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DESIGN FOR THE MAINTAINER: FINAL REPORT

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This report documents a project to study design-for-the-maintainer (DFM) issues relative to the maintenance of Navy aircraft. One task of the project was to identify design features influencing maintenance effectiveness. Toward this end, a new analytical method was developed, incorporating the following features:

- Interrogation of the 3-M data base for an F-14 squadron
- Selection of "strong" and "weak" subsystems to be investigated, based on maintenance error rates and elapsed maintenance time (EMT)
- Interviews of subject matter experts to ascertain the influence of design features (or the lack thereof) on the subsystems thus identified
- Collection, reduction, and analysis of data

An additional project task was to develop a method to evaluate the impact of improvements in maintenance. This method utilized the Aircraft Maintenance Effectiveness Simulation (AMES) Model.

PREFACE

Maintenance in today's era of high technology is a major problem. It has been estimated to comprise in excess of 50 percent of an operational weapons system's operating costs, with signs that it is continuing to increase its share. As a result of this, the Navy is now giving increased attention to a wide range of approaches in which the quality of weapon system maintenance can be improved.

A primary issue in that connection is the matter of design for the maintainer. To date, the design-for-maintainer issue has been largely ignored by the behavioral sciences community in the Navy. The little attention given to design-for-maintainer research has been both sporadic and shallow. One reason for this has been the lack of a mechanism for closing the feedback loop between the operational environment and the R & D community, and for quantitatively establishing the impact of design-for-maintainer on weapon system operational readiness and operating costs. Development of such a mechanism was the goal of this project.

This report documents all work performed by Xyzyx Information Corporation for the Naval Air Development Center, under contract #N62269-80-C-0215. The report is organized as follows:

- Section I provides an overview of the problem, describing various factors in the maintenance environment that affect system performance.
- Section II describes quantitative aspects of the problem and various research approaches.
- Section III describes the method developed to identify design features influencing maintenance.
- Section IV describes the method used in evaluating the impact of improvements in maintenance.
- Section V documents the results obtained during the course of the project.
- Section VI presents the conclusions, implications, and recommendations drawn from these results.

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SECTION I

OVERVIEW OF THE PROBLEM

The design-for-maintainer problem is described under the following major headings:

- Introduction
- Maintenance Errors
- System Design and Support Factors Affecting Maintenance

INTRODUCTION

The goal of Navy Maintenance is to keep weapon systems operationally ready in an efficient manner. Unfortunately, there are indications that this goal, while being approached, is not being met. That is, a number of weapon systems are not being kept in an operationally ready state for an adequate percentage of the time.

In the paragraphs that follow, this problem is discussed further in terms of 1) operational readiness, 2) cost of maintenance, and 3) measures of maintenance technician effectiveness.

Operational Readiness

Operational readiness (OR) data are presented for two current aircraft models, the F-14A and the SH-2F. As shown in Table 1, the F-14A has an operational readiness of only about 58 percent. However, even this figure is somewhat misleading. When only the full systems capability (FSC) is considered, operational readiness reduces to about 52 percent.

There is some indication that the 52 to 58 percent figure for operational readiness is not unusually low. Experts indicate that other weapon systems are experiencing the same or even lower operational readiness. Consider the SH-2F. Operational readiness data for that aircraft are presented in Table 2.

At first glance, the SH-2F appears to have a much higher level of operational readiness, (71 percent, as compared to 58 percent for the F-14A). However, when only the FSC portion of operational readiness is considered, SH-2F OR drops to 49 percent, which is about the same as the F-14A.

TABLE 1. ANALYSIS OF F-14A OPERATIONAL READINESS

RMCM-S (Reduced Material Condition for Maintenance - Scheduled)	0%
RMCM-U (Reduced Material Condition for Maintenance - Unscheduled)	3%
NFE (Not Fully Equipped)	3%
FSC (Full Systems Capability)	52%
Total Operational Readiness (OR)	58%

TABLE 2. ANALYSIS OF SH-2F OPERATIONAL READINESS

RMCM - S	0%
RMCM -U	3%
NFE	19%
FSC	49%
OR	71%

The difference is apparently due to the fact that the SH-2F is basically a single aircraft detachment. Therefore, it often flies a mission without being fully equipped -- wherein all the functional requirements probably cannot and/or are not being met.

Only a few decades ago, missle systems were expected and able to achieve an OR figure of 80 percent or higher. Often, the OR percentage was in the 90s. An operational readiness of 49 to 58 percent in the systems of today represents a decline of significant proportions.

Cost of Maintenance

The true cost of maintenance inadequacies is reflected in the Not Operationally Ready (NOR) parameter. NOR means that the aircraft has lost its value as a weapon system during a particular period of time. Thus, the NOR aircraft represent an important cost item.

Each F-14A is priced at $21 million. However, operational readiness is such that this $21 million delivers only 0.58 aircraft per year. The NOR proportion thus equals .42. Assuming 15 operational squadrons and 11 aircraft per squadron, the value of the NOR aircraft inventory is 15 squadrons x 4.62 NOR aircraft x $21 million = $1.455 billion.

A similar estimate can be made for the forthcoming LAMPS. According to the Los Angeles Times, the Navy plans to acquire 204 LAMPS Mark III Helicopters for $3.5 billion. Using the SH-2F OR/NOR data, the value of the NOR inventory will be $3.5 x 0.29 = $1.015 billion. This NOR value increases considerably if the NFE is included as partial NOR. If we consider half the NFE in our analysis, the NOR increases to 38.5 percent and the value of the NOR inventory increases to $1.35 billion.

Obviously, the value of NOR aircraft is quite large. Even a small reduction of the NOR inventory represents considerable savings. An important question is whether there is any indication or evidence that better design for the maintainer can reduce the NOR inventory.

Measures of Maintenance Technician Effectiveness

Given that maintenance costs are increasing while weapon system availability is declining, a question arises as to the possible causes. One thesis of this project is that one of the major contributors to the problem is the maintenance technician. He is performing well below his natural potential. As a further thesis, it is contended that the technician's performance is inhibited by certain factors in weapon system design.

In the paragraphs that follow, measures of effectiveness are described providing support for these contentions. These measures are based on intensive analysis of 3-M data and experience with a simulation model designed to process the data. The measures of interest are: error rate, elapsed maintenance time, and maintenance manhours.

Maintenance Error Rate

Three types of maintenance errors are disclosed by 3-M data. These are Type I errors, Type II errors, and Type d errors. A Type I error occurs when a good unit is removed erroneously. A Type II error occurs when a bad or malfunctioning unit is not found, which often results in the wrong thing being repaired. A Type d error occurs when the maintenance activity produces damage or malfunction in the system.

The different types of maintenance errors indicate different problems associated with design for the maintainer. Type I error is mostly a troubleshooting problem. That is, the technician removes a good item because he cannot locate the cause of the problem. Associated design problems relate primarily to the inadequacies of information relevant to troubleshooting.

Type II error is usually committed in checkout. That is, the technician can't verify the "squawk." The design problems associated with checkout are similar to those related to troubleshooting

Type d error is associated primarily with handling. It is reflected in problems of accessibility, exposed components, inadequate protection, etc.

These different types of errors occur with varying frequency depending on the kinds of equipment involved. The variation is shown in Table 3, where error rates are listed for the different organizational level work centers supporting the F-14A.

TABLE 3. SUMMARY OF ERROR RATES FOR THE F-14A WORK CENTERS

WORK CENTER	ERROR RATE TYPE I	 TYPE II & d
POWER PLANTS (110)	5.9	15.9
AIRFRAME (120)	6.8	16.0
CORROSION CONTROL (121)	0.	6.4
AVIATOR EQUIP (131)	0.	4.1
SAFETY EQUIP (132)	17.8	11.0
ELECTRONICS (210)	13.0	8.5
ELECTRICAL INST (220)	17.7	6.7
ARMAMENTS (230)	5.4	6.6
ELECTRO-WEAPS CONTROL (232)	15.8	7.3
TROUBLESHOOTERS (320)	0.	12.5
AVERAGE FOR ALL WORK CENTERS	14.5	9.8

Note that Type I errors are more prevalent in the electronic and electrical work centers, such as 132, 210, 220, and 232. Conversely, Type II and Type d errors predominate in those work centers concerned with mechanical equipment such as power plants (110) and airframe (120).

The analysis by subsystem in Table 4 is even more revealing. There, the subsystem with the highest Type I error rate is seen to be the AWG-9. The AWG-9 has been extensively automated to support maintenance. The data indicate that much of that effort may have been counterproductive.

The AWG-9 On Board Computer/Built-In Test Equipment (OBC/BITE) errs 12 percent of the time. In addition, the technicians commit Type I errors 21 percent and Type II and/or d errors 7 percent of the time. This could mean that technicians learn to suspect the OBC/BITE and go on their own. However, what the technicians do not realize is that their own error rate is even higher.

Continuing with Table 4, note the 34 percent Type II/d rate for the TF-30 Engine. Almost all of this is Type d error. This means that every three maintenance actions result in one or more malfunctions (damage) created by the technicians. Undoubtedly, much of this damage is due to hardware design characteristics.

Similar problems are seen in the SH-2F data, presented in Table 5. Although the damage error rate for the T-58 Engine is not as high as the error rate for the TF-30 Engine, it is still quite high. The Type d error rate is also high for the Main Rotor System, another mechanical system. The data tend to indicate that more effective design for the maintainer could have a significant impact on the OR/NOR ratio.

An interesting fact about Table 5 is the absence of any electronic subsystems. Although the concern for electronic maintenance problems in general is valid, the data indicate that the problems in other areas are even greater.

TABLE 4. ERROR RATES OF THE FIVE F-14A SUBSYSTEMS WITH THE GREATEST MAINTENANCE BURDEN

SUBSYSTEM	WORK CENTER	% ERRORS			
		TYPE I*	TYPE II/d**	BAD PARTS	OBC/BITE***
AWG-9	Electronics/Weapons Cntl (232)	21	7	3	12
TF-30 Engine	Power Plants (110)	1	34	-	-
Flight Reference Equip	Electrical/Instr (220)	19	3	-	-
AN/APX 76 & 72	Electronics (210)	13	11	2	-
Flight Hydraulic Power Sys	Airframe - Hydraulics (120)	10.4	18	-	-
All Subsystems	All Work Centers	14.5	9.8	1	2

* Removed/Replaced WRA declared "BAD" actually "GOOD"

** Completed repair declared "GOOD" actually "BAD"

II - wrong thing repaired
d - maintenance induced damage/improper maintenance

*** On Board Computer/Built-In Test Equipment

TABLE 5. ERROR RATES OF THE FIVE SH-2F SUBSYSTEMS WITH THE GREATEST MAINTENANCE BURDEN

SUBSYSTEM	WORK CENTER	MTBCMA* (Flt hrs)	% CM Actions	% CM Manhours
Fuel Sup/Dist	Line Division-300 (All Ratings)	8.23	5	5
T-58 Engine	Line Division-300 (All Ratings)	8.74	5	7
Main Landing Gr	Line Division-300 (All Ratings)	8.79	5	5
Main Rotor System	Line Division-300 (All Ratings)	8.83	5	5
Int/Ext Lighting	Line Division-300 (All Ratings)	10.76	4	2
All Subsystems	All Ratings	0.43**	100%	100%

*MTBCMA - Mean Time Between Corrective Maintenance Actions

**NOTE: The average sortie lasts 1.88 flight hours which means that after a typical sortie, the "bird" returns with an average requirement for 4.37 corrective maintenance actions.

Elapsed Maintenance Time (EMT)

The term EMT refers to the time the aircraft is down for maintenance of a particular system. It denotes active maintenance time only and does not include delays due to lack of other support. When examining EMT, it is useful to present the data in the form of a curve representing cumulative actions versus elapsed time. Such a curve is shown in Figure 1.

This curve was derived from the 3-M data base relative to the F-14A Flight Hydraulic Power System. Two points may be made from inspection of the data shown here. One concerns elapsed time as such. The other concerns the shape of the EMT curve.

Elapsed Time. Half the maintenance actions are completed in an EMT of 2.25 hours or less. That value appears reasonable. But at the opposite extreme, a quarter of the actions require between 4.2 and 12.0 hours of elapsed time on the part of two to four men. That value seems excessive. Experience indicates that most of the high EMT is due to errors and equipment design. Often, the two are related, i.e., poor design fosters errors. Unlike the Types I, II, and d errors, these errors are self-detected and corrected by the same technician. Thus, they do not get counted as errors. Instead, the EMT becomes inflated by their presence.

It is tempting to assume that the limited space available in the F-14A caused packaging and accessibility problems which resulted in the high EMT values. Undoubtedly, dense packaging resulting from space limitation is a major contributor. However, the equally high Type d errors on the SH-2F would indicate that the problem is caused by far more than merely dense packaging.

Shape of EMT Curve. For many years, it has been taken for granted that EMT is distributed exponentially. Yet, detailed analyses of maintenance tasks or steps seldom justify such a distribution. That is, detailed time-line analyses of the tasks required of technicians seldom provide any clues as to why the distribution should be other than normal. The time-line data usually indicate that the EMT should be considerably shorter than what we are currently experiencing.

Maintenance Manhours (MMH)

The MMH portion of the 3-M data bank must be treated very carefully. Technicians and/or managers tend to make MMH entries to justify overtime, more manpower, etc. Also, the "buddy system" tends to inflate the MMH data. Nevertheless, relative MMH data are still useful. Consider the data shown in Table 6. MMH per flight hour (FH) are compared for the F-14A and the SH-2F.

The corrective MMH for the F-14A is over 2.6 times greater than the corrective MMH for the SH-2F. This would tend to support the argument that a major contributor to the problem is the space limitations of the F-14A.

However, there probably are other design problems common to both the F-14A and the SH-2F. For example, even with the lower MMH/FH, the Full Systems Capability (FSC) for the SH-2F (49%) is no better than the FSC for the F-14A (52%). This would indicate that the SH-2F requires less manpower but the effectiveness of maintenance is about the same.

Probably the most alarming part of the MMH/FH ratio is how high it is. For every flight hour of the F-14A, an equivalent of five men working a full day is needed to maintain the aircraft. Even for the SH-2F, each flight hour requires an equivalent of three men working a full day to maintain the aircraft.

Personnel assignment policies alone do not explain the excessively high MMH/FH. Design characteristics clearly should be investigated as contributors to the problem.

Summary

The cost of weapon system maintenance is rising while operational readiness is falling. Evidence has been presented suggesting that one of the contributors to this problem is less-than-adequate performance by the maintenance technician. It is contended that a major cause of inadequate technician performance is the design of the weapon system.

MAINTENANCE ERRORS

In the past, analysts have used time-related measurements (such as maintenance manhours) as the primary measures of maintenance performance. However, as previously suggested, measurements of maintenance errors appear to provide much greater guidance to the source of ineffective maintenance practice.

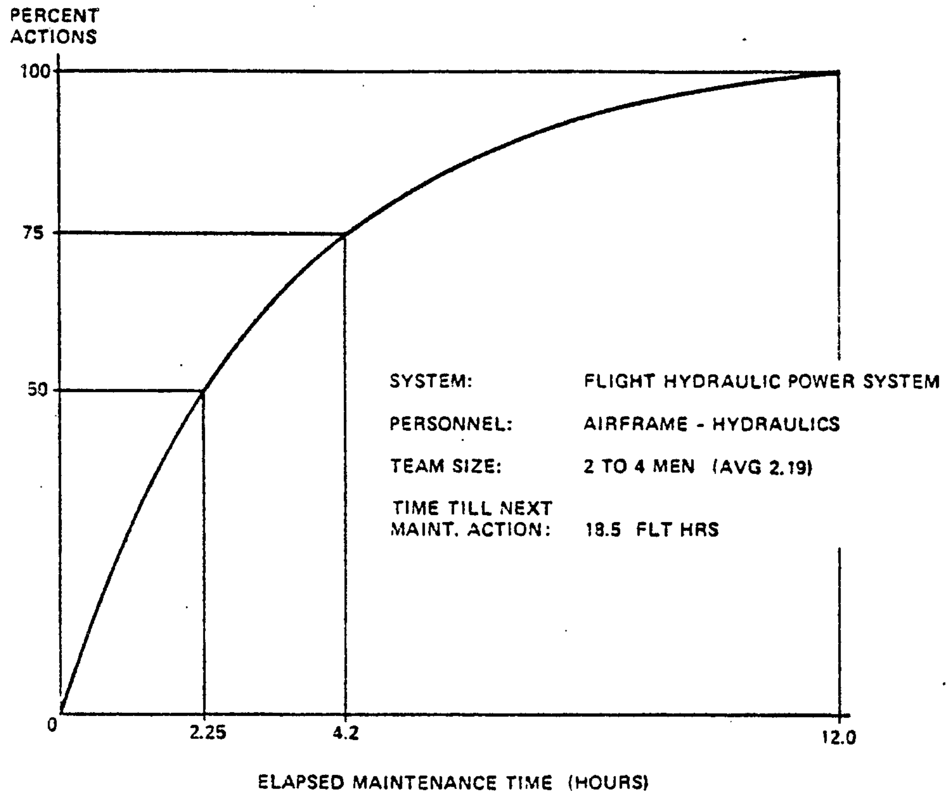


Figure 1. EMT Curve for the Flight Hydraulic Power System

TABLE 6. MMH/FH COMPARISONS FOR THE F-14A AND SH-2F

	F-14A	SH-2F
TOTAL* MMH/FH	43.2	24.7
PLANNED MAINT	6.4	3.2
CORRECTIVE MAINT	16.4	6.2

* Total includes all support actions (SAF) and technical directive compliance (TDC) as well as planned and corrective maintenance.

Curiously, little systematic study has been applied to the problem of errors committed by maintenance technicians. Major efforts have been made to measure and control performance time, but performance quality has gone unquestioned. In this respect, the maintenance research community has taken the same path as was taken earlier by the reliability community. Neither has constructed a viable method of dealing with the errors they know are occurring.

The main problem has been in finding a practical way of measuring both performance time and performance quality, including the inter-relations they represent. These are the elements that comprise the true variable, maintenance effectiveness. Measuring performance quality has rarely been accomplished. Direct detection of errors by special observers, or reliance on technicians themselves to report their own errors, has not been practical.

Xyzyx has devised a means of extracting error rates from 3-M data. Error measurement appears entirely feasible, given the real-world data of the quality provided by the 3-M System. All of the error measurements described here are geared to records normally compiled by 3-M, and identified by number in the 3-M Catalog.

In the discussion that follows, maintenance errors are examined under three headings:

- Kinds of Errors
- Effects of Errors
- Measurement of Errors

The dynamics of errors tend to be similar in nature, regardless of the nature of the maintenance environment. However, the discussion here applies specifically to organizational maintenance on carrier-based Navy aircraft.

Kinds of Errors

Error definition was introduced earlier. It is reiterated here for reader convenience. As shown in Table 7, maintenance errors may be conveniently sorted into three categories: Type I, Type II, and Type d.

A Type I error occurs when the technician troubleshoots the equipment and concludes that a particular unit has failed when, in fact, it has not.

A Type II error occurs when the technician checks out the equipment and concludes that it is okay when, in fact, it contains a defect.

TABLE 7. KINDS OF MAINTENANCE ERRORS

TYPE OF ERROR	EXPLANATION OF ERROR	TYPICAL SOURCE OF ERROR
I	Technician replaces a unit that has not malfunctioned.	Troubleshooting
II	Technician fails to recognize a unit that has malfunctioned or been improperly handled.	Troubleshooting; checkout
d	Technician fails to accomplish a corrective or preventive action properly.	Removal/Installation; service; repair; adjust

A Type d error occurs when the technician damages the equipment or performs a corrective or preventive maintenance action improperly. Examples would be loose connectors, mismatched parts, improper alignment, and inadequate servicing.

