example, a single failure can be reported by several subsystems. It will obviously be an improper detection in all but one (perhaps all). On the other hand, subsystem/system definitions prove to be really important because when a subsystem is viewed as a system, there are no improper detections since these become cannot duplicates. These definitions may be specialized to BITE, ATE, semiautomatic, and manual procedures, but they are not without problems. For example, mathematical cancellation can occur in a variety of ways, including false alarms and maintenance-induced failures among others. This interdependence of terms would lead to the conclusion that while these parameters are important, even necessary to analyze, they are insufficient to solve the testability problem. In building up to an algorithmic definition of these terms, it is necessary to look at several of the set interactions.

2.9 Set Interaction and Maintenance Terms

From a set theory standpoint there are a large number of interactions that can be developed. There are only a few, however, that are significant in terms of the maintenance analysis. These will be developed so that the algorithms for the measurement of FFI, FFD, and FFA can be derived.

Sections 2.10 through 2.28 are discussions of the secondary sets. Each of these sections includes a Venn diagram, algebraic terms, and related maintenance terms, followed by a brief discussion of the set.

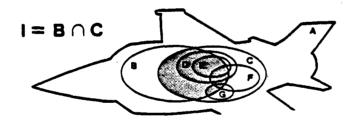
2.10 <u>Undetected Failures</u>



(Maintenance Term: U - Undetected Failures)

The undetected failure (H) is represented by the intersection (\cap) of the failure set (B) and the no-failure-indication set (not C, or complement of C). These are truly unmeasurable. However, meeting mission objectives dictates that all relevant failures will be detected by some means, and detection should reduce to a question of what means. Some noted exceptions to this may be the MAC communications problem discussed earlier, or the failure of a backup system when the primary system is fully functional. By restricting the analysis to relevant failures, we are assuming that H goes to the null set (H \rightarrow null set) and B becomes a subset of C (every member of B is also a member of C). Set H will include latent defects and failures until such time as they are discovered and trigger a maintenance action.

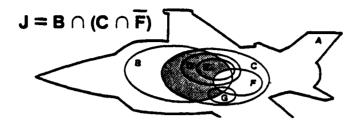
2.11 Valid Detections



(Maintenance Term: FD - Fault Detected)

Valid detections are the events that reside in the failure set and in the detection set. Under the relevant failures assumption, B is a subset of C and, therefore, $B \cap C = B$.

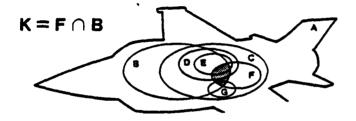
2.12 Valid Detections by Normal System Maintenance



(Maintenance Term: FD - Fault Detected by NSM)

Under the relevant failure assumption. it becomes important to delineate which of the failures were detected by NSM. This set is a subset of C. If $H \rightarrow \Phi$ (B \cap C = B), then B \cap (C $\cap \overline{F}$) = (B \cap C) $\cap \overline{F}$ = B $\cap \overline{F}$, which can be used to simplify the mathematics somewhat.

2.13 Valid Detections by Operators Outside NSM



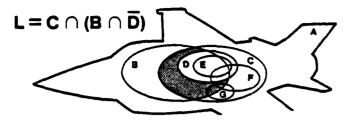
(Maintenance Term: FD_ - Fault Detected not NSM)

In dealing with relevant failures, this set is the B complement of J. The B complement of J means that $K \cup J = B$.

Note: $K \cup J = (F \cap B) \cup (B \cap \overline{F})$ from definition of K and J with relevant failures = $(F \cap (B \cup B)) \cap (B \cup \overline{F})$ = $F \cap B \cap (B \cup \overline{F})$ = $(F \cap \overline{F}) \cup (B \cap B) = \Phi \cup B = B$

This represents a mismatch between the system failure set and the normal system maintenance detection process.

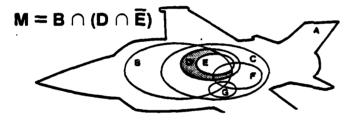
2.14 NITS/NRTS and Improper Cannot Duplicates



(Maintenance Terms: NITS, NRTS, CND - Not Isolatable This Station, Not Repairable This Station, Cannot Duplicate)

This set represents real failures that cannot be verified or isolated and repaired by the organizational-level maintenance system through either defined means or otherwise. There may also be a subset that includes warranty/guarantee items that the organizational-level maintenance is not allowed to repair. Under relevant-failure rules, this reduces to B intersecting the complement of D $(B \cap \overline{D})$.

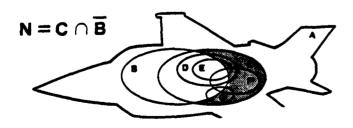
2.15 Isolation by Normal System Maintenance of Real Failures



(Maintenance Term: FI - Fault Isolation by NSM)

A design goal is to make all failures detectable and isolatable by normal system maintenance. The effectiveness of the isolation will then represent the extent to which this set is congruent with the set of all detected failures. The set then is given by the relation between this and set I.

2.16 False Alarms



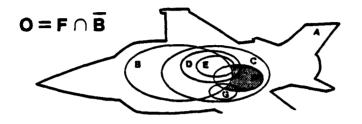
(Maintenance Term: FA - False Alarms)

B-11

This set represents a primary testability factor and represents, by definition, detection of nonfailures. The fact that the diagram shows that so many subsets impinge upon this set reflects the difficulty that might be anticipated in measuring it. The balance of the set definitions will concern false alarm in one way or another.

2.17 Operator-Induced False Alarms

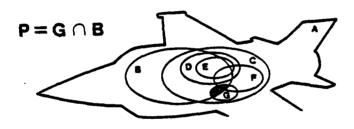
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(Maintenance Term: FA - False Alarm not NSM)

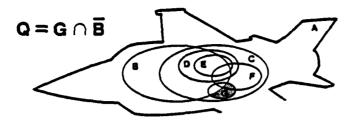
This set represents the false alarms triggered by operator-induced maintenance actions. Recognizable false alarms that do not result in a maintenance action will not affect N or O.

2.18 Cannot Duplicate Events of Real Failures



(Maintenance Term: CND₁ - Improper CND)

This set represents the mismatch between the detection equipment/ environment and the maintenance equipment/environment. In this set, a detection of a real failure cannot be duplicated on the ground, and this may lead to repeated maintenance actions for the same failure. If serial number tracking is installed, some of these may be tagged as "bad actors" and will move from CND to NRTS (set $L = C \cap B \cap D$).

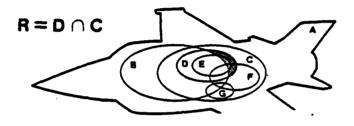


(Maintenance Term: CND_D - Proper CND)

This set is the G complement of Set P ($P \cup Q = G$) and represents only part of the CNDs and part of the false alarms.

2.20 Isolation and Repair of Nonfailures

all apparent states a second literation was a second



(Maintenance Term: FI_u - Unnecessary Fault Isolation

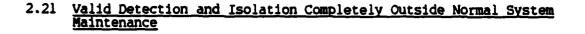
Although this set is recognized as a real problem of maintenance systems, it is often ignored (R assumed to be null set) because of the multiple windows it must pass in order to manifest itself. In a typical sequence a fault is indicated, then verified, isolated, and repaired, and the repair check-out verifies that the problem has been rectified. Finally, the next level yields an RTOK, indicating that it was a false alarm. This should be distinguished from RTOK due to improper fault isolation by either "defined means" or "shotgun" approaches. Under "shotgun"

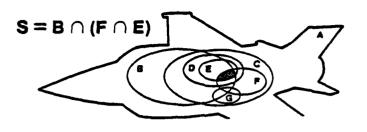
approach is seen in Redball¹ fixes. The degree to which "shotgun" approaches manifest themselves in unnecessary repairs is in inverse proportion to the training and expertise of the maintenance crew. A further

example of use of the "shotgun" approaches² is seen where the normal system maintenance procedures are overly complex or time-consuming. In any event, the problem will manifest itself as a high RTOK rate from the next level of maintenance.

Jack Osborn, <u>CAD/CAM Technology Working Group Report (IDA/OSD R&M</u> <u>Study)</u>, August 1983.

Redball refers to 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 has also been referred to as "Blue Streak" by SAC.

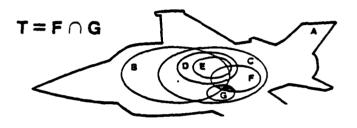




(Maintenance Terms: FD_0 , FI_0 - Fault Detection not NSM, Fault Isolation not NSM)

This set represents mismatches in the normal system maintenance that could probably be easily alleviated. This would take the form of written guidance for at least fault isolation and possibly some detection criteria.

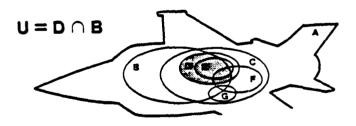
2.22 Operator-Triggered Cannot Duplicate (Note: Not the same as, nor a subset of 0)



(Maintenance Term: CND_O - CND not NSM)

This set represents the subset of operator-triggered maintenance actions that result in CND resolution by maintenance. This set is made up of false alarms and CNDs of real faults.

2.23 Isolation and Repair Events of Real Faults

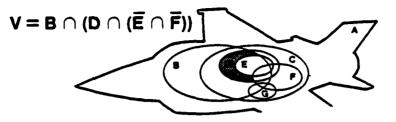


(Maintenance Term: FI - Fault Isolation)

This set is one of the primary measures of a match between the maintenance concept and the system.



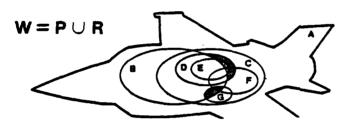
2.24 <u>Isolation and Repair Events of Real Faults Entirely by Normal System</u> <u>Maintenance</u>



(Maintenance Term: FI - Fault Isolation by NSM)

One design goal could be the congruence of D, B, and C, meaning that all faults are detected and isolated by NSM. This set measures the match between the NSM within the maintenance concept and the system. It also includes RTOKs due to ambiguous isolations.

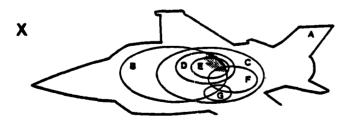
2.25 False-Alarm Confusion Area



(Maintenance Term: None)

This set represents elements that are often misrepresented in discussions of false alarms. It is the CND of real failures (which are not false alarms) and the unnecessary repairs (which are false alarms). Assignment within these two sets represent the most difficult measurement problem.

2.26 Retest-OK

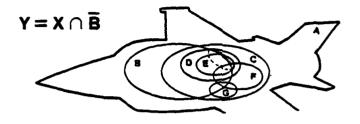


(Maintenance Term: RTOK - Retest-OK)

This set is actually a second-order set and is outside the range of the maintenance system. It is the retest-OK return systems from the next level of repair and is primarily associated with improper fault isolation; that is, fault isolation that includes replacement of subsystems with no fault present. This becomes apparent at the next level of maintenance in the form of RTOK.

2.27 RTOK of Unnecessary Repairs

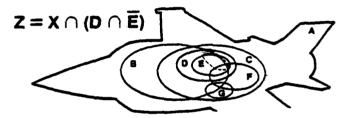
Represent



(Maintenance Term: RTOK_u - Retest-OK of Unnecessary Repairs)

This set is a subset of X and represents only those RTOKs that occur on false alarms.

2.28 System-Generated RTOK From Real Faults



(Maintenance Term: RTOK₅ - System-Generated Retest-OK from Real Faults)

This set represents the inaccuracies associated with fault isolation of real faults. 'ote that this set represents a projection from a lower level onto the organizational maintenance universe, and the population of Z could exceed the population of D.

2.29 Algorithmic Representations

The set theory model provides a vehicle by which we can algorithmically develop the desired parameters. Each measure is based upon a set relationship in Figure B-1. We must first define a population operator Ω . The population operator enumerates the membership of a set and can be given as follows:

$$\Omega(\mathbf{Z}) = \sum \delta_{\mathbf{Z}}$$

where

 $\delta_z = 1$ iff $z \in Z$ $\delta_z = 0$ otherwise

B-16

(1)

This population measure may be directly related to parameters of interest. For example:

 $\Omega(C) = \sum MA$

where C is the universe of maintenance actions. Also,

 $\Omega(D) = \sum FI$ (3) $\Omega(E) = \sum FI$ (4)

(2)

2.29.1 Fraction of Faults Detected (FFD)

From the definitions:

$$FFD = \frac{\Omega(J)}{\Omega(B)} = \frac{\Omega(B \cap (C \cap \overline{F}))}{\Omega(B)}$$
(5)

The numerator term of Equation 5 can be given by

$$\Omega(J) = \Omega(B \cap (C \cap F)) = \Omega(C) - \Omega(C \cap B) - \Omega(F \cap B)$$
(6)

$$\Omega(J) = \Omega(C) - \Omega(N) - \Omega(K)$$
(7)

For each right-hand term of Equation 7.

$$\Omega(C) = \sum MA$$
(8)

$$\Omega(K) = \Sigma FD_{O} = \Sigma MA_{O} - \Sigma FA_{O}$$
(9)

so that:

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$$\Omega(C) - \Omega(K) = \sum MA - \sum FD_{O} = \sum MA_{S} + \sum FA_{O}$$
(10)

$$\Omega(N) = \sum FA \tag{11}$$

Therefore

 $\Omega(J) = \sum MA_{s} + \sum FA_{o} - \sum FA$ (12)

$$\Omega(J) = \sum MA_{s} - \sum FA_{s}$$
(13)

and the denominator term of Equation 5 is given by

$$\Omega(B) = \Omega(C) - \Omega(C \cap \overline{B}) + \Omega(B \cap \overline{C})$$
(14)

$$\Omega(B) = \Omega(C) - \Omega(N) + \Omega(H)$$
(15)

B-17

so that

$$\Omega(B) = \sum MA - \sum FA + \sum U$$
(16)

Then

$$FFD = \frac{\Omega(J)}{\Omega(B)} = \frac{\sum MA}{\sum MA} - \sum FA}{\sum MA} - \sum FA + \sum U}$$
(17)

and finally, since undetected failures (undetected by any means) are considered not relevant and are not measurable, then

 $\sum U = 0 \tag{18}$

and

$$FFD = \frac{\sum MA_{s} - \sum FA_{s}}{\sum MA - \sum FA}$$
(17a)

2.29.2 Fraction of Faults Isolated (FFI)

From the definitions:

$$FFI = \frac{\Omega(M)}{\Omega(B)} = \frac{\Omega(B \cap (D \cap \overline{E}))}{\Omega(B)}$$
(19)

where the numerator is given by

$$P(M) = \sum FI_{s}$$
(20)

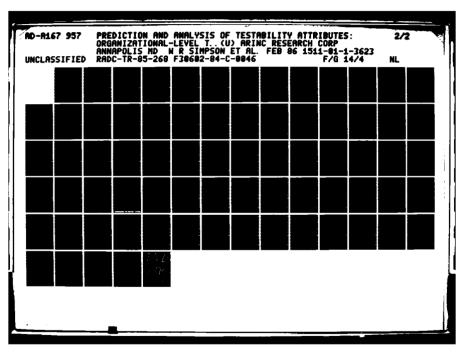
and the denominator is given by Equation 16 so that

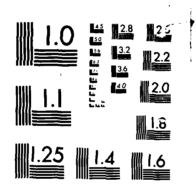
$$FFI = \frac{\sum FI_{s}}{\sum MA - \sum FA + \sum U}$$
(21)

Although the equation is computationally accurate, the FFI parameter can be misused as a design variable, because improper fault isolations are as valid as accurate ones. For example, a "defined means" that dictates wholesale replacement when a verified fault is discovered will achieve a high FFI, but a very high RTOK rate at the next level of maintenance.

It would, of course, be better to use the proper fault isolations -that is. fault isolations that isolate only and all bad elements, or fault isolations that are free from RTOK. The only difficulty is in measurement. To achieve measurability we would have to track each repair by serial number and maintenance action number to a lower level of maintenance and through to a final conclusion. A compromise can be achieved by penalizing the FI_c for RTOK_c, represented algorithmically by

B-18





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$$FFI_p = \frac{\Omega(M) - \Omega(Z)}{\Omega(B)}$$

$$FFI_{p} = \frac{\sum FI_{s} - \sum RTOK_{s}}{\sum MA - \sum FA + \sum U}$$
(21a)

The p subscript here stands for performance. This does achieve a measure that drives the "defined means" toward accurate isolation, but it may have range and domain problems, because a single isolation could develop multiple RTOKs and the overall measure could be 0 or less than 0 when fault isolations are achievable. We recommend that both FFI and RTOK together be considered as performance measures.

Either Equation 21 or Equation 21a can be modified for nonrelevance as

$$FFI = \frac{\sum FI_{s}}{\sum MA - \sum FA}$$
(21b)

and

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$$FFI_{p} = \frac{\sum FI_{s} - \sum RTOK_{s}}{\sum MA - \sum FA}$$
(21c)

2.29.3 Fraction of False Alarms (FFA)

From the definitions:

$$FFA = \frac{\Omega(N)}{\Omega(C)} = \frac{\Omega(C \cap \overline{B})}{\Omega(C)}$$
(22)

The numerator term can be expressed as

$$\Omega(\mathbf{N}) = \Omega(\mathbf{G}) - \Omega(\mathbf{G} \cap \mathbf{B}) + \Omega(\mathbf{C} \cap \mathbf{B}) - \Omega(\mathbf{G} \cap \mathbf{B})$$
(23)

$$\Omega(N) = \Omega(G) - \Omega(P) + \Omega(N) - \Omega(Q)$$
(23a)

where each member on the right side of Equation 23a is defined as

$$Q(G) = \sum CND$$
(24)

$$Q(P) = \sum CND_{T}$$
(25)

$$Q(N) - Q(Q) = other false alarms = [RTOK] = Q(Y)$$
 (26)

B-19

(19a)

and some portion of RTOK events are found primarily in set R (see discussion under R). This is given algorithmically by

$$FFA = \frac{\sum CND - \sum CND_{I} + \sum RTOK_{U}}{\sum MA}$$
(27)

If we approach the estimation of $\sum RTOK_u$ from a probability standpoint and examine the stages necessary for its occurrence, we must first detect a fault, then verify it, then isolate and repair; and, finally, we must verify repair. The estimate of the probability that any item will pass these hurdles to become RTOK_u is

Since every P < 1, if any $P \ll 1$, then $\prod P \ll 1$, we obtain

$$\sum RTOK_{\rm U} \simeq 0 \tag{28a}$$

$$FFA = \frac{\sum CND - \sum CND_{I}}{\sum MA}$$
(27a)

2.29.4 Subsystem-to-System Representation

The preceding discussion applies to system representation. The generation of system data from subsystem data in the set representation requires an accounting of the multiple-membership function. For example, let us take a system made up of n subsystems (1, 2, 3, ..., etc.):

$$\Omega(B_{\tau}) = \sum_{i=1}^{n} \Omega(B_{i}) - \sum_{i=1}^{n} \sum_{j=1}^{n} \Omega(B_{i} \cap B_{j})$$
(29)

where the second term does not exist when B, and B, are mutually exclusive.