The method of categorization used here reflects the manner in which records are kept in the 3-M System. This is very important to the overall effort. Any measurement method seeking to impact the Naval air maintenance community must be as consistent as possible with the 3-M System and its associated data base.

A key fact seen in Table 7 is that each type of error tends to be associated with its own particular maintenance function or functions. This link will be referred to again later in the report, in connection with both design factors and data processing.

Effects of Errors

The effects of the three types of maintenance errors are summarized in Table 8. As shown there, errors may be discovered during post-job inspection, before a flight, or during a flight. Following discovery, the effects may be to abort the flight, repeat the maintenance function, use spare parts wastefully, place an unnecessary load on intermediate maintenance, and, of course, incur a risk of injury or accident.

Abort Flight

Other than the risk of injury or accident, which is present whenever an error is committed in aviation maintenance, the most serious effect of error is an aborted flight. All equipment items do not share equally in this risk. Flights are aborted only when critical components are involved. Criticality is determined by pre-established criteria. Note that errors detected and corrected during post-job inspection normally do not cause a flight to be aborted. Note also that the abort effect is identical for all three types of errors.

Repeat Function

This effect points up the cardinal rule of maintenance productivity: "Every error, regardless of the circumstances, creates a need for rework." Errors thus represent sheer dead weight in the system.

TABLE 8. EFFECTS OF MAINTENANCE ERRORS

Kind Of Error	When Error Is Discovered	Effects				
		Abort Flight	Repeat Function	Use Spare Wastefully	Place Load On IMA	Risk Injury/ Or Accident
I. Good Unit Replaced	Post-Job Inspection		● (B)	●	●	●
	Before Flight	● (A)	● (B)	●	●	●
	During Flight	● (A)	● (B)	●	●	●
II. Bad Unit Not-Replaced	Post-Job Inspection		●			●
	Before Flight	● (A)	●			●
	During Flight	● (A)	●			●
d. Repair Done Incorrectly	Post–Job Inspection		●	● (C)	● (D)	●
	Before Flight	● (A)	●	● (C)	● (D)	●
	During Flight	● (A)	●	● (C)	● (D)	●

(A) Flights aborted by critical equipment items only.
(B) "Function" includes troubleshooting & repair.
(C) Spare parts wasted only when broken.
(D) Load placed on IMA only when broken part repairable.

The extent of the necessary rework varies with the type of error. For Type II and Type d errors, rework is usually limited to the offending maintenance function, i.e., checkout or repair. For Type I errors, however, the rework is usually more extensive. Not only does troubleshooting have to be repeated, but the associated corrective action must be repeated.

Rework produces two kinds of negative results. First, and most obviously, it increases the direct cost of maintenance by requiring the presence of a larger-than-optimum staff. Second, it impedes the work schedule, thus fostering the creation of queues, wherein jobs are waiting for people. In this latter sense, excessive demands for rework always impinge upon aircraft availability.

Use Spares Wastefully

Spare parts are used wastefully in two of the three types of error situations, regardless of the time of discovery. The parts problem is avoided only in those cases where the error is failing to see that a replacement is necessary.

The greatest waste of spare parts probably occurs in troubleshooting because of the trial-and-error approach taken by so many technicians. It is true that good units removed in error may be used again after being recycled through Intermediate Maintenance Activity (IMA). Nevertheless, while they are in that (recycling) mode, they are not available for re-issue. Temporary shortages are thus generated, often leading to reductions in aircraft availability.

The waste may be less in the Type d (improper repair) category, because so many repairs can be corrected without the need for new parts. However, that situation is counterbalanced by the occasional repair error that causes such serious damage that the broken parts cannot be mended, even in IMA. In such cases, the spares inventory is impacted permanently.

Place Load on IMA

Intermediate maintenance shops are burdened unnecessarily every time a part is replaced in error. The Type I error committed in troubleshooting contributes to the problem. IMA must handle all such parts as though they were defective. In fact, only after inspection and/or testing at IMA is it safe for the parts to be declared ready for issue. Since such parts enter IMA without defect, all work done on them must be regarded as wasted effort. The result is an increase in the direct cost of maintenance.

The dynamics are slightly different when repair is done incorrectly at the organizational level (Type II/d error). In such cases, parts go to IMA only if they are damaged. The nature of the waste lies in the time spent by IMA in mending the broken parts. This waste is relieved only when the parts are broken so badly that they cannot be repaired.

Risk of Injury or Accident

As indicated earlier, the risk of injury or accident is present every time an error is committed in aircraft maintenance. Depending on severity, injuries and accidents may impact all aspects of maintenance and operational productivity. That is, they can affect direct costs, aircraft availability, personnel availability, the spares inventory, support equipment availability, and even facility availability. Injuries and accidents are thus known to be highly disruptive of normal operations.

Measurement of Errors

All of the error measurements described here can be obtained from the 3-M System and most can be identified by number in the 3-M Catalog. Where necessary, additional procedures are provided by Xyzyx to guide the analyst in extracting error data from those records.

Type I Error -- Good Unit Replaced

Information on Type I errors is obtained from a 3-M report generated in IMA. The report is MSOD 4790.A2551-01, "No Defect Item Analysis Summary." This report summarizes equipment items processed by Aircraft Intermediate Maintenance Departments for which reported defects could not be duplicated. Such items thus reflect erroneous removals from the aircraft.

Type II Error -- Bad Unit Not Replaced

Information on Type II errors is obtained by a time-sequence analysis of 3-M records CT11, CT21 and CT41. The analysis is inferential in nature. Where successive flights are accompanied by corrective maintenance actions on the same system, and those actions suddenly stop, a particular condition may be inferred. That is, the final corrective action was successful, but each preceding action must have been in error. Analysis for Type II errors requires engineering knowledge covering system equipment, operating theory, and maintenance practices.

Type d Error -- Repair Done Incorrectly

Information on Type d errors is obtained from malfunction codes used on 3-M records CT11 and CT21. Two subsets of the Malfunction Code list appear in Tables 9 and 10. The codes shown in Table 9 indicate the definite occurrence of a Type d error. The codes shown in Table 10 indicate a probable Type d error.

Probable errors must be verified through reverse time sequence analysis wherein records are checked for prior maintenance actions. If the equipment has been worked on in the two days immediately preceding discovery of the problem, the defect is assumed to have been induced by maintenance rather than by equipment failure. Engineering knowledge is needed to distinguish between equipment failure and maintenance error.

Error Rate

Error rate is expressed as a percentage of the number of relevant corrective maintenance actions. The denominator includes only the maintenance actions in which the particular category of error could be committed. Thus, the denominator for Types I and II errors are all maintenance actions minus cannibalization. However, the denominator for Type d error is all maintenance actions, including cannibalization. As a rule, error rates are determined at the subsystem level by work center. This level is identified by the first three digits of the Work Unit Code (WUC).

Summary

Three kinds of maintenance errors have been defined. Each has been examined to disclose the kinds of effects it produces. Effects include abort flight, repeat function, use spares wastefully, place load on IMA, and risk injury or accident. Methods of error measurement have been described and shown to be feasible, given real-world data of the quality provided by the 3-M System.

SYSTEM DESIGN AND SUPPORT FACTORS AFFECTING MAINTENANCE

Maintenance performance at the organizational level is influenced by the nature of the aircraft design and the interplay of its various support elements. In this section, factors within design and support are examined for their general characteristics and direction of effect.

TABLE 9. MALFUNCTION CODES INDICATING DEFINITE TYPE d ERROR

CODE	DESCRIPTION
086	Improper handling
087	Improper identification
246	Improper or faulty maintenance
301	Foreign object damage (FOD)
304	FOD-Self inducted
651	Air in system
931	Inadvertent operation

TABLE 10. MALFUNCTION CODES INDICATING PROBABLE TYPE d ERROR

CODE	DESCRIPTION
093	Missing part
105	Loose bolts, nuts, screws, rivets, fasteners, etc.
106	Missing bolts, nuts or screws
108	Broken, faulty, or missing safety wire or key
127	Adjustment or alignment improper
135	Binding, stuck, jammed
410	Lack of, or improper lube
730	Loose

In the paragraphs that follow, the work of maintenance is interfaced with the performance measures introduced earlier. After that, key factors in design and support are examined for their effects on those measures.

Maintenance Functions and Performance Measures

The work of maintenance is best expressed in terms of maintenance functions, e.g., troubleshoot, remove/replace, service, and so on. At the organizational level, maintenance functions may be sorted into two general categories, as shown in Table 11. The functions in one category are concerned with assessing system status. The functions in the other category are concerned with correcting or preserving system condition. The functions thus represented cover both corrective and preventive maintenance.

Functions for assessing system status are information-oriented in nature. They consist of troubleshooting and checkout, within which reside lower-level tasks including operate, test, and inspect. Normally, decision-oriented tasks apply at the system level. Their object is to obtain data needed to answer questions about the condition of the system.

Functions for correcting or preserving system condition are action-oriented in nature. They consist of remove/install, repair-in-place, and service. Repair-in-place includes lower-level tasks such as adjust, align, and replace piece parts. Service includes tasks such as clean and lubricate. Normally, action-oriented tasks apply at the unit level. Their object is to bring the system into compliance with established criteria by acting on units within the system.

Using the maintenance performance measures defined earlier, the following steps can be taken relative to effectiveness evaluation:

- The effectiveness of maintenance functions for assessing system status can be measured in terms of the Type I error rate.
- The effectiveness of maintenance functions for correcting or preserving system condition can be measured by the Type II/d error rate.
- The effectiveness of all maintenance functions can be measured by elapsed (active) maintenance time.

With this connection made, we can now look at system design and support, and examine the effects of each on maintenance performance.

TABLE 11. MAINTENANCE FUNCTIONS SORTED BY PURPOSE

PURPOSE	FUNCTION	DESCRIPTION
To assess status of system	Troubleshoot	The process of isolating a system problem to a removable unit or to a repairable item.
	Checkout	The process of determining whether a system is in an operational condition. (Troubleshoot and Checkout include other tasks such as operate, test, and inspect.)
To correct or preserve condition of system	Remove/Install	The process of taking out a unit and putting another unit in its place.
	Repair-in-Place	The process of correcting a malfunction without replacing a unit. (Repair-in-Place includes other tasks such as adjust, align, and replace piece parts.)
	Service	The process of replenishing consumables or restoring the system/equipment. (Service includes other tasks such as lubricate.)

System Design Factors Affecting Maintenance

System design is the physical means through which the engineer seeks to promote maintenance effectiveness by reducing error rate, elapsed maintenance time, and maintenance workloads. System design factors affecting maintenance are summarized in Table 12 and explained further in the paragraphs that follow.

Design Factors Affecting Assessment of System Status

System status can be assessed by using symptoms and cues. Symptoms are system outputs that fall beyond allowable operating limits. Cues are bits of information concerning the relationships among the constituent parts of the system. Cues help identify the cause of system failures in terms of parts not performing as designed.

As a general rule, symptoms are relatively easy to define and are readily available for observation. The problem for the technician in status assessment is recognizing and interpreting the cues. The problem for the designer is to assure that cues are furnished in a usable form.

Cues indicating system status occur on at least three points of a continuum. At one end are natural cues. At the other end are processed cues. Between these extremes are cue measurement provisions.

Natural cues are most typically found in mechanical systems where the parts relate to each other in concrete and observable ways. Parts move in predictable patterns; they become worn, loose, misaligned, and broken; they react to heat and pressure; they make noises. Natural cues correlate highly with system output, thus providing valuable information with little help from the system designer. Natural cues can be identified by the technician by a relatively simple inspection.

Processed cues are most typically found in electronic systems, where relationships among the parts are not readily observable. The designer must provide for sensing, measurement, and indication. Processed cues may be relatively simple, such as flight indicator malfunction flags, or extremely complex, such as those driven by digital computers. If correctly designed, processed cues demand from the technician little more than acknowledgement of final results.

TABLE 12. SYSTEM DESIGN FACTORS SORTED BY MAINTENANCE PURPOSE

MAINTENANCE PURPOSE	MAINTENANCE FUNCTION MEASURE	SYSTEM DESIGN FACTORS
To assess status of system	Troubleshoot Checkout Type I Error Rate Elapsed Maintenance Time*	Provision of: Status information Action ease (on test equipment)
To correct or preserve condition of system	Remove/Install Repair-in-Place Service Type II/d Error Rate Elapsed Maintenance Time*	Provision of: Physical access Visual access Action accuracy Action ease Secondary damage prevention Handling ease Unit, feature identification Procedural information Personal safety
None	None Mean Time Between Maintenance Actions	Reliability

* Elapsed maintenance time is time spent actually doing the work (active maintenance time). It does not take into account the effects of multiple-man work crews.

Cue measurement provisions are needed when natural cues do not suffice and processed cues are not feasible. Examples of cue measurement provisions are electrical test points and wear bars on tires. Cue measurement provisions must be provided by the designer. By definition, such provisions require action from the technician in the form of testing and inspection.

Systems that provide natural cues have little adverse effect on the maintenance error rate but inadequacies may increase elapsed maintenance times. Natural cues require human judgment for correct interpretation. Where experienced judgment is lacking, cues are often misinterpreted initially, then corrected later in the same maintenance action. The penalty in such cases is an excess of repair time rather than undetected errors.

Systems that provide processed cues may have widely variable effects on the maintenance error rate. To produce maximum reduction of error rate, processed cues must have high validity (in terms of their correlation with system malfunctions) and low ambiguity in displayed results. Further, to the extent that the technician is called upon to resolve the results when they are ambiguous, the technician must be given enough information to perform that role effectively. Systems dependent on processed cues not meeting these requirements tend to exhibit high maintenance error rates.

One source of such error is incomplete provision for measurement opportunities. Another source is excessive demand for reasoning by the technician. Either type of hardware deficiency can create problems. Therefore, both must be given close attention by the prime equipment designer.

Provisions for cue measurement often necessitate the use of support equipment. In such cases, the design of the support equipment can have a bearing on maintenance effectiveness. The support equipment must provide for ease of action (as discussed later in this section). Where ease of action is not promoted, the most typical consequence is an increase in elapsed maintenance time. Maintenance errors seldom result, unless the equipment is so difficult to use that the technician attempts to do without it.

Design Factors Affecting Correction or Preservation of System Condition

Design factors affecting correction or preservation of system conditions are covered quite well in MIL-STD-1472B, Section 5.9, Design for Maintainability. For purposes of convenience, these factors are represented here under a small number of key headings:

- Physical access
- Action accuracy
- Action ease

Each heading is discussed briefly in the paragraphs that follow. Examples are given from MIL-STD-1472B.

Physical Access. Physical access concerns the relative location of equipment. It is important in all maintenance tasks requiring movement or manipulation of hardware items. It always involves physical obstructions in one form or another, and the means of avoiding them. Where such obstructions are removable prior to reaching the object unit, they influence maintenance time. Where obstructions are not removable, they may influence both maintenance time and the Type d error rate. Some examples of access provisions in MIL-STD-1472B are:

> 5.9.4.4 Rear Access Units - Sliding, rotating or hinged units to which rear access is required shall be free to open or rotate their full distance and remain in the open position without being supported by hand. Rear access shall also be provided to plug connectors except where precluded by any other operational requirements.
>
> 5.9.4.5 Relative Accessibility - In determining the relative accessibility of units, those units which are critical to system operation and which require rapid maintenance shall be most accessible. When relative criticality is not a factor, those units requiring most frequent access shall be most accessible.
>
> 5.9.4.6 High-Failure-Rate Items - The physical arrangement of units and components should be such that high-failure-rate items will be accessible for replacement without moving non-failed components or units. Mechanical replacement items shall be removable with common hand tools and simple handling equipment.

Action Accuracy. Design provisions for action accuracy represent direct efforts to prevent maintenance errors. They may take various forms. One is by constraining incorrect actions. Another is by providing information enabling incorrect actions to be avoided or corrected. Action accuracy provisions may influence both the Type d error rate and maintenance time. Some examples of action accuracy provisions in MIL-STD-1472B are:

> 5.9.12.4 Alignment - Guide pins or their equivalent shall be provided to assist in alignment during mounting, particularly on modules that are connectors themselves.

5.9.12.5 Coding - All replaceable items shall be coded (i.e, keyed) so that it will be physically impossible to insert a wrong item. Coding by such means as color or labels shall identify the correct item and its proper orientation for replacement.

5.9.8.2 Instructions - If the method of opening a cover is not obvious from the construction of the cover itself, instructions shall be permanently displayed on the outside of the cover.

Action Ease. Design provisions on behalf of action ease seek to align the maintenance task with the known limitations and capabilities of the technician. Such provisions aim to reduce the demand for skill, strength, time, and even patience on the job. The relative degree of action ease built into the hardware may influence both the Type d error rate and maintenance time. Some examples of action ease provisions in MIL-STD-1472B are:

5.9.10.8 Number of Turns - Fasteners for mounting assemblies and sub-assemblies shall require only one complete turn, provided that stress and load considerations are not compromised. When bolts are required, the number of turns needed to tighten and loosen them shall be minimized.

5.9.11.2 Extensions - Irregular, fragile, or awkward extensions, such as cables, wave guides, hoses, etc., shall be designed for easy removal from a unit before the unit is handled.

5.9.7.4 Guides - Guides, tracks, and stops shall be provided as necessary to facilitate handling and to prevent damage to units and components, and injury to personnel.

5.9.11.4 Horizontal Push and Pull Forces - Manual horizontal push and pull forces required, to be applied initially to an object to set it in motion or to be sustained over a period of time, shall not exceed the values of Table XXII [not shown here], as applicable.

Hardware Reliability

One other design factor critical to the maintainer is hardware reliability. While reliability changes nothing about the performance of any given action, it exerts a powerful influence on the frequency with which that action must be taken. The higher the reliability, the greater the time between maintenance actions, and hence the lighter the workload on affected personnel.

Summary

The effects of system design on maintenance performance are summarized in Table 13. The data there show the following relationships:

- Provisions for status information affect the Type I error rate and active maintenance time.
- Provisions for physical access, action accuracy, and action ease affect the Type II/d error rate and active maintenance time.
- Hardware reliability affects only the maintenance work load.

Status information and action ease concern troubleshooting. Physical access, action accuracy, and action ease concern maintenance actions aimed at correcting or preserving system condition. Hardware reliability influences the frequency with which maintenance actions must be taken.

System Support Factors

It has been shown that system design has an impact on all key measures of maintenance performance at the organizational level. In the paragraphs that follow, system support factors are considered in connection with these same measures. The support factors involved are facilities and equipment, spares, manning, technical information, and maintenance management.

Facilities and Equipment

Facilities and equipment are vital to maintenance, but as a general rule, they have limited influence on maintenance error rates or active maintenance time. They also have limited influence on any of the other listed support factors.

Facilities and equipment can, however, directly affect administrative and supply downtime, as a function of their availability when needed.

Spares

Spares influence maintenance performance in a manner similar to that described for facilities and equipment. They directly affect supply downtime only.

TABLE 13. EFFECTS OF SYSTEM DESIGN FACTORS ON MAINTENANCE PERFORMANCE

SYSTEM DESIGN FACTOR EXERTING EFFECT	MAINTENANCE PERFORMANCE MEASURES AFFECTED			WORK LOAD AFFECTED
	TYPE I ERROR RATE	TYPE II/d ERROR RATE	MAINTENANCE TIME*	
STATUS INFORMATION	Yes	No	Yes	No
PHYSICAL ACCESS	No	Yes	Yes	No
ACTION ACCURACY	No	Yes	Yes	No
ACTION EASE	No	Yes	Yes	No
HARDWARE RELIABILITY	No	No	No	Yes

* active (elapsed) maintenance time

Spares have no effect on active maintenance time, maintenance error rate, or any of the other listed support factors.

Manning

Maintenance manning directly affects all measures of maintenance performance. Technical personnel can vary widely in both quality and quantity. Personnel quality influences performance in terms of error rate and active maintenance time. Personnel quantity influences administrative downtime as a function of the availability of personnel when needed.

Manning also exerts indirect effects on maintenance performance. Manning quality influences the demand for spares. As the need for spares varies, supplydown time varies also.

Technical Information

Technical information is delivered to maintenance personnel through training and publications. Training seeks to place information into long-term memory. Publications aim to provide a reference file for use in the job environment.

Where technical information is incomplete, inaccurate, or low in usability at the point of need, it can increase both the error rate and active maintenance time. However, technical information has no effect on administrative and supply downtime.

Technical information has no effect on facilities and equipment, but it does influence spares, manning, and management.

Technical information affects spares by altering the error rate. It affects manning by influencing personnel performance, quality, and flexibility. It affects management by altering the number of options available to supervisors. These options concern technician development and work assignment.

Maintenance Management

Maintenance management covers both supervision and higher-level planning. Technical supervision can directly influence the error rate and active maintenance time, through day-by-day methods of motivating, developing, and disciplining personnel.

Higher-level planning can directly affect the error rate and administrative downtime through the application of priorities in scheduling.

Like technical information, maintenance management has no effect on facilities and equipment but does influence all other listed maintenance support factors.

Management affects the availability of spares by its handling of the diagnostic function. The demand for spares is highly sensitive to diagnostic accuracy. Trial and error methods tend to be wasteful of spares. Where management priorities emphasize work speed rather than accuracy, the problem is aggravated further.

Management affects manning in maintenance in the same way as is seen elsewhere. Supervisory quality influences personnel motivation and development. These factors, in turn, impact the error rate, active maintenance time, and willingness to remain in service.

Management affects technical information by establishing rules concerning its use. Management can encourage or discourage technicians from referring to publications for help; it can use or ignore information designed to promote personnel development. Where management properly exploits high-quality information, the error rate declines, active maintenance time decreases, and low-skill personnel become available for a wider range of assignments.

Summary

The effects of the various support factors on maintenance performance are summarized in Table 14. The data there indicate that the support factors with the greatest influence are maintenance management and technical information. The factors with the least influence are facilities and support equipment, and spares. Manning has a strong direct influence but has little effect on other support factors.

Facilities and support equipment, and spares have little or no effect on the error rate or active maintenance time but do influence other downtime.

Manning, technical information, and maintenance management influence the error rate, active maintenance time, and administrative and supply downtime. Such downtime includes time waiting for spares, equipment, and personnel.

TABLE 14. EFFECTS OF SYSTEM SUPPORT FACTORS ON MAINTENANCE PERFORMANCE

SYSTEM SUPPORT FACTOR EXERTING EFFECT	MAINTENANCE PERFORMANCE MEASURES AFFECTED			FACTORS AFFECTED				
	ERROR RATE	ELAPSED MAINT. TIME *	OTHER DOWN TIME **	FACILITIES AND EQUIPMENT	SPARES	MANNING	TECHNICAL INFORMATION	MAINTENANCE MANAGEMENT
FACILITIES AND EQUIPMENT	NO	NO	YES	--	NO	NO	NO	NO
SPARES	NO	NO	YES	NO	--	NO	NO	NO
MANNING	YES	YES	YES	NO	YES	--	NO	NO
TECHNICAL INFORMATION	YES	YES	NO	NO	YES	YES	--	YES
MAINTENANCE MANAGEMENT	YES	YES	YES	NO	YES	YES	YES	--
KIND OF EFFECT	DIRECT			INDIRECT				

* Elapsed maintenance time is time spent actually doing the work (active maintenance time). It does not take into account the effects of multiple-man work crews.

** Other downtime refers to delays in work completion, due to any reason other than elapsed maintenance time.

SECTION II

QUANTITATIVE ASPECTS OF THE PROBLEM

The design-for-maintainer problem is explored quantitatively under the following headings:

- The AMES Model
- Other Research on Link Between Maintenance Effectiveness and System Readiness

THE AMES MODEL

Several key points have been made relative to maintenance effectiveness. One is that maintenance performance is influenced by system design and support factors. Another is that maintenance performance can be measured in terms of error rate and maintenance time. A third point is that a quantitative connection can be made between maintenance effectiveness and system readiness.

From these facts, a linkage can be constructed, from design for the maintainer, through measurements of maintenance effectiveness, to projections of system readiness.

The linkage referred to here has huge implications for weapon system planning. What it means is that maintenance effectiveness correlates with system readiness well enough to function as a predictor. Therefore, any proposed improvement in maintenance effectiveness can be evaluated in advance by projecting a corresponding impact on system readiness. The potential thus exists for conducting cost-effectiveness studies in advance of funding commitments.

Given the validity of this statement, a natural question arises: how can the linkage be exercised efficiently, in the face of a maintenance environment containing so many interacting variables? The answer is simulation modeling. Aircraft Maintenance Effectiveness Simulation (AMES) is a model designed specifically for this purpose.

General Characteristics

The AMES Model is a computer program representing the operating and maintenance environment of a designated squadron of aircraft for a given period of time. Its purpose is to permit the economical study of the various personnel/human factors in maintenance that contribute to aircraft operational readiness.

The operating and maintenance environments are expressed as a set of related functions, such as Dispatch Aircraft, Fly Mission, Conduct Post-Flight Inspection, and Provide Spare Parts. The model exercises each function and its logical relationships with other functions. Information flows from function to function as real-life events are simulated.

Thus, aircraft are dispatched in accordance with a set flight schedule. In the course of their missions relevant subsystems are operated. Some subsystems malfunction, as a reflection of component failure rates. Others perform as intended.

Upon returning to the carrier, the (simulated) aircraft are serviced in the normal manner. Technicians are assigned from duty rosters in established work centers. They perform troubleshooting and corrective maintenance on the malfunctioned subsystems. These actions consume time analogous to that shown in the 3-M records. In some cases, the technicians commit errors.

The effects of time consumption are treated in familiar ways. While working on one job, a given technician is not available for assignment to another. In addition, until that job is completed, the aircraft is considered not operationally ready. As the workload (for a personnel specialty) increases, queues begin to form, wherein jobs are waiting for people. In extreme cases, flights are scrubbed.

The effects of errors are treated in ways that show interaction with other key variables. A troubleshooting error, for example, is "remembered" and allowed to be discovered during a subsequent pre-flight inspection or in-flight operation. If rework is found to be necessary, it is handled in the same manner described for an original job.

Detailed records are kept concerning aircraft status and the availability of all the resources needed for proper maintenance. All variables, including error rate, are expressed quantitatively. Reports are issued tracking operational readiness and other selected measures.

Key Particulars

A complete description of AMES is presented in Aircraft Maintenance Effectiveness Simulation (AMES) Model: Final Report (NAVTRAEQUIPCEN 77-D-0028-1). Provided here, in summary form, are descriptions of three key particulars: inputs required, outputs required, and outputs produced. The model's treatment of variables with undetermined values is also described.

Inputs Required

The inputs to AMES include operating schedules, equipment item reliability values, maintenance manpower levels, time-to-repair values, and personnel error rates. All such data are directly available from existing records. A listing of prominent variables handled by the model appears in Table 15. These inputs are best described in terms of type and form.

Types of Input Data. Six types of input data are used by the model. They are:

- subsystem data
- component data
- manpower data
- planned maintenance data
- multipliers data
- run data

Subsystem data refers to those factors required by the computer to simulate each subsystem of the aircraft. For example, CRITICALITY expresses the probability that a particular component failure in the subsystem causes the aircraft to be NOR (not operationally ready).

Component data refers to a subsystem combined with a work center (a technical maintenance specialty area). As can be seen in Table 15, fourteen variables comprise a definition for each component. Many of these have already been defined for the reader.

Manpower data refers to personnel assigned to work centers. A work center identifies a group of specialized personnel responsible for a designated area of aircraft maintenance.

Planned maintenance data refers to maintenance actions that must be performed on a regular basis. These actions are included in the model because they impose a significant workload on the work centers.

The model identifies the different planned maintenance requirements by performance intervals. Each planned maintenance requirement is divided into several segments. Each segment requires a specified amount of time for the work to be performed. A segment may require work at several centers.

Multipliers data are used to make uniform changes of human performance variables. For each of the components or subsystems, the chosen variable is multiplied by the data multiplier in question. A data multiplier of 1.00 leaves values unchanged. For example, the Type I error rate for

TABLE 15. INPUTS REQUIRED BY AMES MODEL

FORMS OF INPUT DATA	INPUT VARIABLE	TYPES OF INPUT DATA
Integer Variables	Subsystem	Component
	Work Center	Component
	Number of Work Centers	Manpower
	Number of Shifts	Manpower
	Number of CDIs	Manpower
	Number of Seniors	Manpower
	Number of Juniors	Manpower
	PM Type	Planned Maintenance
	Number of Segments	Planned Maintenance
	Number of Work Centers	Planned Maintenance
	PM Work Center	Planned Maintenance
	PM Number of Men	Planned Maintenance
Real Variables	Criticality*	Subsystem
	Facilities*	Subsystem
	RIP Inventory*	Component
	RR Inventory*	Component
	RR Inventory Part Bad*	Component
	Error I*	Component
	Error II/d*	Component
	MTBF	Component
	MTBND	Component
	Mean Technicians	Component
	Length of Shift	Manpower
	Segment Time	Planned Maintenance
	Error Type I Multiplier	Multiplier
	Error Type II/d Multiplier	Multiplier
	Elapsed Maintenance Hours Multiplier	Multiplier
	Parts Bad from Supply Multiplier	Multiplier
	No Defect Multiplier	Multiplier
Compound Variable	Action Taken*	Component
Distribution Variables	Facilities Delay Time*	Subsystem
	RIP Parts Delivery Time*	Component
	RR Parts Delivery Time*	Component
	Elapsed Maintenance Hours*	Component

* variables treated probabilistically

all components can be reduced to one-half of its original value by setting the ERROR TYPE I MULTIPLIER to 0.5. For each variable, a data multiplier will modify the associated variable for all components in a uniform manner.

Run data include other miscellaneous entries such as mission schedule, report intervals, RUN DURATION, and traces. Mission schedule includes a MISSION START TIME and a MISSION DURATION for each mission. The report intervals are variables that adjust the time between reports. RUN DURATION is the duration of the simulation in days. Traces are used for testing and validating the model.

Forms of Input Data. To be used by the model, input data must be expressed in one of the following forms:

- integer
- real number
- compound variable
- distribution

Integer variables denote quantity or identification. They are described in terms of whole numbers. For example, two senior technicians at Work Center 4.

Real Variables are used on single-dimensional measures that do not lend themselves to treatment as integers. For example, 12.5 hours as the mean time between failures, and .34 as the probability of a Type I error occurring.

Compound variables are used in situations where a selection must be made from several alternative courses of action. A typical selection situation occurs when one of three kinds of maintenance jobs must be executed.

Distribution variables are used in situations where a range of values may apply, each with its own probability of occurrence. Elapsed maintenance time is best described by a distribution.

Outputs Produced

The outputs produced by the model consist of permanent reports and processing traces. Permanent reports are documents designed for use by squadron commanders and maintenance managers. They cover operational variables such as system readiness, maintenance manhours per flight hour, missions completed, and reasons for delay. Traces are designed for use by personnel running the model. They concern the detailed workings of the program.

Permanent Reports. The following reports are available whenever the model is run:

- Monthly Readiness Reporting Status (RRS) report by aircraft
- History of RRS
- Manhour summary
- Additional reports

Monthly Readiness Reporting Status (RRS) report by aircraft cover such statistics as: hours operationally ready, hours full systems capable, total flight hours, and numbers of sorties flown. In addition, aircraft unavailability (NOR) and Reduced Material Conditions (RMC) are categorized in terms of: unscheduled maintenance hours, hours awaiting maintenance, and not fully equipped (NFE).

History of RRS (12 month) contains RRS percentages, total flights, and total flight hours during the period, as well as aircraft utilization. The percentages are taken from the bottom of the RRS report for each of the preceding 12 reports. Aircraft utilization is the average number of flight hours per aircraft during the period.

Manhour summary records manhour statistics by manhours of maintenance time required. The manhours and manhours per flight hour (MMH/FH) are obtained from 3-M records. The manhour summary of the model does not go into the same detail with Preventive Maintenance (PM) as do the 3-M reports. PM is not considered in detail because it is not central to the model.

The manhour summary also includes miscellaneous information applicable to model operation: number of II/d errors; number of missions flown, scrubbed, or deferred; and the averages of the percent of time OR and the percent of missions flown.

Additional reports cover the total number of jobs by type, total elapsed maintenance time (EMT), total flights, total flight hours, and the location of each aircraft at the time of the report. These reports are useful for comparison when error rates are changed.

Processing Traces. Processing traces are outputs selected at the time the simulation is begun. They were originally built into the program as debugging tools. Such traces are useful for examining in detail the workings of the model. They include such specific items as takeoffs, landings, and mission deferrals. The model offers more than 30 traces covering detailed information on inputs, corrective maintenance jobs, inspection reports, component failures, etc. Traces are essential for model testing.

Treatment of Variables with Undetermined Values

Many of the variables dealt with by the model have specific values that are unknown at the time the model is run. One example would be whether or not a Type I error should be simulated in a given situation. Another would be the number of elapsed maintenance hours (to be simulated) on a given job. These and other variables with undetermined values are marked with an asterisk in Table 15.

As shown in the footnote of Table 15, these variables are treated probabilistically by the model. The method used is the Monte Carlo technique. A brief description of this technique is given below.

In preparation for a model run, a table is constructed for each variable to be handled probabilistically. The table contains all possible values of the variable. A listing of random numbers is then provided along with a decision rule connecting the list to the table. During the run, when the need for a value occurs, a number is selected randomly from the list. When the decision rule is applied, the random number determines the value to be drawn from the table.

As an illustration, consider the question of when to simulate a component failure. Assume that the real-life failure rate is such that, in any given hour, the probability of the component's failure is 15 percent. The table of possible values is constructed to show two conditions: Failed and Not Failed. The list of random numbers is made to contain all percent values between zero and one. The decision rule dictates that all numbers from zero to .15 will represent the Failed condition, while those above .15 will represent the Not Failed condition. At the time of need, a number is selected at random from the list. The size of the number determines which of the two conditions is to be invoked by the model.

Typical Application

In a typical application, the AMES Model would be used to measure the relationship between a particular aspect of maintenance effectiveness and a system effectiveness parameter such as missions completed.

The 3-M data bank for the aircraft of concern could be interrogated to fill the input requirements of the model. The model would be run several times, to stabilize the relationship between those inputs and the output of interest.

Assume the aspect of maintenance effectiveness to be studied is the Type I error rate under the influence of a postulated design change affecting troubleshooting. An estimate would be made of improvement in the Type I error rate that would result if the design change were implemented.

A revised set of error rates would be entered, relative to every subsystem to be impacted by the design change. The model would be run again. The resulting expression of missions completed could then be compared to the pre-change value, and the extent of the gain easily determined.

OTHER RESEARCH ON LINK BETWEEN MAINTENANCE EFFECTIVENESS AND SYSTEM READINESS

The relationship between maintenance effectiveness and system readiness has been explored many times. Because of the complexity of the maintenance/operations environments, with their multitude of interacting variables, all studies of any consequence have made use of computer technology. Most typically, they have taken the form of simulation models. Six of the most representative efforts are reviewed in this section. They are:

- Logistics Composite Model (L-COM)
- Validated Aircraft Logistics Utilization Evacuation (VALUE IV)
- Carrier Aircraft Integrated Requirements (CAIR)
- Comprehensive Aircraft Support Effectiveness Evaluation (CASEE)
- Ship Simulation Model
- Military Manpower vs. Hardware Procurement (HARDMAN)

Logistics Composite Model (L-COM)

Logistics models have been used extensively in the past for maintenance management. L-COM (Fisher, 1968) is a computer-based model for simulating a composite of operations and support functions at an Air Force base. L-COM simulates sortie requirements, aircraft flights, servicing task accomplishments, equipment malfunctions, repair and maintenance operations, and resource utilization. L-COM enables a determination of the "best mix" of resource elements for increased cost effectiveness in system support.

The model consists of three main programs: a pre-processor, a simulation program, and a post-processor.

Extensions and refinements to L-COM have incorporated a repair-level decision model, multibase operations, weather effects, an equipment cannibalization model, and various other representations of compatible and conflicting maintenance operations.

Validated Aircraft Logistics Utilization Evaluation (VALUE IV)

VALUE IV (Systems Analysis and Engineering Department, NADC, 1969) allows for concurrent exercising of multiple squadrons of different types of aircraft. Each has its own operating philosophy, manpower requirements, shift assignments, and aircraft characteristics. The model provides a complete profile of flight operations, maintenance activities, and other related operational factors by aircraft type and squadron. It is capable of differential analysis of the aircraft, the carrier, and the support system. Many decision points within the model, such as repair times, maintenance action frequency by inspection, delays due to ground support equipment, etc., are obtained by employing Monte Carlo techniques. It was validated for several aircraft types using the Navy's 3-M data system.

Carrier Aircraft Integrated Requirements (CAIR)

The CAIR simulation model (Engineering Management Department USN, 1975), is designed to assess Level of Repair (LOR) assignments for carrier-based airborne equipment and to determine their impact on operational effectiveness. The various segments of the CAIR analysis provide information concerning the relative costs of maintenance-support alternatives and the effectiveness of each support alternative.

The model may be used to specify LOR assignments that minimize life-cycle logistics support costs. It may also evaluate the life-cycle logistics support cost for a prescribed set of assignments of the components, e.g., avionic equipment.

In order to exercise the model, quantitative data are required for each assembly operational site, support equipment type, and type of manpower. By using this data in association with LOR assignments, the simulator can predict the ability of the carrier to meet its demand for missions. The simulator can also identify those personnel, ground support equipment, and spares that may cause bottlenecks in the maintenance support system.

Comprehensive Aircraft Support Effectiveness Evaluation (CASEE)

THE CASEE model (U.S. Naval Air Systems Command, 1977) is primarily intended as a system analysis tool to help evaluate various factors that influence fleet readiness and mission availability in a carrier operational environment. The model considers such factors as reliability and maintainability of the aircraft systems and subsystems, spare parts availability, and maintenance facility availability. The model also considers in some detail the manpower requirements for both organizational and intermediate maintenance levels.

By exercising the model with appropriate inputs (Navy 3-M Data, fleet records, aircraft technical manuals, etc.), CASEE can be used as a management tool to help managers make analytical decisions based on quantified information. These decisions can revolve around such areas as equipment design improvements, reliability and maintainability optimization, support planning, fleet readiness improvement, and life-cycle cost studies. In addition, CASEE can be used to determine trade-offs between spares provisioning and fleet readiness.

CASEE is capable of simulating up to 127 individual aircraft of various types from as many as 10 different organizational units. The current version of CASEE has been numerically validated against real-world Naval aircraft operations and support.

Ship Simulation Model

The total Ship Simulation Model was developed in the mid-1960's to provide the Navy with a means of performing personnel research at the total systems level. Many of the development procedures first established in the Ship Simulation Model have been employed in subsequent models such as AMES.