2.30 Set Theory Algorithmic Summary

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The results of the final equation set are summarized below. The fractions of faults detected is

$$FFD = \frac{\sum MA_{s} - (\sum CND - \sum CND_{I} + \sum TOK_{u})_{s}}{\sum U + \sum MA - (\sum CND - \sum CND_{I} + \sum TOK_{u})}$$
(30)

(combined Equations 17 and 27)

or, with stated relevancy assumptions:

$$FFD = \frac{\sum MA_{s} - (\sum CND - \sum CND_{I})_{s}}{\sum MA - (\sum CND - \sum CND_{I})}$$
(30a)

The fraction of faults isolated is

$$FFI = \frac{\sum FI_{s}}{\sum U + \sum MA - (\sum CND - \sum CND_{I} + \sum RTOK_{u})}$$
(31)

and

$$FFI_{p} = \frac{\sum FI_{s} - \sum RTOK_{s}}{\sum U + \sum MA - (\sum CND - \sum CND_{I} + \sum RTOK_{u})}$$
(31a)

or, with stated relevancy assumptions:

$$FFI = \frac{\sum FI_{S}}{\sum MA - (\sum CND - \sum CND_{I})}$$
(31b)

and

$$FFI_{p} = \frac{\sum FI_{s} - \sum RTOK_{s}}{\sum MA - (\sum CND - \sum CND_{T})}$$
(31c)

The fraction of false alarms is simply given by Equations 27 and 27a. Finally, the false-alarm rate can be written as:

$$FAR = \frac{\sum FA}{T} = \frac{\sum CND - \sum CND_{I} + \sum RTOK_{U}}{T}$$
(32)

and, with relevancy assumptions:

$$FAR = \frac{\sum CND - \sum CND}{T}$$
(32a)

2.31 Measurability and the Set Theory Representation

The set theory approach will require the resolution of each maintenance event into its membership in the six sets (B through G). This is a difficult task because nonmaintenance events occur in B. These we have called nonrelevant. Even under the relevancy assumption, B becomes the most difficult set to map. In many instances this will require "back-filling" data. That is, the membership of set B will be determined at some time after the maintenance event by examining a collection of subsequent data.

For example, CND_I requires set membership in CND (set G) and real faults (set B). One could, through serial number tracking, resolve "bad actors." If through this analysis a particular system is tagged a "bad actor," then previous CNDs could be assumed to be members of set B (real faults). Other backward tracings might include RTOK_S (if considered

necessary), or the unnecessary repairs, RTOK ... In this last case, at

least a rationale has been developed for ignoring this problem. Other measurement considerations include how the maintenance action came about (with or without NSM - set C or set F) and how the isolation came about (without or with NSM - set D or set E). These latter are handled only in the comments section of the normal AFTO 349 reports.

The equation set 30a, 31b, 27a, and 32a illustrates the reliance of all of the parameters on the false-alarm measure. The separation of CND into its component parts is a necessity for continuing with any degree of confidence. Our interviews with SAC, MAC, and TAC have indicated that this measurement under the current reporting system may be the least reliable. This is attributable partly to the dual use of the data for management grading and maintenance reporting, leaving the measure open to biases.

2.32 Set Theory Approach Summary

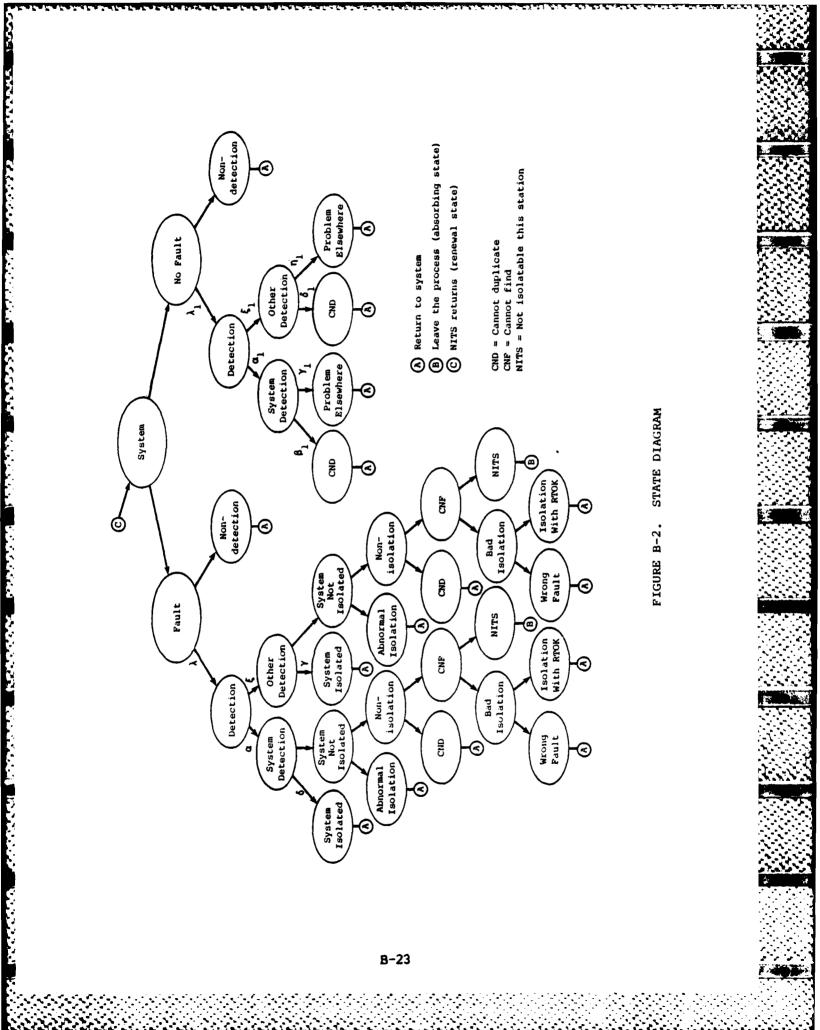
The set theory approach has delineated the requirements of a "clean" measurement system. "Clean" as used here means that we measure only and all information necessary in the system to define our parameters of interest. Of note is that the necessary measures are not included in any one measuring system at this time. Two other models will be developed that may help to resolve these differences.

3. A MODIFIED STATE REPRESENTATION

The maintenance process and its relation to the FFD. FFI. and FFA parameters is complicated because the state of the system is unknown. In fact, maintenance actions are devised to discover the state of the system. These actions are imperfect and result in misidentification, nondetection, false alarms, and other errors. It is this mismatch that we are trying to measure. A perfect match could be defined as one in which maintenance activity yielded 100 percent for FFD and FFI while yielding 0 percent for FFA. Despite the fact that maintenance is not structured as in a normal state analysis format, we will proceed with a state analysis.

3.1 State Breakdown Analysis

Figure B-2 shows the state breakdown, with each node representing a state. A logical place to start is at the system states "Fault" and "No Fault." Note that both have a detection state and a nondetection state.



As shown in the next state, we are interested in what triggered the maintenance action. This will become critical for counting detections. There is a critical point to be made about the detection phase: A nondetection of a real fault will never be noticed in the field. Awareness of the non-.detection occurs only in a perfect information state where we know that a fault is inserted. Actual faults will eventually be detected by an operator, a maintenance history, or some other means, or simply will not matter.

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After detection, a number of states are available. Where there are no real faults, we are confronted with false alarms or we trigger maintenance in some other system. The distinction is important, because at the subsystem level there is not necessarily a false alarm, i.e., subsystem A manifesting a problem that is actually in subsystem B -- a real problem exists and is detected by A. The system may contain both a false alarm and a nondetection in subsystem B. This relationship highlights the necessity of specifying system and subsystem boundaries carefully. If a system boundary has been drawn around subsystem A, then the detection just described is a false alarm since there is no fault in the system.

When faults are present and detected, the state moves from detection through either system detection or detection by other means. From here, the state may move to either system isolation or system nonisolation, and the FFI term is simply the product of the previous transition (α) and the direct transition (δ) plus the non-NSM detections (ξ) and the systemisolated transition (γ). The states that exist for system nonisolation when a fault is present are the same regardless of where detection occurs. Abnormal isolation includes all correct isolations by other than normal system maintenance and all bad isolations (including cannot duplicate [CND] and cannot find [CNF]). A bad isolation state exists when the isolation is to the wrong fault or includes isolation of items without fault. In this simplified, non-real-world, full-information model, false alarms are given by λ_1 (detection of no fault). A recap is given as follows:

$FFD = \lambda$	(33)
$FFD_{S} = \lambda \times \alpha$	(33a)
FFI _S = λ × α × δ + λ × ξ × γ	(34)
$FFA = \lambda_1$	(35)
$FFA_{S} = \lambda_{1} \times \alpha_{1}$	(36)

FFA =	$\beta \frac{\sum CND}{\sum MA}$				
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(36a)

where

 β represents a compound probability factor for a CND that is the result of a nonfailure.

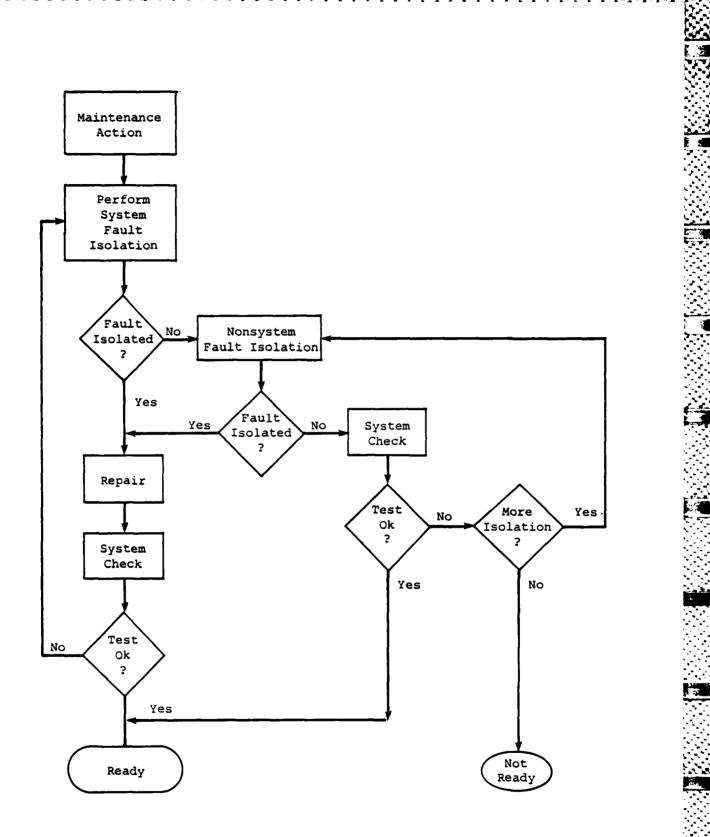
The maintenance action flow in the real situation proceeds along different paths, because the maintenance personnel are unaware of the true state. Figure B-3 shows this flow. A maintenance action is initiated when a fault is indicated or reported to the maintenance system. The same procedure is involved regardless of whether detection was initiated by normal system maintenance, an operator complaint, or some other means. Once a fault is detected in a subsystem, a normal system fault-isolation procedure is started.

If a fault is correctly isolated to the replaceable unit containing the fault, a repair action is undertaken. Following the repair, the subsystem is given a "go" check. If the system "checks OK," the subsystem is returned to the ready state. This sequence can occur from two true states: (1) the fault was correctly isolated to a set of replaceable units and repaired, or (2) there was an incorrect fault isolation and an unnecessary repair was made. This second action can occur when there is an intermittent failure and an incorrect fault isolation or when a false alarm occurs and an incorrect fault isolation leads to repair of a replaceable unit. It should be noted that a correct fault isolation may result in removals of good replaceable units because of inherent design ambiguities.

Following a repair, the system check-out may indicate a "no go" situation. This indication can be caused by several states, including (1) an incorrect fault isolation and an unnecessary repair, and (2) a multiple-failure condition. The multiple failure may be solved by multiple passes through fault isolation; at each pass, a single fault is identified and repaired. This process continues until the "go" check is successfully accomplished.

One branch of the flow chart shows the actions that occur when normal system fault isolation cannot reduce the fault to a set of replaceable units. Several nonstandard fault-isolation procedures may be invoked -for example, checking the circuits using a voltmeter, calling in contractor expertise, swapping boxes, or simply doing "shotgun repairs." If a fault is isolated, the replaceable units are sent to repair and the system is checked out as in a normal fault isolation and repair. Abnormal fault isolation may result in high RTOK rates, since good units may be unnecessarily removed.

Whenever nonstandard fault isolation is unable to locate failures. the subsystem is generally submitted to a "go" check. If the check is passed, the subsystem is returned to the ready state. This sequence can





be caused by three events: (1) intermittent failure. (2) a faise alarm. or (3) an improper input from a fault in another subsystem. In any case the subsystem is returned to the ready status. A history check may be used to identify further action.

If a "go" check has failed and no fault has been isolated, the subsystem is called NITS (not isolatable this station). A NITS may occur for subsystems that are designated for repair at a different maintenance level. The subsystem remains in a not-ready status.

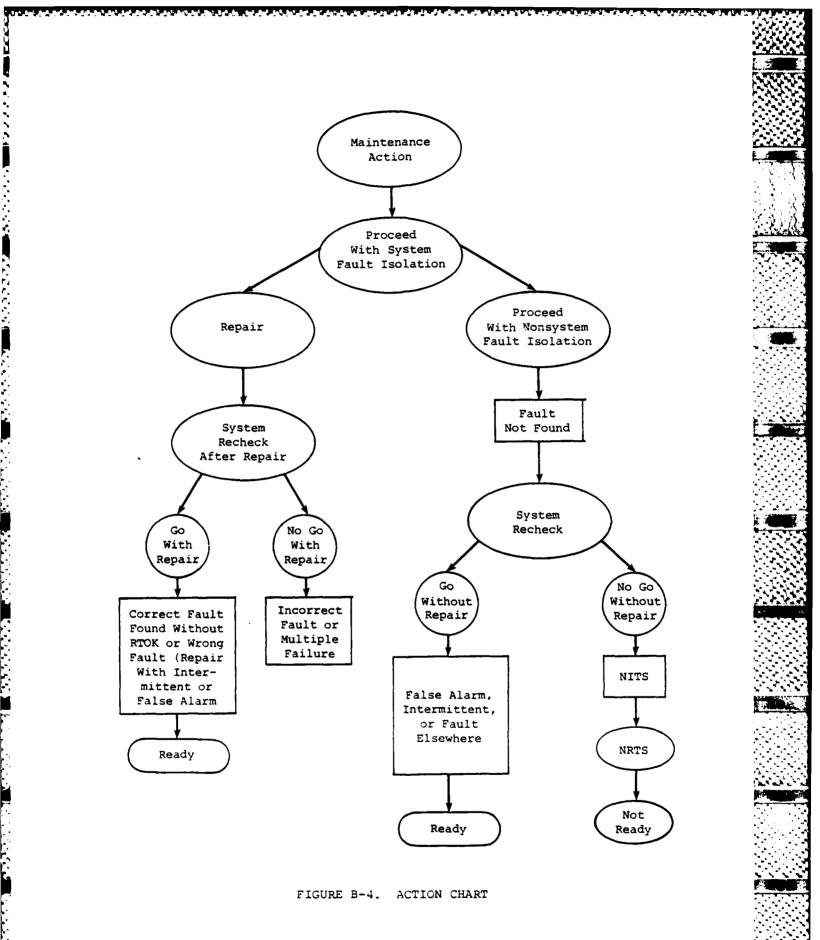
Figure B-4 summarizes the possible outcome of the maintenance action flow chart. One type of maintenance problem is caused by intermittent failure. Intermittents are generally discovered by keeping a history of the subsystem. After several CNDs, an abnormal (i.e., outside NSM) faultisolation action may be initiated to discover the cause of the problem.

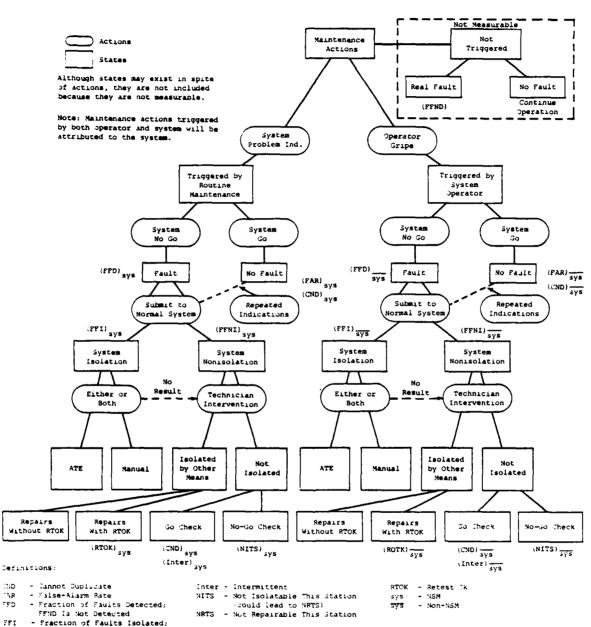
The model that results when actions and states are combined is depicted in Figure B-5. The general case is fairly complicated and helps to illustrate the reasons for the traditional difficulties encountered in attempting to measure parameters such as FFD. FFI, and FFA. The problem decomposition shown in Figure B-5 is our model for analyzing the measurable components of FFD, FFI, and FFA. Again, faults that never trigger maintenance actions will be ignored.

The main division occurs between maintenance actions triggered by normal system maintenance and those triggered by something else. Proper fault detection occurs when normal system maintenance discovers the fault. Similarly, proper fault isolation occurs when normal system maintenance isolates the fault to the minimum number of replaceable units.