Once the objectives and constraints are generated and measures of system performance identified, a functions analysis is conducted. The functions analysis is essentially a process of tracing the demands placed on a ship through the various functions which the ship performs. A functional representation based on this analysis is coupled with detailed Navy Doctrine Procedures to develop functional specifications for the simulation model. Data from representative maintenance actions are processed through the model, and a rank order analysis of equipment is performed.

Outputs from the model provide a summary of corrective and planned maintenance activities. Problems in system readiness can be traced to specific equipment to determine the causes of equipment downtime. The model also produces a summary of the personnel training readiness resulting from the simulation run.

Potential applications of the ship simulation model range from establishing the optimum mix of personnel and evaluation of proposed automation concepts, to identification of system problems.

The model was originally designed and validated using the DDG-2 class Guided Missile Destroyer as its object system.

Military Manpower vs. Hardware Procurement (HARDMAN)

HARDMAN is not a computer simulation model, but rather a methodological approach to maintenance manpower requirements. The HARDMAN methodology (Dynamics Research Corp., 1979) is used to address manpower, personnel, and training requirements in the weapon system acquisition process (WSAP). It is a relatively new method based on 3-M data collected from proposed weapon systems (known as reference systems). These data include information that characterizes the equipment, maintenance concept, operator tasks, and manpower requirements of the system. This is in terms of speed and certain accuracy measures.

The HARDMAN system indicates where maintenance manhour requirements can be reduced without a loss of overall system effectiveness. This results in lower maintenance personnel requirements for the baseline weapons system. Data are provided on potential improvements in system reliability and aircraft availability.

The concept of maintenance errors and reduction of maintenance error rates is not really considered when assessing the effect of a proposed systems design change. The HARDMAN methodology was initially applied to the Shipboard Intermediate Range Combat System (SIRCS).

Summary

A review has been made of six major efforts to explore the connection between maintenance effectiveness and system readiness. The following conclusions can be drawn regarding these studies.

First, they show promise in that they attend to both the logistic and the human aspects of maintenance and associated operations.

Second, they show a limitation in their handling of the human aspect. That is, they dwell entirely on maintenance *time*. They do not take into account maintenance *errors*.

Finally, they appear to be concerned chiefly with improving the *cost-effectiveness of maintenance* at a given level of system readiness. Little attention is paid to the possibility of *improving* system readiness.

In contrast, the AMES Model focuses primary attention on system readiness and human-related variables contributing to system readiness. The model is useful in looking for ways to improve system readiness through the mechanism of a *reduced error rate* among maintenance personnel.

SECTION III

METHOD TO IDENTIFY DESIGN FEATURES INFLUENCING MAINTENANCE EFFECTIVENESS

Task III of the DFM project had two purposes. One was to identify design features associated with maintenance effectiveness. The other was to obtain an estimate of the gain that could be achieved if the design problems were alleviated. The work of Task III is described under the following major headings:

- Basic Planning
- Selection of Subsystems for Investigation
- Preparation for Investigation
- Performance of Investigation

BASIC PLANNING

Basic planning covered three aspects of preparation for the work of Task III. The first concerned the method of estimating achievable gain. The second concerned the selection of subsystem candidates for investigation. The third concerned the method of treating maintenance effectiveness data.

Plan for Estimating Gain

Assuming that maintenance weaknesses on a particular subsystem could be traced to features of system design, and assuming corresponding changes in design were implemented, some improvement could be expected in maintenance effectiveness. The question is, how much improvement? In addressing that question, investigators in other studies have made estimates based on the judgment of knowledgeable maintenance personnel.

After some consideration, that approach was rejected. An alternate source of information was found within the F-14 data base itself. Represented there were subsystems showing strong as well as weak maintenance effectiveness. It was reasoned that records of strength (in terms of low error rates and elapsed maintenance times) were just as valid as records of weakness. Records of strength, therefore, were designated for use as indications of the levels of effectiveness achievable when the subsystems are properly designed.

Plan for Selecting Subsystem Candidates

Given the decision to use examples of both strong and weak maintenance effectiveness, the idea of pairing was adopted. A plan was devised to select a group of strong subsystems opposite a set of weak subsystems, with each (strong/weak) pair matched by type of hardware involved. It was further decided to confine the sample to one work center instead of five as originally contemplated. The one chosen was Work Center 220, Electrical/Instrumentation.

Plan for Treating Maintenance Effectiveness Data

Two kinds of data were expected from the study: data pertinent to the design features under investigation, and data pertinent to the impact of those design features on maintenance effectiveness.

It was planned from the beginning to handle design feature data in narrative form. This plan remained intact. However, the plan for treating maintenance effectiveness data had to be changed because of the decision to use strength and weakness records from the F-14 data base.

The following agreement was made regarding the treatment of maintenance effectiveness data. Maintenance weakness would be represented by the actual values of all Type I and Type II/d error rates, and elapsed maintenance times found in the data base. Maintenance strength would be represented by the averages of such values, as obtained for the examples selected for investigation.

The purpose of this arrangement was to prepare for the comparisons to be made in Task IV. Records reflecting the weakness condition would provide a baseline against which various estimates of improvement could be measured. Estimates of improvement would be made possible by the averaged values of strength.

SELECTION OF SUBSYSTEMS FOR INVESTIGATION

Subsystems were selected for investigation in two steps. First, a listing of candidates was assembled. Then subsystems were selected for actual use. In the process, quantitative values of maintenance strength were determined for use in Task IV.

Listing of Candidates

Within the F-14 data base, maintenance summary records from Work Center 220 were isolated for analysis. A search was made for subsystems with the following characteristics:

- Large number of corrective maintenance actions
- High Type I error rate
- Low Type I error rate
- High Type II/d error rate
- Low Type II/d error rate
- High elapsed maintenance time
- Low elapsed maintenance time

All subsystems had to show the first characteristic. With regard to the remaining characteristics, each subsystem had to show at least one. In addition, the listing had to be large enough to contain two examples of each kind of maintenance strength and each kind of weakness.

The final listing of candidates is presented in Table 16. It contains 22 subsystems. Subsystems are identified at the left and maintenance effectiveness at the right.

Subsystem Identification. The meanings of WUC (Work Unit Code) and NAME are obvious.

Maintenance Effectiveness. The rates for Type I and Type II/d errors are shown as percentages of R/R actions. Elapsed maintenance times (EMT) are shown as percentages of R/R actions exceeding 3.5 manhours.

Selection of Subsystems for Actual Use

From the listing given in Table 16, 12 subsystems were selected for investigation. As shown in Table 17, they fell into three groups:

- Subsystems with high and low Type I error rates
- Subsystems with high and low Type II/d error rates
- Subsystems with high and low elapsed maintenance times

Each group contained two examples of its respective conditions.

Within each group, provision also was made for the matching of subsystems (strong vs. weak) having similar types of hardware. Thus, the Lateral Control System, WUC 142 (showing strong maintenance) was matched with the Longitudinal Control System, WUC 144 (showing weak maintenance); the Approach Power Control System (strong) was matched with the Power Plant Installation Associated Equipment (weak); and so on.

TABLE 16. CANDIDATES FOR INVESTIGATION

SUBSYSTEM WUC	NAME	% ERRORS I	 II/d	EMT %>3.5
138	Wheel Brake System	17.1	9.0	5
139	Nose Wheel Steering	0.0	4.2	32
142	Lateral Control System	0.0	3.8	45
144	Longitudinal Control System	22.6	7.4	16
146	Flap/Slat Control System	0.0	12.2	42
148	Wing Sweep System	0.0	9.2	34
292	Air Inlet Control System	12.8	3.5	32
293	Power Plant Control System	23.8	4.9	18
29C	Approach Power Control System	10.7	4.0	14
29X	Power Plant Installation Assoc. Eq.	32.5	4.8	8
421	AC/DC Power System	0.0	9.7	18
425	Misc. Electrical System Comp.	0.0	7.4	28
49X	Misc. Utility Associated Equipment	21.5	6.1	3
511	Flight Instruments	0.0	9.9	8
512	Navigation Instruments	6.8	5.9	6
513	Engine Instruments	30.6	6.0	13
514	Position Indicators	29.4	6.0	13
515	Utility System Indicators	14.4	6.4	25
564	Attitude Hdg. Ref. Set/Mag. Det.	0.0	5.8	13
56X	Flight Reference Assoc. Equipment	22.1	4.5	8
573	Wing/Flap/Glove Vane Control Set	12.2	4.9	18
577	Auto Flight Control	25.6	4.7	11

TABLE 17. SUBSYSTEMS SELECTED FOR INVESTIGATION

SUBSYSTEMS WITH HIGH AND LOW TYPE I ERROR RATES

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	TYPE I ERROR RATES
Strong	142	Lateral Control System	0.0
Weak	144	Longitudinal Control System	22.6
Strong	29C	Approach Power Control System	10.7
Weak	29X	Power Plant Installation Assoc. Eq.	32.5

SUBSYSTEMS WITH HIGH AND LOW TYPE II/d ERROR RATES

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	TYPE II/d ERROR RATES
Strong	292	Air Inlet Control System	3.5
Weak	146	Flap/Slat Control System	12.2
Strong	512	Navigation Instruments	5.9
Weak	511	Flight Instruments	9.9

SUBSYSTEMS WITH HIGH AND LOW ELAPSED MAINTENANCE TIMES

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	% ACTIONS >3.5 HRS.
Strong	138	Wheel Brake System	5.0
Weak	139	Nose Wheel Steering	32.0
Strong	56X	Flight Reference Assoc. Eq.	8.0
Weak	573	Wing/Flap/Glove Vane Control Set	18.0

The purpose of the matching was to establish a basis for comparison later in the investigation.

Determination of Quantitative Values Denoting Maintenance Strength

Once the subsystem selections were made, it became possible to determine the quantitative values needed to denote maintenance strength relative to Type I errors, Type II/d errors, and elapsed maintenance time. Those values were:

Type I error rate (percentage)	5.4
Type II/d error rate (percentage)	4.7
EMT (percentage of actions >3.5 hours)	6.5

Each value represents a simple average of two prior values. The basis of computation is shown in Table 18. Note that in this step, pairs of subsystems were brought together in a way that differed from the matching explained earlier. The reason is that a different purpose was served in each case.

The information presented in Table 18 was set aside for use in Task IV, where the effects of postulated improvements in maintenance effectiveness were to be calculated by the AMES model.

PREPARATION FOR INVESTIGATION

The plan called for technical discussions with maintenance personnel, aimed at discovering which design features had the most impact on maintenance effectiveness. Preparation for those discussions occurred in two stages. One was the establishment of a point of contact. The other was the development of an interview plan.

Point of Contact

The closest base operating and maintaining the F-14 was NAS, Miramar. We visited Miramar and made contact with Commander Gibb Patterson, COMFIT Maintenance officer. Also participating in the discussions were Commander John Mathews and Lieutenant Commanders Ed Pryor and Ray Wegrin.

These people were familiar with Xyzyx, having interacted with us on past contracts involving the F-14 data base and the portions of it in our possession. They knew of the AMES model. We explained our current project and our need for their help. They agreed to furnish personnel to answer our questions.

TABLE 18. QUANTITATIVE VALUES DENOTING MAINTENANCE STRENGTH

STRENGTH IN TYPE I ERRORS

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	TYPE I ERROR RATES	AVERAGE RATE
Strong	142	Lateral Control System	0.0	
Strong	29C	Approach Power Control	10.7	5.4

STRENGTH IN TYPE II/d ERRORS

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	TYPE II/d ERROR RATES	AVERAGE RATE
Strong	292	Air Inlet Control System	3.5	
Strong	512	Navigation Instruments	5.9	4.7

STRENGTH IN ELAPSED MAINTENANCE TIME

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	% ACTIONS >3.5 HRS.	AVERAGE RATE
Strong	138	Wheel Brake System	5.0	
Strong	56X	Flight Reference Assoc. Eq.	8.0	6.5

We provided a listing of the subsystems selected for investigation. Arrangements were made for a series of visits to Miramar for discussions with representatives of Work Center 220.

Interview Plan

An interview plan was developed to assist in the collection of relevant information during the visits.

The interview plan is summarized in Figure 2. There were two objectives. The first objective was to explore the influence of system support factors on the maintenance of all subsystems dealt with in Work Center 220. This objective was served by Item 1. The second objective was to identify design features impacting maintenance effectiveness on the 12 particular subsystems listed in Table 17. This objective was served by Items 2 through 5 in Figure 2.

In the paragraphs that follow, the interview plan is described under the following headings:

- System Support Questionnaires
- Interview Guides
- Design Feature Checklist
- Data Collection Sheet
- Interview Instructions

System Support Questionnaires

System support was dealt with by a pair of questionnaires. One concerned troubleshooting. The other concerned elapsed maintenance time. The questionnaires are represented here as Exhibits A and B, respectively. Since the two are completely alike, except for the subsystem examples they cite, both can be covered effectively by a single explanation.

Each questionnaire referred to F-14 maintenance data from Table 16 and made two initial points. First, the data reflect the efforts of one work center during a one-year period. Variations in maintenance resources are thus highly constrained. Second, the data show large differences between subsystems, with regard to elapsed maintenance time and the various error rates. The respondent was then asked to account for those differences.

1. EXPLORE INFLUENCE OF SYSTEM SUPPORT FACTORS

- Supervisory leadership
- Technician capability
- Tech pub quality/usability
- Troubleshooting
- Corrective maintenance

2. IDENTIFY DESIGN FEATURES IMPACTING TROUBLESHOOTING

High Type I Error Rate	• Lateral Control System • Approach Power Control System
Low Type I Error Rate	• Longitudinal Control System • Power Plant Installation Assoc. Eq.

3. IDENTIFY DESIGN FEATURES IMPACTING ELAPSED MAINTENANCE TIME

Many Actions >3.5 hrs.	• Nose Wheel Steering • Wing/Flap/Glove Vane Control Set
Few Actions >3.5 hrs.	• Wheel Brake System • Flight Reference Assoc. Eq.

4. IDENTIFY DESIGN FEATURES IMPACTING CORRECTIVE MAINTENANCE

High Type d Error Rate	• Flap/Slat Control System • Flight Instruments
Low Type d Error Rate	• Air Inlet Control System • Navigation Instruments

5. IDENTIFY DESIGN FEATURES IMPACTING CHECKOUT

High Type II Error Rate	• Flap/Slat Control System • Flight Instruments
Low Type II Error Rate	• Air Inlet Control System • Navigation instruments

Figure 2. Summary of Interview Plan

EXHIBIT A

QUESTIONNAIRE ON SYSTEM SUPPORT FACTORS FOR TYPE I ERROR RATE CASES

Table 1 lists some of the subsystems maintained in this work center. The column marked with an arrow shows the error rates scored by technicians in troubleshooting the various subsystems over a one-year period. Note that in some cases, the error rate is very low, while in others it is quite high. How do you account for that? Please read on.

TABLE 1. CANDIDATES FOR INVESTIGATION

	SUBSYSTEM	▼ % ERRORS		EMT
WUC	NAME	I	II/d	%>3.5
138	Wheel Brake System	17.1	9.0	5
139	Nose Wheel Steering	0.0	4.2	32
142	Lateral Control System	0.0	3.8	45
144	Longitudinal Control System	22.6	7.4	16
146	Flap/Slat Control System	0.0	12.2	42
148	Wing Sweep System	0.0	9.2	34
292	Air Inlet Control System	12.8	3.5	32
293	Power Plant Control System	23.8	4.9	18
29C	Approach Power Control System	10.7	4.0	14
29X	Power Plant Installation Assoc. Eq.	32.5	4.8	8
421	AC/DC Power System	0.0	9.7	18
425	Misc. Electrical System Comp.	0.0	7.4	28
49X	Misc. Utility Associated Equipment	21.5	6.1	3
511	Flight Instruments	0.0	9.9	8
512	Navigation Instruments	6.8	5.9	6
513	Engine Instruments	30.6	6.0	13
514	Position Indicators	29.4	6.0	13
515	Utility System Indicators	14.4	6.4	25
564	Attitude Hdg. Ref. Set/Mag. Det.	0.0	5.8	13
56X	Flight Reference Assoc. Equipment	22.1	4.5	8
573	Wing/Flap/Glove Vane Control Set	12.2	4.9	18
577	Auto Flight Control	25.6	4.7	11

1. The subsystems themselves may vary in complexity and design, thus making some easier to troubleshoot than others. Could that be the reason?____________

2. Supervisors are known to have a strong impact on the effectiveness of their people. Supervisors handling the Wing Sweep System, for example, might have shown better leadership than the supervisors

EXHIBIT A
(continued)

handling The Power Plant Control System. Could that have happened?__________ Do the supervisors in this work center specialize in that way?__________ If so, how are the subsystems divided among them? Please show by grouping of WUCs.

3. Technicians vary in capability. Those assigned to Wing Sweep System might have been brighter or better trained than those assigned to the Power Plant Control System. Could that have happened? __________ Are the technicians within this work center specialized in that way?__________ If so, how are the subsystems divided among them? Please show by grouping of WUCs.

4. Tech pubs vary in quality and usability. Those written for the Wing Sweep System might have been better than the ones written for the Power Plant Control System. Could that have happened?__________ Do the manuals differ very much?__________ Are they used enough for the differences to affect quality of work?__________

5. In summary, please complete the table shown below, giving your estimate of the relative contribution of the factors just introduced. State your estimate in the form of a percentage, such that all entries total to 100 percent. Note that space is provided for some other possible explanation. If you know of one, name it on Line E.

REASONS WHY SUBSYSTEMS DIFFER IN RECORDS OF MAINTENANCE EFFECTIVENESS WITHIN WORK CENTER 220

REASONS	PERCENTAGE OF CONTRIBUTION
A. Design for maintainability	
B. Supervisory leadership	
C. Technician capability	
D. Tech pubs quality and usability	
E. Other?	

EXHIBIT B

QUESTIONNAIRE ON SYSTEM SUPPORT FACTORS FOR EMT CASES

Table 1 lists some of the subsystems maintained in this work center. The column marked with an arrow shows the percentage of high elapsed maintenance times required by the various subsystems over a one-year period. Note that in some cases, the percentage is very small, while in others it is quite large. How do you account for that? Please read on.

TABLE 1. CANDIDATES FOR INVESTIGATION

WUC	SUBSYSTEM NAME	% ERRORS		⬇ EMT
		I	II/d	%>3.5
138	Wheel Brake System	17.1	9.0	5
139	Nose Wheel Steering	0.0	4.2	32
142	Lateral Control System	0.0	3.8	45
144	Longitudinal Control System	22.6	7.4	16
146	Flap/Slat Control System	0.0	12.2	42
148	Wing Sweep System	0.0	9.2	34
292	Air Inlet Control System	12.8	3.5	32
293	Power Plant Control System	23.8	4.9	18
29C	Approach Power Control System	10.7	4.0	14
29X	Power Plant Installation Assoc. Eq.	32.5	4.8	8
421	AC/DC Power System	0.0	9.7	18
425	Misc. Electrical System Comp.	0.0	7.4	28
49X	Misc. Utility Associated Equipment	21.5	6.1	3
511	Flight Instruments	0.0	9.9	8
512	Navigation Instruments	6.8	5.9	6
513	Engine Instruments	30.6	6.0	13
514	Position Indicators	29.4	6.0	13
515	Utility System Indicators	14.4	6.4	25
564	Attitude Hdg. Ref. Set/Mag. Det.	0.0	5.8	13
56X	Flight Reference Assoc. Equipment	22.1	4.5	8
573	Wing/Flap/Glove Vane Control Set	12.2	4.9	18
577	Auto Flight Control	25.6	4.7	11

1. The subsystems themselves may vary in complexity and design, thus making some easier to repair than others. Could that be the reason?______________

2. Supervisors are known to have a strong impact on the effectiveness of their people. Supervisors handling the Wheel Brake System, for example, might have shown better leadership than the supervisors

EXHIBIT B
(continued)

handling the Lateral Control System. Could that have happened? __________ Do the supervisors in this work center specialize in that way?__________ If so, how are the subsystems divided among them? Please show by groupings of WUCs.