Detection and repairs by means other than normal maintenance will be counted as faults not detected or faults not isolated. For example, fault isolation at the organizational level occurs when sufficient information is known to initiate repair actions even if good units must be removed in the process. Fault isolation <u>ought to</u> isolate to a minimum number of faulty replaceable units in a short time with limited use of resources. A <u>proper</u> fault isolation will be achieved when the normal maintenance procedures isolate to the minimum number of replaceable units allowed by the subsystem design. An isolation will have occurred when all faults have been removed from the system. The fault isolation illustrated will be further broken down into categories on the basis of the type of testing that performed the isolation: BIT. ATE. manual, or semiautomatic.

False alarms are counted if normal system maintenance reports a fault when there is no fault in the subsystem. The chart shows that CNDs due to intermittents are clearly confused with false alarms. In addition, if the fault was originally in another subsystem, it is easy to imagine the maintenance technicians assuming a false alarm unless results from the other faulty subsystem are cross-referenced.





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FFD

FIGURE B-5. MODIFIED STATE MODEL FOR REPAIR OF COMPLEX ELECTRONICS

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The final goal of these analyses is to determine the impact of maintenance actions on readiness. Figure B-6 shows the readiness flow model. The boxed activity represents the contribution of the maintenance activity. The main influence on readiness is the time factor. For example, if a false alarm occurs but requires no time or resources, it has no impact on readiness. The time factors are typically recorded as maintenance man-hours per flight hour, mean time to repair, mean time to faultisolate, and similar values.

3.2 Algorithmic Representations

The modified state model provides a vehicle by which we can begin to develop the desired parameters algorithmically. Each measure shown is based on Figure B-5 state and action relationships and evolves from the given definitions.

(37)

3.2.1 Fraction of Faults Detected (FFD) - System Level

Theoretical FFD is expressed as follows:

$$FFD = \left(\frac{\Sigma FD_{s}}{\Sigma F}\right)_{T}$$

where

1

s = system

FD_ = faults detected by the system

, M

F = all faults in the system

and the subscripts T and M indicate time and mode, respectively, as either all events in a time period or all failure mode types as matched with the FMECA. It should be noted that the latter may take a significantly longer time to obtain experimentally. (The T and M breakdown is implicit in all of the following equations, and these subscripts are consequently deleted.)

Operational FFD is expressed as follows:

$$\sum FD_{s} = \sum MA_{s} - \sum FA_{s}$$
(38)

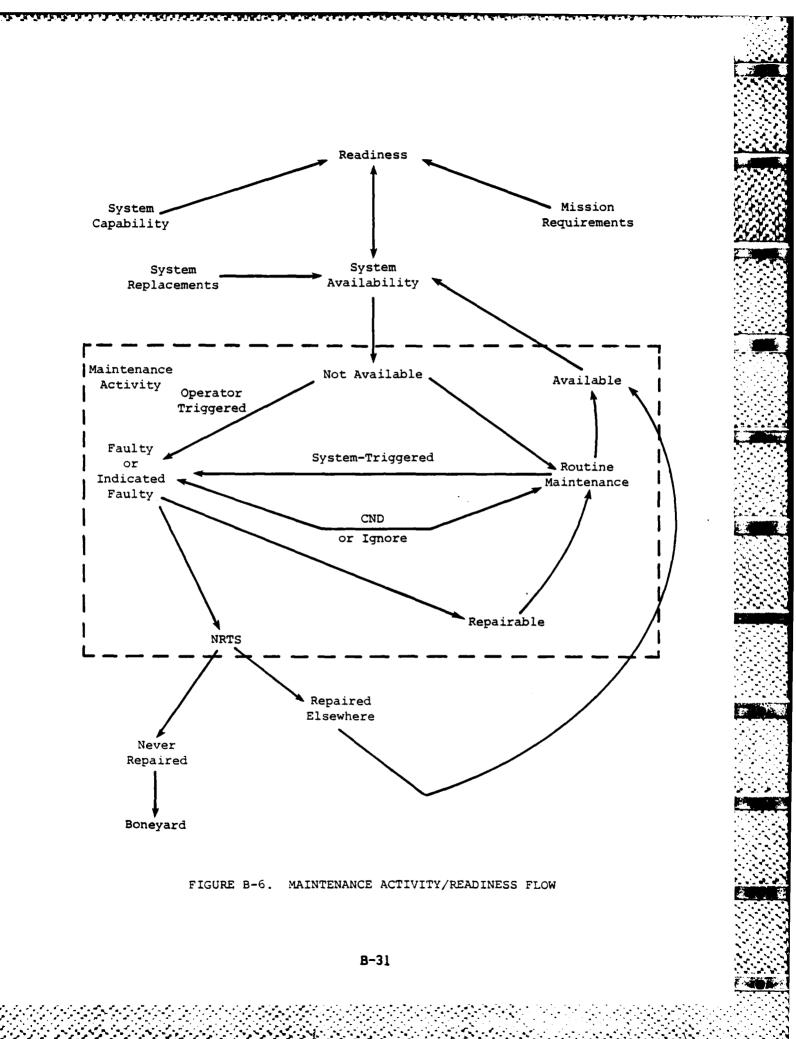
and

 $\sum \mathbf{F} = \sum \mathbf{M} \mathbf{A} - \sum \mathbf{F} \mathbf{A}$ (39)

where

MA = maintenance action

FA = is false alarm



.

Consideration of subsystems can be accommodated as follows:

$$FFD_{SSC} = \left(\frac{\Sigma FD_{SS}}{\Sigma F}\right)$$

(40)

where ssc refers to a subsystem contribution.

The hierarchy of system/subsystem is important here because of the proper and improper fault detections: It can be seen that if the subsystem is viewed as the system, then the improper detections become the cannot duplicates and the detections become the maintenance actions, so that Equation 40 reduces to the same set as Equations 37 through 39.

The system and subsystem detections can be related by the following:

$$\sum_{S} FD_{S} = \sum_{SS} (\sum FD_{SS} - \sum FD_{SS} \text{ improper})$$
(41)

so that

$$FFD = \sum_{SS} \left(\frac{FD_{SS}}{\Sigma F} - \frac{\Sigma FD_{SS}}{\Sigma F} \right)$$

$$= \sum_{SS} \left(FFD_{SSC} - \frac{\Sigma FD_{SS}}{\Sigma F} \right)$$
(42)

3.2.2 Fraction of Faults Isolated (FFI) - System Level

Theoretical FFI is expressed as follows:

$$FFI = \left(\frac{\Sigma FI_{s}}{\Sigma F}\right)$$
(43)

where FI represents faults isolated.

 $FFI = \left(\frac{\Sigma FI_{s}}{\Sigma FD_{s}}\right) \left(\frac{\Sigma FD_{s}}{\Sigma F}\right)$ (44)

$$= \left(\frac{\Sigma FI_{s}}{\Sigma FD_{s}}\right) FFD_{s}$$

 $FFI = r_{s} \times FFD_{s}$ (45)

where r_{c} is the system conversion of detections into isolations.

As discussed in the set theory model, this algorithm tends to be unusable when we are dealing with specification, so that a penalty of operational FFI (FFI) is expressed as follows:

$$\sum FI_{s} = \sum (FI_{s})_{proper}$$

$$= \sum (FI_{s}) - \sum RTOK_{s} - \sum V_{ig} \cong \sum (FI_{s}) - \sum RTOK_{s}$$
(46)

The purpose of the approximation is measurability. It overpenalizes improper isolation by a second-order RTOK factor because of a nondetection and an improper fault isolation. This cross product is given by V_{ig} , but intuitively it is small and also not measurable under current reporting systems; it is therefore assumed to be 0 in the approximation.

Consideration of subsystems can be accommodated as follows:

$$FFI_{SS} = \left(\frac{\Sigma FI_{SS}}{\Sigma F}\right)$$
(47)

but

÷

$$\sum FI_{z} = \sum FD_{z} \text{ proper } + \sum (FI_{z}, \neq ss)$$
(48)

$$\sum_{s} FI_{s} = \sum_{s} FD_{s} \text{ proper } + \varepsilon \sum_{s} FD_{s} \text{ improper }$$
(48a)

where c is the fraction of improper detections that are converted to system isolations. This can be expanded as follows:

$$\sum_{s} \sum_{s} (FD - FD \text{ improper}) + c \sum_{s} \text{ improper}$$
(48b)

$$\sum FI_{s} = \sum (FD_{s} + (1 - c) FD_{s} \text{ improper})$$
(48c)

3.2.3 Fraction of False Alarms (FFA) - System Level

Theoretical FFA is expressed as follows:

$$FFA = \left(\frac{\sum FA_{S}}{\sum FA + \sum F}\right)$$
(49)

The denominator is modified to control the range of the FFA parameter to be between 0 and 1.

Operational FFA is expressed as follows:

$$FFA = \left(\frac{\Sigma FA_s}{\Sigma MA}\right)$$
 (by substitution of Equation 39) (50)

where

$$\sum FA_s = \sum (CND_s) roper$$

= $\beta_s \sum CND_s$

and

$$\sum FA = \beta \sum CND$$
(51a)

The CNDs are the "cannot duplicate" maintenance events: β is an empirically derived coefficient that relates system-generated CND values to false alarms (see Equation 36a).

Consideration of subsystems can be accommodated as follows:

$$FFA_{SS} = \left(\frac{\Sigma FA_{SS}}{\Sigma FA_{SS} + \Sigma F_{SS}}\right)$$
(52)

$$FA_{s} = \sum_{i=1}^{n} \left(FA_{ss} \right)_{i} - \sum_{i=1}^{n} \sum_{j=1}^{n} \tau_{ij} \left(FA_{ss} \right)_{j}$$
(53)

where τ_{ij} is the cross-detection of subsystem i as a result of failures in subsystem j (note: $\tau_{ii} = 0$).

3.2.4 Algorithmic Summary

The final operational definitions are given by:

$$FFD = \left(\frac{\sum MA_{s} - \beta_{s} \sum CND_{s}}{\sum MA_{s} - \beta_{s} \sum CND_{s}}\right)$$
(54)

$$FFI = \left(\frac{\sum FI_{S}}{\sum MA - \beta \sum CND}\right)$$
(55)

$$FFI_{p} = \begin{pmatrix} \frac{\sum FI_{s} - \sum RTOK_{s}}{\sum MA - \beta \sum CND} \end{pmatrix}$$
 (combination of
Equations 46, 39, and 51) (56)

$$FFA_{s} = \left(\frac{\beta_{s}\Sigma CNDs}{\Sigma MA}\right), FFA = \left(\frac{\beta\Sigma CND}{\Sigma MA}\right)$$
 (combination of Equations 40 and 41) (57)

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(51)

Finally.

$$FAR = \frac{\sum FA}{T} = \frac{\beta}{T} \sum CND$$

where T is a time measure.

3.3 Measurability and the State Representation

Equations 54 through 58 are derived in terms of measurable quantities from maintenance reporting, with the exception of β and RTOK. RTOK can be measured elsewhere, but β is not available by any means currently and may be a complex function of many factors (including desire on the part of the maintenance crew). The approach to be taken with this model is to choose a particularly robust data set. The coefficients β and β_s can be computed by regression for the robust data set, and their relationships can be determined. While this is easy to assert, it may not be so easy to do.

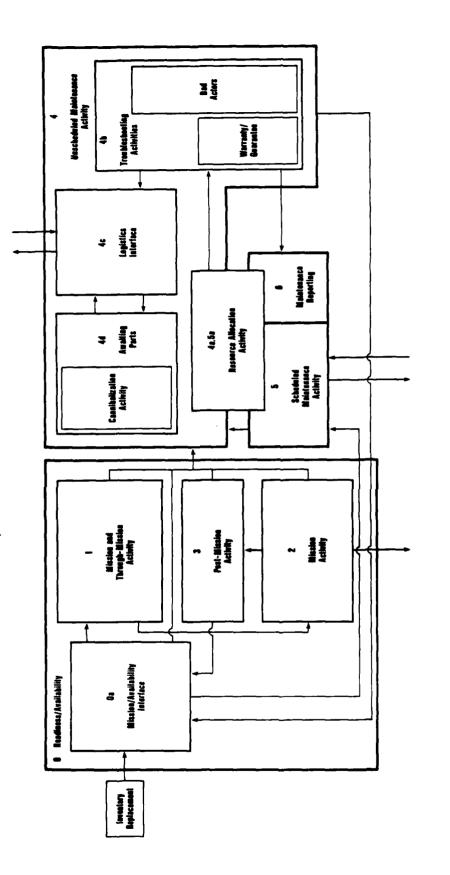
Of particular concern is the interaction and interdependence of the three terms. Although β was derived as a coefficient in the determination of false alarms (Equation 51), the interaction occurs in all three of the principal terms (Equations 54 to 58). It would make the entire model critically linked to the proper determination of β and, hence, to false alarms. It has been noted that the false alarm is the most difficult to measure.

4. A FLOW MODEL REPRESENTATION

The preceding state representation has been useful in showing the essence of the maintenance process, but still has some shortcomings in representing false alarms and time-dependent parameters. The state model has only an indirect interface to readiness. The flow model was developed to help provide insight into these processes. The flow model is an attempt, at least in a generic sense, at capturing the flow of events in a maintenance system. Further, the development of the reporting process can be modeled into this representation. Figure B-7 shows the gross-level breakdown of the flow model. It consists of six modules with appropriate submodules:

- 0. Readiness/Availability
- Oa. Mission Availability Interface
- 1. Mission and Through-Mission Activity
- 2. Mission Activity
- 3. Post-Mission Activity
- 4. Unscheduled Maintenance Activity
 - 4a. Resource Allocation Activity
 - 4b. Troubleshooting
 - 4c. Logistics Interface
 - 4d. Awaiting Parts
- 5. Scheduled Maintenance Activity
- 5a. Resource Allocation Activity

(58)





Each module is represented by a flow process and will be discussed in detail in the following subsections.

4.1 Some Mathematical Basics

The interface between Readiness/Availability and Mission/Availability is shown in Figure B-8, which contains most of the modules and types of flow mechanism shown in the model. Since this model is flow-driven, we need to define a measurement base. Also note that any flows will be controlled by the decision gates (diamonds in the figures).

Let ϕ_i represent a flow parameter for any element i.

Let ψ represent the yes output and ν represent the no output of a decision box.

then

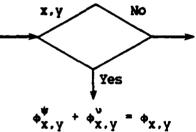
 $\phi_{3a,6}$ represents the yes output rate of decision box 3a,6.

 $\phi_{2a,4}$ represents the flow to box 2a,4 (no superscript).

The model will be written in terms of the previously defined definitions and on a per-system basis. That is, each term refers to the rates of accumulation by only one system at a time. In a hierarchical sense, the whole aircraft could be such a system; but one LRU or SRU could also be a system. depending on the introspection level required. Some relationships follow.

4.1.1 Decision Node

For a decision node (assumed nonaccumulating):



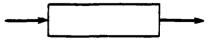
(example 0a,9 in Figure B-8)

(59)

This assumes that decision nodes do not accumulate anything but only pass through in a branching form.

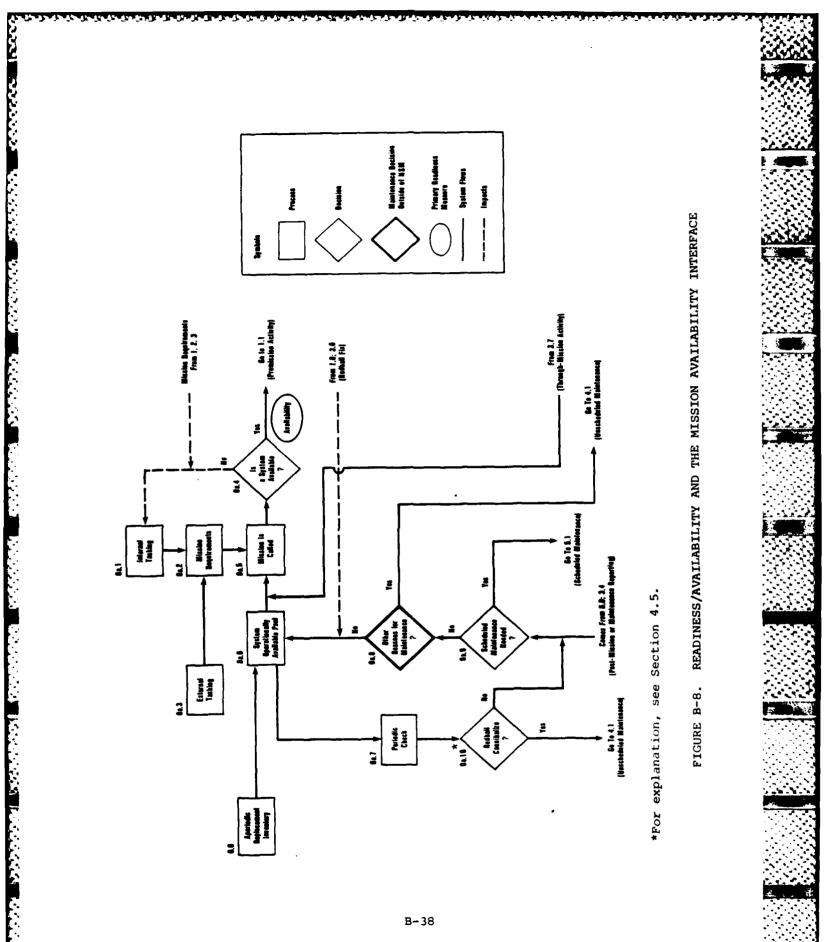
4.1.2 Other Nodes

For other nodes:



(example 0a,5 in Figure B-8)





4.1.2.1 Accumulating Nodes

For accumulating nodes:

$$\phi_{\text{out}} = \int C(\phi_{\text{in}}, \eta) dt$$
(60)

where C is the rate at which the accumulation is processed.

Where

 $n = \int (\phi_{in} - \phi_{out}) dt$ (61)

4.1.2.2 Nonaccumulating Nodes

For nonaccumlating nodes:

$$h_{\text{in}} = \Phi_{\text{out}}$$
(62)

which implies

$$n = 0$$
 (63)

and

$$C(\phi,\eta) = \phi_{in} \tag{64}$$

4.1.3 Absorbing Nodes

For absorbing nodes:

	(example 2.10 in Figure B-11)	
¢ = 0 out		(65)

This implies

 $C(\phi,\eta) = 0 \tag{66}$

and

 $\eta = \int \phi_{in} dt$

(67)

This is sometime called a sink.