3. Technicians vary in capability. Those assigned to Wheel Brake System might have been brighter or better trained than those assigned to the Lateral Control System. Could that have happened? __________ Are the technicians within this work center specialized in that way?__________ if so, how are the subsystems divided among them? Please show by groupings of WUCs.

4. Tech pubs vary in quality and usability. Those written for the Wheel Brake System might have been better than the ones written for the Lateral Control System. Could that have happened?__________ Do the manuals differ very much?__________ Are they used enough for the differences to affect quality of work?__________

5. In summary, please complete the table shown below, giving your estimate of the relative contribution of the factors just introduced. State your estimate in the form of a percentage, such that all entries total to 100 percent. Note that space is provided for some other possible explanation. If you know of one, name it on Line E.

REASONS WHY SUBSYSTEMS DIFFER IN RECORDS OF MAINTENANCE EFFECTIVENESS WITHIN WORK CENTER 220

REASONS	PERCENTAGE OF CONTRIBUTION
A. Design for maintainability	
B. Supervisory leadership	
C. Technician capability	
D. Tech pubs quality and usability	
E. Other?	

Subsystem design was offered as one possible explanation. Also offered were three factors of system support: supervisory leadership, technician capability, and tech pubs quality/usability. Each was explained in such a way as to get the respondent to think before reaching a conclusion.

The respondent was then asked to estimate the relative contribution of the factors introduced. Space was provided for an additional reason, should the respondent elect to name one.

The hypothesis was that in these particular situations, most of the variability in maintenance effectiveness came not from system support, but from system design.

It will be noted that the system support questionnaires made no reference to Type d errors or Type II errors. These aspects of maintenance effectiveness were omitted intentionally. The assumption was that the effects of variations in system support could be explored adequately through Type I errors and elapsed maintenance time alone.

Interview Guides

In order to provide structure for the interviews, two guides were developed. One concerned problem situations (subsystems with high error rates or EMT). The other concerned non-problem situations (subsystems with low error rates or EMT). The interview guides are represented here as Exhibits C and D, respectively. Since the two are equivalent except for problem/non-problem orientation, they will be covered with a single explanation.

Each application of a guide focused on one specific subsystem drawn from Table 17. The investigator prepared for the interview by bringing together a guide sheet and a Data Collection Sheet (Exhibit F). On the data collection sheet, he identified the subsystem selected. In the lead statement of the guide, he inserted a relevant phrase to particularize the situation. Relevant phrases came from the following set:

- technicians made many errors in troubleshooting
- technicians made few errors in troubleshooting
- many maintenance actions took longer than 3.5 hours
- few maintenance actions took longer than 3.5 hours
- technicians made many errors in corrective maintenance
- technicians made few errors in corrective maintenance
- technicians made many errors in checkout following repair
- technicians made few errors in checkout following repair

EXHIBIT C

INTERVIEW GUIDE FOR PROBLEM SITUATIONS

The record shows that this subsystem was hard for the techicians to work with. That is, ____.

1. What is there about system design that could have made the work hard?

2. You have mentioned ______________________ as an aspect of design that tends to make the work hard to do. Please explain further.

3. In the past two years, has this subsystem been changed in any way?_________ Has the change made the work harder or easier?

4. Please explain your answer to Item 3.

5. If you had the power to make other changes in system design, what would they be?

6. What other aircraft had (or has) a better design for the maintainer, on the functions covered by this subsystem?

7. Please explain your answer to Item 6.

EXHIBIT D

INTERVIEW GUIDE FOR NON-PROBLEM SITUATIONS

The record shows that this subsystem was easy for the technicians to work with. That is, ______________________________________.

1. What is there about system design that could have made the work easy?

2. You have mentioned ________________________ as an aspect of design that tends to simplify the work. Please explain further.

3. In the past two years, has this subsystem been changed in any way?___________ Has the change made the work harder or easier? ______________

4. Please explain your answer to Item 3.

5. If you had the power to make other changes in system design, what would they be?

6. What other aircraft had (or has) a better design for the maintainer, on the functions covered by this subsystem?

7. Please explain your answer to Item 6.

The purpose of the lead statement was to set the stage for inquiry into the design features of the object subsystem. That inquiry was structured by Questions 1 through 7, which were meant to be read to the respondent by the investigator.

Questions 1 and 2 sought to extract detail comments regarding subsystem parts and corresponding design features that influenced maintenance effectiveness.

Questions 3 through 7 sought further comments, from viewpoints slightly different from the first. One such viewpoint was that of design change. The other was that of comparison with other designs.

Comments from the respondent were intended to be captured on data collection sheets.

Design Feature Checklist

A listing was prepared showing examples of design features affecting maintenance. It is represented here as Exhibit E. The listing was not intended as a full account of all possible design features. The aim was merely to provide assistance to the investigator conducting the interviews. The listing was meant to help him formulate questions and process the comments heard in return.

Data Collection Sheets

A blank form was provided for use by the investigator in recording the comments of the respondent. It is represented here as the Data Collection Sheet, Exhibit F.

Prior to the interview, the investigator prepared a data collection sheet for each subsystem drawn from Table 17. In addition to the WUC and name of the subsystem, he entered two qualifiers: situation and problem orientation.

Situation was denoted by one of the following:

- Type I Error Rate
- Type II Error Rate
- Type d Error Rate
- Elapsed Maintenance Time

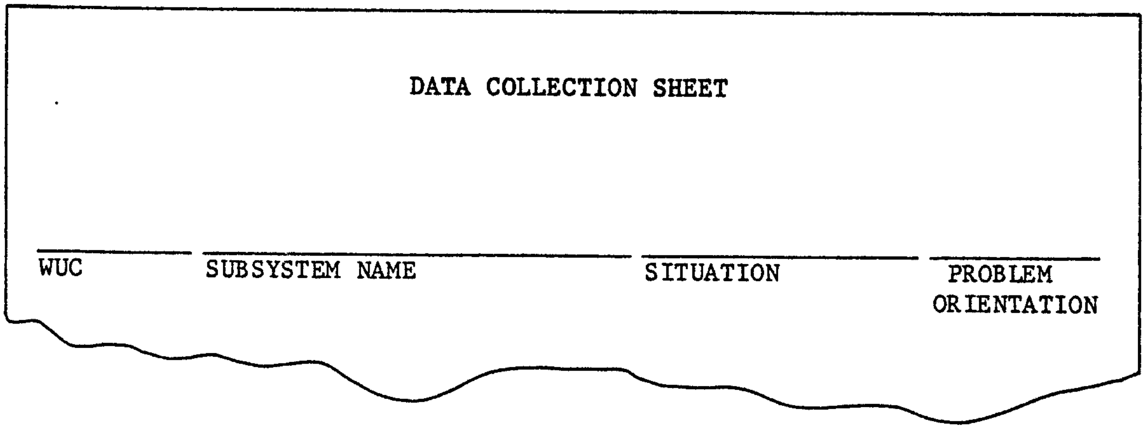
EXHIBIT E

DESIGN FEATURES AFFECTING MAINTENANCE

1. Parts Not Easily Accessible for Checking
2. Checkout Routine Excessively Long
3. Some Modes of Operation Hard to Check on Ground
4. LRU BITE Tests Incomplete
5. Subsystem Not Fully Covered by Malfunction Indic.
6. Malfunction Indic. Fail to Distinguish Between LRUs
7. Some Parts of Circuitry Not Covered by Test Points
8. Circuitry Hard to Trace
9. Test Equipment Inconvenient or Inaccessible
10. Circuitry Subject to Intermittents
11. Parts Not Easily Accessible for Corrective Actions
12. Special Tool Required
13. Awkward Work Position Required
14. Parts Not Well Labeled
15. Delicate Components Given too Little Protection.
16. Fasteners Require too Much Work

EXHIBIT F

DATA COLLECTION SHEET



DATA COLLECTION SHEET

WUC	SUBSYSTEM NAME	SITUATION	PROBLEM ORIENTATION

Problem orientation was denoted by one of the following:

- Problem: High error rate or EMT
- Non-Problem: Low error rate or EMT

The remainder of the sheet consisted of an open field for use in conjunction with the Interview Guides, Exhibits C and D.

Interview Instructions

The various elements of the interview plan were tied together by a set of written procedures and a listing of materials. The result is represented in Exhibit G as the Interview Instructions.

The materials listed were the exhibits described earlier. The procedures were sequential statements directing the investigator to use the materials in certain combinations on subsystems drawn from Table 17. Table 17 was made part of the plan for the convenience of the investigator.

PERFORMANCE OF INVESTIGATION

The investigation is described under the headings of data collection, data reduction, and data analysis.

Data Collection

Data collection was accomplished by three members of the technical staff during three visits to NAS, Miramar. Commander Pryor gave them access to a group of highly qualified technicians, who cooperated fully in the investigation. A listing of the technicians appears in Table 19.

The first order of business was to focus attention on hardware design as opposed to the various support factors. That was accomplished through the use of the questionnaires shown in Exhibits A and B. One questionnaire dealt with problems in troubleshooting. The other dealt with factors contributing to excessive elapsed maintenance time. All technicians agreed that the differences in maintenance performance on the subsystems under study were primarily the result of design differences rather than differences in personnel or supervisory quality.

EXHIBIT G

INTERVIEW INSTRUCTIONS

MATERIALS

Exhibit A:	Questionnaire on System Support Factors for Type I Error Rate Cases
Exhibit B:	Questionnaire on System Support Factors for EMT Cases
Exhibit C:	Interview Guide for Problem Situations
Exhibit D:	Interview Guide for Non-Problem Situations
Exhibit E:	Design Features Affecting Maintenance
Exhibit F:	Data Collection Sheet
Table 2:	Subsystems Selected for Investigation

PROCEDURES

1. System Support Factors

   a. Apply questionnaire from Exhibit A, for Type I error rate cases. Record results directly on questionnaire.

   b. Apply questionnaire from Exhibit B, for EMT cases. Record results directly on questionnaire.

2. Type I Errors

   a. Apply interview guide from Exhibit C, for two problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

   b. Apply interview guide from Exhibit D, for two non-problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

EXHIBIT G
(continued)

3. EMT

   a. Apply interview guide from Exhibit C, for two problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

   b. Apply interview guide from Exhibit D, for two non-problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

4. Type d Errors

   a. Apply interview guide from Exhibit C, for two problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

   b. Apply interview guide from Exhibit D, for two non-problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection sheet, Exhibit F.

5. Type II Errors

   a. Apply interview guide from Exhibit C, for two problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

   b. Apply interview guide from Exhibit D, for two non-problem situations. Use design features from Exhibit E, as necessary. Record results on Data Collection Sheet, Exhibit F.

EXHIBIT G
(continued)

TABLE 2. SUBSYSTEMS SELECTED FOR INVESTIGATION

SUBSYSTEMS WITH HIGH AND LOW TYPE I ERROR RATES

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	TYPE I ERROR RATES
Strong	142	Lateral Control System	0.0
Weak	144	Longitudinal Control System	22.6
Strong	29c	Approach Power Control System	10.7
Weak	29x	Power Plant Installation Assoc. Eq.	32.5

SUBSYSTEMS WITH HIGH AND LOW TYPE II/d ERROR RATES

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	TYPE II/d ERROR RATES
Strong	292	Air Inlet Control System	3.5
Weak	146	Flap/Slat Control System	12.2
Strong	512	Navigation Instruments	5.9
Weak	511	Flight Instruments	9.9

SUBSYSTEMS WITH HIGH AND LOW ELAPSED MAINTENANCE TIMES

MAINT. EFFECT.	WUC	SUBSYSTEM NAME	% ACTIONS >3.5 HRS.
Strong	138	Wheel Brake System	5.0
Weak	139	Nose Wheel Steering	32.0
Strong	56X	Flight Reference Assoc. Eq.	8.0
Weak	573	Wing/Flap/Glove Vane Control Set	18.0

TABLE 19. WORK CENTER 220 PERSONNEL INTERVIEWED

DATE	TECHNICIAN	RATING	ORGANIZATION
5-21-80	Harding	AECS	VF-51
	Akridge	AE1	VF-124
6-17-80	Havlu	AE2	VF-124
	Castro	AE1	VF-124
	Babbcock	AE1	VF-1
	Morgan	AE2	VF-1
6-18-80	Meir	AE1	FRAMP
	Havlu	AE2	VF-124

Interviews were then conducted dwelling on the 12 problem and non-problem situations identified in Table 17. The interviewers asked questions derived from the Interview Guide and the Design Features Checklist. The technicians responded with explanations based on their F-14 experience. In some cases, the aircraft itself was used to clarify particular points.

The interviewer employed the data collection sheets to capture what key points he could. However, the objective was to let the technician talk with a minimum of interruptions or requests to slow down. Therefore, a parallel means was used to collect technician outputs. That means was a tape recorder. In all, 570 minutes of discussion were recorded, on nine cassettes.

All data were brought back to Canoga Park for reduction and analysis.

Data Reduction

The staff members played back their respective tapes and transferred relevant bits of data to corresponding data collection sheets. A typical data collection sheet completed in this manner is shown in Figure 3.

From each completed data collection sheet, a matrix was developed, cross-referencing subsystem components with the listing of design features that affect maintenance. An example of a completed matrix is shown in Figure 4. There, the components are identified by WUC and name, and the design features are referred to by number.

Each cell in the matrix represents an interaction between a design feature and a component. An open circle (o) means that the analyst searched his records for some mention of that interaction. A closed circle (●) means that he found one. Each closed circle is described further in the numerically encoded statements below.

It is recognized that the various design features apply differentially to the maintenance situations under analysis. For example, Item 16 (Fasteners require too much work) could contribute to Type d errors but not to Type I errors, while Item 8 (circuitry hard to trace) would apply in the opposite direction. The original plan was to use this fact to structure the data collection/reduction processes.

DATA COLLECTION SHEET

14650	Flap/Stat Control/ Electrical Comp.	High d Error	Problem
WUC	SUBSYSTEM NAME	SITUATION	PROBLEM ORIENTATION

Auxiliary flap retract switch (14655) is difficult to access. The cove door and other components have to be removed to access switch.

Checkout is included in OBC of flaps and wing sweep. System is easy to check. Simply operate flap/slats and observe sequence of operation. System indicators are mainly for the pilot to let him know if flaps/slats are up/out, down/in or in transition. Check identifies problem area, still have to isolate faulty component.

Sensors (14651 & c) have connectors but switches are hard wired. Switch wires are cut to remove and spliced to reinstall. Keeping water out of splices is a problem. Water collects on wires and flows down them to the splices, connectors, and/or components. If wires are too short, G-forces can pull wires out of splices and pins out of unpotted (sealed) connectors.

Some degree switches have to be cut during troubleshooting to help isolate faulty switch. (Series-installed switches.)

Damage to wiring of switches can occur if an eyebrow or cove door is out of adjustment (improperly rigged) or improperly removed/installed.

There are no mods to this system that made the work harder. However, on the hydraulic indication system, a fire suppression mod installed a bracket which must be removed to get at one of the pressure switches. Also, some fire extinguisher lines are in the way and make it a little more difficult to access one of the pressure switches

Switch and wiring labels get lost. Referenced designators are pull-off tags, not always put back when new switch is installed. Some switches are not labelled permanently because they may be used in other places on this or other aircraft.

Figure 3. Typical Completed Data Collection Sheet

SITUATION: Type d Error High Problem

SUBSYSTEM/COMPONENTS		EXHIBIT: E															
WUC	NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
14650	Flap/Slat Control Electrical	●	○	○	○	●	●	●	○	○	●	●	○	○	●	●	○
14651	Slat Asymetry Sensor Assembly	○	○	●	○	●	●	○	○	○	○	○	○	○	●	○	○
14652	Slat In Switch	○	○	○	○	○	○	○	○	○	●	●	○	○	●	○	○
14653	Slat Out Switch	○	○	○	○	○	○	○	○	○	●	●	○	○	●	○	○
14654	Auxiliary Flap Extend Switch	○	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○
14655	Auxiliary Flap Retract Switch	●	○	○	○	○	○	○	○	○	●	●	○	○	●	●	○
14656	Flap 0 degree Position Switch	○	○	○	○	●	●	●	○	○	○	●	○	○	●	●	○
14657	Flap 25 degree Position Switch	○	○	○	○	●	●	●	○	○	○	●	○	○	●	●	○
14658	Flap 35 degree Position Switch	○	○	○	○	●	●	●	○	○	○	●	○	○	●	●	○
1465A	Flap/Slat Drive Set FLR Detect	○	○	○	○	●	●	●	○	○	○	○	○	○	●	●	○
1465B	Flap 0 degree Overtravel Switch PCT	○	○	○	○	●	●	●	○	○	○	●	○	○	●	●	○
1465C	Flap Asymetry Sensor Assembly	○	○	○	○	●	●	●	○	○	○	○	○	○	●	●	○

① 14655 Flap Retract Switch is difficult to access.

⑤,⑥ Checkout will identify problem area but technician must isolate faulty component

⑦ Certain degree switch wires have to be cut to isolate faulty switch during troubleshooting. Cutting and resplicing wires introduces a potential water collection point (and improper splice) which can cause arcing and damage. If wire not long enough when spliced, G-force flexing can pull wires out of splice.

⑩ Switches and splices are exposed and get wet.

⑪ Sensors and 1465A have connectors. Other switches are hand-wired. Wires must be cut and replacement switch spliced in. Flap Retract Switch is difficult to access.

⑭ Referenced designators which identify switches and wiring are pull-off tags. These tags are not always replaced on changed switch and wires. Some switches are not labeled permanently because they are used for other functions on this or other aircraft.

⑮ If core or eyebrow doors are not properly adjusted (rigged), or removed/installed, snagging or damage to switch wires is a possibility.

Figure 4. Example of Matrix Used in Technical Data Reduction

As it turned out, there was no way to confine the technicians to the target situation. They talked about things they considered relevant. Thus, their comments often exceeded the planned boundaries. For this reason, the matrix shown in Figure 4 and all other matrices typically contain cell entries and explanations that, strictly speaking, should apply elsewhere. These excursions are tolerable because each was explained by the analyst in terms of its "proper situation."

The matrix thus was used as a data organizer, for analysis to be done later. Aside from that purpose, the principal reason for the matrix approach was to force the analyst to consider every possible interaction when reviewing his work.

Data Analysis

Data analysis proceeded in a manner designed to answer two questions:

- Do DFM features correlate with maintenance performance?
- Is the interview process efficient?

The first question was addressed by restructuring the data stored in the matrices. The second question was addressed by comparing the matrix data to historical records located in the F-14 maintenance data base.

Design Features

To check on the correspondence between DFM features and maintenance performance, four more matrices were created, covering Type I errors, Type II errors, Type d errors, and elapsed maintenance time. Each matrix was constructed as illustrated in Figure 5.

At the left, subsystems were ranked by the quantitative value of the key variable involved. At the upper right, DFM features were always listed in the same order. This list equates to the design features cited earlier in Exhibit E and in the first set of matrices.

Each matrix had cells in which to place significant symbols. A closed circle (●) meant the feature had been mentioned by the technician. An X meant the feature did not apply to the situation under analysis. An open circle (o) meant the feature applied but had not been mentioned by the technician.

When a matrix was complete, the pattern of closed circles provided a visual indication of correspondence between each DFM feature and subsystem maintenance performance.

SUBSYSTEMS RANKED BY TYPE I ERROR RATES			DESIGN FEATURE AFFECTING MAINTENANCE															
WUC	SUBSYSTEM NAME	TYPE 1 ERROR RATES	1. Parts Not Easily Accessible for Checking	2. Checkout Routine Excessively Long	3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests Incomplete	5. Subsystem Not Fully Covered by Malfunction Indicators	6. Malfunction Indicators Fail to Distinguish Between LRUs	7. Some Parts of Circuitry Not Covered by Test Points	8. Circuitry Hard to Trace	9. Test Equipment Inconvenient or Inaccessible	10. Circuitry Subject to Intermittents	11. Parts Not Easily Accessible for Corrective Actions	12. Special Tool Required	13. Awkward Work Position Required	14. Parts Not Well Labeled	15. Delicate Components Given Too Little Protection	16. Fasteners Require Too Much Work
29X	Power Plant Installation Assoc. Eq.	32.5	●	X	○	○	○	●	○	○	○	GENERAL PROBLEM DUE TO MOISTURE INTRUSION	X	X	X	X	X	X
144	Longitudinal Control System	22.6	●	X	●	○	○	●	●	●	●		X	X	X	X	X	X
56X	Flight Reference Assoc. Eq.	22.1	○	X	●	○	○	●	○	○	○		X	X	X	X	X	X
138	Wheel Brake System	17.1	○	X	○	○	○	○	○	○	○		X	X	X	X	X	X
292	Air Inlet Control System	12.8	○	X	○	○	○	●	○	○	●		X	X	X	X	X	X
573	Wing/Flap/Glove Vane Control Set	12.2	○	X	○	○	○	○	○	○	○		X	X	X	X	X	X
29C	Approach Power Control System	10.7	●	X	○	○	○	○	○	○	○		X	X	X	X	X	X
512	Navigation Instruments	6.8	○	X	○	○	○	○	○	○	○		X	X	X	X	X	X
139	Nose Wheel Steering	0.0	○	X	○	○	●	●	○	○	○		X	X	X	X	X	X
142	Lateral Control System	0.0	○	X	○	○	○	○	●	○	○		X	X	X	X	X	X
146	Flap/Slat Control System	0.0	●	X	○	○	○	●	●	○	○		X	X	X	X	X	X
511	Flight Instruments	0.0	●	X	○	○	○	○	○	○	●		X	X	X	X	X	X

Figure 5. Example of Matrix Used in Analysis of Design Features

Interview Efficiency

The interview process is generally considered to be inefficient unless structured in some significant way. In the present case, an opportunity for structure is provided by the F-14 data base. The question is, would such structure produce a gain in the information yielded?

To answer that question, the F-14 data base was queried for components involved in high error rate and EMT situations. The initial matrices were then checked to see whether or not each component had been mentioned by the technician. Wherever a component had not been mentioned, the omission was taken as a sign of weakness in the interview process that could have been prevented by better structuring.

In this analysis, only a small sampling of the F-14 data base was employed. Data sources were as follows:

Type I Errors:	A799 (3M Aviation No Defect Item Analysis Summary M50.4790.A25551-01) July 1977 through January 1978 (all Navy)
Type II/d Errors:	3M Data Records for 6 squadrons, June 1976 through July 1977
Elapsed Maintenance Time:	3M Data Records for 6 squadrons, June 1976 through July 1977

SECTION IV

METHOD TO EVALUATE THE IMPACT OF IMPROVEMENTS IN MAINTENANCE

The purpose of Project Task IV was to evaluate the impact of potential maintenance improvements on operational performance. This was accomplished through the use of a dynamic simulation model called AMES (Aircraft Maintenance Effectiveness Simulation). The AMES model is designed to exploit the idea that maintenance effectiveness, as measured by error rates and work times, has an impact on system-level performance, as measured by such parameters as operational readiness, mean flight hours between failures, etc.

Using 3-M data, an historical baseline was established, reflecting fleet records of maintenance effectiveness and system performance. The model was then run several times to reflect various changes in maintenance effectiveness that could conceivably result from improvements in design for the maintainer. Results were then examined to see to what extent these changes in maintenance effectiveness produced corresponding changes in operational performance.

PRELIMINARY DISCUSSION OF MEASUREMENT PROBLEMS

The data used in this study were factual, i.e., derived from established Navy records. In and of themselves, the data present no drawbacks in either constructing or accomplishing measurements. However, when seeking to draw inferences from them at a higher level, certain problems arise. These problems are characterized by difficulty in showing high-magnitude differences when various conditions of operation are compared.

In this particular case, the difficulty appears to be rooted in three principal causes. One is that existing measures of system performance contain high variability. The second is the conservative error rates derived from existing 3-M data. The third is that the AMES Model, in its present form, is not designed for optimum sensitivity. These causes are further elaborated in the paragraphs that follow.

Variability of System-Level Performance

Many factors contribute to the overall performance of a squadron or fleet of aircraft. Thus, the variance of system-level performance measures is usually very high. Also, no single statistic adequately describes the capability of an aircraft, squadron, or fleet. Unfortunately, this fact is usually ignored in discussions of systems by individuals not familiar with the characteristics of operating weapon systems. Attention is usually focused on operational readiness with little or no attention given to other statistics, including the variance of operational readiness. For example, using a month as a basic unit of time, the average and standard deviation of operational readiness was calculated for six squadrons of F-14A aircraft over a year of operation. The average is 46.62 but the standard deviation is 10.84.

Some of the factors contributing to the operational readiness statistic are:

1. Failure rate or Mean Time Between Failures (MTBF).
2. Spares availability which in turn is affected by:
    a. The inventory of spares and
    b. Turn-around time of spares through intermediate maintenance and/or the depot.
3. Number and quality of maintenance personnel available.
4. Mission schedule. This item is especially important. A very low-demand mission schedule could artificially inflate the operational readiness figure. As mission demands increase, more flights are flown, thereby creating more opportunities for failures. Consequently, a high-demand mission schedule will tend to reduce operational readiness as compared to a low-demand mission schedule.
5. Available facilities and tools.
6. Error rates and Elapsed Maintenance Time (EMT) or the more commonly known Mean Time To Repair (MTTR). This factor is affected by Design-For-the-Maintainer (DFM), as well as training and availability of effective job performance aids.

The factor having the greatest impact on operational readiness is spares. Currently, spares account for approximately half of the F-14A's 42% Not Operationally Ready (NOR) status. About 18% of all corrective maintenance actions entail a delay greater than five days. These delays (greater than five days) average 38 days.

An item often not given proper consideration in studies of spares is the high level of interaction between spares and errors in corrective maintenance. Maintenance errors increase the total number of corrective maintenance actions as well as increase the consumption of spares.

Type I error increases the Corrective Maintenance Actions (CMA) as well as the consumption of spares. In Type I error, a good unit is erroneously removed from the system. This can occur in two ways. In one case, a good unit is removed but the malfunctioning unit is still in the system. In this case the work has to be repeated at some later time, and at least one additional spare has been consumed unnecessarily. In the second case, the malfunctioning unit is removed as well as one or more "good" units. The work does not have to be repeated, but at least one additional spare has been consumed.

Type II error is the failure to detect a malfunction. This increases CMA but does not increase the consumption of spares. Type d error is the cause of damage by a human action. This action obviously increases both CMA and the consumption of spares. Thus, all errors increase CMA, and Types I and d errors increase both CMA and the consumption of spares.

Limitations of 3-M Data

Although measures of time-to-perform and error can and have been derived from 3-M data, the measures thus obtained are often highly conservative. For example, Type I errors (treating a good unit as bad) are identified only by the 3-M 791 report, i.e., "bench check OK." This report covers only Remove and Replace (R/R) actions.

Analysis of maintenance records shows that Repair-in-Place (RIP) actions outnumber R/R by almost 2 to 1. Unfortunately Type I errors during RIP actions cannot be detected with 3-M data.

It is reasonable to assume that Type I errors are made in RIP as well. Even if Type I errors in RIP are assumed to be one-half the Type I errors in R/R, considering such errors would essentially double the total Type I errors.

The identification of Types II and d errors has also been highly conservative. Thus, the actual errors are anticipated to be considerably higher than the approximately 14% error rate noted to date and used in the model runs. Previous studies with more supportive data (for the Air Force) resulted in an error rate of about 35%.

Limitations of the AMES Model

The AMES model used in this study is not a logistics model. Thus, its handling of spares is quite limited. This limitation is not of much concern when the system level performance (e.g., operational readiness) is very high and the spares contribution to downtime is relatively low.

However, the interaction with spares starts to become an item of concern when the contribution of spares to downtime is as high as the current 22%. As a result, any improvement potential determined with the model will tend to be very conservative. That is, the model will underestimate the effect of reducing errors since it will not account "properly" for the benefits accrued from reducing spares consumption.

Another precaution necessary in viewing the results of the model is its "newness." The AMES Model was recently developed for the Navy Training Equipment Center. The original model development plan included a phase to systematically exercise the model and determine its variance and sensitivity. For various reasons, this phase was never conducted.

The high variance of system performance parameters indicates the tremendous complexity of a weapon system, which includes the operational aspects, the maintenance aspects, and the logistics aspects. This complexity is what contributes to the high variance. This complexity is also the reason why a model is needed to adequately study the relationship between subystem variables and system parameters. However, models are also quite complex, albeit not as complex as the system they are representing. Consequently, model development is usually an iterative process wherein each iteration increases the representativeness of the model as well as its credibility. Unfortunately, the AMES model has not had time to go through its second or later iterations. This was the first attempt at using the model.

SUMMARY OF ANALYSIS PROCEDURE

The analysis procedure used consisted of three basic steps. First, an historical baseline was established reflecting actual 3-M records. Second, a sensitivity analysis was conducted by running the model with various adjustments to the input data. Third, the baseline was modified to take into account the factors discussed earlier, i.e., system variability and limitations of the 3-M data and the model.

Historical Baseline

To verify that the model agreed with actual squadron performance, a baseline was established using performance time and error rates derived from existing 3-M data. This baseline reflected an average squadron, based on a sample of six. No adjustments were made to the input data. The model simulated 24 months of squadron operation. The same mission profile was used for this and all subsequent runs.

Sensitivity Analysis

A sensitivity analysis was conducted to determine the effects of adjusting variables that would be impacted by improved DFM. These variables included error rates (of various types) and Elapsed Maintenance Time (EMT). The model was run a total of six times, with various combinations of adjustments to the input variables. Each of the six runs encompassed the entire aircraft, and was not limited to any individual system. In summary, the adjustments made in each of the six runs were as follows:

Run 1: All errors reduced to zero

Run 2: EMT reduced to 95% 2.5 hours, all errors reduced 95%

Run 3: All errors reduced 50%

Run 4: Type I errors reduced 95%

Run 5: Type II/d errors reduced 95%

Run 6: EMT reduced to 95% 2.5 hours

The outputs of each run were then examined to determine the effects of these adjustments on various system-level performance measures such as Operational Readiness (OR), Mean Flight Hours Between Failure (MFHBF), and Maintenance Manhours per Flight Hour (MMH/FH).

Modified Baseline

The error rates derived from the 3-M data are known to be conservative. Therefore, a second baseline was developed to simulate an error rate 75% greater than that of the historical baseline. This modified baseline was then compared to the historical baseline to determine whether the resulting change in system level performance was statistically significant.

SECTION V

RESULTS

Results of this project are presented under three headings:

- Design Features Affecting Maintenance
- Interview Efficiency
- Results of Model Runs

DESIGN FEATURES AFFECTING MAINTENANCE

Design features affecting maintenance are examined in Tables 20, 22, 23, and 25, covering Type I error, Type II error, Type d error, and elapsed maintenance time situations, respectively. Note that, throughout the discussion, design features are expressed negatively. This allows them to be dealt with as problem conditions wherever they appear.

Type I Error Situations

Table 20 identifies nine design features that theoretically should affect Type I errors (symbol ● or o), and seven features that theoretically should not (symbol X). The features that should have an impact are listed below.

1. Parts Not Easily Accessible for Checking
3. Some Modes of Operation Hard to Check on Ground
4. LRU BITE Tests Incomplete
5. Subsystem Not Fully Covered by Malfunction Indicators
6. Malfunction Indicators Fail to Distinguish Between LRUs
7. Some Parts of Circuitry Not Covered by Test Points
8. Circuitry Hard to Trace
9. Test Equipment Inconvenient or Inaccessible
10. Circuitry Subject to Intermittents

Given the potential for effect, two questions arise in each case. First, did the technician report it as a problem in the interview? Second, is the problem reflected in the Type I error rate?

The first question is answered by the presence of the symbol (●). Each filled circle indicates that the technician mentioned that problem in connection with that particular subsystem.

For the subsystem examined in this study, the technician reported only eight design features affecting Type I errors. They were:

1. Parts Not Easily Accessible for Checking
3. Some Modes of Operation Hard to Check on Ground
5. Subsystem Not Fully Covered by Malfunction Indicators
6. Malfunction Indicators Fail to Distinguish Between LRUs
7. Some Parts of Circuitry Not Covered by Test Points
8. Circuitry Hard to Trace
9. Test Equipment Inconvenient or Inaccessible
10. Circuitry Subject to Intermittents

The second question is answered by the location of the symbol (●) relative to Type I error value. Each such symbol aligned with a subsystem having a high error rate indicates that the effect was actually felt by the hardware. A symbol (o) aligned with a subsystem having a low error rate indicates that the effect was not felt.

TABLE 20. MAINTENANCE PERFORMAN FEATURES IN TYPE I ERRO

SUBSYSTEMS RANKED BY TYPE I ERROR RATES					
WUC	SUBSYSTEM NAME	TYPE 1 ERROR RATES	1. Parts Not Easily Accessible for Checking	2. Checkout Routine Excessively Long	3. Some Modes of Operation Hard to Check on Ground
29X	Power Plant Installation Assoc. Eq.	32.5	●	X	○
144	Longitudinal Control System	22.6	●	X	●
56X	Flight Reference Assoc. Eq.	22.1	○	X	●
138	Wheel Brake System	17.1	○	X	○
292	Air Inlet Control System	12.8	○	X	○
573	Wing/Flap/Glove Vane Control Set	12.2	○	X	○
29C	Approach Power Control System	10.7	●	X	○
512	Navigation Instruments	6.8	○	X	○
139	Nose Wheel Steering	0.0	○	X	○
142	Lateral Control System	0.0	○	X	○
146	Flap/Slat Control System	0.0	●	X	○
511	Flight Instruments	0.0	●	X	○

CE PERFORMANCE VERSUS DESIGN
N TYPE I ERROR SITUATIONS

DESIGN FEATURE AFFECTING MAINTENANCE															
Accessible for Checking	2. Checkout Routine Excessively Long	3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests Incomplete	5. Subsystem Not Fully Covered by Malfunction Indicators	6. Malfunction Indicators Fail to Distinguish Between LRUs	7. Some Parts of Circuitry Not Covered by Test Points	8. Circuitry Hard to Trace	9. Test Equipment Inconvenient or Inaccessible	10. Circuitry Subject to Intermittents	11. Parts Not Easily Accessible for Corrective Actions	12. Special Tool Required	13. Awkward Work Position Required	14. Parts Not Well Labeled	15. Delicate Components Given Too Little Protection	16. Fasteners Require Too Much Work
)	X	○	○	○	●	○	○	○	GENERAL PROBLEM DUE TO MOISTURE INTRUSION	X	X	X	X	X	X
)	X	●	○	○	●	●	●	●		X	X	X	X	X	X
)	X	●	○	○	●	○	○	○		X	X	X	X	X	X
)	X	○	○	○	○	○	○	○		X	X	X	X	X	X
)	X	○	○	○	●	○	○	●		X	X	X	X	X	X
)	X	○	○	○	○	○	○	○		X	X	X	X	X	X
)	X	○	○	○	○	○	○	○		X	X	X	X	X	X
)	X	○	○	○	○	○	○	○		X	X	X	X	X	X
)	X	○	○	●	●	○	○	○		X	X	X	X	X	X
)	X	○	○	○	○	●	○	○		X	X	X	X	X	X
)	X	○	○	○	●	●	○	○		X	X	X	X	X	X
)	X	○	○	○	○	○	○	●		X	X	X	X	X	X

The correspondence between design feature and Type I error rate is summarized in the tabulation below.

Design Feature	Subsystem Occurrence Type I Error Rate High	Low	Total
1. Parts Not Easily Accessible for Checking	3	2	5
3. Some Modes of Operation Hard to Check on Ground	2	0	2
5. Subsystem Not Fully covered by Malfunction Indicators	0	1	1
6. Malfunction Indic. Fail to Distinguish Between LRUs	4	2	6
7. Some Parts of Circuitry Not Covered by Test Points	1	2	3
8. Circuitry Hard to Trace	1	0	1
9. Test Equipment Inconvenient or Inaccessible	2	1	3
10. Circuitry Subject to Intermittents	(General problem; no distinction)		0
TOTAL	13	8	21

This summary indicates that two-thirds (13) of the occurrences behaved as expected, while the remaining third (8) pointed in the opposite direction. That is, they aligned themselves with subsystems having low Type I error rates. Five design features fell into this latter category. A brief accounting of the resulting occurrences is given in Table 21.

TABLE 21. NEGATIVELY EXPRESSED DESIGN FEATURES ALIGNED WITH SUBSYSTEMS HAVING LOW TYPE I ERROR RATES

DESIGN FEATURE	SUBSYSTEM	EXPLANATION
1. Part Not Easily Accessible for Checking	146 Flap/Slat Control System	Auxiliary Flat Retract Switch hidden by Cove Door and other components. However, circuit status readily discernable by visual observation of Auxiliary Flap.
	511 Flight Instruments	Pitot Static Probe difficult to access for static line leak check. When leaks occur, all connected components are affected. However, OBC points to Air Inlet Control Programmer rather than Flight Instruments.
5. Subsystem Not Fully Covered by Malfunction Indicators	139 Nose Wheel Steering	Nose Wheel misalignment is not denoted by malfunction indicators. Technicians must reconcile differences with Hydraulic Damper. Troubleshooting method holds down Type I error rate but tends to lengthen EMT.
6. Malfunction Indicators Fail to Distinguish Between LRUs	146 Flap/Slat Control System	OBC identifies problem area only. Technician must isolate faulty LRU. Troubleshooting method appears to be effective.
	139 Nose Wheel Steering	Same as 5 above.

TABLE 21.
(continued)

DESIGN FEATURE	SUBSYSTEM	EXPLANATION
7. Some Parts of Circuitry Not Covered by Test Points	142 Lateral Control System	Technicians cannot check current draw of Trim while under load. Such a check would make troubleshooting easier. They are able to troubleshoot accurately without it but tend to lengthen EMT.
	146 Flap/Slat System	Certain degree switches are installed in such a way as to make testing impossible without cutting the wires. Wire cutting enables high quality troubleshooting but tends to lengthen EMT and increases Type d errors.
9. Test Equipment Inconvenient or Inaccessible	511 Flight Instruments	TTV-205 Tester unpopular among technicians. However, it is not needed for all tests. It is used only when an inflight malfunction cannot be duplicated on the ground. Tests that are necessary are time consuming but not inaccurate.