4.1.4 Creating Nodes

For creating nodes:

(example 0.0 in Figure B-8)

$$\phi_{\rm in} = 0 \tag{68}$$

This implies

 $\eta = -\int \phi_{\text{out}} dt \tag{69}$

$$C(0,\eta) = \phi_{\text{out}}$$
(70)

This is sometimes called a source.

The exact function of C may have several forms, and empirical data may be needed to best describe it.

4.2 Time Representations, Stationarity, and Steady State

In the accumulation of parameters throughout the system, the time lags are significant to the transient behavior, and the instantaneous response may vary widely over time. When one considers the input rate to a series of nodes at time t. the output response occurs at time $(t + \tau)$, where τ represents the amount of time it takes the system to respond to this input. In order to make an expected value statement, one must accumulate data over a period of time sufficient to include normal cycles present in the system. For example, the number of inputs over this time could be represented as:

 $N_{i} = \int_{0}^{t} \phi_{in} dt$ (71)

and the number of outputs by

$$N_{o} = \int_{\tau}^{t+\tau} \phi_{out} dt$$
 (72)

In order to keep the integral limits the same when comparing N_i with N_o , we must assure that the length of time is long enough that the transient effect of τ is small to the problem. That is, $t + \tau \rightarrow t$, and the data periods are statistically significant. This can be

illustrated by Figure B-9, which shows the time integrals as areas. For the data shown, ϕ is assumed always positive and the integrals are related by the shading. The assumption is that the integral over 0 to t and the integral over τ to t + τ are approximately equal:

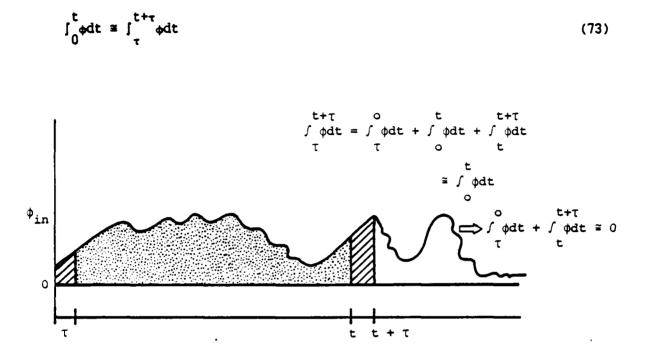


FIGURE B-9. INTEGRAL REPRESENTATIONS

There are three conditions that must be satisfied for this to be true:

- 1. ϕ must be positive. This is true for the maintenance problem, where negative flows to the nodes have no physical meanings.
- 2. The integral must be significantly greater than zero. That is, the integrand cannot be small over a large portion of the data. This prevents the small shaded regions of the integral from approaching a significant part of the total integral.
- 3. t » τ . For the maintenance problem, τ is on the order of MTTR, so that t must be many multiples of MTTR.

Finally, representativeness places one further requirement on the data. If there are natural cycles (such as seasonal changes), the data should be taken over complete cycles or a large number of cycles so that the effect of partial cycles does not significantly affect the answer. With these requirements enforced on data sets, we will drop the integration limits from notations in equation development. Further, any rate

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term not designated by φ will have a dot above it (') to represent a time derivative.

4.3 <u>Subsystem/System Relations</u>

For the flow model, the conservation of flow through the system and the total flow through a node is the governing law. For example, the flow into a node is equal to the sum of all its parts with some exceptions:

$$\phi_{in} = \sum_{ss} (\phi_{in_s} - \phi_{error})$$

(74)

where ϕ error represents a misplaced repair action. This misplaced repair action causes a counting of a single event to occur in two of the subsystem models (e.g., an improper isolation of subsystem A [fault in subsystem B] is a false alarm when we are dealing only with A as the "system").

4.4 Readiness/Availability and Mission/Availability Interface

Figure B-8 shows the module to be discussed.

This interface module starts with the system operational available pool (0,6 of the figure). This pool, at any given time, may or may not a contain systems for mission tasking. On the left is the periodic check of systems for scheduled maintenance, such as calendar checks. Note that this check is also made as systems return to the availability pool from repair or mission completion. Also in this loop is the analysis decision for maintenance, and this would include repeated gripes of CND or nonmission-critical needed repairs, or just a trend noted by the maintenance chief. This is outside normal system maintenance (NSM). The loop on the right is for mission tasking. A mission is called on the basis of mission requirements due to either internal or external tasking. For purposes of stationarity we will assume that external tasking, at least in the near term, is not affected by the organizational maintenance flow. Internal tasking may be effected by any of the mission elements or by a "no" answer to system availability.

For the readiness/availability interface, the operational availability (\mathbf{A}_{n}) can be given by



(no dimensions)

(75)

 $A_{o} = \frac{\int \Phi_{0a,4}}{\int \Phi_{0a,4}^{*} + \int \Phi_{0a,4}}$

[since 0a,4 is a decision node
(using Equation 59)] (76)

Simply stated, this gives the operational availability as the percentage of requests for missions that can be filled over a time period.

One other term from this chart that will be needed later is $\phi_{0a,8}$ which is the readiness detection of failures, which is outside NSM. This is given by

 $\dot{R}F_{DS} = \phi_{0a,8}$ (77)(rate term)

The Redball activity in Oa, 10 is discussed in the next section.

4.5 Pre-Mission and Through-Mission Activity

The detailed breakdown of the pre-mission and through-mission activity is given in Figure B-10. The pre-mission activity will include

maintenance and operator pre-mission checks and may include Redball¹ activity, which is a last-ditch attempt to get a mission off. This Redball activity may include cannibalization if necessary, and it represents a mini-form of the unscheduled maintenance activity. This is done with little or no reporting (at least directly). Parts cannibalization during the Redball activity will be charged to the cannibalized system and appear as a multiple gripe. While this activity appears to hopelessly complicate the maintenance flow, it is somewhat self-compensating in that the failures and repairs are eventually reported, albeit against another system. The Redball activity also appears in the periodic-check loop of the readiness/availability interface because the cannibalization might be from an available system, thus removing it from the available systems pool.

Two important variables noted in the pre-mission phase are the problem detection by non-NSM at 1,5:

 $\dot{P}M_{ps} = \phi_{1,5}^{\Psi}$ (rate term)

and the pre-mission reliability (R_{DM}) :

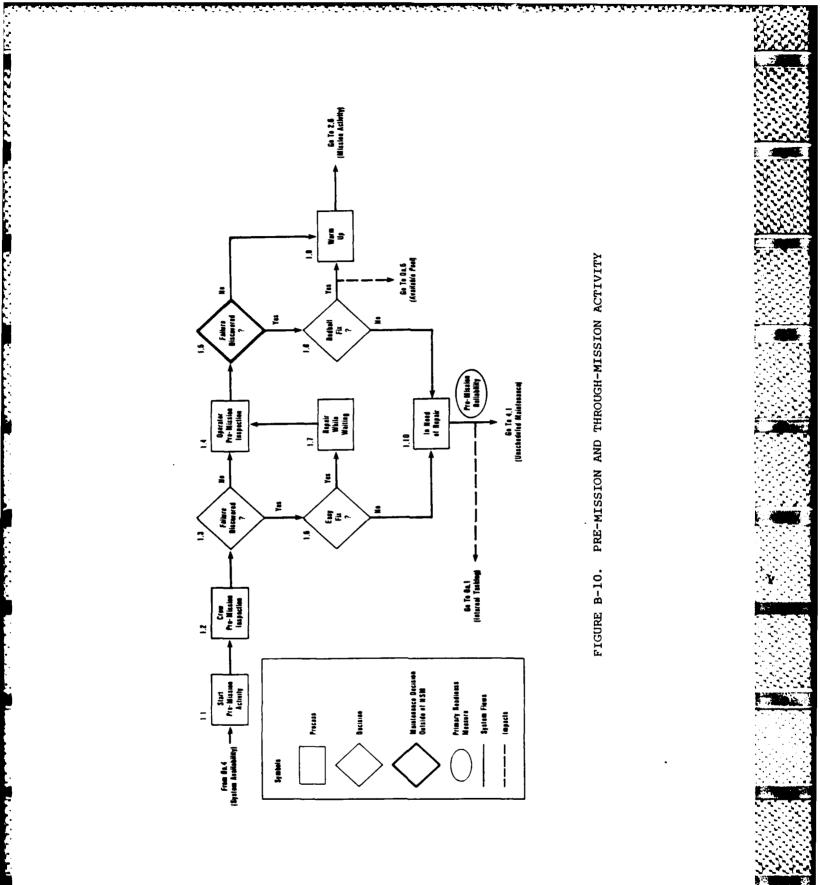
$$R_{pm} = \frac{\int \phi_{1,10}}{\int \phi_{1,1}} = \frac{\int \phi_{1,10}}{\int \phi_{0a,4}^{\psi}}$$

TAC term; MAC and SAC use Red Streak. SAC had previously used a Blue Streak designation.

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(79)

(78)



By use of Equation 75

$$R_{pm} = \frac{\int \Phi_{1,10}}{\int \Phi_{0a,4} \Phi_{0}}$$
(80)

and

$$\mathbf{A}_{0} \times \mathbf{R}_{pm} = \frac{\int \Phi_{1,10}}{\int \Phi_{0a,4}}$$
(81)

4.6 Mission Activity

The detailed breakdown of mission activity is shown in Figure B-11. The MAC loop covers segmented missions and repairs during the mission, such as MAC activities. This section is the most robust in terms of descriptors of system readiness. The overall system reliability (R) is measured as

$$R = \frac{\int \phi^{0}_{2,5}}{\int \phi_{1,1}} = \frac{\int \phi^{0}_{2,5}}{\int \phi^{\psi}_{0a,4}}$$
(82)

Survivability (S) is measured as

$$s = \frac{\int \phi^{v}_{2,4}}{\int \phi_{2,4}} = \frac{\int \phi^{v}_{2,4}}{\int \phi^{v}_{2,5}} = \frac{\int \phi_{2,3}}{\int \phi^{v}_{2,5}}$$
(83)

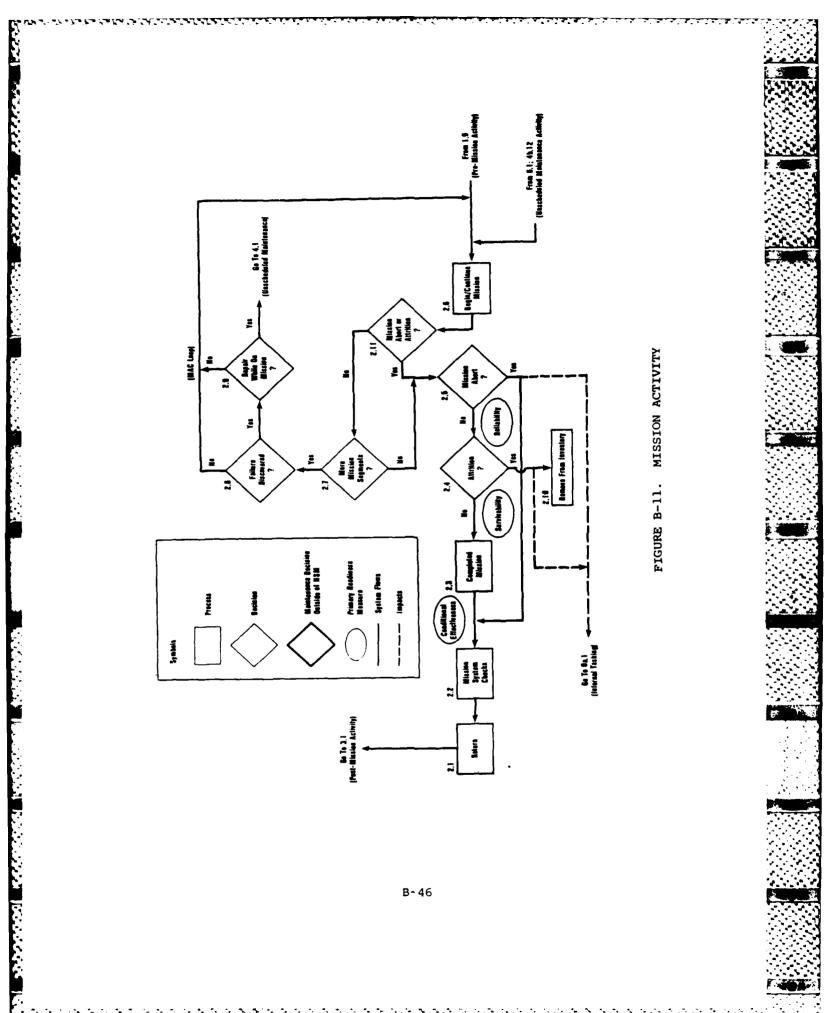
and conditional effectiveness (E) is measured as

$$\hat{E} = \frac{\int \Phi_{2,3}}{\int \Phi_{0a,4}}.$$
(84)

conditioned upon having capability.

These several parameters can be related as

$$\hat{\vec{E}} = \frac{\int \phi_{0a,4}}{\int \phi_{0a,4}} \times \frac{\int \phi_{2,5}}{\int \phi_{0a,4}} \times \frac{\int \phi_{2,3}}{\int \phi_{0a,4}}$$
(85)



$$E = A_0 \times R \times S$$

The simplified model to this point has assumed that the mission is a go/no-go decision. In dealing with subsystems, this is normally adequate. However, in dealing with full systems (such as aircraft), mission capability is usually broken down by full, partial, marginal, and notmission-capable, so that the conditional effectiveness will be

 $\hat{\mathbf{E}} = \sum_{i=1}^{n} \mathbf{A}_{oi} \times \mathbf{R}_{i} \times \mathbf{S}_{i}$ (87)

or the component products are summed over the i states involved. This is in direct agreement with the WSEIAC model¹.

4.7 Post-Mission Activity

The post-mission activity, detailed in Figure B-12, contains several parameters of interest.

The post-mission failure reporting outside NSM is given by

$$MP_{NS} = \phi_{3,3}$$
(88)

From here, we can write the total of all failure reporting rates outside normal maintenance as maintenance actions not $NSM = \dot{M}A$: NNS

$$\dot{M}A_{NNS} = \dot{\phi}_{3,3}^{\psi} + \dot{\phi}_{1,5}^{\psi} + \dot{\phi}_{0a,8}^{\psi}$$
 (90)

The mission returns to the available pool $(\dot{A}_{_{\rm MR}})$ is

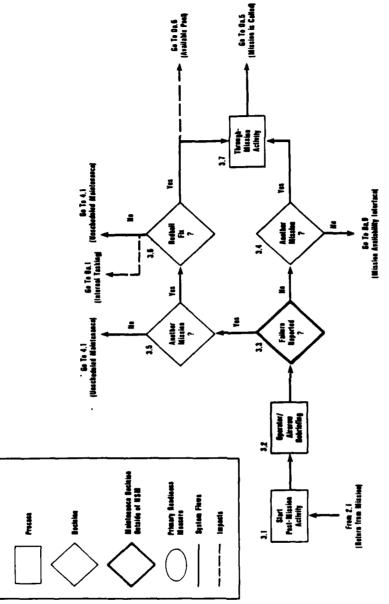
$$\dot{A}_{MR} = \dot{\phi}_{3,4}^{\nu}$$
(91)

Weapon System Effectiveness Industry Advisory Committee, <u>Chairman's</u> <u>Final Report</u>, AFSC-TR-65-6, January 1965.

· (86)

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FIGURE B-12. POST-MISSION ACTIVITY



Symbolic

and the total up mission returns (\dot{U}_{MD}) is

$$\dot{U}_{MR} = \phi_{3,4}^{\nu} + \phi_{3,4}^{\mu} = \dot{A}_{MR} + \dot{A}_{TM}$$
 (92)

where A_{TM} is the through-mission availability, which may need adjustment for Redball action.

This concludes the analysis of the readiness/availability side of the flow model.

4.8 Maintenance Activity

The scheduled and unscheduled maintenance activities, together with the resource allocations, are shown in Figure B-13.

4.8.1 <u>Unscheduled Maintenance Activity/Scheduled Maintenance Activity</u> and Resource Allocation

The resource allocation actually resides in both the scheduled and unscheduled maintenance activity, and the two will be handled together. Figure B-13 shows the flow model of these activities. Important rates to be examined occur at the start of unscheduled and scheduled maintenance activities ($\dot{M}A$ and $\dot{M}A_{\rm Sched}$). We have not subscripted the unscheduled

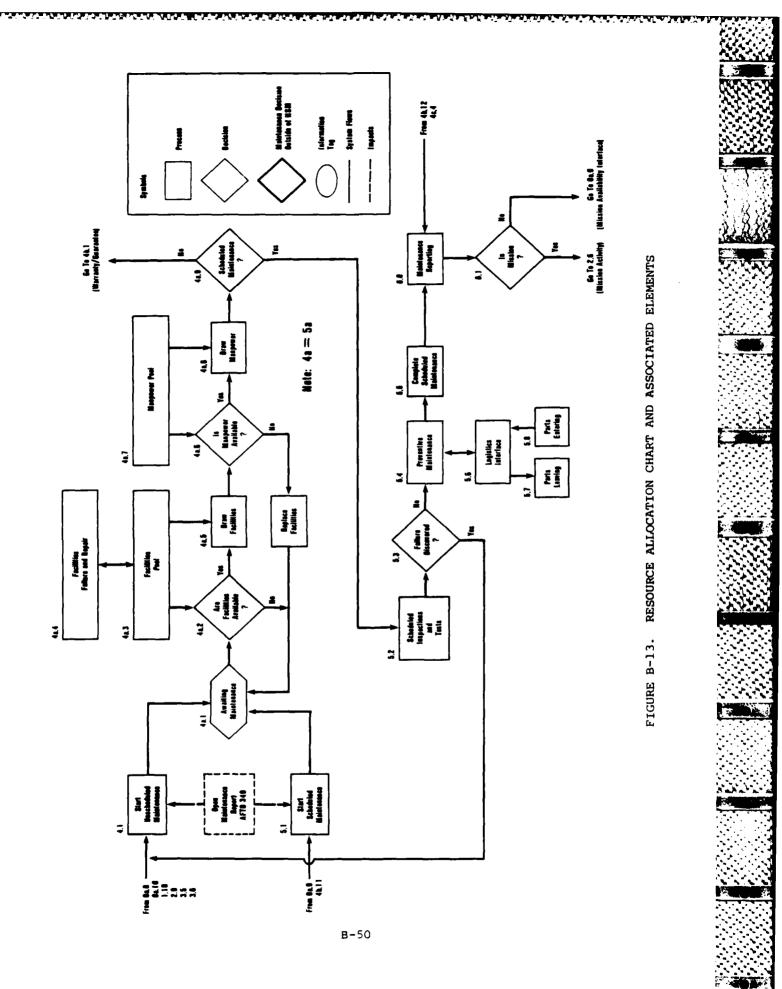
maintenance activity, because this is the variable that will be examined most closely. These terms are given by

 $\dot{M}_{sched} = \phi_{5,1}$ (93)

 $\dot{\mathbf{M}} = \boldsymbol{\phi}_{4.1} \tag{94}$

 $\dot{\mathbf{M}}_{\mathbf{total}} = \dot{\mathbf{M}}_{\mathbf{sched}} + \dot{\mathbf{M}}_{\mathbf{A}}$ (95)

Among other interesting parameters are the logistics interface parameters and resource allocation parameters, but these will not be dealt with in detail here.



The unscheduled maintenance activity has two components. Those which occur from normal system maintenance are called \dot{M}_{NSM} . Those which occur from outside normal system maintenance are called $\dot{M}_{A_{NNS}}$:

$$\dot{\mathbf{M}}_{\mathbf{A}} = \dot{\mathbf{M}}_{\mathbf{NNS}} + \dot{\mathbf{M}}_{\mathbf{NSM}}$$
 (96)

$$\dot{M}A = \dot{M}P_{NS} + \dot{P}M_{NS} + \dot{R}F_{NS} + \dot{M}A_{NSM}$$
 (from Equation 89) (97)

4.8.2 Troubleshooting Activity

The troubleshooting activity is given in Figure B-14. From the troubleshooting activity, we see that CND is given by

$$\dot{CND} = \dot{\phi}_{4b,9} + \dot{\phi}_{4b,6} + \dot{\phi}_{4b,8} + \dot{\phi}_{4b,5} + \dot{\phi}_{4b,13}$$
 (98)

Of these, a portion of the CNDs and some portion of the NRTS are taken to be real failures. The false alarm rate will then be

$$\dot{\mathbf{F}}\mathbf{A} = [\beta \dot{\mathbf{C}}\mathbf{N}\mathbf{D} + \beta, \dot{\mathbf{N}}\mathbf{R}\mathbf{T}\mathbf{S}]$$
 (99)

$$FAR = \frac{1}{T} \int FA$$
(100)

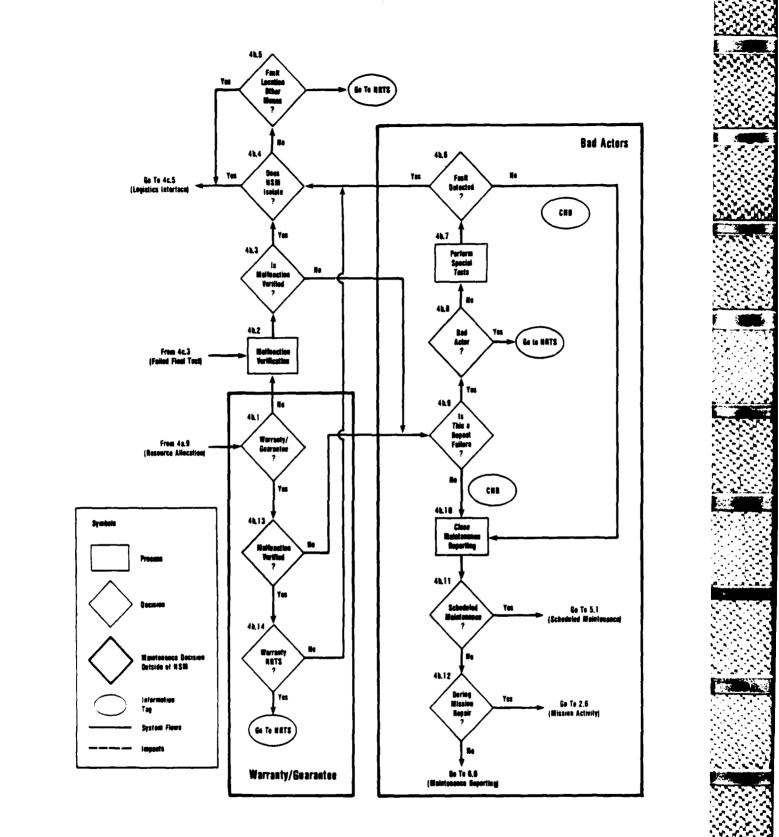
where β is the undefined (but assumed stationary) coefficient representing the portion of CNDs that are not real failures, and β_1 is the undefined

(but assumed stationary) coefficient representing the portion of NRTS that are not real failures. T is the integration period or mission-hour figure. With warranty ignored for the moment, β_1 approaches zero because "bad

actors" are nearly always real faults. Some exceptions to this might include improper test procedures or test tolerances. NRTS from nonisolatable but verified faults have a high probability of being real faults. One other component is the isolatable but not repairable NRTS shown in Figure B-15. Warranty/guarantee (W/G) on the other hand, will be a false alarm to the extent of good returns from warranty service (very hard to measure):

(101)

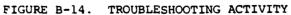
$$\dot{F}A_{W/G} = \dot{R}TOK_{W/G}$$



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so that for $\beta_1 = 0$ in all but warranty/guarantee, the false alarm is given by

$$\mathbf{F}\mathbf{A} = [\beta(\mathbf{C}\mathbf{N}\mathbf{D}) + \mathbf{R}\mathbf{T}\mathbf{O}\mathbf{K}_{\mathbf{M}/\mathbf{C}}]$$
(102)

If one assumes that the warranty/guarantee RTOK rate approaches zero (this is, after all, one purpose of a warranty) or is unmeasurable, then

 $\dot{F}A = \beta \dot{C}ND$ (103)

The fraction of false alarms will be given by

$$FFA = \frac{\int \dot{F}A}{\int \dot{M}A} = \frac{\beta \int \dot{C}ND}{\int \dot{M}A}$$
(104)

This excludes the scheduled maintenance actions.

Figure B-14 can be used to generate the other primary parameters. The fraction of faults detected will be given by

$$FFD = \frac{\int FD_{s}}{\int \dot{F}}$$
(105)

where \dot{F} is the rate at which faults occur and \dot{FD}_{S} is the rate at which faults are detected. If the rate functions are based on operating hours, then

 $\dot{F} = \frac{1}{MTBF} = \phi_{4,1} - \dot{F}A + \dot{U}$ (106)

and

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$$\dot{\mathbf{F}} = \dot{\mathbf{M}}\mathbf{A} - \dot{\mathbf{F}}\mathbf{A} + \dot{\mathbf{U}} \tag{107}$$

where U is the rate of failure occurrences that do not trigger maintenance actions ($\mathfrak{s0}$; see set theory discussion on relevance). This reduces to

 $\dot{\mathbf{F}} = \dot{\mathbf{M}} - \dot{\mathbf{F}} \mathbf{A} \tag{108}$

$$\dot{\mathbf{F}} = \dot{\mathbf{M}}\mathbf{A} - \boldsymbol{\beta} \, \dot{\mathbf{C}}\mathbf{N}\mathbf{D}$$
 (using Equation 103) (109)

The detections can be related through the rate of maintenance actions triggered by the system and the false-alarm rate as

$$\dot{F}D_s = \dot{M}A_s - \dot{F}A_s$$
 (110)

$$\dot{FD}_{S} = \dot{M}_{S} - \beta_{S} \dot{C} ND_{S}$$
(111)

٥r

$$FFD = \frac{\int (\dot{M}A_s - \beta_s \dot{C}ND_s)}{\int (\dot{M}A - \beta_s \dot{C}ND)}$$
(112)

The distinction between β_{S} CND and just β CND is that the subscript represents NSM-generated maintenance actions.

Isolation may be similarly written by

$$FFI = \frac{\int \dot{FI}_{s}}{\int (\dot{M}A - \dot{F}A)}$$
(113)

where

$$\dot{\mathbf{FI}}_{\mathbf{s}} = \boldsymbol{\phi}_{\mathbf{4c},\mathbf{5}}^{\Psi} \tag{114}$$

and

$$\dot{\mathbf{M}}\mathbf{A} - \dot{\mathbf{F}}\mathbf{A} = \dot{\mathbf{M}}\mathbf{A} - \mathbf{\beta} \, \dot{\mathbf{C}}\mathbf{N}\mathbf{D} \tag{115}$$

Thus

$$FFI = \frac{\int \dot{FI}_{s}}{\int (\dot{M}A - \beta \dot{C}ND)}$$
(116)

This equation suffers from the inherent specification problems pointed out in each of the previous models, so that

$$FFI_{p} = \frac{\int (\hat{F}I_{s}) proper}{\int (\dot{M}A - \beta \dot{C}ND)}$$
(117)

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while

$$(\dot{F}I_s)_{proper} \cong \dot{F}I_s - \dot{R}TOK_s$$
 (118)

Thus

$$FFI_{p} = \frac{\int (\dot{F}I_{s} - \dot{R}TOK_{s})}{\int (\dot{M}A - \beta \dot{C}ND)}$$
(119)

We can also note:

$$FFI_{p} = \frac{\int (\dot{F}I_{s})_{proper}}{\int \dot{F}D_{s}} \times \frac{\int \dot{F}D_{s}}{\int \dot{F}}$$
(120)

$$FFI_{D} = r_{S} \times FFD$$
(121)

$$r_{s} = \frac{\int (\dot{F}I_{s})_{proper}}{\int \dot{F}D_{s}}$$
(122)

where $r_s = conversion$ of detection rate to isolation rate.

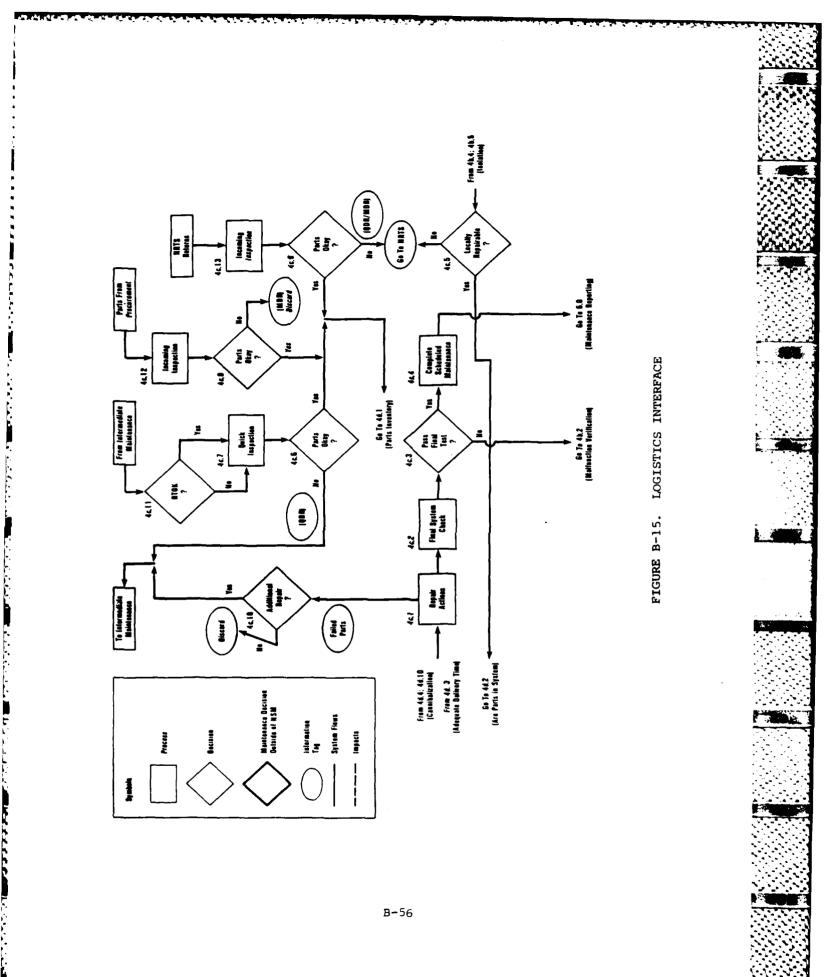
Since the bulk of the mathematical parameters of interest have been developed to this point, the remainder of the model will be discussed only in passing for completeness.

4.8.3 Logistics Interface

Figure B-15 shows the logistics interface model and includes incoming and outgoing systems and parts, as well as inspection and tests and the repair actions. Two measures of note are generated by this section. The mean time to repair can be computed by tracking repairs through the system. It should include only those which are repaired. The MTTR can be given by

$$MTTR = \frac{1}{n} \sum_{i=1}^{n} (T_{i} - t_{i})$$

(123)



where T_i is the exit time measured at node 4c,4 and t_i is the entrance time at node 4.1. In general, there does not exist a t_i for every T_i , because there are exit paths other than repair, so that i should include only completed repairs. The second term of interest is the RTOK rate, measured in the returns from intermediate maintenance:

$$\dot{R}TOK = \phi_{4,11}^{\Psi}$$
(124)

This is the basis of the term that appears in Equation 118, where

 $\dot{R}TOK_{s} = \xi \dot{R}TOK$ (125)

If the RTOK rate is assumed to be in proportion to the detection rate, then

 $\xi \cong FFD \tag{126}$

and

$$\dot{R}TOK_{\pm} \equiv FFD \times \dot{R}TOK$$
 (127)

The approximation is made to avoid a difficult measurement. The rationale is as follows:

- 1. Returns from intermediate maintenance that are tagged no fault found (NFF) are RTOKs. These are sent from organizational-level maintenance to intermediate-level maintenance as a result of the following sequence of events: a detection followed by a verification followed by an isolation.
- 2. This process leads to the conclusion that RTOK is associated with verified faults to a high level of confidence.
- 3. The FFD term is a natural partition between system fault indications and fault indications outside NSM.
- 4. The proportionality of faults to RTOK partitioning can therefore be assumed to be the same proportionality as detections to faults.

4.8.4 Awaiting Parts and Cannibalization

Figure B-16 shows the inventory, parts supply, and cannibalization representation. The primary parameters of interest here relate to the cannibalization and inventory questions. For example, the ratio of repair conversions directly from inventory to cannibalization and back order (\hat{R}) is given by

$$\hat{R} = \frac{\int \Phi_{4d,2}}{\int \Phi_{4d,5}}$$
(128)

This term must be controlled through inventory. If $\hat{R} = 0$, then spares are probably too numerous or logistics pipelines are very small. It would appear that $\hat{R} = c^+$, where c is sized in relation to mission criticality, failure rate, and other repair systems, would be a design goal. Finally, $\hat{R} \gg c^+$ indicates a spares or logistics problem.

4.9 Flow Model Algorithmic Summary

The parameters of interest (FFD, FFI, and FFA) are summarized below for the flow model.

Fraction of Faults Detected (FFD)

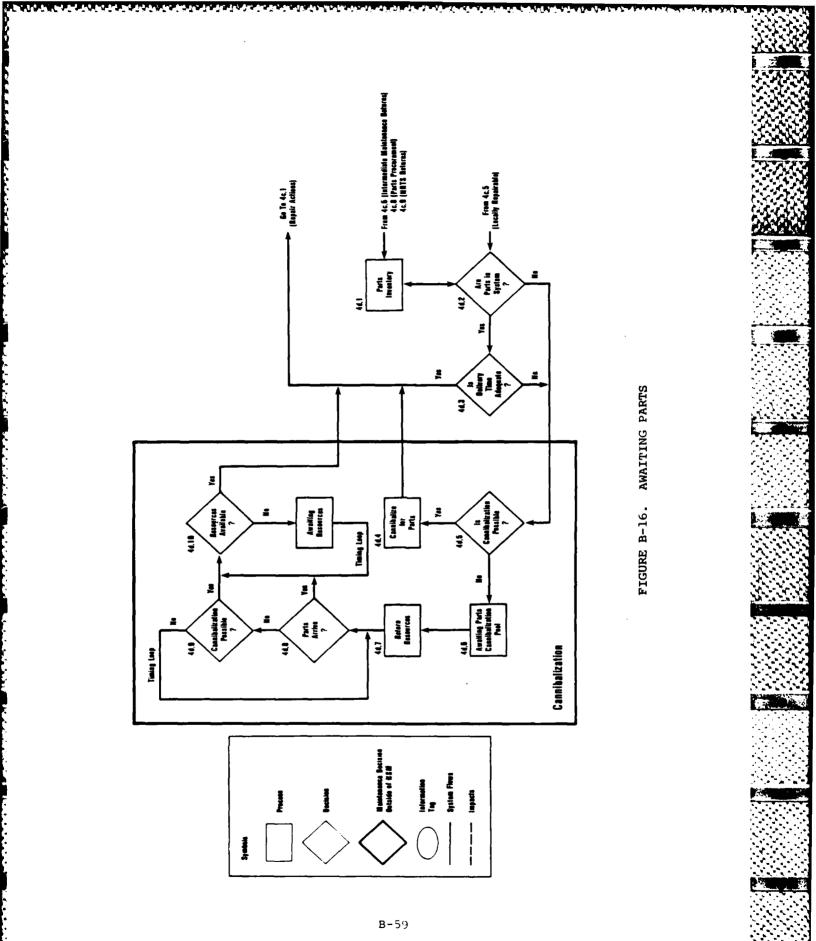
$$FFD = \frac{\int (\dot{M}A_s - \beta_s \dot{C}ND_s)}{\int (\dot{M}A - \beta_s \dot{C}\dot{N}D)}$$
(112)

Fraction of Faults Isolated (FFI)

$$FFI = \frac{\int \dot{F}I_s}{\int (\dot{M}A - \beta \dot{C}ND)}$$
(116)

and

$$FFI_{p} = \frac{\int (\dot{FI}_{s} - FFD \times \dot{R}TOK)}{\int (\dot{M}A - \beta \dot{C}ND)}$$
 (combined Equations 119 and 127) (129)



Ő.