Type II Error Situations

Table 22 identifies four design features that theoretically should affect Type II errors (symbol ● or o), and 12 features that theoretically should not (symbol X). The features that should have an impact are listed below.

2. Checkout Routine Excessively Long
3. Some Modes of Operation Hard to Check on Ground
9. Test Equipment Inconvenient or Inaccessible
10. Circuitry Subject to Intermittents

For the subsystems examined in this study, the technician reported all four. Furthermore, a high proportion of the problems reported appear to be felt by the hardware. The correspondence between design feature and Type II error rate is summarized in the tabulation below.

Design Feature	Subsystem Occurrence Type II Error Rate High	Low	Total
2. Checkout Routine Excessively Long	1	0	1
3. Some Modes of Operation Hard to Check on Ground	1	0	1
9. Test Equipment Inconvenient or Inaccessible	2	1	3
10. Circuitry Subject to Intermittents	(General problem; no distinction.)		0
Total	4	1	5

This summary indicates that four of the five occurrences behaved as expected, while one pointed in the opposite direction. That is, it aligned itself with a subsystem having a <u>low</u> Type II error rate.

The design feature involved is Item 9, Test Equipment Inconvenient or Inaccessible. The explanation is similar to that already given relative to Type I errors. That is, the TTV-205 Tester is not needed for all tests. It is used only when an in-flight malfunction cannot be duplicated on the ground. Tests that are necessary are time consuming but not inaccurate.

TABLE 22. MAINTENANCE PERFORMANCE VER IN TYPE II ERROR SITUATIONS

SUBSYSTEMS RANKED BY TYPE II ERROR RATES					
WUC	SUBSYSTEM NAME	TYPE II ERROR RATES	1. Parts Not Easily Accessible for Checking	2. Checkout Routine Excessively Long	3. Some Modes of Operation Hard to Check on Ground
146	Flap/Slat Control System	12.2	X	○	○
511	Flight Instruments	9.9	X	○	○
138	Wheel Brake System	9.0	X	○	○
144	Longitudinal Control System	7.4	X	●	●
512	Navigation Instruments	5.9	X	○	○
573	Wing/Flap/Glove Vane Control Set	4.9	X	○	○
29X	Power Plant Installation Assoc. Eq.	4.8	X	○	○
56X	Flight Reference Assoc. Eq.	4.5	X	○	○
139	Nose Wheel Steering	4.2	X	○	○
29C	Approach Power Control System	4.0	X	○	○
142	Lateral Control System	3.6	X	○	○
292	Air Inlet Control System	3.5	X	○	○

CE VERSUS DESIGN FEATURES
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DESIGN FEATURE AFFECTING MAINTENANCE													
3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests Incomplete	5. Subsystem Not Fully Covered by Malfunction Indicators	6. Malfunction Indicators Fail to Distinguish Between LRUs	7. Some Parts of Circuitry Not Covered by Test Points	8. Circuitry Hard to Trace	9. Test Equipment Inconvenient or Inaccessible	10. Circuitry Subject to Intermittents	11. Parts Not Easily Accessible for Corrective Actions	12. Special Tool Required	13. Awkward Work Position Required	14. Parts Not Well Labeled	15. Delicate Components Given Too Little Protection	16. Fasteners Require Too Much Work
○	X	X	X	X	X	○	GENERAL PROBLEM DUE TO MOISTURE INTRUSION	X	X	X	X	X	X
○	X	X	X	X	X	●		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
●	X	X	X	X	X	●		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	○		X	X	X	X	X	X
○	X	X	X	X	X	●		X	X	X	X	X	X

Type d Error Situations

Table 23 identifies two design features that theoretically should affect Type d errors (symbol ● or o), and 14 features that theoretically should not (symbol X). The features that should have an impact are listed below.

11. Parts Not Easily Accessible for Corrective Actions
15. Delicate Components Given Too Little Protection

For the subsystem examined in this study, the technician reported both features. Only a modest proportion of the problems reported appear to be felt by the hardware. The correspondence between design feature and the Type d error rate is summarized in the tabulation below.

Design Feature	Subsystem Occurrence Type d Error Rate High	Low	Total
11. Parts Not Easily Accessable for Corrective Actions	2	2	4
15. Delicate Components Given too Little Protection	2	2	4
Total	4	4	8

This summary indicates that only half (4) the occurrences behaved as expected, while the other half (4) pointed in the opposite direction. That is, they aligned themselves with subsystems having low Type d error rates. Two design features fell into this latter category. A brief accounting of the resulting occurrences is given in Table 24.

EMT Situations

Table 25 indicates that all 16 design features listed theoretically could affect elapsed maintenance time. The technicians reported all except two:

4. LRU BITE Tests Incomplete
13. Awkward Work Position Required

Three other features represent general problems, with no distinction in effect from system to system. These features are:

10. Circuitry Subject to Intermittents
14. Parts Not Well Labeled
16. Fasteners Require Too Much Work

That leaves 11 features with differential impact on EMT. These features and their correspondence with EMT values are summarized in the tabulation below.

Design Feature	Subsystem Occurence % High EMT High	Low	Total
1. Parts Not Easily Accessable for Checking	4	2	6
2. Checkout Routine Excessively Long	1	0	1
3. Some Modes of Operation Hard to Check on Ground	1	0	1
5. Subsystem Not Fully Covered by Malfunction Indicators	4	0	4
6. Malfunction Indic. Fail to Distinguish Between LRUs	2	1	3
7. Some Parts of Circuitry Not Covered by Test Points	2	0	2
8. Circuitry Hard to Trace	1	0	1
9. Test Equipment Inconvenient or Inaccessible	2	1	3
11. Parts Not Easily Accessible for Corrective Actions	2	0	2
12. Special Tool Required	1	0	1
15. Delicate Components Given too Little Protection	2	2	4
	22	7	29

This summary indicates that three-fourths (22) of the occurrences behaved as expected, while one-fourth (7) pointed in the opposite direction. That is, they aligned themselves with subsystems having a low EMT. Five design features fell into this latter category. A brief accounting of the resulting occurrences is given in Table 26.

TABLE 23. MAINTENANCE PERFORMANCE VERS IN TYPE d ERROR SITUATIONS

SUBSYSTEMS RANKED BY TYPE d ERROR RATES						
WUC	SUBSYSTEM NAME	TYPE d ERROR RATES	1. Parts Not Easily Accessible for Checking	2. Checkout Routine Excessively Long	3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests
146	Flap/Slat Control System	12.2	X	X	X	X
511	Flight Instruments	9.9	X	X	X	X
138	Wheel Brake System	9.0	X	X	X	X
144	Longitudinal Control System	7.4	X	X	X	X
512	Navigation Instruments	5.9	X	X	X	X
573	Wing/Flap/Glove Vane Control Set	4.9	X	X	X	X
29X	Power Plant Installation Assoc. Eq.	4.8	X	X	X	X
56X	Flight Reference Assoc. Eq.	4.5	X	X	X	X
139	Nose Wheel Steering	4.2	X	X	X	X
29C	Approach Power Control System	4.0	X	X	X	X
142	Lateral Control System	3.6	X	X	X	X
292	Air Inlet Control System	3.5	X	X	X	X

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DESIGN FEATURE AFFECTING MAINTENANCE													
3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests Incomplete	5. Subsystem Not Fully Covered by Malfunction Indicators	6. Malfunction Indicators Fail to Distinguish Between LRUs	7. Some Parts of Circuitry Not Covered by Test Points	8. Circuitry Hard to Trace	9. Test Equipment Inconvenient or Inaccessible	10. Circuitry Subject to Intermittents	11. Parts Not Easily Accessible for Corrective Actions	12. Special Tool Required	13. Awkward Work Position Required	14. Parts Not Well Labeled	15. Delicate Components Given Too Little Protection	16. Fasteners Require Too Much Work
X	X	X	X	X	X	X	X	●	X	X	X	●	
X	X	X	X	X	X	X	X	●	X	X	X	●	GENERAL PROBLEM ON ALL ACCESS COVERS
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	●	X	X	X	○	
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	○	X	X	X	●	
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	○	X	X	X	○	
X	X	X	X	X	X	X	X	●	X	X	X	●	

TABLE 24. NEGATIVELY EXPRESSED DESIGN FEATURES ALIGNED WITH SUBSYSTEMS HAVING LOW TYPE d ERROR RATES

DESIGN FEATURE	SUBSYSTEM	EXPLANATION
11. Parts Not Easily Accessible for Corrective Actions	292 Air Inlet Control System	Delta Pressure Sensor on starboard side is difficult to replace. However, because this component rarely fails, it exerts little influence on the Type d error rate.
	573 Wing/Flap/ Glove Vane Control Set	Mounting screws on Wing/Flap/Glove Vane Control hard to reach with screwdriver. However, this problem normally results in lengthened EMT rather than Type d error.
15. Delicate Components Given Too Little Protection	292 Air Inlet Control System	Nylon static line fittings easily damaged by overtorqueing. When detected immediately, problem may result in static line leak, which can be mistaken for a malfunction elsewhere in system. Example: Type I error in Air Inlet Control Programmer.
	56x Flight Reference Associated Equipment	Same as above.

TABLE 25. MAINTENANCE PERFORMANCE VERS
IN ELAPSED MAINTENANCE TIME SI

SUBSYSTEMS RANKED BY PERCENT ELAPSED MAINTENANCE TIMES						
WUC	SUBSYSTEM NAME	% ACTIONS >3.5 HRS.	1. Parts Not Easily Accessible for Checking	2. Checkout Routine Excessively Long	3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests
142	Lateral Control System	45	●	○	○	○
146	Flap/Slat Control System	42	●	○	○	○
292	Air Inlet Control System	32	○	○	○	○
139	Nose Wheel Steering	32	○	○	○	○
573	Wing/Flap/Glove Vane Control Set	18	○	○	○	○
144	Longitudinal Control System	16	●	●	●	○
29C	Approach Power Control System	14	●	○	○	○
29X	Power Plant Installation Assoc. Eq.	8	●	○	○	○
511	Flight Instruments	8	●	○	○	○
56X	Flight Reference Assoc. Eq.	8	○	○	○	○
512	Navigation Instruments	6	○	○	○	○
138	Wheel Brake System	5	○	○	○	○

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DESIGN FEATURE AFFECTING MAINTENANCE													
3. Some Modes of Operation Hard to Check on Ground	4. LRU BITE Tests Incomplete	5. Subsystem Not Fully Covered by Malfunction Indicators	6. Malfunction Indicators Fail to Distinguish Between LRUs	7. Some Parts of Circuitry Not Covered by Test Points	8. Circuitry Hard to Trace	9. Test Equipment Inconvenient or Inaccessible	10. Circuitry Subject to Intermittents	11. Parts Not Easily Accessible for Corrective Actions	12. Special Tool Required	13. Awkward Work Position Required	14. Parts Not Well Labeled	15. Delicate Components Given Too Little Protection	16. Fasteners Require Too Much Work
○	○	○	○	●	○	○		○	○	○	GENERAL PROBLEM ON SWITCHES/WIRING PULL-OFF TAGS	○	
○	○	○	○	○	○	○	GENERAL PROBLEM DUE TO MOISTURE INTRUSION	●	○	○		●	GENERAL PROBLEM ON ALL ACCESS COVERS
○	○	●	○	○	○	●		○	○	○		●	
○	○	●	○	○	○	○		○	○	○		○	
○	○	○	●	○	●	○		●	●	○		○	
●	○	●	●	●	○	●		○	○	○		○	
○	○	●	○	○	○	○		○	○	○		○	
○	○	○	●	○	○	○		○	○	○		●	
○	○	○	○	○	○	●		●	○	○		●	
○	○	○	○	○	○	○		○	○	○		○	
○	○	○	○	○	○	○		○	○	○		○	
○	○	○	○	○	○	○		○	○	○		○	

TABLE 26. NEGATIVELY EXPRESSED DESIGN FEATURES ALIGNED WITH SUBSYSTEMS HAVING LOW EMT

DESIGN FEATURE	SUBSYSTEM	EXPLANATION
1. Parts Not Easily Accessible for Checking	29x Power Plant Installation	Certain connectors on engine firewall are out of reach due to absence of an access hole. Use of substitute test points produces an increase in troubleshooting time. However, the increase is not great enough to impact overall EMT.
	511 Flight Instruments	Pitot Static Tube difficult to access for static line leak check. This produces an increase in troubleshooting time. However, increase not great enough to impact overall EMT.
6. Malfunction Indicators Fail to Distinguish between LRUs	29x Power Plant Installation	OBC identifies problem area only. Technicians must isolate faculty LRU. Troubleshooting consumes EMT but easy replacement of components makes up for loss.
9. Test Equipment Inconvenient or Inaccessible	511 Flight Instruments	TTU-205 Tester needed for some tests but not all. Impact therefore felt infrequently.
11. Parts Not Easily Accessible for Corrective Actions	511 Flight Instruments	Pitot Static Probe difficult to replace. However, because this component rarely fails, it exerts little influence in overall EMT.
15. Delicate Components Given Too Little Protection	56x Flight Reference Associated Equipment	Nylon static line fittings easily damaged by overtorqueing. However, since they are easily replaced, they exert little influence on overall EMT.

INTERVIEW EFFICIENCY

Measurements of interview efficiency are shown in Tables 27, 28, and 29, covering Type I error, Type II/d error, and elapsed maintenance time situations, respectively.

Type I Error Situations

Table 27 identifies three subsystems discussed in the interview as having high Type I error rates. Historical records disclosed that, for each subsystem, one particular component was heavily involved in the "No Defect" reports.

For example, the Throttle Control Computer had been replaced 190 times and had been found not defective 30 of those times. The Pitch and Mach Trim Actuator had been found nondefective in 7 out of 26 replacements. The Air Inlet Control Programmer reflected a similar condition 115 out of 354 times it was replaced.

All three components denote serious maintenance problems. Yet, only two of them had been mentioned by the technician during the interview. This suggests that the interviewer did not focus the technician well enough with respect to the analysis of design features affecting troubleshooting.

Type II/d Error Situations

Table 28 identifies three subsystems discussed in the interview as having high Type II and/or Type d error rates. Historical records disclosed that for each subsystem, one particular component, or group of components, was prominently involved in the "Improper Action" reports.

For example, the Flap/Slat Control Electrical Components had been cited 11 times, the Clock three times, and various Flight Instrument components, from one to three times.

Of the seven items named in the historical records, only four had been mentioned by the technician during the interview. This suggests that the interviewer did not focus the technician well enough with respect to the analysis of design features affecting checkout and other maintenance actions.

EMT Situations

Table 29 identifies four subsystems discussed in the interview as requiring excessive maintenance time. Historical records disclosed that for each subsystem, certain components required disproportionate amounts of time to maintain.

TABLE 27. INTERVIEW EFFICIENCY RELATIVE TO TYPE I ERROR SITUATIONS

WUC	NAME	DOCUMENTED NO DEFECTS	MENTIONED IN INTERVIEW
29C	APPROACH POWER CONTROL SYSTEM	—	--
29C31	Throttle Control Computer	30 out of 190	NO
144	LONGITUDINAL CONTROL SYSTEM	—	--
14441	Pitch and Mach Trim Actuator	7 out of 26	YES
29X	POWER PLANT INST. ASSOC. EQ.	—	--
29X11	Air Inlet Control Programmer	115 out of 354	YES

TABLE 28. INTERVIEW EFFICIENCY RELATIVE TO TYPE II/d ERROR SITUATIONS

WUC	NAME	DOCUMENTED IMPROPER ACTIONS	MENTIONED IN INTERVIEW
146	FLAP/SLAT CONTROL	—	--
14765	Flap/Slat Control Elec. Comp.	11	YES
512	NAVIGATION INSTRUMENTS	—	--
51211	Clock	3	NO
511	FLIGHT INSTRUMENTS	—	--
51111	Counter Drum Altimeter	3	YES
51112	Altimeter	2	NO
51122	Counting Accelerometer	1	YES
51132	Mach Speed Indicator	2	NO
51141	Pitot Static Probes	2	YES

TABLE 29. INTERVIEW EFFICIENCY RELATIVE TO EMT SITUATIONS

WUC	NAME	AVERAGE EMT (HRS/MANHRS)	MENTIONED IN INTERVIEW
573E	WING/FLAP/GLOVE VANE CONTROL SET	—	--
573E1	Wing/Flap/Glove Vane Control	5.8/10.3	YES
573E2	Electromechanical Rotary Actuator	3.3/13.0	NO
573E3	ELectromechanical Rotary Actuator	5.5/12.0	NO
139	NOSE WHEEL STEERING	—	--
13921	Damper (Hydraulics)	7.5/21.5	YES
142	LATERAL CONTROL SYSTEM	—	--
1424	Lateral Control Electrical Components	4.3/12.0	NO
14241	Lateral Transducer	7.0/21.0	NO
14242	Trim Actuator	6.0/12.0	YES
29C	APPROACH POWER CONTROL	—	--
29C33	Linear Elec. Accelerometer	12.0/36	NO

As against an average EMT of 2.5 hours, the EMTs shown for the components in this sample ranged between 3.3 and 12 hours. Since each job is handled by more than one technician, the loading in manhours is even higher. That value ranges from 10.3 to 36.

Of the eight items extracted from the historical records, only three had been mentioned by the technician during the interview. This suggests that the interviewer did not focus the technician well enough with respect to the analysis of design features affecting elapsed maintenance time.

RESULTS OF MODEL RUNS

One hypothesis of this study was that adjusting EMT and error rate would result in corresponding changes in system-level performance measures. Each of the model runs described in Section IV was therefore examined for a change in the following parameters:

- Operational Readiness
- Flight Hours per Squadron
- Mean Flight Hours Between Failures
- Maintenance Manhours per Flight Hour

The changes in each of these parameters are discussed in the paragraphs that follow.

Changes in Operational Readiness

The results of the model runs with regard to operational readiness are summarized in Table 30. No statistically significant difference was noted when Elapsed Maintenance Time (EMT) was reduced to about 2.5 hours or less, and errors were eliminated. This lack of statistical significance is attributed to the lack of adequate sensitivity of the model rather than to any lack of relationship between technician performance and operational readiness.

Part of the problem is due to the overly conservative measures of error rate. As discussed earlier, the estimated error rates do not account for Type I error committed during almost two-thirds of all maintenance actions. Thus, a second baseline run was made with the error rate increased from the 14% in Baseline 1 to about 25%. This run is designated as Baseline 2.

The t-statistic for Baseline 2 is for the comparison between the two baseline runs. The significance indicates that a more realistic measurement of error rate is needed. Given a

TABLE 30. CHANGES IN OPERATIONAL READINESS

	BASELINE (1)	RUN-1	RUN-2	RUN-3	RUN-4	RUN-5	RUN-6	BASELINE (2)
MEAN	53.87	54.02	55.18	53.03	52.06	53.06	55.40	50.71
S.D.	3.59	3.94	3.57	4.10	2.58	4.11	3.68	3.36
Mean Difference Between Paired Values		0.15	1.30	-0.84	-1.81	-0.81	1.53	-3.55
Standard Deviation of the Differences Between the Paired Values		5.93	4.60	6.23	4.43	5.73	6.03	5.34
Obtained t-statistic		0.12	1.39	-0.66	-1.99	-0.69	1.24	-2.97
One-Tailed Significance test .05 level		not signif.	not signif.	not signif.	not signif.	not signif.	not signif.	signif.
Type I, II/d errors Approximately 14%		Type I,II/d Errors Reduced to 0	Adjusted EMT to 95% ≤ 2.5 hrs. Errors reduced 95%	Type I,II/d Errors Reduced 50%	Type I Errors Reduced 95%	Type II/d Errors Reduced 95%	Adjusted EMT to 95% ≤ 2.5 hrs	Type I, II/d Error Rates Increased 75% (to 25%) SIM. Time=20 months

more realistic error rate in the baseline, reduction of errors would probably show a statistically significant improvement in operational readiness, despite the problem in model sensitivity.