Finally.

Product and the second

$FFA = \frac{\beta \int \dot{C} N D}{\int \dot{M} A}$	(104)
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 $FAR = \frac{\beta}{T} \int CND$ (combined Equations 100 and 103) (130)

4.10 Measurability and the Flow Representation

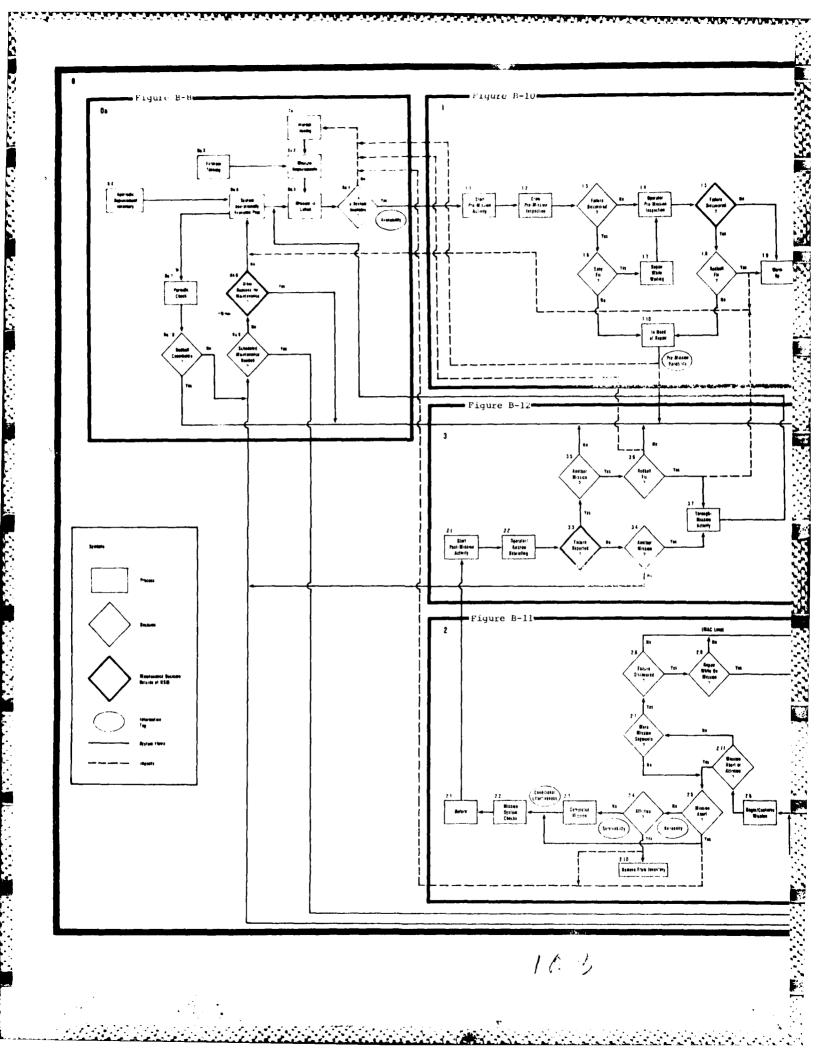
The total integrated flow representation with cross-references to the individual figures is provided in Figure B-17. The preceding equation set can be used to measure the desired parameters in terms of maintenance reporting. Individual reports will include CND, MA, and FI events from which numerical rates can be developed. Summary data collection systems often report these rate terms for certain periods of time. However, two measures are not easily developed: the coefficient β , which represents the partition between false-alarm CND and real-fault CND; and the RTOK rate, which may be lagged by a significant amount of time from the other maintenance activity. β may be discernible in a particularly robust data set. We have three basic methods of accounting for RTOK rate:

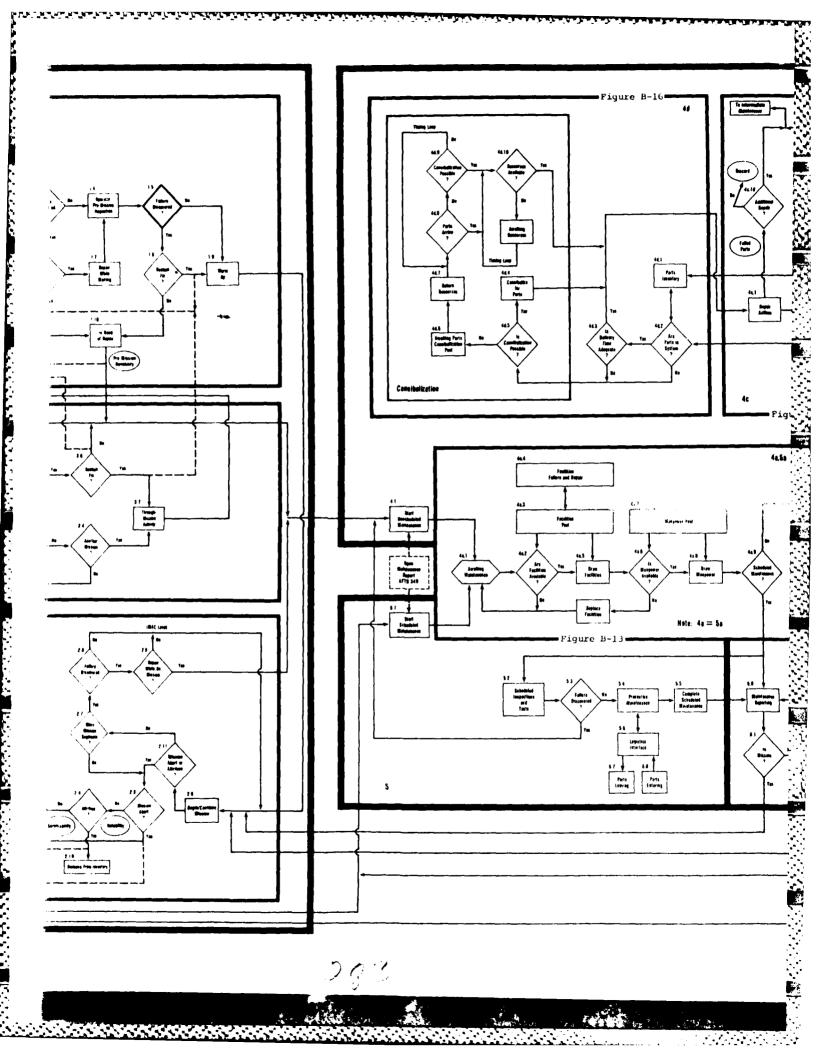
- 1. Measure over extremely long periods of time.
- 2. Assume stationarity (this assumption needs checking).
- 3. Compute the time shift and utilize different integration limits on the RTOK data.

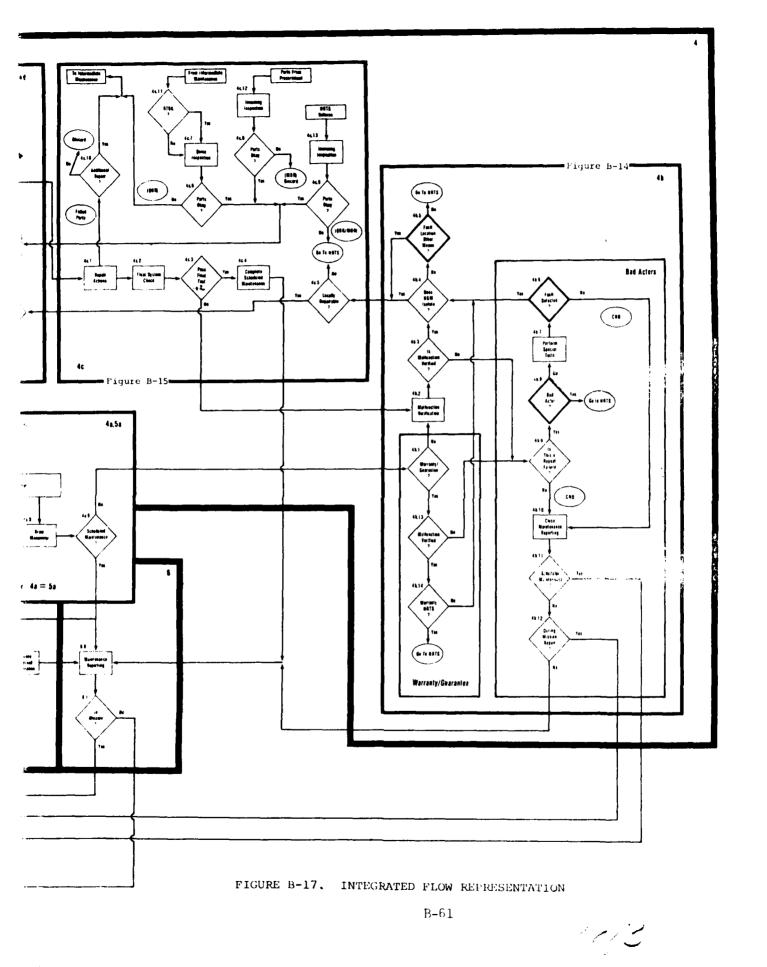
5. MODEL INTERACTIONS AND CONSEQUENCES

Table B-1 summarizes the key parameters as developed in each of the three models. All three models agree on functionality. For example, FFA is a function of CND and maintenance actions in each of the models. The form of each key parameter is identical. Each model points out that it is important to know what triggers maintenance activity and how fault isolation was achieved. These latter two items are not consistently recorded at present in the AFTO reporting system. Each model further points out the difficulty in relating CND to false alarms. In the set theory model, it is manifested by CND_T for improper CND. In each of the state and flow

models, it is manifested by an empirical coefficient (β), which represents a partitioning of the CNDs. Each model has also pointed out the criticality of the false-alarm measure. In every case, each of the parameters of interest requires an accurate measure of false alarm to be considered accurate. Finally, each of the models has pointed out separate insights into the process. The set theory model forces an explicit statement of assumptions that are inherent in all three models but not explicitly stated (such as $\sum_{u} RTOK_{u}$, that is, RTOK due to unnecessary repairs are assumed to be zero). The set theory model further provides a method







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CT 7.7

Pa r amet e r	Set Theory Representation	Model Representation	Representation
PED	$\sum_{\mathbf{M}_{\mathbf{S}}} - (\sum_{\mathbf{N}_{\mathbf{N}}} - \sum_{\mathbf{C}} - \sum_{\mathbf{N}_{\mathbf{N}}} $	ΣMA _s - β _s Σcnd Σma - βΣcnd	$\int (\dot{\mathbf{H}}_{\mathbf{S}}^{\mathbf{A}} - \boldsymbol{\beta}_{\mathbf{S}}^{\mathbf{C}} \dot{\mathbf{H}}_{\mathbf{S}}^{\mathbf{D}})$ $\int (\dot{\mathbf{H}}_{\mathbf{A}}^{\mathbf{A}} - \boldsymbol{\beta}_{\mathbf{C}} \dot{\mathbf{H}}_{\mathbf{D}})$
	(Equation 30)	(Equation 54)	(Equation 112)
Idd	$\frac{\Sigma FI_{S}}{\Sigma U + \Sigma MA - (\Sigma CND - \Sigma CND_{I} + \Sigma RTOK_{U})}$	ΣFI Σma - βΣcnd	$\int (\hat{\mathbf{FI}}) \int (\hat{\mathbf{MA}} - \hat{\mathbf{B}} \hat{\mathbf{CMD}})$
	(Equation 31)	(Equation 55)	(Equation 116)
eri p	$\Sigma FI_{S} - \Sigma RTOK_{S}$ $\Sigma U + \Sigma MA - (\Sigma CND - \Sigma CND_{I} + \Sigma RTOK_{U})$	ΣPIS - ΣRTOKS ΣMA - βΣCND	$\int (FI_{S} - FFD \times RTOK) \\ \int (HA - B CHD)$
	(Equation 31a)	(Equation 56)	(Equation 129)
FFA	Σcnd - Σcnd _I + Σrtok _u Σha	<u>escand</u> Sma	<u>efcn</u> J MA
	(Equation 27)	(Equation 57)	(Equation 104)
FAR	\sum_{T} CND - \sum_{T} + \sum_{T} RTOK	B.SCND	e ford
	(Equation 32)	(Equation 58)	(Equation 130)

of specifying what <u>should</u> be measured. The flow model representation provides a direct link between the maintenance model and readiness and has pointed out the limits that we must place on data gathering in terms of time sufficiency, cycle breakdown, and quantity of data. Finally, because of its inherent simplicity and conformity with current data gathering, the modified state model represents the best computational fit. This fit notwithstanding, there are several areas of concern:

- The relationship between RTOK and RTOK_S is critical. We have an estimator derived in the flow model (i.e., $RTOK_{s} = FFD \times RTOK$).

This estimator will allow us to proceed on measured RTOK data or RTOK rate data. Further, the flow model has shown that if data time and sufficiency requirements are met, we can make this measurement without invoking serial number tracking.

- We do not have an estimating procedure for the relationship (B_S) between system-generated CND and system-generated false alarms.
 B_S may be inherently related to "bad actors" that are identified by system fault indications. This would require serial number tracking.
- We do not have an estimating procedure for the relationship (β) between total CND and false alarms. An estimate could be made by relating past CNDs to "bad actor" determinations. This would require serial number tracking.

All three models point out what we cannot do with field-measured data, unless we are willing to devote inordinate amounts of resources. That is, an analyst would be required on site at the organizational level to define failures that are undetected by any means, or false alarms that are recognizable as such and ignored and do not trigger a maintenance action. These two events have been placed in the nonrelevant category not only because they can justifiably be considered not relevant, but also because they cannot be measured.

A final note has to do with the breakdown in fraction of faults isolated that has provided us with two measures: FFI and FFI. While the former may be more easily related to design variables, its value for specification is questionable, because it can be easily manipulated. The latter, while attractive for specification purposes, is much harder to measure and may not be directly relatable to design measures.

The value of β is currently not measurable and enormously complicates all three of the measures. An arbitrary assignment of $\beta = 1.0$ may be used for specification. since it really only separates CNDs that are due to inability to verify faults from CNDs that are due to bad detection. Both of these are negative properties. Care must be taken, however, to report CNDs accurately; and if the latter course is taken, it must be recognized that FAR no longer fits intuitive or widely recognized definitions. Finally, an arbitrary $\beta = 1.0$ may reduce the ability to predict any of the measures. BIBLIOGRAPHY

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A CANADA

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(DATA ACCESSION LIST)

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The objective of this study was to develop an analytical base of methodology and procedures to be used in the testability area. Testability is a subset of system maintainability and is defined by the system faultdetection and isolation capability. During this effort a comprehensive survey of the open and closed literature was performed to identify the analytical concepts, models, algorithms, and definitions currently used in the testability area. The report includes a comprehensive listing, definition, and discussion of commonly used testability parameters and their components.

ARINC Research Corporation. <u>Maintainability Prediction and Demonstration</u> <u>Techniques</u>, 573-01-2-1032, March 1970. UNCLASSIFIED

A study was performed to develop and validate improved maintainabilityprediction and -demonstration techniques for use on all major classes of Air Force electronic systems at the on-equipment level of maintenance. The prediction techniques are design-oriented and predict individual categories of time (preparation, fault location, item obtainment, fault correction, and preventive maintenance).

ARINC Research Corporation. <u>Special Report on Operational Suitability</u> (OS) Verification Study Focus on Maintainability, 1751-01-2-2395, February 1981. UNCLASSIFIED

This report presents findings of an investigation of system maintainability assessment for USAF tactical fighter aircraft. A typical mission turnaround cycle (MTC) is presented, and the driving elements of MTC time and maintenance resources are identified. Special emphasis is placed on the assessment of troubleshooting characteristics: specifically, testability parameters of time, accuracy, and thoroughness are identified. A concept of testability design assessment is outlined.

Baran, Harry A. (School of Systems and Logistics, Wright-Patterson Air Force Base). <u>Effect of Test Result Uncertainty on the Performance of a</u> <u>Context-Free Troubleshooting Task</u>, LSSR 86-82, 17 December 1982. UNCLASSIFIED

This paper attempts to determine whether human bias exists under conditions of test result uncertainty such that troubleshooting performance is systematically affected. A knowledge of such bias might be useful in assessing the utility of powerful signal detection-in-noise analytical tools, e.g., the ROC curve analysis, to improve predictions of troubleshooting performance and reduce troubleshooting error by allowing man-made machine troubleshooting systems to be optimized on the basis of the response characteristics of both machine and man. This paper contains considerable discussion of false alarms and percentages of all types of isolation errors.

Boring, G., and Rayburn, J. (ARINC Research Corporation). <u>AN/APS-96 Radar</u> <u>System Product-Improvement Program</u>, 1173-01-1-1677, November 1977. UNCLASSIFIED

This report describes significant engineering improvements in the AN/APS-96 Radar System installed in E-2B aircraft. The reliability improvements from these equipment improvements are also addressed.

Clyman, Milton, and Grenetz, Philip (Information Spectrum Inc.). <u>Mainte-</u> <u>nance Improvement: An Analysis Approach Including Inferential Techniques</u>, Vol. I, ISI-W-7958-02A, 15 March 1979. UNCLASSIFIED

This final report (in four volumes) presents the results of research into assessing the economic impact of potentially avoidable maintenance actions for selected Naval aircraft subsystems. Maintenance actions requiring no repair and those resulting in induced defects and failure-tocorrect are identified. A coarse evaluation of BIT effectiveness is made.

Cook, Thomas N. (Sikorsky Aircraft), and Ariano, John (Applied Technology Laboratory). "Analysis of Fault-Isolation Criteria/Techniques." <u>1980</u> Proceedings, Annual Reliability and Maintainability Symposium, pg. 29.

This paper documents an investigation by Sikorsky of fault-isolation criteria and techniques related to Army aviation. The investigation confirmed that fault-isolation maintenance is a significant factor in the cost of operating Army helicopters. The most frequent criticism voiced by Army personnel in the field concerns the generally poor quality of troubleshooting data in maintenance publications. Fault-isolation analysis technique (FIAT) was developed to facilitate the identification of symptom/ cause relationships and the collection, processing, and organization of data required for the preparation of maintenance manuals. Cases of repetitive troubleshooting on the aircraft were analyzed, with the following conclusions:

- Slightly more than one-fourth of the symptoms associated with nonavionics systems of the CH-54 involved one or more errors in troubleshooting.
- An improperly performed fault-isolation task occurred approximately every 76 flight hours.

It was recognized, however, that the errors in fault isolation documented in the ORME data represented only a fraction of the errors that actually occurred.

Cook, Thomas N. (Sikorsky Aircraft). <u>Analysis of Helicopter Maintenance</u> <u>Fault-Isolation Criteria/Techniques</u>, USARTL-TR-79-21, October 1979. UNCLASSIFIED

Army aviation fault-isolation maintenance was investigated. An improved approach to the development of fault-isolation maintenance data for complex systems was developed. This approach (FIAT) facilitates the identification of symptom/cause relationships and the collection, processing, and organization of data required for the preparation of maintenance manuals. (Man-hours and costs of no-defect maintenance actions are tabulated.)

Coppola, Anthony (Rome Air Development Center). <u>A Design Guide for Built-</u> <u>In-Test (BIT)</u>, RADC-78-224, April 1979. UNCLASSIFIED

This report summarizes available information for use in designing built-in-test (BIT) capabilities in electronic systems. It describes the various types of BIT, design considerations and examples, data used in BIT design, display options, coupling and shielding considerations, and optimization models.

Cummings, Kathy, and Hardesty, Walter (Naval Weapons Center). <u>Automation</u> of a <u>Maintainability Prediction</u>, NWC TP 6198, August 1980. UNCLASSIFIED

A maintainability prediction is automated through the use of the Pascal programming language on the UNIVAC 1110. This report provides the information necessary to describe the process for automating a maintainability prediction. It also includes instructions necessary for operating the maintainability Prediction Computer Program. (Does not use RTOK rates, FD, or FI.)

Dussault, Heather B. (Rome Air Development Center). <u>The Evolution and</u> <u>Practical Applications of Failure Modes and Effects Analyses</u>, RADC-TR-83-72, March 1983. UNCLASSIFIED

This report is intended to give reader a broad, general background in the techniques available for failure effects analysis and their usefulness. Sixteen separate techniques, ranging from tabular failure modes and effects analysis and fault tree analysis to newer techniques such as hardware/ software interface analysis, are discussed.

Dynamics Research Corporation, Systems Division. <u>Program Management Review</u> (<u>PMR</u>) <u>Minutes (AFLC WSMIS</u>), E-9296-U, 14 May 1984. UNCLASSIFIED

Among other things, these minutes present information about the Air Force Equipment Maintenance Management Information Systems (AFEMMIS), including the Core Automated Maintenance System (CAMS), the Generic Integrated Maintenance Diagnostics System (GIMADS), and the Equipment Maintenance Data Base (EMDB). Everly, Lt. Col. Julian R. (U.S. Army War College). <u>Maintenance Quality</u> Control: <u>A Critical Appraisal</u>, AD Al29757, 15 April 1983. UNCLASSIFIED

The ambiguity in maintenance inspection standards, the inconsistency among various technical inspectors, and the impact of developmental and fielding policies concerning test measurement and diagnostic equipment (TMDE) are examined relative to the conduct of sound quality and production management practices. An alternative approach to quality management is proposed in the interpretation and application of sound maintenance standards, conduct of in-house and TRADOC training programs, development of TMDE and special tools, and greater utilization of warrant officers in the role of quality managers. (No definitions provided.)

Ferguson, Capt. Gerald (Air Force Institute of Technology). <u>Aircraft</u> <u>Maintenance Expert Systems</u> (Master's Thesis), AFIT/GCS/EE/83D-9. November 1983. UNCLASSIFIED

This thesis provides design considerations for implementation of an "expert system" to assist in the diagnosis of aircraft problems. It illustrates the characteristics required for an automated diagnostic system to assist the average aircraft technician in the performance of his or her duties. The design of a "knowledge base" and "inference procedure" for such a system are presented. A working system model was developed on a microcomputer to demonstrate the feasibility for a full-scale maintenance expert system.

Fiorentino, Eugene (Rome Air Development Center). <u>The Use of Air Force</u> <u>Field Maintenance Data for R&M Assessments of Ground Electronic Systems</u>, RADC-TR-79-13, April 1979. UNCLASSIFIED

The R&M estimates derived from field data are compared with similar estimates obtained from the R&M design and development program. The study identifies the major limitations in the field data for use in field R&M assessment. Recommendations for improving the quality and usability of the field data are also made.

Fleming, Dr. R., and Dehoff, Dr. R. (Systems Control Technology, Inc). <u>Turbine Engine Fault Detection and Isolation Program, Vol II: Maintenance</u> <u>Model Development</u>, AFWAL-TR-82-2058, August 1982. UNCLASSIFIED

Maintenance decision analysis models for evaluation of the TF-34 maintenance process are formulated. These models form the foundation for the U.S. Air Force to establish techniques for determining optimal policy for troubleshooting and maintenance of its aircraft engines using decision analysis methods. Model structures and parameters as well as input and output are treated.

Fuller, Richard (Anacapa Sciences, Inc). <u>Maintenance Performance System-</u> <u>Organizational Operating Manual, Maintenance Management Information System</u> <u>for Division 86</u>, Research Note 84-18, January 1984. UNCLASSIFIED

The purpose of this effort is to develop the Maintenance Performance System-Organizational (MPS-O), which is an integrated system for measuring maintenance performance, diagnosing performance problems, taking corrective actions, and providing training. This report provides instructions for operating the maintenance management information systems of MPS-O. (No definitions provided.)

Fuqa, N. (IIT Research Institute). <u>Electronic Equipment Maintainability</u> <u>Data</u>, EEMD-1, Fall 1980. UNCLASSIFIED

This is the first of a series of maintainability data publications at the system/equipment level. The data are intended to complement MIL-HDBK-217, MIL-STD-883, MIL-STD-785, MIL-STD-470, and MIL-HDBK-472.

Garfield, J. (Gould NAVCOM Division), and Razovsky, I. "Economical Fault Isolation Analysis," <u>1985 Proceedings, Annual Reliability and Maintaina-</u> <u>bility Symposium</u>, pg. 480.

This paper presents a rationale for, and the results of, a tailoring process applied to the failure analysis described, for example, in MIL-STD-1629A, MIL-STD-1543A, and ARP 926A, which is used for fault isolation of shop repairable units (SRUs).

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This study focuses on the aircraft avionic maintenance problems of cannot duplicate (CND) and retest-OK (RTOK) for three sampled F-16 wings. Analytical and survey methods were used to determine causes of CND and RTOK occurrences.

Gilmore, Jordan, and Pisano (General Electric Company, Aircraft Engine Group). <u>Assessment of Augmented Electronic Fuel Controls for Modular</u> <u>Engine Diagnostics and Condition Monitoring</u>, USARTL-TR-78-32, December 1978. UNCLASSIFIED

Fault isolation to the module and LRU levels by means of a diagnostic and condition monitoring (D&CM) system integrated with a full-authority digital electronic control (FADEC) is evaluated in this study. A preliminary assessment of D&CM system parameters required for performing the diagnostic functions on the current T-700 engine is also included. An integral part of the GE FADEC system is failure indication and corrective action (FICA) based on extended Kalman-Bucy filtering techniques.

Gleason, Capt. Daniel (Rome Air Development Center). "Analysis of Built-In-Test Accuracy." <u>1982 Proceedings, Annual Reliability and Maintainability</u> <u>Symposium</u>, pg. 370.

Built-in-test accuracy is a combined measure of fault-detection capability and false-alarm occurrences. This paper provides a Markovian analysis of BIT accuracy. The results of the analysis are used to develop trade-off techniques for achieving optimal BIT accuracy levels (gives probability equations of false alarm and failure detections).

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This report describes a project to develop and test a functional simulation model of aircraft maintenance. The model, called AMES, measures the effects of human errors in maintenance.

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This report presents RAM information (background and principles), RAM complexities and methods for enhancing RAM. TACC automation RAM complexities are discussed in terms of definitions, system definition deficiencies, and RAM predictions.

Griffin, Lt. Col. L. D. (Institute for Defense Analysis), and Kern, George A. (Hughes Aircraft Company), <u>R&M Parameter Analysis Document</u>, IDA D-27, August 1983. UNCLASSIFIED

This document describes the four categories of R&M parameters (readiness, reliability, maintainability, and manpower) used by each of the services (Army, Navy, Air Force) for typical military systems and equipments. In addition to the descriptions of each parameter (and its subsets), parameter strengths and weaknesses are discussed. The document includes definitions and related information.

Grumman Aerospace Corporation. <u>Design Guidelines and Optimization Proce</u>-<u>dures for Test Subsystem Design</u>, RADC-TR-80-111, April 1980. UNCLASSIFIED

Guidelines and procedures for optimizing design of BIT equipment are provided. Optimization of the test subsystem is achieved by properly specifying three key design parameters (test effectiveness, mean corrective maintenance time, and test subsystem production costs) during the conceptual phase. This report provides mathematical tools, algorithms, and trade-off procedures to assist the designer during each design phase.

Harz, C. R. (Rand Corporation). <u>Problems in Army Maintenance: Results of</u> <u>a Questionnaire Survey</u>, R-2487-ARPA, June 1981. UNCLASSIFIED

This document presents results and comments of a survey of civilian and uniformed Army maintenance specialists on U.S. Army land vehicle maintenance problems. Major findings of the survey are the dominance of manpower-related problems and the lack of reliable basic data on many facets. (No definitions provided.)

Hughes Aircraft Company. <u>Analysis of Built-In-Test (BIT) False Alarm Con-</u> <u>ditions</u>, RADC-TR-81-220, August 1981. UNCLASSIFIED

The objectives of this study were to determine causes of false-alarm problems and develop design guidelines to minimize the occurrence and effects of false alarms. False-alarm rates were established for the three systems investigated, and prediction factors were defined.

Hughes Aircraft Company. <u>BIT/External Test Figures of Merit and Demon-</u> stration Techniques, RADC-TR-79-309, December 1979. UNCLASSIFIED

Current maintainability parameters and corresponding analysis/ demonstration techniques lack the capability of expressing the adequacy of BIT/ETE. Figures of merit (FOM) have been identified that can be used to express the adequacy of BIT/ETE. Methodologies have been developed for analyzing and demonstrating the defined BIT/ETE FOMs. A methodology has also been developed for methodically selecting the BIT/ETE FOMs required in system/equipment specifications based on the desired system equipment objectives and requirements.

Hughes Aircraft Company. <u>Combined HW/SW Reliability Models</u>, RADC-TR-82-68, April 1982. UNCLASSIFIED

A methodology is developed for combining hardware and software reliability. On the basis of this general methodology, a baseline combining HW/SW reliability is developed that incorporates and verifies the SW reliability theory of Jelinski-Moranda and Goel-Okumoto with the traditional HW reliability theory. The baseline model is computerized; it includes HW/SW failure and repair characteristics, allowance for imperfect SW debugs, and modes of HW/SW interaction. A HW/SW trade-off procedure is developed through the use of a combined HW/SW availability measure.

Hughes Aircraft Company. <u>Maintainability Prediction and Analysis Study</u>, RADC-TR-78-169, July 1978. UNCLASSIFIED

A new time-synthesis prediction technique is developed that directly relates diagnostic/isolation/test subsystem characteristics and other design characteristics to equipment/system maintainability parameters. The developed methodology includes a detailed prediction procedure for use

when final design data are available. Predicted parameters include mean time to repair, maximum (percentile) time to repair, maintenance man-hours per repair, and fault-isolation resolution. The technique includes a set of time standards applicable to physical maintenance actions associated with current construction and packaging techniques.

Hughes Aircraft Company. <u>RADC Testability Notebook</u>, RADC-TR-82-189, June 1982. UNCLASSIFIED

Inherent testability must be systematically developed and integrated with the design of the system, and the requirements for testability must be accorded the same level of recognition as performance, reliability, maintainability, availability, supportability, and safety. This testability notebook provides fundamental guidance for systematic establishment throughout the development cycle of the requisite inherent testability and comprehensive testability of the test-resource mix in combination with the prime system design.

Hughes Aircraft Company <u>tudy of the Causes of Unnecessary Removals of</u> <u>Avionic Equipment</u>, RADC-TR-83-2, January 1983. UNCLASSIFIED

This study investigated and verified the causes of unnecessary removals of suspect items from selected avionic equipment. The report recommends actions that are useful in minimizing unnecessary removals.

IIT Research Institute/Reliability Analysis Center. <u>Correlation of Field</u> <u>Data with Reliability Prediction Models</u>, RADC-TR-81-329, November 1981. UNCLASSIFIED

This report considers the factors influencing the goodness of fit of MIL-HDBK-217C prediction models. Areas in which the models are deficient are identified and quantified. Where positive inferences are possible, a range of statistical methods are used to give an unbiased assessment. The underlying distribution of time to failure is investigated, since MIL-HDBK-217C assumes a constant-failure-rate model.

IIT Research Institute. Least Cost Test Profile, Vol. I, RADC-TR-82-84, April 1982. UNCLASSIFIED

This study developed test profiles for rigid-wall tactical shelters. Test cost data and test results were obtained, and an effort to determine the correct text sequences was instituted. The operational data, test costs, test results, and output from the test sequence effort were used to develop test profiles for eight members of the standard family of shelters.

IIT Research Institute. <u>Least Cost Test Profile</u>, Vol. II, RADC-TR-82-84, April 1982. UNCLASSIFIED

This study developed test profiles for rigid-wall tactical shelters. Test cost data and test results were obtained, and an effort to determine the correct test sequences was instituted. The operational data, test costs, test results, and output from the test sequence effort were used to develop test profiles for eight members of the standard family of shelters.

Institute for Defense Analysis. <u>Built-In-Test Equipment Requirements</u> <u>Workshop</u>, Paper P-1600, August 1981. UNCLASSIFIED

A workshop was held for the purpose of assessing progress and problems in specifying and testing BIT used in complex electronic equipment. The recommendation is that the current specification and test approach be broadened to include all capabilities associated with the detection and isolation of faults. The report emphasizes BIT specification, testing, and evaluation.

Kiener, William L., and Coppola, Anthony. "Joint Services Program in Design for Testability," <u>1981 Proceedings, Annual Reliability and</u> <u>Maintainability Symposium</u>, pg. 268.

This paper is divided into three parts. The first part is an overview of testability, including its definition, its relationship to reliability and maintainability, and its importance in supporting complex weapon systems. The second part is a summary of Navy subtasks under the JLC DFT program. The third part is a summary of the Air Force testability program.

Knaizuk, J. (Syracuse University). <u>Manual Fault Detection Test Set Mini-</u> <u>mization</u>, RADC-TR-77-149, May 1977. UNCLASSIFIED

This report describes a manual procedure for minimizing the number of tests necessary to detect a single "stuck at" fault in a large-scale integrated circuit.

Krause, George S., Jr. (Westinghouse Electric Corporation). "Distributed Versus Centralized BIT/FIT Processing," <u>1985 Proceedings, Annual Relia-</u> <u>bility and Maintainability</u> Symposium, pg. 291.

This paper describes two system testability concepts for electronic systems. The first is centralized BIT/FIT processing (for fault detection and isolation testing), and the second is distributed BIT/FIT processing.

Lahore, H. (Boeing Aerospace), and Gozzo, L. (RADC). "Artificial Intelligence Applications to Testability." <u>1985 Proceedings, Annual Reliability</u> <u>and Maintainability Symposium</u>, pg. 276.

This study provides a foundation for applying AI to electronic testability for the military. Applications include system-level maintenance expert and smart maintenance expert in order to reduce false alarms and improve fault isolation and detection.

Liu, Nakajima, Olivier, et al. (Texas Tech University). <u>Nonlinear Fault</u> <u>Diagnosis</u>, AD-Al01053, May 1981. UNCLASSIFIED

Several research projects in nonlinear fault diagnosis are summarized. Alternative algorithms for the solution of the nonlinear fault-diagnosis problem are presented. together with a diagnosibility theory and a set of criteria that an "ideal" fault-diagnosis problem should strive to meet. (No definitions -- only mathematical theory.)

Lockheed California Company. <u>Built-In-Test and External Tester Reliability</u> Characteristics. RADC-TR-80-32, March 1980. UNCLASSIFIED

This report presents the results of a study of the reliability impact of BIT and external test equipment on prime equipment design and maintenance downtime. Sixty units were analyzed from the S-3A, C-5A, and Mk 86 weapon systems to develop BIT and external tester measurement effectiveness versus unit design characteristics. Trade-off criteria were developed for predicting BIT and test-equipment reliability during the acquisition of new systems.

Malcolm, J. G. (Hughes Aircraft Company). "BIT False Alarms: An Important Factor in Operational Readiness," <u>1982 Proceedings, Annual Reliability and</u> <u>Maintainability Symposium</u>, pg. 206.

The premise of this paper is that current avionic systems are inherently reliable and potentially maintainable at high rates of operational readiness. This paper describes some root causes of false alarms and identifies solution approaches, including improved specifications, improved analysis techniques, and expanded use of new technology. Resolving the false-alarm problem can result in a major improvement in operational readiness.

Malcom, J. G. (Hughes Aircraft Company). "Practical Applications of Bayes' Formulas," <u>1983 Proceedings, Annual Reliability and Maintainability</u> <u>Symposium</u>, pg. 180.

Five practical applications of Bayes' formulas are presented. One of these deals with the problem that the military has been wrestling with for years, namely, the excessive number of units checking no fault in the intermediate-level shop. This problem is variously known as the retest-OK (RTOK) problem or the bench check serviceable (BCS) problem or the cannot duplicate (CND) problem. Traditionally, this problem is attacked as though it represents a deficiency in the test that was used to cause the unit to be removed and replaced in the system, typically built-in test (BIT). This paper demonstrates that the RTOK rate can be a function of the prevalence of faulty systems. Statistical guidelines are presented in the paper, indicating how designers can develop tests that will provide an optimal balance between false alarms and missed faults.

McWhirter, Johnson, and McLane (David W. Taylor Naval Ship R&D Center). <u>A Shipboard Machinery Performance Monitoring System Concept</u>, DTNSRDC/PAS-78/30, February 1979. UNCLASSIFIED

This report describes a concept for an instrumentation and monitoring system for Naval shipboard monitoring. Specific topics addressed in this report include system capability requirements, data collection, and local remote processing. This system is being developed to enable shipboard personnel to predict maintenance action, to reduce maintenance time required, and to provide a tool for maintenance management. (No definitions provided.)