In order to improve the sensitivity of the model, the same mission demand profile was used for each week simulated. This approach helped to reduce the standard deviation from about 10.84 in the actual fleet to 3.59 in the baseline run -- a reduction of about 67%.

The reduction in standard deviation demonstrates one of the advantages of the model. That is, the model can be used to study the isolated effects of specific variables. Such an approach is generally not possible with an actual system.

Despite the reduced variance, the results in Table 30 show that the model has not been sufficiently fine-tuned to measure relatively small changes in operational readiness.

The model <u>can</u> detect larger changes in operational readiness. A set of runs was made to eliminate any delays due to spare parts or facilities. As expected, the operational readiness increased considerably. The increase was from an average operational readiness of 53.7% to an average of 81.1%. This is an increase of 51%.

As mentioned before, maintenance errors <u>increase</u> the number of Corrective Maintenance Actions (CMAs). This is equivalent to decreasing reliability or Mean Time Between Failures (MTBF). It appears reasonable to assume that <u>improving</u> reliability or reducing CMAs should improve operational readiness. Thus, we concluded that the lack of significance is due to inadequate sensitivity of the model to small changes in operational readiness. Significant changes in other system performance statistics are discussed later.

An alternative method was used to estimate the relationship between technician performance and operational readiness. The method selected was to first determine the effect of errors on CMAs, and then determine the relationship between CMAs and operational readiness.

The curve* in Figure 6 was used to estimate the extent to which operational readiness could be improved by improving <u>system</u> reliability. It is important to note that the curve does not account for any variance in either Mean Flight Hours Between Failures (MFHBF) or operational readiness.

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*R.L. McGee Reliability and maintainability contribution to Hornet mission success. In Proceedings 1979 Annual Reliability and Maintainability Symposium.

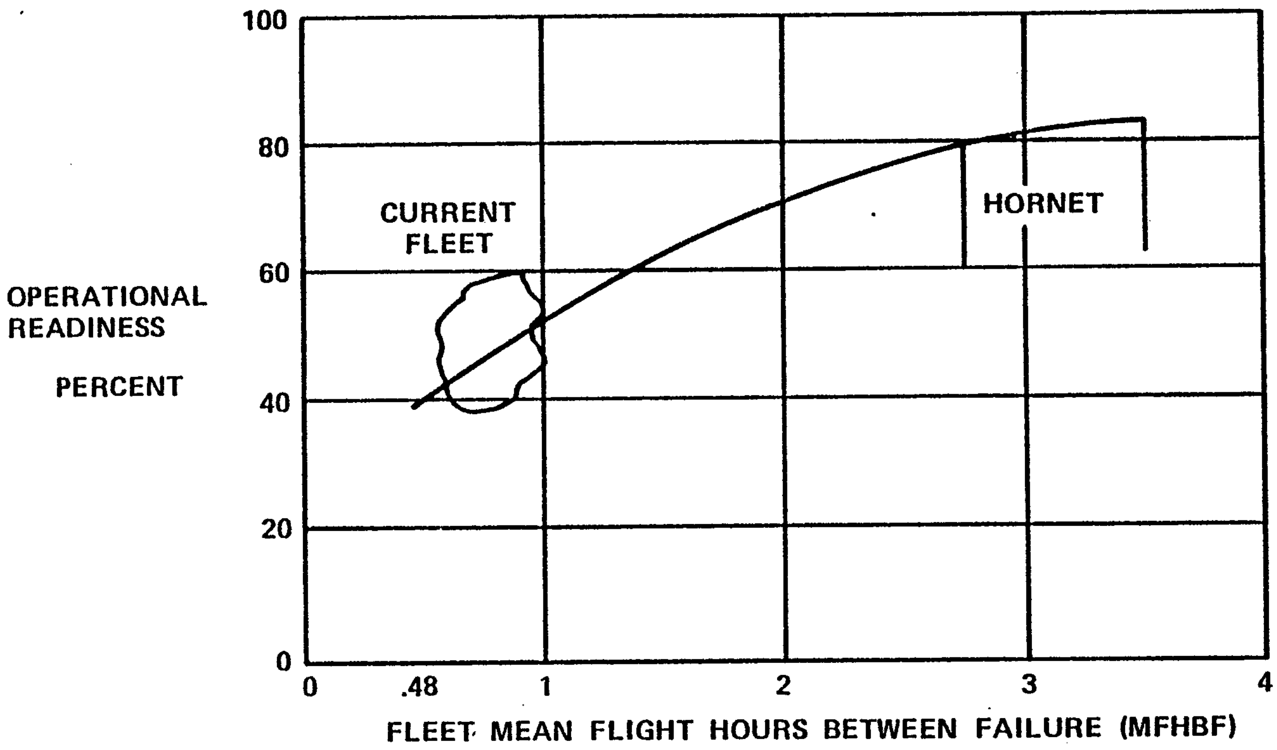

Figure 6. Relationship Between Reliability And Operational Readiness

Also, the curve is based on numerous unstated assumptions such as levels of spares support, mission demands, mean time to repair, turn-around time, personnel availability, etc. As these factors vary, the relationship between fleet MFHBF and operational readiness will also vary. However, the curve can be used to establish that relationship, under the assumption that other relationships will remain relatively the same when maintenance errors are reduced.

The key to utilizing the curve is to translate both the curve and performance improvements into numbers of corrective maintenance actions (CMAs). Table 31 presents a translation of the curve into CMAs and MFHBF.

The first two columns are based on the following:

Mean Flight Hours Between Failures (MFHBF) equals flight hours divided by failures. Failures (as measured with field data) equals total CMAs minus cannibalization CMAs. Also, failures consist of CMAs due to actual malfunctions and CMAs due to errors. The first column has the percent of total CMAs due to errors. The second column shows what the MFHBF would be if the respective CMAs due to errors were reduced to 0.

The .48 is the actual MFHBF measured with 3-M data. The .48 includes CMAs due to errors. The reason for considering different CMAs is the previously discussed conservative manner used in identifying maintenance errors. In order to be consistent with our conservative approach to date, the first column was extended only to include a possible error rate of 25%.

The third column shows the increase in MFHBF if the corresponding possible error rate in Column 1 were eliminated. The final column shows the difference of operational readiness percent from the start point. This calculation is based on an interpretation of the curve. According to the curve, each hour of MFHBF (on the lower end of the scale) represents about 27% of operational readiness. Thus, the increase in operational readiness is determined by multiplying 27 by the delta MFHBF, e.g., 27 times .05 equals 1.4%.

Obviously the model is not sensitive enough to detect a change of operational readiness of 2.2% to 4.0%. It is important to note that the actual system has an even larger variance, and therefore will require an even larger change to achieve statistical significance.

TABLE 31. RELATIONSHIP BETWEEN CMAs DUE TO ERRORS AND OPERATIONAL READINESS

	CMAS DUE TO ERRORS	MFHBF IF CMAS DUE TO ERROR WERE ELIMINATED	IMPROVEMENT (FROM BASELINE)	
			MFHBF	OR
Baseline:	0%	.48	--	--
	10%	.53	.05	1.4%
	15%	.56	.08	2.2%
	20%	.59	.11	3.0%
	25%	.63	.15	4.0%

It is also important to note that a small change of a weapon system performance parameter represents a large amount in cost. For example, consider how much it would cost to increase equipment reliability by 15% to 25%. It appears logical to assume that the efforts to reduce human error by 90% to 95% would cost significantly less.

Changes in Flight Hours per Squadron

Table 32 shows the results of each of the model runs in terms of flight hours per squadron. As before, two baseline runs are provided. Baseline 1 is with the measured error rates. Due to the highly conservative nature of the error measurements, a second run was made with an error rate of approximately 25%.

Run 1 shows the results when errors are eliminated. The improvement from Baseline 1 is 13.7%. Run 3 shows the results from reducing the errors by approximately one-half. The improvement from Baseline 1 is 7.5%. Using Baseline 2 as the reference, the improvements for 90% and 50% would be 28% and 21%, respectively.

Given a fleet of 180 aircraft, a 13.7% increase in flight hours of existing aircraft is equivalent to adding 24.66 aircraft (180 x .137) to the fleet. At a cost of approximately $20 million per aircraft, the additional aircraft represent $493.2 million or nearly half a billion dollars. With Baseline 2 as the reference, the figures increase to 50.4 aircraft and $1.008 billion.

If the improvements include error reduction as well as limiting elapsed maintenance time to no more than 2.5 hours as simulated by Run 2, the improvement in flight hours increases by 16%. This is still equivalent to adding 28.8 aircraft to the fleet at a cost of approximately $576 million or half a billion dollars. With Baseline 2 as the reference, reducing errors only (Run 3) increases the flight hours by 27.8%, which is equivalent to 50 aircraft or $1 billion.

Note that the improvement levels for all runs but Run 4 are statistically significant. The reason for Run 4 being the exception is the aforementioned treatment of Type I errors. Type I errors are attributed only to R/R, which account for only one-third of the CMAs. Thus, reducing the Type I errors to near zero only effects one-third of the CMAs. In reality, Type I errors probably occur for all types of CMA resulting from some diagnostic action.

TABLE 32. CHANGES IN FLIGHT HOURS/SQUADRON

	BASELINE (1)	RUN-1	RUN-2	RUN-3	RUN-4	RUN-5	RUN-6	BASELINE (2)
MEAN	249.70	284.00	290.10	268.50	253.50	270.80	262.50	222.20
S.D.	22.22	15.06	20.01	19.92	21.06	20.41	23.53	17.29
Mean Difference Between Paired Values		34.33	40.42	18.83	3.83	21.17	12.83	-25.60
Standard Deviation of the Differences Between the Paired Values		23.88	33.22	29.66	35.84	37.40	35.27	27.66
Obtained t-statistic		7.04	5.96	3.11	0.52	2.77	1.78	-4.14
One-Tailed Significance Test .05 level		signif.	signif.	signif.	not signif.	signif.	signif.	signif.
Type I, II/d errors Approximately 14%		Type I,II/d Errors Reduced to 0	Adjusted EMT to 95% ≦ 2.5 hrs. Errors Reduced 95%	Type I,II/d Errors Reduced 50%	Type I Errors Reduced 95%	Type II/d Errors Reduced 95%	Adjusted EMT to 95% ≦ 2.5 hrs	Type I, II/d Error Rates Increased 75% (to 25%) SIM. Time=20 months

Changes in Mean Flight Hours Between Failure

Table 33 shows the improvement in Mean Flight Hours Between Failure (MFHBF) resulting from reducing error rates. Reducing error rates decreases CMAs which is equivalent to increasing system reliability or MFHBF. Using Baseline 1 as the reference, eliminating errors is equivalent to increasing reliability by 18.2%. If Baseline 2 is used as the reference, the improvement increases to 37%.

Changes in Maintenance Manhours per Flight Hour

Table 34 shows the reduction in Maintenance Manhours per Flight Hour (MMH/FH). In view of the current shortage of maintenance technicians, this statistic is quite important. By eliminating errors only, the MMH/FH can be improved by 13%. By reducing both errors and EMT (Run 2), the MMH/FH improves by 25.4%, or almost double the improvement possible by eliminating errors alone. This is about the same amount of reduction from Baseline 2 to Run 1.

TABLE 33. CHANGE IN MFHBF

SIMULATION	FH/MONTH	AVG CMAs/MONTH	MFHBF (FH/CMA)
Baseline 1	249.7	465	0.537
Run 1	284.0	447	0.635
Run 2	290.1	456	0.636
Run 3	268.5	457	0.588
Run 4	253.5	454	0.558
Run 5	270.8	455	0.595
Run 6	262.5	487	0.539
Baseline 2	222.5	480	0.463

TABLE 34. CHANGES IN TOTAL MMH/FLIGHT HOUR

	BASELINE (1)	RUN-1	RUN-2	RUN-3	RUN-4	RUN-5	RUN-6	BASELINE (2)
MEAN	28.03	24.29	20.92	25.91	27.69	24.6	23.72	31.79
S.D.	2.14	1.15	0.97	1.60	1.70	1.33	1.57	2.10
Mean Difference Between Paired Values		-3.73	-6.00	-2.11	-0.34	-3.41	-4.30	3.98
Standard Deviation of the Differences Between the Paired Values		1.78	5.19	1.89	1.66	1.49	2.02	1.78
Obtained t-statistic		-10.26	-5.74	-5.47	-1.00	-11.20	-10.45	10.01
One-Tailed Significance Test .05 level		signif.	signif.	signif.	not signif.	signif.	signif.	signif.
Type I, II/d errors Approximately 14%		Type I,II/d Errors Reduced to 0	Adjusted EMT to 95% ≤ 2.5 hrs. Errors Reduced 95%	Type I,II/d Errors Reduced 50%	Type I Errors Reduced 95%	Type II/d Errors Reduced 95%	Adjusted EMT to 95% ≤ 2.5 hrs	Type I, II/d Error Rates Increased 75% (to 25%) SIM. Time=20 months

SECTION VI

CONCLUSIONS, IMPLICATIONS, AND RECOMMENDATIONS

The information presented in this report leads to the following conclusions, implications, and recommendations.

CONCLUSIONS

1. There is a definite correspondence between maintenance performance and DFM problems as rationally conceived. That is, negatively expressed DFM features align themselves with subsystems having high error rates and high EMT far more often than with subsystems having low error rates and low EMT.

2. DFM problems apply differentially to the various error rate situations. That is, some DFM features are aligned with Type I errors, while others are aligned with Type II or Type d errors.

3. All DFM problems apply to EMT situations. These features can increase EMT even when the error rates themselves are not changed.

4. A DFM feature may apply in a given situation and have no significant effect on error rate or EMT. The reason is that other factors can overcome such effects.

5. The interview process, where properly structured, shows a great deal of promise as a way of gaining insight into DFM problems. The principal means of structure is prior knowledge of maintenance history and system operation, by the interviewers.

6. The interview process could also be improved by focusing on engineering personnel as well as maintenance technicians. Maintenance technicians perform effectively as problem sensors but not as subject matter experts.

7. The methods described here would enable analysts to identify and describe significant DFM problems to the advantage of system/equipment designers.

IMPLICATIONS

The results discussed above have some important implications for the DFM program:

1. The total population of improvement potentials is huge, i.e., equivalent to increasing the fleet by 7% to 12%, or higher, as well as reducing manpower demands by nearly 25%. Thus, a smaller number of technicians can achieve a higher level of performance. However, this potential for improving the maintenance technician's performance is not due to DFM alone.

   The equipment design features (from DFM), training, and job performance aids are the three main contributors to improving technician performance. At the system level of performance, it is doubtful that the relative contribution of each can be isolated.

   Related studies indicate that it is possible to reduce errors to near zero. Under study conditions covering only one or two of the three items, errors have been reduced by as much as 50% to 97%.

   In order to reduce the error rate to near zero in an operational setting, we anticipate that all three items will have to be given proper attention. No one item can be expected to be so all-encompassing in its effect that it can virtually eliminate errors.

2. Despite the huge potentials, the actual change of system statistics is relatively small. A small change in system parameters represents a huge amount in dollars because of the tremendous cost of modern weapon systems. Since the change in system statistics is relatively small and system variance is usually large, field data will not necessarily reflect an actual improvement at the system level of measurement. Eventually, a true improvement will be reflected in the statistics, but the long time required for measurement may not be practical.

   For example, improving only Work Center 210 (Electronics), one of the more active work centers, will reduce the number of improvements to about 25% of those noted earlier. This reduces the flight hour improvements to a range of 2% (for a 50% reduction of errors) to about 3% (using Baseline 1). Although this still translates into large dollars, field data probably will not reflect the improvements for a long time.

3. Relatively small changes in performance time or errors will have no appreciable effect on system level performance parameters. Thus, attention should be focused on systems/areas exhibiting high error rates which can be attributed to related causes, e.g., inadequate diagnostics information. Solving the DFM problem should be reflected in the maintenance of all weapon systems sharing the same problem and sharing the solution.

   The latter point is important. When the topics are properly selected, DFM has the potential of affecting many different weapon systems. This increases the improvement potential to all the weapon systems amenable to the solution. Thus, the potential may be savings equivalent to $250 million to $1,008 million for each of many different weapon systems.

4. As expected, establishing an accurate and reliable measure of the current level of performance is important. Relying on 3-M data alone provides an overly conservative measure of error rate. Corollary data should be used to supplement the 3-M data. It is anticipated that an accurate measure will show the error rate to be closer to 30% to 35%. If so, DFM improvements will be more readily seen in system performance measures -- especially with the model.

5. The AMES model is an important tool in helping to relate technician performance to system performance. However, the results should be viewed as preliminary since too little is currently known about the inherent characteristics of the model. The model needs to be exercised more to determine its variance and sensitivity. Also, the model should be compared to other existing models to determine which should be utilized in future efforts.

6. There is a distinct possibility that the AMES or an equivalent model can be used to help develop a mathematical expression of the relationship between technician and system performances. This should greatly facilitate trade-off studies in the future. More important, it should help put human factors considerations on a relatively equal footing with equipment considerations.

RECOMMENDATIONS

This project resulted in the development of a feasible method of identifying and evaluating improvements in design-for-the-maintainer. The applicability of this method needs to be studied further. It is recommended that such a study be authorized to refine the investigative method along the following lines:

1. Extend Level of Detail of Investigation. The project examined sources of maintenance error rates and EMT at the subsystem level. The 3-M data should be prepared and probed at a more specific level of detail, i.e., down to the individual component level. The data are capable of providing this level of detail. The generation of information on design factors affecting maintenance performance at such a level would clearly offer systems engineers more precise pointers about possible design improvements than would information at a higher level of generality. The preparation of error rate data at this level of detail would also improve the precision with which questions could subsequently be asked -- and answered -- during the interview stage.

2. Modify Preparation of Interviewers. In the course of this project, it was found that the Xyzyx staff who interviewed Navy personnel would have been able to conduct this task more effectively if they had been more familiar with systems they were investigating.

   One of the major problems with eliciting information in a relatively unstructured interview format is ensuring the relevance of the information generated; the interviewer is better able to do this if he can ask probing questions, and sift the answers he is given, on the basis of some degree of informed system knowledge.

   It is suggested, therefore, that future investigative teams undertake a short informal study course in the operations of the F-14 and/or SH-2F aircraft systems to be studied. This course of study should include reading the manual, meeting with engineers, and attending (if possible) Navy training sessions.

3. Revise Investigative Procedures and Techniques. This project indicated that a number of improvements could be made in the way the investigative interviews were handled. Examples of the kind of procedural items needing improvement include:

   - scheduling of interviews
   - use of more than one interviewer in each interview
   - use of tape recorders to assist interviewers' recollection of points made

   Interviews need to be scheduled well in advance, and after careful discussion with Navy personnel regarding potential interviewees who would be able to provide the most useful information about the relationship between maintenance problems and system design features. In the detailed scheduling, it is important to ensure that interviews are scheduled for times when these individuals can be guaranteed (to the extent possible) to be available.

   The use of two interviewers is greatly preferable to using a single interviewer. It is often difficult for one person both to pursue an unstructured interview dialogue and to record all pertinent data provided by the respondent.

   Tape recorders can offer both benefits and penalties in an interview situation. They enable a complete record of the interview to be available for repeated analysis, but they can also inhibit the spontaneity of responses.