Miehle, William, and Siegel, Arthur (Applied Psychological Services). Development of Performance Evaluative Measures, December 1967. UNCLASSIFIED

The logic of a technique for employing technician "confidence that a defect exists" for maximizing the probability of malfunction recognition is described. Operator characteristics curves are derived for a variety of distributions of "confidence." The implications of the work for training and post-training performance evaluation are pointed out. Probabilities of saying "yes" or "no" when there is a defect or saying "yes" or "no" when there is no defect are given. (No definitions, but numerous formulas.)

MIL-HDBK-217D. <u>Reliability Prediction of Electronic Equipment</u>, 9 April 1979.

This handbook establishes uniform methods for predicting the reliability of military electronic equipment and systems. It provides a common basis for reliability predictions during acquisition programs for military electronic systems and equipment. It establishes a common basis for comparing and evaluating reliability predictions of related or competitive designs. Two methods of reliability prediction are used -- part stress analysis and parts count.

MIL-HDBK-472. Handbook, Maintainability Prediction, 24 May 1966.

The purpose of this handbook is to familiarize managers and design engineers with current maintainability prediction procedures. Four procedures are described.

MIL-STD-471A. <u>Maintainability Verification/Demonstration/Evaluation</u>, 27 March 1973.

The purpose of this standard is to establish uniform procedures, test methods, and requirements for verification, demonstration, and evaluation of the achievement of specified maintainability requirements and for assessment of the impact of planned logistics support. The standard includes lengthy discussion (in addendum) on procedures for evaluation and demonstration of equipment/system BIT and ETE fault isolation and testability attributes (fault isolation/detection), but no specific definitions can be derived from the context of the entire discussion.

MIL-STD-1309B. <u>Definitions of Terms for Test, Measurement, and Diagnostic</u> Equipment, 30 May 1975.

Test, measurement, and diagnostic equipment key terms are defined in order to improve communications and to facilitate coordination. Definitions include fault, false alarm, fault detection, fault isolation, and organizational maintenance.

MIL-STD-1591. <u>Analysis/Synthesis_of On-Aircraft Fault Diagnosis</u> <u>Subsystems</u>, 3 January 1977.

This standard establishes uniform criteria for conducting trade studies to determine the optimal design for an on-aircraft fault-diagnosis/ isolation system, referred to as the On-Board Built-In Test (OBBIT) System. The standard is applicable to DoD procurements that include the development of on-aircraft fault-diagnosis/isolation systems where a selection can be made between such alternatives as central computer controlled, on-board centrally polled built-in test equipment (BITE), decentralized BITE, detached aerospace ground equipment (AGE), or combinations of the preceding.

MIL-STD-2076(AS). <u>General Requirements for Unit Under Test Compatibility</u> with Automatic Test Equipment, 1 March 1978.

This standard presents the design requirements for a UUT that will make it compatible for test on an ATE. Thus designed, the UUT will possess the attributes necessary to maximize the benefits possible through use of ATE and minimize the cost of achieving those benefits.

MIL-STD-2077(AS). <u>General Requirements for Test Program Sets</u>, 15 July 1975.

This standard establishes the requirements for the development, test documentation, configuration management, quality assurance, and preparation for delivery of test programs (TPs) and related hardware and documentation to be used in conjunction with an appropriate ATE to test UUTs.

MIL-STD-2165. <u>Testability Program for Electronic Systems and Equipments</u>, 26 January 1985.

This standard prescribes a uniform approach to testability program planning, establishment of testability (including BIT) requirements, testability analysis, prediction and evaluation, and preparation of testability documentation. It includes testability program planning, testability requirements, testability design, testability prediction, testability demonstration, testability data collection and analysis, documentation of testability programs, and testability review.

Mulligan, Joseph (Management and Technical Services Company [Air Force]). Logic Tree Troubleshooting Aid: Organizational and Intermediate Maintenance, AFHRL-TR-79-49, January 1980. UNCLASSIFIED

This report provides a draft military specification for use in the procurement of logic tree troubleshooting aids (LTTAs). A thorough review of the state of the art in preparing and using LTTAs was made to provide the basis for developing the draft specification. The draft specification provides specific and general requirements for the development of LTTAs, including task analysis and development of troubleshooting procedures and check-out procedures. (No definitions provided.)

NAVMATINST 3960.6B. <u>Procedures for Acquisition Category IV Test and</u> <u>Evaluation Plans (TEPS)</u>, 9 February 1981.

This instruction applies to all Navy Acquisition Category I. II, III, and IV programs except nuclear weapon subsystems and nuclear propulsion subsystems. Product assessment through tests and evaluations, including early participation by the commander, is seen as a realistic method of ensuring that new systems will be operationally effective and suitable before being approved for service use.

Neuman, George W. (Giordano Associates, Inc.). <u>Testing Technology Working</u> <u>Group Report (IDA/OSD R&M Study)</u>, IDA D-41, August 1983. UNCLASSIFIED

This study report addresses the requirements for a testing technology development program. The study is part of a larger Reliability and Maintainability Improvement Study Program. The first portion of this report describes the entire study and how testing technology fits into its framework. This is followed by a description of the problem, scope, goals, objectives, approach, content, payoffs, conclusions, and recommendations related to a testing technology program. (Addresses false-alarm-rate requirements but provides no definitions.)

Osborn, Jack (Institute for Defense Analysis). <u>CAD/CAM Technology Working</u> <u>Group Report (IDA/OSD R&M Study)</u>, AD-A137761, August 1983. UNCLASSIFIED

The goal of the report is to identify means by which computer-aided technologies can lead to quantum improvements in R&M. The report articulates a model of the process of taking a weapon system from concept to product using computer-aided technologies. Two major issues concerning these technologies are developed: effective application of existing computer-aided technologies and communications among subsets of computer-aided technologies, e.g., CAE, CAD, CAM. (No definitions provided.)

Ramirez, Miguel A. (Westinghouse Electric Corporation). "Achieving Maintainability by Random Fault Injection," <u>1982 Proceedings, Annual Relia</u>bility and Maintainability Symposium, pg. 291.

This paper describes a random fault-injection testing technique that, when implemented, will significantly improve the probability of meeting maintainability requirements in the field. The proposed random faultinjection technique provides a testability-growth program that concentrates on fault-detection/isolation effectiveness and mean time to repair (MTTR).

Rouse, Rouse, Hunt, et al. (Coordinated Science Laboratory, College of Engineering). <u>Human Decision-Making in Computer-Aided Fault Diagnosis</u>, TR 434. January 1980. UNCLASSIFIED

This report summarizes six experiments conducted to increase our understanding of human performance on diagnostic tasks and, in the process, to investigate the feasibility of using context-free computer-based simulations to improve troubleshooting skills. Results provide a data base for both theoretical issues in fault diagnosis and practical application of computer aiding to live system performance. (No definitions provided.)

Sievers, Kravetz, Dussia, and Jackson (Fail-Safe Technology Corporation). <u>Military Standard Fault-Tolerant Microcomputer</u>, FR-OOlAD, July 1982. UNCLASSIFIED

This report includes the results of a feasibility study, preliminary design, and recommendations for subsequent work. Fault tolerance is the unique attribute of a computer system that enables that system to continue its program-specified behavior in spite of the occurrence of faults. The computer system described in this report provides fault detection, isolation, and repair. An overview of the state-of-the-art concepts and techniques employed in fault-tolerant computer designs is added. Simpson. Gutmann, and Jarosz (Anacapa Sciences Inc). <u>Information and</u> <u>Evaluation System Design Considerations</u>, Research Note 84-2, January 1984. UNCLASSIFIED

This report addresses design considerations related to the Information and Evaluation System (I&ES) of the Maintenance Performance System-Organizational (MPS-O). The I&ES will be a system for obtaining, analyzing, tabulating, and disseminating maintenance performance information. This report describes the analyses that underlie the design and makes preliminary design recommendations. False replacement rate is a measure of maintenance quality. (No definitions provided.)

Simpson, W. R., and Agre, J. R. (ARINC Research Corporation). "Experiences Gained in Testability Design Trade-offs," <u>IEEE AUTOTESTCON</u>, November 1984.

Experience in using STAMP to analyze system design trade-offs is discussed for such areas of testability as component ambiguities, packaging, redundant test, false-alarm tolerance, and multiple failures. Analytical measures are proposed to aid in the design trade-off process, and their relationship to fault isolation is illustrated.

Smith, George, II (Boeing Wichita Company). "Testability Analysis: Predict It More Closely," <u>1979 Proceedings, Annual Reliability and Main-</u> tainability Symposium, pg. 187.

This paper presents a technique for using a computer-aided design (CAD) test-generation program for testability and analysis of digital circuit cards.

Sohar Incorporated. <u>Fault Tolerance, Reliability, and Testability for</u> <u>Distributed Systems</u>, RADC-TR-83-36, February 1983. UNCLASSIFIED

The objective of this study is to provide a foundation for the development of design measures and guidelines for the design of fault-tolerant systems. Taxonomies of fault tolerance and distributed systems are developed, and typical Air Force $C^{3}I$ needs in both fault-tolerant and distributed computer systems are characterized. Key issues in the design of fault-tolerant distributed systems are identified. Fault-location techniques for specific computer configurations found in $C^{3}I$ applications are detailed.

Sperry Corporation. <u>Design Guide, Built-In-Test (BIT), and Built-In-Test</u> <u>Equipment (BITE) for Army Missile Systems</u>, TR-RL-CR-81-4, 17 April 1981. UNCLASSIFIED

This report documents the first draft of a design guide and has been prepared as an aid to the project manager. beginning with the conceptual phase through development, and as a guide to the system design engineer concerned with the incorporation of built-in-test (BIT) and built-in-test equipment (BITE) into the weapon system. It is not the intent of this document to detail the "how to" but rather to identify those subject areas that need to be considered in determining the requirement for BIT. Uses MIL-STD-1309.

Stander, Carvel R. (The Boeing Company). "Fault Isolation BITE for Increased Productivity," <u>1982 Proceedings, Annual Reliability and Maintainability Symposium</u>, pg. 365.

With digital avionics comes a quantum leap in system complexity and the need for a comparable increase in fault-isolation ability, with its related ramifications. The Boeing Company began early in its new airplane design to study the fault-isolation problem. From the studies came new design criteria, numerical objectives, and verification methods. The results produced major gains in fault-isolation capability on complex digital systems through the development of a new generation of BITE. The new 757/ 767 BITE is designed for the mechanic, not the engineer. It eliminates many of the existing problems with today's BITE, such as the inability to deal with intermittent faults.

Towne, Douglas M.; Johnson, Mark; and Corwin, William (Behavioral Technology Laboratory). <u>A Performance-Based Technique for Assessing Equipment</u> <u>Maintainability</u>, AD-A133518, August 1983. UNCLASSIFIED

Maintainability projections were made for a digital inferred transmitter/receiver system, specially constructed to be configured in two functionally equivalent forms. Technicians worked to identify and resolve eight inserted malfunctions each, using built-in indicators and standard test equipment. A measure of design complexity is proposed for the evaluation of maintainability. This measure, mean number of indicators necessary to accomplish fault isolation, is sensitive to multiplicity of fault modes and to the extent to which fault symptoms are confounded at the maintainer interface. (No definitions provided.)

Wardell, Howard (Directorate of Training Developments). <u>Final Independent</u> <u>Evaluation Plan for XMl Turret Organizational Maintenance Trainer</u>, TRADOC ACN 39377, March 1981. UNCLASSIFIED

The major objectives of this Independent Evaluation Plan (IEP) are to determine the effectiveness of XMI TOMT, the logistics supportability of the XMI TOMT, and the adequacy of the XMI TOMT human-factors design with respect to operability and acceptability. Appendix A has failure definitions -- what does and does not constitute a failure -- but no other definitions.

Weapon System Effectiveness Industry Advisory Committee. <u>Chairman's Final</u> <u>Report</u>, AFSC-TR-65-6, January 1965. UNCLASSIFIED

The Weapon System Effectiveness Industry Advisory Committee (WSEIAC) developed a measure of the extent to which a system may be expected to achieve a set of specific mission requirements. The WSEIAC approach is based on the concept of system-state occurrence probabilities and systemstate capabilities for performing the mission. A system state is a distinguishable condition of the system that results from events occurring prior to and during the mission.

Wells, C. F. (ARINC Research Corporation). <u>Organizational Maintenance</u> <u>Requirements for Augmenting Fault-Isolation Procedures for P-3C Avionics</u>, 928-02-3-1049, May 1970. UNCLASSIFIED

This report describes the avionic systems of the P-3C aircraft for which modules are needed in troubleshooting by the substitution method, the modules needed to outfit a module caddy, alternative maintenance concepts, and the effect of using initially provisioned spares for outfitting module caddies. (No definitions provided.)



GLOSSARY

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

AFTO 349 - Air Force Maintenance Data Collection Record.

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 (e.g., LRU type) or specific (i.e., a given serial number).

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

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.

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.

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. Fault detection may be subdivided into the following categories: BITE fault detection, automatic fault detection, and manual or semiautomatic fault detection.

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

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, ATE, semiautomatic, 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.

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 has additionally 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.

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.

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

System Go-Check - Normal maintenance procedure 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.

ACRONYMS AND SYMBOLS

AFEMMIS	Air Force Equipment Maintenance Management Information System
AFTO	Air Force Technical Order
AGS	Aircraft Generation Squadron
ANG	Air National Guard
AT	Action taken
ATE	Automatic test equipment
BCS	Bench check serviceable
BIT	Built-in-test
BITE	Built-in-test equipment
CAMS	Core Automated Maintenance System
CFD	Component feedback dominance
CND	Cannot duplicate
CNDI	Cannot Duplicate events of real failures
CND	Operator-induced cannot duplicate
CND	Cannot duplicate events of false alarms
CNDS	Cannot duplicate results of NSM-generated maintenance actions
CND	Improper cannot duplicate
CNF	Cannot find
CRS	Component Repair Squadron
D&CM	Diagnostic and condition monitoring
DFT	Design for testability
DP	Degree of parallelism
Ê	Conditional effectiveness
ED	External dependency
EDF	External dependency factor
EMDB	Equipment maintenance data base
ETE	Electronic test equipment
EW	Electronic warfare

F	Maintenance term for failures
FA	False-alarms
FAO	Operator-induced false alarms
FAR	False-alarm rate
FCND	Fraction of maintenance actions that result in CND
FD	Maintenance term for valid detection
FD	Maintenance term for valid detections by operators
FD _s	Maintenance term for valid detections by normal system maintenance
FFA	Fraction of false alarms
FFA	Fraction of false alarms that measures the contribution of
5	the j th component to FFA (e.g., system/operator/BIT)
FFASS	Fraction of false alarms in the subsystem
FFA SSC	Subsystem contribution of fraction of false alarms
FFD	Fraction of faults detected
FFD SS	Fraction of faults detected in the subsystem
FFD SSC	Subsystem contribution of fraction of faults detected
FFI	Fraction of faults isolated
FFI _P	Fraction of faults isolated performance
FFI	Fraction of faults isolated in the subsystem
FFI SSC	Subsystem contribution of fraction of faults isolated
FI	Maintenance term for faults isolated and repaired
FIO	Maintenance term for faults isolated and repaired not by normal system maintenance
FI _S	Fault isolation (of real failures) by normal system maintenance
FI _{SS}	Faults isolated and repaired in the subsystem
fi _u	Fault isolation and repair of nonfailures (unnecessary repair)
FIAT	Fault-isolation analysis technique
FICA	Failure identification and corrective action
FL	Feedback loop
FMECA	Failure modes and effects criticality analysis
FOM	Figure of merit
GIMADS	Generic Integrated Maintenance Diagnostics System
How Mal	How malfunctioned (how did the system/subsystem malfunction?)
HW	Hardware
INS	Inertial navigation system
1/0	Input/output

JCN Job control number Ratio of fault in the ith subsystem to total faults ĸ LOGMOD Logic Model; testability model developed by DETEX Systems, Inc. Line replaceable unit LRU Logic tree troubleshooting aids LTTA MA Maintenance term for maintenance action MA Maintenance term for failure indications outside normal system maintenance MAS NSM-generated maintenance actions MA sched Scheduled maintenance actions MAunsched Unscheduled maintenance actions MAC Military Airlift Command MADARS Malfunction Analysis Detection and Recording System MDC Maintenance document check - Air Force data collection system MDCS Maintenance Data Collection System MDR Maintenance Discrepancy Report MFLS Maintenance fault listing summary - Air Force data collection system MODAS Maintenance and Operational Data Analysis System MTC Mission turnaround cycle MTFI Mean time to fault-isolate Mean time to repair MTTR Normalized elements NE NFF No fault found Number of feedback loops NFL Not isolatable this station NITS Not normal system maintenance NNS NRTS Not repairable this station Normal system maintenance NSM On-board built-in test OBBIT OPSREADY Operations ready Operational test and evaluation OT&E PRD Pilot report discrepancies QDR Quality Deficiency Report R System reliability RAM Reliability, availability, and maintainability **R&M** Reliability and maintainability RTOK Retest-OK RTOK System-generated RTOK from real faults RTOK Retest of unnecessary repairs

S System survivability SAC Strategic Air Command SPO System Program Office SRU Shop replaceable unit SS Subsystem SSC Subsystem contribution ST Self-test STAMP System Testability and Maintenance Program SUT Subsystem under test SW Software TAC Tactical Air Command TE Test equipment TMDE Test measurement and diagnostic equipment TP Test program TPs Normalized test point U Maintenance term for undetected failures (not measurable) W/G Warranty/guarantee WSEIAC Weapon System Effectiveness Industry Advisory Committee WSMIS Weapon System Management Information System Empirical coefficient that represents the percentage of ß total generated CND that are false alarms Empirical coefficient that represents the percentage β_s of NSM-generated CND values to false alarms Allocates the portion of the subsystem contribution to Υ₁ detection that applies to the system ^ه1 Allocates the portion of the subsystem contribution to false alarm that carries forward to the system Flow model functional n Small time increment or temporary variable τ Represents the cross-detection of subsystem j as a result ^Tij of failures in subsystem i and $\tau_{ii} = 0$ Ω Population operation that enumerates the membership of a set Proportion of RTOK due to system-generated detections Ε Threshold value for cannibalization and back-order inventory data

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